FLORIDA A&M UNIVERSITY-
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# Development of the Optimization Model for Improving Safety at Rail Crossings in Florida

Project Number: BDV30-977-26

A Technical Report Submitted to the Florida Department of Transportation, Freight & Multimodal Operations Office

## FINAL REPORT

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## METRIC CONVERSION CHART

| **When You Know** | **Multiply by** | **To Find** |
|---|---|---|
| | | |
| **Length** | | |
| inches (in) | 25.4 | millimeters (mm) |
| feet (ft) | 0.305 | meters (m) |
| yards (yd) | 0.914 | meters (m) |
| miles (mi) | 1.61 | kilometers (km) |
| | | |
| **Volume** | | |
| fluid ounces (fl oz) | 29.57 | milliliters (mL) |
| gallons (gal) | 3.785 | liters (L) |
| cubic feet ($ft^3$) | 0.028 | meters cubed ($m^3$) |
| cubic yards ($yd^3$) | 0.765 | meters cubed ($m^3$) |
| | | |
| **Area** | | |
| square inches ($in^2$) | 645.1 | millimeters squared ($mm^2$) |
| square feet ($ft^2$) | 0.093 | meters squared ($m^2$) |
| square yards ($yd^2$) | 0.836 | meters squared ($m^2$) |
| acres | 0.405 | hectares (ha) |
| square miles ($mi^2$) | 2.59 | kilometers squared ($km^2$) |

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## EXECUTIVE SUMMARY

The State of Florida has been recognized for its freight mobility and increasing volumes of international trade. The movement of freight within and outside the state is a major contributor to its economy. A significant portion of freight handled in the State of Florida is transported by rail. Along with the growing demand for rail-freight transportation, safety at highway-rail grade crossings has posed a significant challenge to the Florida Department of Transportation (FDOT). Accidents at highway-rail crossings may result in negative externalities, including loss of lives, severe injuries, release of hazardous materials, property damage, etc. A significant number of accidents have been reported at the highway-rail grade crossings in the State of Florida over the years, which highlights the necessity of safety improvement projects at certain crossings. The main objective of this project was to develop methodologies and decision support tools that can improve safety at the highway-rail grade crossings in the State of Florida, considering the available budget constraints.

In order to assist the FDOT personnel with resource allocation among the highway-rail grade crossings in the State of Florida, a standalone application, "HRX Safety Improvement", was designed. The standalone application is able to estimate the potential hazard values of the highway-rail grade crossings in the State of Florida based on the Florida Priority Index Formula. The Federal Railroad Administration (FRA) crossing inventory database and the FRA highway-rail grade crossing accident database are used to provide necessary inputs regarding the physical and operational characteristics of highway-rail grade crossings during the estimations of Florida Priority Index values for these highway-rail grade crossings. The Florida Priority Index Formula assesses a potential hazard of a given highway-rail grade crossing based on the average daily traffic volume, average daily train volume, train speed, protection factor, and accident history parameter. Unlike the commonly used accident and hazard prediction methodologies, the Florida Priority Index Formula computes the accident history parameter based on the total number of accidents in the last five years or since the year of last improvement (in case there was an upgrade).

Furthermore, the standalone application "HRX Safety Improvement" is able to conduct resource allocation among the most hazardous highway-rail grade crossings with the aim to minimize the overall hazard or the overall hazard severity at the highway-rail grade crossings. The latter objectives are achieved by employing a set of optimization algorithms, which prioritize highway-rail grade crossings for upgrading and select the appropriate upgrading type (e.g., installation of flashing lights, gates, barrier curbs, cameras) based on either hazard reduction-to-cost ratios or hazard severity reduction-to-cost ratios. The developed methodology was applied to the highway-rail grade crossings in the State of Florida. The sensitivity of resource allocation decisions to the following attributes was analyzed: (1) changes in the total available budget; (2) changes in the number of available countermeasures; (3) changes in the hazard severity weight values; and (4) changes in crossing types considered (i.e., public or private or both). Finally, some additional attributes of highway-rail grade crossings that could be considered throughout prioritization of the highway-rail grade crossings in the State of Florida for upgrading were highlighted.

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# 1. INTRODUCTION

This section of the report provides the background information for this project, including the following: (1) Florida's rail system; (2) safety at highway-rail grade crossings; (3) Florida's Highway-Railroad Improvement Program; (4) existing challenges; and (5) project objectives. Furthermore, the structure of the report will be outlined in this section as well.

## 1.1. Florida's Rail System

Freight transportation is a major contributor to the economy in the State of Florida. According to the Florida Department of Transportation (FDOT), more than 1.02 billion tons of commodities (imports and exports) are handled in the State of Florida annually (FDOT, 2015). A total of 798,200 rail carloads originated from the State of Florida in 2013, which is an increase of 4.4% as compared to 2012 (FDOT, 2015). On the other hand, a total of 1,265,900 rail carloads were destined for the State of Florida in 2013, which is an increase of 3.7% as compared to 2012 (FDOT, 2015). Florida's rail system is composed of 2,786 miles of trackage, which is owned by 15 line-haul railroads and terminal companies, in addition to 81 track miles owned by the State of Florida (FDOT, 2011). Track miles are defined as the total centerline length of mainline trackage in a corridor. The American Association of Railroads (AAR) classifies freight railroads into Class I, Class II, or Class III, based on the annual gross operating revenue (GOR). Specifically, freight railroads with a minimum annual GOR of $261.9 million belong to Class I, while freight railroads, which belong to Class II, are those with an annual GOR within the range of $21.0 million and $261.9 million. Freight railroads with an annual GOR less than $21.0 million are classified as Class III railroads (Xiong et al., 2007).

The State of Florida has two Class I Railroads (CSX Transportation and Norfolk Southern Corporation), one Class II Railroad (Florida East Coast Railway), and 11 Class III Railroads (Alabama and Gulf Coast Railway, Apalachicola Northern Railway, Bay Line Railroad, First Coast Railroad, Florida West Coast Railroad, Florida Central Railroad, Florida Midland Railroad, Florida Northern Railroad, Georgia and Florida Railway, Seminole Gulf Railway, and South Central Florida Express) (FDOT, 2011). Both Class I railroads connect the state to the national rail network and provide service to the Eastern United States. The Class II railroad serves the densely populated Atlantic Coast Area (Jacksonville to Miami). Class III railroads in Florida serve various seaports and manufacturing industries. Moreover, Florida's rail system provides access to 14 deep-water seaports. Approximately 114 million tons of different commodities were transported by rail in 2008 (FDOT, 2011).

Freight flows are forecasted to increase in Florida within the next years. Figure 1 presents the projected growth in freight flows by value between 2007 and 2040. Note that Figure 1 was prepared using the data reported by Mysore (2013). It can be observed from the chart that the freight flows (by value) within the State of Florida are forecasted to increase by 150% from 2011 to 2040, while exports and imports are projected to increase by 350% and 115%, respectively. A substantial increase of freight flows in Florida is expected to further increase the amount of commodities, transported by rail.

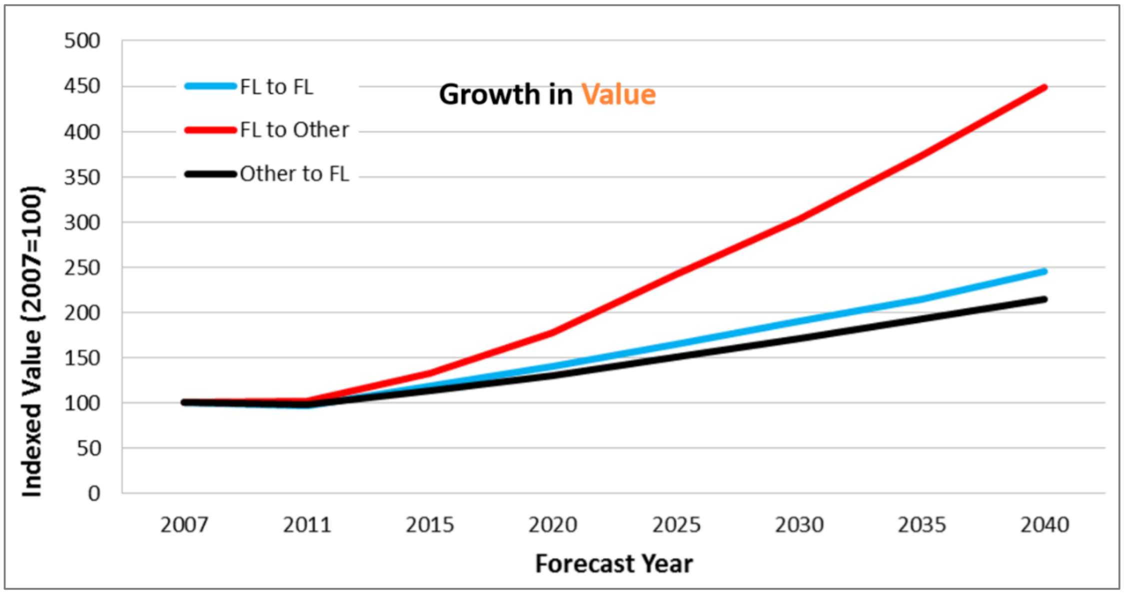


**Figure 1** Forecasted growth in freight flows by value in the State of Florida.
*Source: Mysore (2013). Florida Statewide Multi-Modal Freight Model*

A highway-rail grade crossing is an intersection of a roadway and a rail track. Highway-rail grade crossings can be divided into three major categories, which include: (1) public crossings (comprise of all rail crossings on highways open to the traveling public, which are controlled and maintained by a public authority); (2) private crossings (consist of all rail crossings on highways owned and used by the landowner or other entities licensed to gain access); and (3) pedestrian crossings (comprise of all rail crossings on highways used by pedestrians only). FDOT reported that there are 4,503 highway-rail grade crossings (3,549 of them or 79% are public highway-rail grade crossings and 954 of them or 21% are private highway-rail grade crossings) in the State of Florida based on the 2011 data (FDOT, 2011). A map, which depicts the locations of highway-rail grade crossings in Florida (based on the data obtained for 2011), is presented in Figure 2. In addition, there are 22 pedestrian crossings in the State of Florida (with 15 at-grade crossings and 7 grade-separated crossings) (FDOT, 2011). Table 1 shows the statistics of highway-rail grade crossings in Florida. Note that Table 1 was prepared using the data reported by Florida's Highway-Rail Grade Crossing Safety Action Plan (FDOT, 2011) [page 12 of the report].

**Table 1** Florida's highway-rail grade crossings.

| Crossing Type | Location | Crossings | Percent |
|---|---|---|---|
| Public | At-Grade | 3,549 | 73.4% |
| Public | Railroad Over | 49 | 1.0% |
| Public | Railroad Under | 280 | 5.8% |
| Public Total | | 3,878 | 80.2% |
| Private | At-Grade | 954 | 19.7% |
| Private | Railroad Over | 2 | 0.0% |
| Private | Railroad Under | 0 | 0.0% |
| Private Total | | 1,012 | 19.8% |
| ***Grand Total*** | | ***4,905*** | ***100.00%*** |


**Figure 2** Highway-rail grade crossing locations in Florida (2011).
*Source: FDOT (2011). Highway-Rail Grade Crossing Safety Action Plan*

### 1.2. Safety at Highway-Rail Grade Crossings

In the middle of the 18$^{th}$ century, safety at highway-rail grade crossings was not considered as a major concern in the United States (U.S.), because there were only a few trains and they were running at fairly low speeds. However, as the number of highway-rail grade crossings increased with more vehicle miles traveled, the number of highway-rail accidents increased by the end of the century; thus, safety at highway-rail grade crossings became a primary source of concern. There were approximately 255,000 highway-rail grade crossings in the U.S. in 2010, 52% of which were open for public use (Chadwick et al., 2014). At every highway-rail grade crossing, there is a possibility of a collision between a vehicle and a train. Moreover, there is a risk of an accident that does not involve a train, such as rear-end collisions between a vehicle, stopped at a highway-rail grade crossing, and another vehicle on the roadway, collision with a warning device at highway-rail grade crossings (e.g., signal equipment or signs), and non-collision accidents (whereby a driver loses control of the vehicle).

Accidents at highway-rail grade crossings may result in negative externalities, such as loss of lives, severe injuries, release of hazardous materials, property damage, etc. Improving safety at highway-rail grade crossings has posed a major challenge to relevant federal and state authorities, as they seek to improve safety and operations of both highway and rail traffic at highway-rail grade crossings. About $3.8 billion has been devoted to the improvement of highway-rail grade crossings in the U.S. through Federal transportation funding alone since 1974 (FDOT, 2011). The implemented safety improvements brought approximately 84% reduction in highway-rail accidents between 1970s and 2009. Figure 3 shows the number of accidents, injuries, and fatalities at the highway-rail grade crossings in the U.S. from 2007 to 2017. Note that Figure 3 was prepared using the data reported by the Federal Railroad Administration (FRA, 2018a). Also, note that the statistical data, which are presented in Figure 3, may change due to updates in the FRA highway-rail grade crossing accident/incident database.

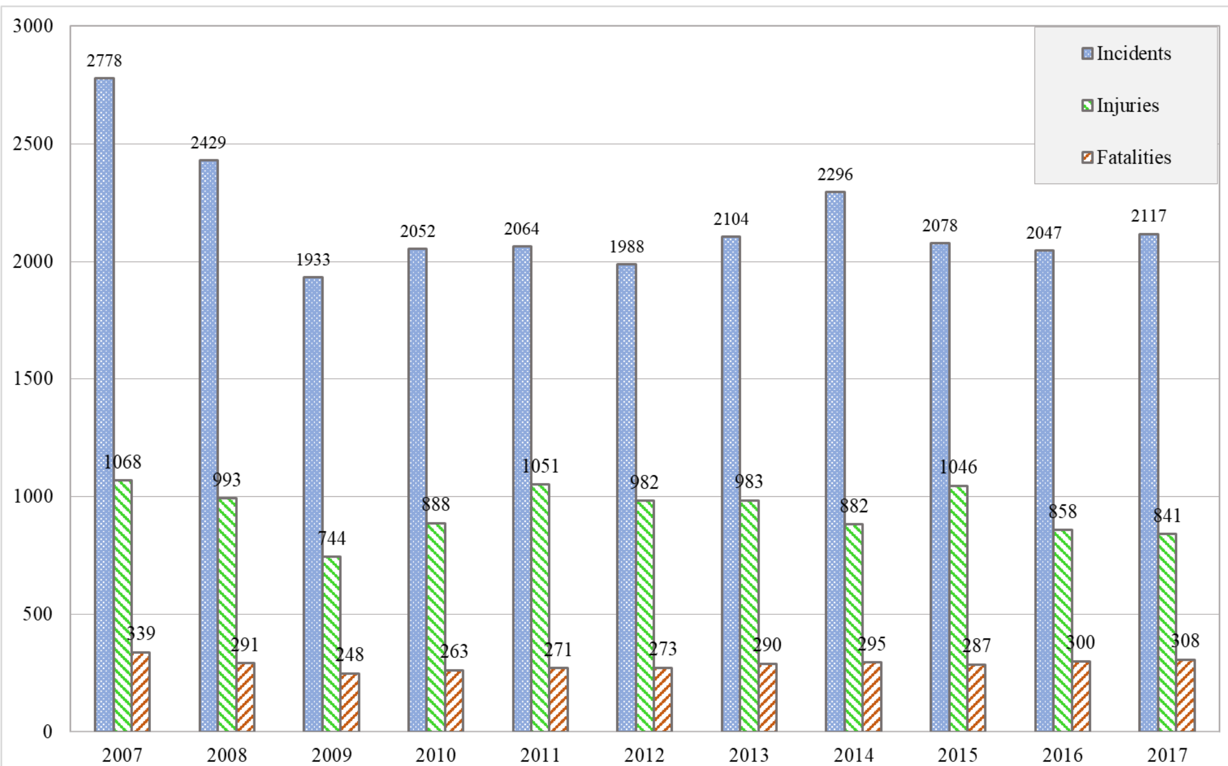

**Figure 3** Highway-rail grade crossing accident statistics in the U.S. (2007 to 2017).

FRA classifies rail accidents into three major types, including the following (FDOT, 2010): (1) train accidents – rail accidents that involve on-track rail equipment (e.g., derailments, major rail collisions); (2) highway-rail accidents – rail accidents that involve a rail and highway users; and (3) other accidents – rail accidents that do not fall under "train accidents" and "highway-rail accidents" types (e.g., the accidents within a rail yard, involving employees and contractors). FRA collects the data on the aforementioned types of rail accidents. Table 2 presents a distribution of injuries and fatalities recorded between 2004 and 2009 by various types of rail-related accidents in Florida. Note that Table 2 was prepared using the data reported by the Florida Rail System Plan (FRSP) (FDOT, 2010) [page 2-36 of the report]. Based on the collected data, it can be observed that the majority of fatalities occurred due to highway-rail accidents and trespassing, while the majority of injuries occurred due to other accidents. The following sections of this report provide more detailed information regarding highway-rail accidents and trespassing accidents, which generally occur at highway-rail grade crossings.

**Table 2** Distribution of injuries and fatalities by incident type in Florida (2004 to 2009).

| | Year | Train Incidents | Highway-Rail Incidents | Trespassing | Other Incidents | Total |
|---|---|---|---|---|---|---|
| **Fatalities** | 2004 | 1 | 19 | 20 | 0 | 40 |
| | 2005 | 0 | 17 | 33 | 1 | 51 |
| | 2006 | 0 | 10 | 28 | 0 | 38 |
| | 2007 | 0 | 20 | 33 | 1 | 54 |
| | 2008 | 0 | 25 | 26 | 0 | 51 |
| | 2009 | 0 | 10 | 19 | 0 | 29 |
| | *Subtotal* | *1* | *101* | *159* | *2* | *263* |
| **Injuries** | 2004 | 2 | 35 | 14 | 193 | 244 |
| | 2005 | 6 | 21 | 22 | 178 | 227 |
| | 2006 | 0 | 35 | 20 | 143 | 198 |
| | 2007 | 2 | 66 | 16 | 160 | 244 |
| | 2008 | 0 | 30 | 14 | 120 | 164 |
| | 2009 | 1 | 8 | 8 | 127 | 144 |
| | *Subtotal* | *11* | *195* | *94* | *921* | *1,221* |
| | **Total** | **12** | **296** | **253** | **923** | **1,484** |

### *1.2.1. Highway-Rail Accidents*

FRA defines a highway-rail accident as “any impact between a rail and highway user (both motor vehicles and other users) of the crossing at a designated crossing site, including walkways, sidewalks, etc., associated with the crossing” (FDOT, 2010). FRA reported an average of ≈75 accidents at the highway-rail grade crossings in Florida with the number of fatalities in a range of 7 and 25 every year between 2007 and 2017 (see Figure 4). Note that Figure 4 was prepared using the data reported by FRA (2018a). Also, note that the statistical data, which are presented in Figure 4, may change due to updates in the FRA highway-rail grade crossing accident/incident database. Moreover, a significant reduction in the number of accidents at the highway-rail grade crossings after 2008 was attributed to a number of factors, which include (FDOT, 2011): (1) improved highway-rail grade crossings warning devices; (2) increased outreach and education; (3) safer driving behavior; and (4) changes in travel patterns. Based on more recent FRA data, a total of 106 accidents were recorded at Florida’s public and private highway-rail grade crossings in 2017 with 23 fatalities and 54 injuries. A significant number of highway-rail accidents was recorded in large metropolitan areas of the State of Florida (the top 10 counties with the highest number of accidents have a population of approximately two-thirds of the state’s population). Furthermore, out of 67 counties in Florida, there are 60 counties with the highway-rail grade crossings. A total of 53 counties recorded highway-rail accident(s) between 2000 and 2009 (FDOT, 2011).

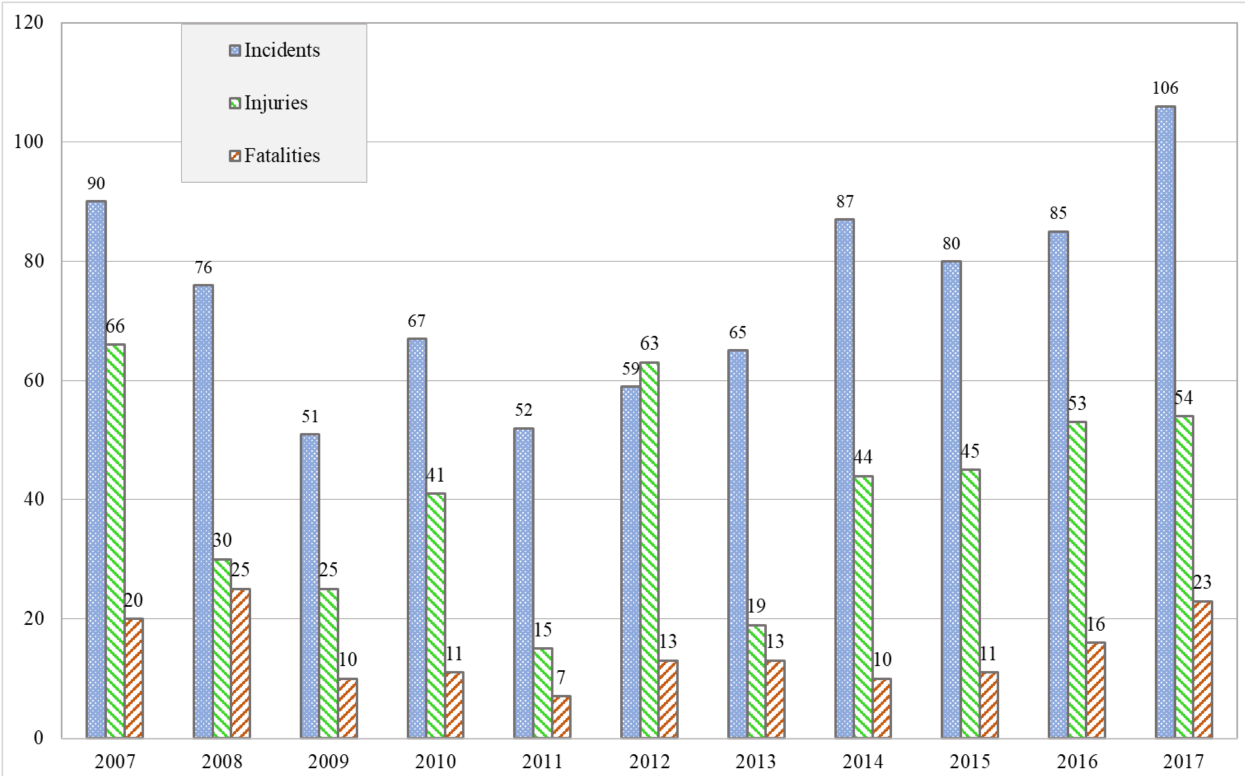


**Figure 4** Highway-rail grade crossing accident statistics in the State of Florida (2007 to 2017).

Table 3 presents a distribution of highway-rail accidents by user type from 2004 to 2009 in Florida. Note that Table 3 was prepared using the data reported by FRSP (FDOT, 2010) [page 2-34 of the report]. The majority of the reported accidents (450 accidents or 83% of accidents) occurred as a result of a train striking a highway user. A total of 387 accidents (or 71% of accidents) were caused by a motor vehicle being struck by a train, while 63 accidents (or 12% of accidents) occurred as a result of a pedestrian being struck by a train. Other accidents (94 accidents or 17% of accidents) resulted from a train being struck by a motor vehicle. Furthermore, during the six-year period (2004 to 2009), the fatality rate recorded from the accidents, where a train struck a pedestrian, was higher as compared to the fatality rate recorded from the accidents, involving a motor vehicle and a train. Specifically, 65% of the accidents, involving a pedestrian and a train, resulted in a fatality. Although the accidents, involving a pedestrian and a train, accounted for only 12% of all accidents, they resulted in 40% of the total fatalities. U.S. DOT reported that the majority of fatalities recorded at highway-rail grade crossings are caused by risky behavior of drivers (FDOT, 2011).

**Table 3** Distribution of highway-rail accidents by user type in Florida (2004 to 2009).

| Type and Highway User | Total Incidents | Casualties | |
|---|---|---|---|
| | | **Killed** | **Nonfatal** |
| Train Struck Highway User | 450 | 92 | 174 |
| *Motor Vehicle* | 387 | 51 | 164 |
| *Pedestrian or Other* | 63 | 41 | 10 |
| Train Struck by Highway User (Consists Totally of Motor Vehicles) | 94 | 9 | 34 |
| **Total Figures** | **544** | **101** | **208** |

FRA Office of Safety Analysis data also indicate that a large number of accidents and fatalities, recorded in Florida between 2005 and 2009, occurred at the highway-rail grade crossings equipped with active warning devices, such as automatic flashing lights/automatic flashing lights and gates, and cantilever flashing lights and gates (FDOT, 2011). According to FRA Office of Safety Analysis, the majority of rail-related accidents in Florida between 2005 and 2009 had the following attributes: (1) occurred at public crossings; (2) occurred as a result of risky driver behavior; (3) involved motor vehicles; and (4) occurred at locations with active warning devices. The latter conclusions can be supported by the information presented in Figure 5, Table 4 and Table 5. Figure 5 shows the percentage of accidents, which occurred between 2000 and 2010 at the highway-rail grade crossings with active warning devices in Florida. A detailed information regarding the accident type at the highway-rail grade crossings in Florida between 2005 and 2009 is presented in Table 4, while a detailed information regarding the warning device type at the highway-rail grade crossings in Florida, where accidents were reported between 2005 and 2009, is presented in Table 5. Note that Figure 5, Table 4, and Table 5 were prepared using the data reported by FDOT (2011) [pages 14, 15, and 18 of the report].

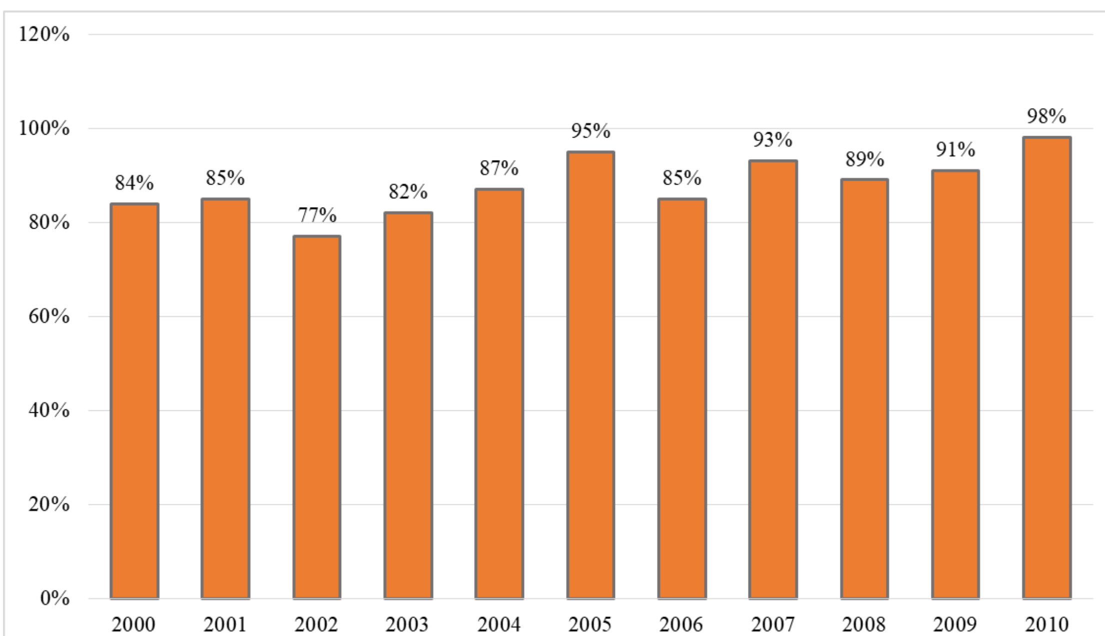


**Figure 5** Percentage of accidents at the highway-rail grade crossings with active warning devices in Florida (2000 to 2010).

**Table 4** Type of incident – all incidents (2005 to 2009).

| Type of incident - Vehicle | Incidents | Percentage |
|---|---|---|
| Stopped on | 87 | 20.00% |
| Around gate | 118 | 27.20% |
| Did not stop/yield | 90 | 20.70% |
| Stalled | 27 | 6.20% |
| Vehicle Abandon | 10 | 2.30% |
| Car Crash | 13 | 3.00% |
| Onto to Tracks | 19 | 4.40% |
| Traffic | 12 | 2.80% |
| Distracted | 10 | 2.30% |
| Low Ground Clearance | 3 | 0.70% |
| Suicide | 2 | 0.50% |
| Device Malfunction | 1 | 0.20% |
| *Sub Total* | 392 | 90.30% |
| **Type of incident - Non-vehicle** | **Incidents** | **Percentage** |
| Pedestrian | 30 | 6.90% |
| Pedestrian-Suicide | 6 | 1.40% |
| Bicycle | 6 | 1.40% |
| *Sub Total* | 42 | 9.70% |
| Total | 434 | 100.00% |

**Table 5** Type of warning device at crossings – all incidents (2005 to 2009).

| Type of Crossing | Incidents | Percentage |
|---|---|---|
| ***Passive Crossings*** | | |
| Crossbuck | 75 | 17.30% |
| None | 6 | 1.40% |
| *Sub Total* | 81 | 19% |
| ***Active Crossings without Gates*** | | |
| Flashing Lights | 12 | 2.80% |
| Cantilever Flashing Lights | 8 | 1.80% |
| Traffic Signal | 2 | 0.50% |
| *Sub Total* | 22 | 5% |
| ***Active Crossings with Gates*** | | |
| Flashing Lights and Gates | 146 | 33.60% |
| Cantilever Flashing Lights and Gates | 181 | 41.70% |
| *Sub Total* | 327 | 75% |
| ***Other Crossings*** | | |
| Flagged by Crew | 4 | 0.90% |
| Total | 434 | 100.00% |

### *1.2.2. Trespassing Accidents*

One of the primary causes of rail-related accidents, which result in fatalities, is the trespass on railroad right-of-way. Trespasser fatalities have exceeded the fatalities recorded at highway-rail grade crossings after 1996, and, since then, has become a leading cause of rail-related fatalities. Note that some trespassing accidents occur at highway-rail grade crossings. A total of 2,775 trespassers were killed in the U.S. between 2005 and 2010 (FDOT, 2011). Figure 6 presents the number of trespass accidents in the U.S, as well as the number of injuries and fatalities among trespassers between 2000 and 2010. Note that Figure 6 was prepared using the data reported by Florida's Highway-Rail Grade Crossing Safety Action Plan (FDOT, 2011) [page 5 of the report]. From Figure 6, it can be observed that there is no significant reduction in the number of trespass accidents within the 11-year time period. The average fatality rate of trespass accidents comprises ≈478 fatalities per year over the considered 11-year time period.

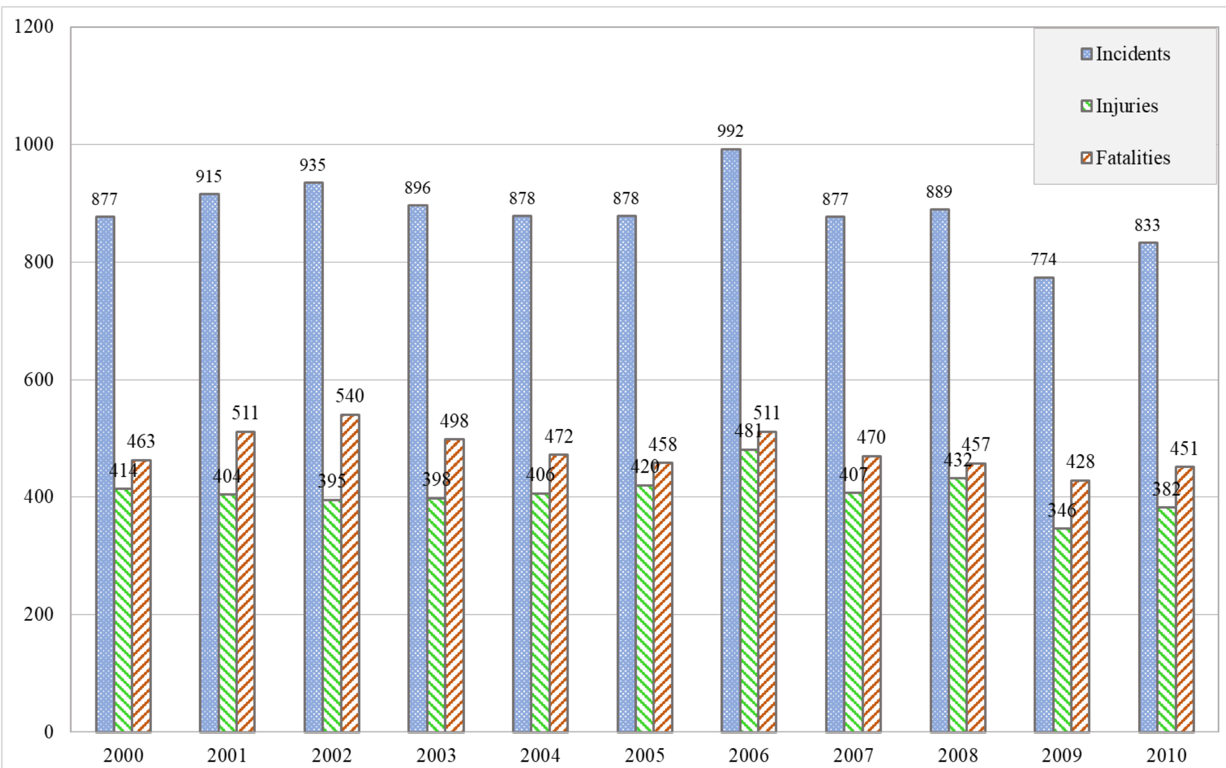


**Figure 6** Railroad trespass statistics in the U.S. (2000 to 2010).

According to FRA, a total of 175 trespassers were killed (which accounted for approximately 65% of the recorded trespass accidents) in the State of Florida between 2005 and 2010. Moreover, 268 trespasser accidents resulted in 93 injuries between 2005 and 2010. Figure 7 presents the number of trespass accidents in the State of Florida, as well as the number of injuries and fatalities among trespassers between 2000 and 2010. Note that Figure 7 was prepared using the data reported by Florida's Highway-Rail Grade Crossing Safety Action Plan (FDOT, 2011) [page 6 of the report]. Based on the analysis of the collected data, the average number of trespass accidents between 2000 and 2010 comprised approximately ≈46 accidents per year with the average fatality rate of ≈29 fatalities per year. A large number of trespassers in the U.S. are pedestrians, who decide to walk across or on rail tracks in order to arrive faster at their destination. Others engage in various activities very close to railroad tracks, such as loitering, hunting, dog walking, bicycling, and riding all-terrain vehicles, snowmobiles, and others (FDOT, 2010). Therefore, the majority of rail accidents due to trespass could be prevented if the aforementioned human activities near railroad tracks are restricted, and the appropriate educational activities regarding potential hazards near railroad tracks are conducted for the public.

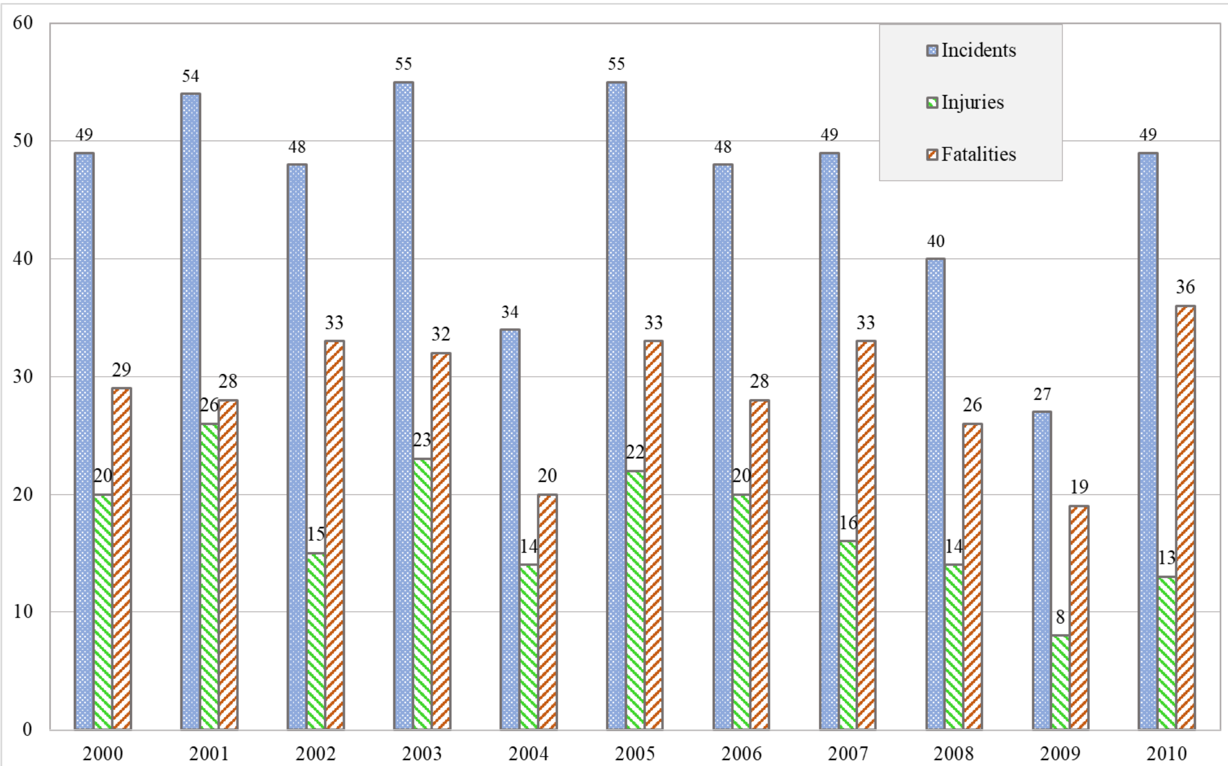


**Figure 7** Railroad trespass statistics in the State of Florida (2000 to 2010).

The severity of accidents at highway-rail grade crossings demands special attention. A set of countermeasures, which have been widely used at the highway-rail grade crossings in order to reduce the number of accidents and their severity in the State of Florida, include the following (FDOT, 2011): (1) installation of flashing lights at passive highway-rail grade crossings with stop signs only; (2) installation of gates at passive highway-rail grade crossings with stop signs only; (3) installation of gates at active highway-rail grade crossings with flashing lights; (4) grade separation (i.e., construction of bridges, overpasses, underpasses); (5) implementation of methods, aiming to improve traffic preemption before arrival of trains at highway-rail grade crossings (e.g., installation of advanced train detection systems, improvement of coordination between signals at highway-rail grade crossings and adjacent intersections, implementation of advanced traffic signal control systems, installation of appropriate warning devices); and others.

### 1.3. Florida's Highway-Railroad Improvement Program

The Highway-Railroad Improvement Program in the State of Florida is an initiative of the Federal Highway Administration (FHWA), which was started on December 7, 1973 (FDOT, 2011). FDOT's Central Safety Office was assigned to manage the program. Under the program, FDOT's Central Safety Office was required to perform the following major tasks: (1) conduct inventory of all highway-rail grade crossings in the state; (2) assign a U.S. DOT inventory number to each highway-rail grade crossing; and (3) develop a formula to identify and prioritize the most hazardous highway-rail grade crossings for safety improvement projects. The inventory data, collated by Florida State Central Safety Office and other State DOTs, is used by FRA to prepare the highway-rail grade crossing database for the entire U.S. Over the past decades, funding for the program has been increased by FHWA from $4.2 million to $7.5 million (FDOT, 2011). The State of Florida also provides some funds to support highway-rail grade crossing safety improvement programs. The provided Federal funds are generally sufficient to perform safety improvement projects at nearly 35 to 45 candidate highway-rail grade crossings annually. The "Before and After" analysis, conducted by the Central Safety Office at the candidate highway-rail grade crossings that were selected for safety improvements, indicated a reduction in fatalities over the years.

A Safety Index Formula (which will be referred to as the Florida Accident Prediction and Safety Index Formula in this report) was designed under the program by the Central Safety Office. The formula assists the Central Safety Office to identify and prioritize highway-rail grade crossings, which had the highest number of accidents. Specifically, the safety index, which ranges between 0 and 90, is used to rank the highway-rail grade crossings in the State of Florida (Elzohairy and Benekohal, 2000; U.S. DOT, 2007). The highway-rail grade crossings with a safety index value of 70 are considered as safe, while the highway-rail grade crossings with a safety index value of 60 (which is interpreted as one accident in nine years) are considered as marginal. Some of the variables that are used in the formula include the number of predicted accidents, train traffic, vehicular traffic, train speeds, and vehicle speeds (U.S. DOT, 2007). The formula was revised in 2005 to account for other important parameters, and a sensitivity analysis was conducted on all the parameters. A detailed description of the Florida Accident Prediction and Safety Index Formula, used in the State of Florida, is provided in section 2.4.5 of this report. Based on the formula and additional field reviews, the Central Safety Office along with the District Railroad Coordinators make recommendations on the type of countermeasures to be implemented at the highway-rail grade crossings that are considered as unsafe.

Under the Highway-Railroad Improvement Program, FDOT does not require that local governments fund safety improvement projects; however, cities and counties still cover a part of the equipment maintenance cost (FDOT, 2011). In the mid-1990's, the Central Rail Office became responsible for the Highway-Railroad Improvement Program. The organizational change enhanced efficiency of the program, as well as facilitated compliance with the FHWA policies and regulations. The Central Rail Office put a lot of emphasis on implementation of a wide range of countermeasures at the highway-rail grade crossings. Some of the fairly low-cost countermeasures, introduced at the highway-rail grade crossings, include the following: (1) upgrade the highway-rail grade crossing surfaces; (2) installation of constant warning time program at the highway-rail grade crossings with variable train speeds; (3) gate mechanism replacement program; (4) replacement of aged warning signs and installation of reflective strips; (5) installation of new pavement markings on and off the State Highway System; (6) replacement of incandescent lights with light emitting diode (LED) at the highway-rail grade crossing approaches; (7) installation of median barrier systems; and (8) replacement of the existing 8-inch lens with 12-inch lens.

In order to improve safety of the surface transportation system in Florida and reduce roadway fatalities, FDOT developed the Florida Strategic Highway Safety Plan in 2005. The plan was designed to allocate limited resources to safety improvement projects that would significantly reduce the number of fatalities on roadways in Florida. In order to achieve the latter objective, the plan exploits engineering, enforcement, education, and emergency management strategies. Moreover, the 2060 Florida Transportation Plan (FTP) highlights that the suggested strategies are found to be effective as they continuously improve safety of all transportation system users in Florida (FDOT, 2011). As indicated in Florida's Highway-Rail Grade Crossing Safety Action Plan (FDOT, 2011), a large number of fatalities recorded on roadways in the State of Florida is attributed to the following: (1) intersection accidents (41.2% of fatalities); (2) aggressive driving (34.8% of fatalities); (3) vulnerable road users (19.8% of fatalities); and (4) lane departure accidents (63.6% of fatalities) (FDOT, 2011). FDOT implements highway-rail grade crossing safety improvement projects, which address each of the four main types of accidents that have been reported to increase the percentage of fatalities in the State of Florida. Moreover, FDOT has the constitutional authority to enhance safety at all public highway-rail grade crossings in the state. However, safety improvements at pedestrian crossings are jointly carried out by the local government agencies and the railroad partners.

FDOT considers a variety of highway-rail grade crossing safety improvement strategies. However, when a highway-rail grade crossing is identified as unsafe, FHWA specifies that the elimination of the highway-rail grade crossing must be considered as the first option. Elimination options include: (1) grade separating the highway-rail grade crossing; and (2) closing the highway-rail grade crossing to highway traffic through relocation or abandonment of the rail line. Elimination substantially reduces the risk of accidents by removing the point of intersection between the highway and the railroad. The decision to eliminate a highway-rail grade crossing depends on safety, operational, and financial considerations. Moreover, the Federal-Aid Policy Guide (FAPG) specifies that all grade crossings on freeways (roadways with full control of access) must be eliminated irrespective of the highway or railroad traffic volume (U.S. DOT, 1991). FDOT conducts a diagnostic field review annually to identify the highway-rail grade crossings for potential closure. Between 2002 and 2011, FDOT has closed more than 85 public highway-rail grade crossings and reduced the number of highway-rail grade crossings equipped with passive warning devices (FDOT, 2011). Before a highway-rail grade crossing is closed, FDOT serves all parties involved with a notice of potential closure.

Furthermore, FDOT uses a record of rail system to produce the annual safety index, which ranks the highway-rail grade crossings in order of potential risk. A Diagnostic Field Review is performed at the selected highway-rail grade crossings, which are identified as unsafe. However, certain highway-rail grade crossings that have higher priorities do not undergo field reviews because safety improvements to the crossings will require elimination. FDOT evaluates various safety improvement projects across the State of Florida and selects projects for implementation based on the following factors: (1) safety index; (2) cost of implementation; (3) accident history; (4) corridor emphasis; and (5) input from local governments and transportation partners. The Diagnostic Field Review team identifies remedial measures (that are also referred to as countermeasures or upgrades), which may include the following (FDOT, 2011):

***Warning Device Upgrades:*** Improvements to warning device may consist of: (1) installation of new, more reflective crossbuck warning signs at crossings that do not require automatic warning devices; (2) installation of other warning signs ("Do Not Stop" signs on tracks, advanced warning signs, quiet zone signs) and pavement markings/treatments; (3) installation of automatic flashing light signals and gates at public highway-rail grade crossings currently not equipped with automatic warning devices; (4) installation of automatic flashing light signals and gates at public highway-rail grade crossings currently equipped only with automatic flashing light signals; (5) signal circuitry improvements at public highway-rail grade crossings currently equipped with automatic warning device; and (6) replacement of outdated bulbs with brighter LEDs, allowing for greater visibility.

***Interconnection:*** Signal circuitry improvements at highway-rail grade crossings may allow coordination/signal integration of neighboring highway traffic signals and highway-rail grade crossing signals (automatic warning devices). Coordinated preemption may reduce conflicts at crossings and give adequate clearing time to downstream vehicles. Some of the major challenges of this measure include varying train speeds and types, as well as train stops at some highway-rail grade crossings.

FDOT works closely with local governments and railroad companies to implement safety improvements at the highway-rail grade crossings on the state, county, and city roads using the funds, provided by FHWA, to support the Highway-Railroad Improvement Program. State funds are primarily used to implement safety improvements at the highway-rail grade crossings, which are located on the state roads (FDOT, 2011).

**1.4. Existing Challenges**

Based on the statistical data, provided by the U.S. Census Bureau for 2018, the State of Florida is considered the third most populous state in the U.S. and comprises 6.5% of the total U.S. population (U.S. Census, 2018). Florida is also the 22$^{nd}$ largest state by total area in the U.S. (FDOT, 2011). Moreover, due to the high population and average land mass, the population density of Florida (343.8 persons/sq mi) is considered in one of the highest in the U.S. and the highest in the southeastern region of the country. FDOT reported that about 201,040 million vehicle miles of travel (VMT) were recorded in the State of Florida in 2015 (FDOT, 2015). The annual VMT is an indicator of the highway usage intensity. The VMT further increased by 4.3% in 2014, and a 3.0% increase was recorded in the VMT per capita (which represented the first increase in a decade) (FDOT, 2015). The majority of the population travels to work by automobiles, and the average travel time to work is estimated to be approximately 26 minutes (FDOT, 2015). The aforementioned statistics demonstrates that the State of Florida is largely urbanized. Based on the fact that the state is urbanized, there is a large number of highway-rail grade crossings in metropolitan areas, which further contributes to traffic congestion and high accident rate on roadways (especially, at highway-rail grade crossings).

Furthermore, the metropolitan areas in the State of Florida (which generally have a high density of crossings per rail mile) record a high volume of freight and passenger rail traffic. A total of 798,200 rail carloads were transported out of Florida in 2013, while 1,265,900 carloads were moved into the state (FDOT, 2015). Also, approximately 274,000 passengers traveled by train in

2014. Florida East Coast Industries (FECI) have been developing an intercity passenger rail service, which will shuttle between the major cities in the State of Florida, including Miami, Orlando, Fort Lauderdale, and West Palm Beach. The new rail service will further increase rail traffic volume and speed in the metropolitan areas, where the majority of highway-rail grade crossing accidents have occurred. Approximately 70% of the reported highway-rail grade crossing accidents, which occurred during the Rail Safety Improvement Act of 2008 (RSIA) period (between 2006 and 2008), were recorded in the 10 most urbanized counties in Florida (FDOT, 2011). A map of the State of Florida, showing the population density by county, is presented in Figure 8.

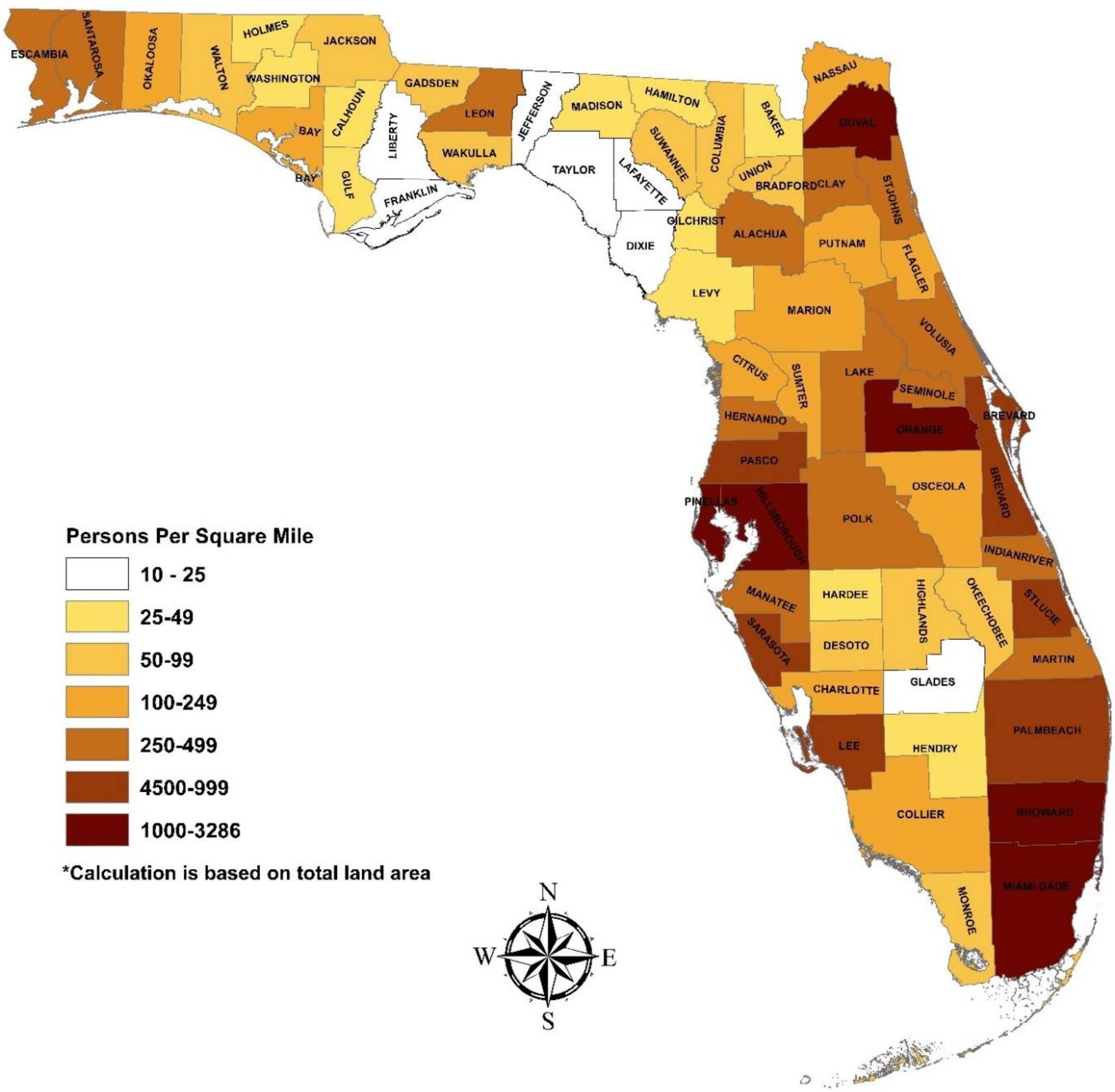


**Figure 8** Population density by county (2015).
*Source: U.S. Census (2015). Florida Demographic Information*

Furthermore, Figure 9 shows a map, which depicts highway-rail grade crossing accidents by county in Florida between January 2013 and December 2017. Note that Figure 9 was prepared using the data available through the FRA highway-rail grade crossing accident/incident database (FRA, 2018a). Also, note that the statistical data, which are presented in Figure 9, may change due to updates in the FRA highway-rail grade crossing accident/incident database. Based on the information, presented in Figure 8 and Figure 9, it can be concluded that there is a close relationship between highway-rail grade crossing accidents and urbanization in Florida. Specifically, counties that had the highest population density generally had a significant number of accidents at the highway-rail grade crossings.

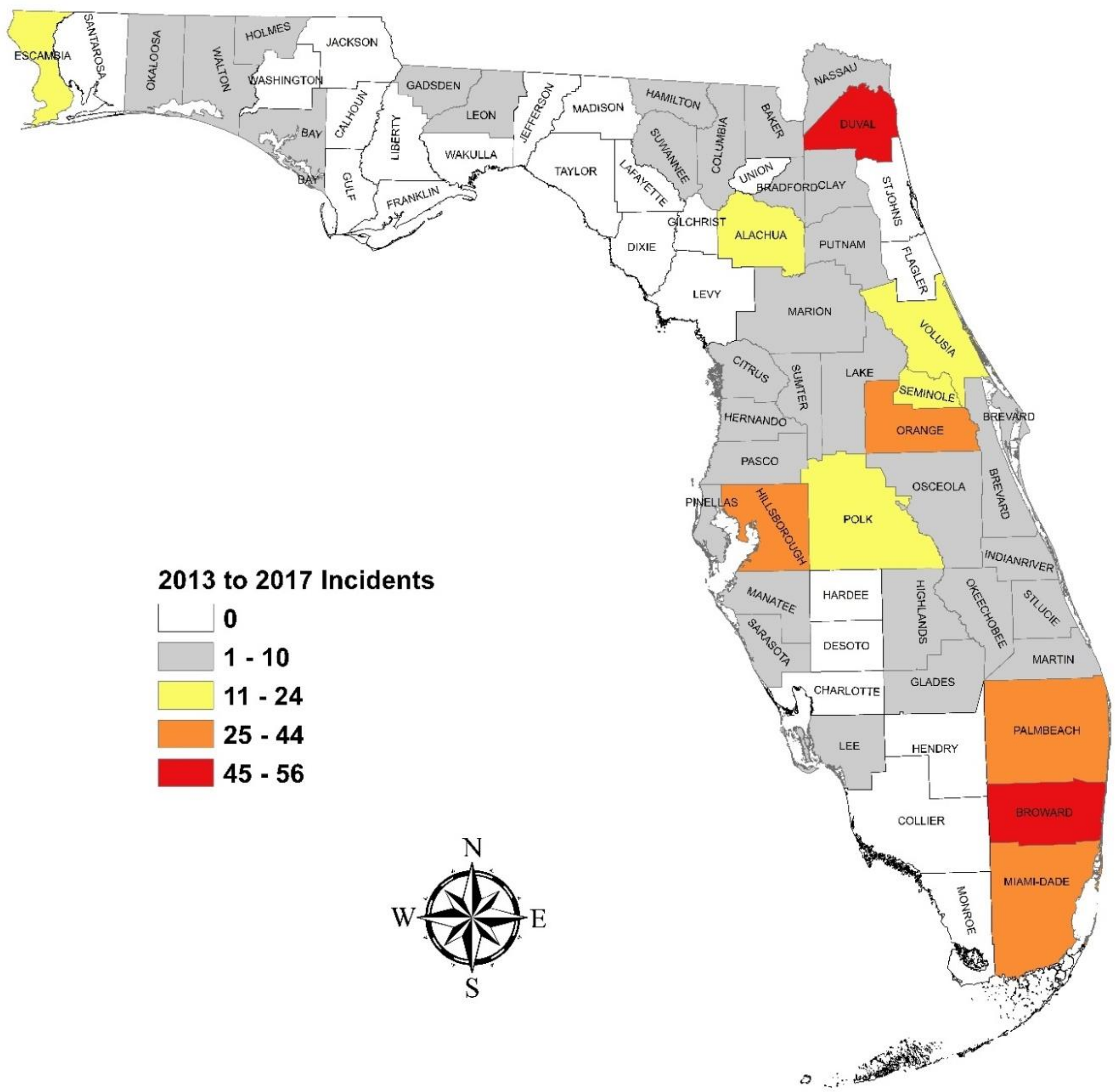


**Figure 9** Florida highway-rail grade crossing accidents by county (January 2013 to December 2017).

*Source: FRA (2018a). Accident/Incident Data*

### 1.5. Project Objectives

Considering the growing demand for passenger and freight transport in the State of Florida and a significant number of accidents, reported at the highway-rail grade crossings in the State of

Florida, this project aims to evaluate the existing accident and hazard prediction models, used by State DOTs and determine the model that would be a good fit for Florida's highway-rail grade crossings (based on its ability to prioritize the highway-rail grade crossings for safety improvement projects). The model will be used to forecast the number of accidents or the highway-rail grade crossing hazard (i.e., susceptibility of a given highway-rail grade crossing to accidents) based on certain characteristics of a given highway-rail grade crossing (e.g., number of rail tracks; number of trains; Annual Average Daily Traffic [AADT]; maximum train speed; posted highway speed limit; type of warning device used at a highway-rail grade crossing; and others). The number of predicted accidents or the highway-rail grade crossing hazard will be further used to prioritize Florida's highway-rail grade crossings for upgrading.

Different types of countermeasures will be considered (e.g., upgrading the warning device, improving traffic preemption, or even grade separation for the highway-rail grade crossings that experience a significant number of accidents). An optimization model-based decision support tool will be developed in order to assist FDOT with selection of the highway-rail grade crossings for upgrading and identification of the appropriate upgrading type, aiming to minimize the overall hazard at the highway-rail grade crossings and considering the available budget constraint. Moreover, the hazard severity will be taken into account by the developed optimization model-based decision support. A set of case studies will be conducted using the data available for Florida's highway-rail grade crossings to showcase efficiency of the developed decision support tool. This project is not only expected to improve safety of roadway travelers at the highway-rail grade crossings but also to ensure continuity of freight flows in the State of Florida.

### 1.6. Report Structure

This technical report is structured in the following manner. The next section provides an extensive review of the state-of-the-art and the state-of-the-practice, discusses the existing accident and hazard prediction models, which are recognized nationally, accident and hazard prediction models used by State DOTs, as well as the methods that are used for resource allocation. Section 3 presents a comprehensive analysis of the existing methods used for accident and hazard prediction at highway-rail grade crossings, describes the most common factors that are considered by the discovered accident and hazard prediction models, and discusses performance and implementation challenges of these accident and hazard prediction models. Section 4 describes the FRA crossing inventory database and the FRA highway-rail grade crossing accident database, which will be further used throughout this project. Section 5 presents the candidate accident and hazard prediction models, which will be analyzed as a part of this project for the highway-rail grade crossings in the State of Florida, and provides a description of the methodology and criteria that will be used to evaluate the candidate accident and hazard prediction models. Section 6 exhibits the results obtained from analysis of the candidate accident and hazard prediction models and presents the model that is recommended to rank the highway-rail grade crossings in the State of Florida for safety improvement projects.

Section 7 presents the optimization models, which were developed to perform resource allocation among the highway-rail grade crossings in the State of Florida, describes the input data, required by both models, and discusses the computational complexity of the models. Section 8 provides a detailed description of the solution algorithms, which were developed to solve the proposed optimization models. Section 9 evaluates the developed solution algorithms for all the public highway-rail grade crossings in the State of Florida and provides recommendations regarding the most promising solution approach for each one of the proposed optimization models. Section 10 describes the standalone application "HRX Safety Improvement", which was developed to prioritize the highway-rail grade crossings in the State of Florida for upgrading based on the Florida Priority Index (FPI) values and distribute the available monetary resources among the highway-rail grade crossings to upgrade them by implementing the available countermeasures. Section 11 presents a detailed description of the computational experiments, which were performed to showcase applicability of the proposed methodology for assessing potential overall hazard and hazard severity of the highway-rail grade crossings in the State of Florida and performing resource allocation among the existing highway-rail grade crossings in the State of Florida. Section 12 concludes this technical report and provides a number of directions for future research.

## 2. REVIEW OF THE EXISTING METHODS FOR ACCIDENT AND HAZARD PREDICTION AT HIGHWAY-RAIL GRADE CROSSINGS

This section of the report provides a detailed review of the existing methods for accident and hazard prediction at highway-rail grade crossings, which was performed based on the available literature. The identified accident and hazard prediction models have been widely used by State DOTs over the past years. Note that the scope of this study did not include a survey among State DOTs to determine whether the states made any changes in the accident and hazard prediction procedures that were used in the past. Such survey can be conducted as a part of future research.

### 2.1. Previous Research Efforts by State DOTs

Different State DOTs have taken a number of research attempts to predict the occurrence of accidents at highway-rail grade crossings. Throughout the literature search, nine State DOT reports, which are relevant to the theme of this project, were identified. The reports were prepared by the States of Virginia (1986), Alabama (1994), Illinois (2000), Missouri (2003), Tennessee (2012), Texas (2013), Iowa (2015), Nevada (2017), and Ohio (2017). This section summarizes findings from the previous research efforts, undertaken by State DOTs.

#### *2.1.1. State of Virginia (1986)*

Virginia Highway & Transportation Research Council performed a study on the existing accident prediction and hazard index models that were recognized nationally at that time (Faghri and Demetsky, 1986). A total of 13 nationally recognized models were identified under that study, which are presented in Table 6. Some of those models were evaluated in terms of the models' abilities to employ the available data and predict the number of accidents and hazard indexes at highway-rail grade crossings.

**Table 6** Models identified by Virginia Highway & Transportation Research Council.

| | | |
|---|---|---|
| Coleman-Stewart | Wisconsin | Utah |
| Peabody-Dimmick | Costa Contra County (California) | City of Detroit |
| Mississippi | Oregon | DOT (U.S. DOT) |
| New Hampshire | North Dakota Rating System | |
| Ohio | Idaho | |

In addition to the identification and evaluation of the existing formulae, the study performed a survey on the current methodologies applied by 45 different states as of March 1986. The survey results indicated that 32% of the states formulated their own models, while 30% of the states employed the U.S. DOT Accident Prediction Formula. Also, 22% of the states used the New Hampshire Hazard Index Formula or a modified version of the New Hampshire Hazard Index Formula, and 8% of the states used the Peabody-Dimmick Formula (see Figure 10). Note that Figure 10 was prepared using the data reported by Faghri and Demetsky (1986) [page 6 of the report]. Moreover, the study identified different factors, included in various formulae, and reported the number of states using each factor in their formula (see Table 7). Note that Table 7 was prepared using the data reported by Faghri and Demetsky (1986) [page 7 of the report]. It was found that the number of vehicles per day and the number of trains per day were the most commonly used factors (used by 13 existing formulae and 43 states).

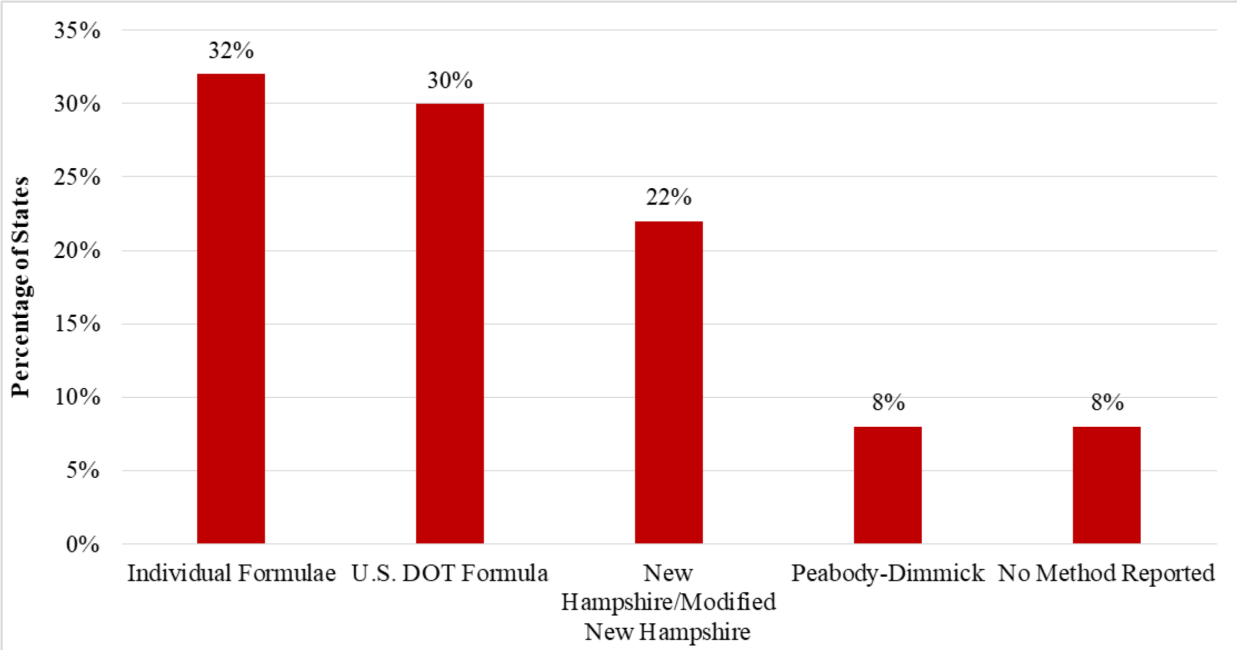


**Figure 10** Formulae employed by states (1986).

**Table 7** Factors considered in the existing formulae (1986).

| **Factor Considered** | **Number of Formulae Containing the Factor (n=13)** | **Number of States Using the Factor in their Formulae (n=45)** |
|---|---|---|
| Vehicles per day | 13 | 43 |
| Trains per day | 13 | 43 |
| Existing protection | 10 | 37 |
| Sight distance | 7 | 14 |
| Train Speed | 6 | 13 |
| Number of tracks | 9 | 22 |
| Highway vehicular speed | 5 | 22 |
| Accident records | 5 | 23 |
| Condition or type of highway-rail grade crossing | 3 | 20 |
| Condition of approaches | 3 | 6 |
| Type of train | 3 | 5 |
| Approach gradient | 2 | 6 |
| Angle of highway-rail grade crossing | 2 | 5 |
| Pedestrian hazard | 2 | 1 |

**Table 7** Factors considered in the existing formulae (1986) (cont'd).

| **Factor Considered** | **Number of Formulae Containing the Factor (n=13)** | **Number of States Using the Factor in their Formulae (n=45)** |
|---|---|---|
| Distribution of vehicular and/or train volumes throughout the day | 3 | 14 |
| Time highway-rail grade crossing is blocked | 1 | 1 |
| Darkness | 1 | 1 |
| Number of traffic lanes | 2 | 15 |
| School buses and/or carriers of hazardous materials | 0 | 5 |

The study evaluated five most commonly used formulae and divided them into two groups: (1) relative formulae; and (2) absolute formulae. The absolute formulae estimate the expected number of accidents at highway-rail grade crossings, whereas the relative formulae determine a hazard index value that is further used to rank the highway-rail grade crossings. A list of the absolute and relative formulae, evaluated throughout the study, is shown in Table 8. The results from the conducted statistical analyses showed that the U.S. DOT Accident Prediction Formula outperformed the other four formulae in terms of raking the most hazardous highway-rail grade crossings in the State of Virginia.

**Table 8** Methods selected for evaluation and testing.

| **Relative Formulae** | **Absolute Formulae** |
|---|---|
| New Hampshire | DOT (U.S. DOT) |
| | Peabody-Dimmick |
| | NCHRP No. 50 (Virginia's Method: the current applied method by the conducting organization at that time) |
| | Coleman-Stewart |

### *2.1.2. State of Alabama (1994)*

Bowman (1994) conducted a comprehensive study, aiming to improve Alabama's Rail-Highway Safety Program. Under the study, a survey was performed among the Highway-Rail Program coordinators in each state of the U.S. (except Hawaii). The survey included a total of 34 questions, which were directly related to the program administration, state policies, current practices, and planned enhancements. A total of 41 responses were obtained from the State Highway-Rail Program coordinators. Based on the analysis of the collected responses, it was found that each state is mandated to have a priority schedule for safety improvement projects at highway-rail grade crossings. The priority schedule is generally developed based on potential accident reduction, project cost, relative hazard, and other state-specific criteria. The following accident and hazard prediction formulae were reported by states (Bowman, 1994): (1) the U.S. DOT Accident Prediction Formula – used by 11 states; (2) the New Hampshire Hazard Index Formula – used by six states; (3) the Peabody Dimmick Formula – used by two states; and (4) the NCHRP Report 50 Accident Prediction Formula – used by one state. A total of 13 states indicated that they used their own accident and hazard prediction formulae.

Furthermore, four states did not use any accident and hazard prediction formulae at the moment and developed the priority schedule based on public complaints, accident history, feedback from railroad companies, and field inspections of highway-rail grade crossings. Certain states, which used the New Hampshire Hazard Index Formula, underlined that some modifications were made to the original formula to capture important operational features and ensure the ranking accuracy of highway-rail grade crossings. Some State Highway-Rail Program coordinators mentioned a number of challenges, associated with implementation of the accident and hazard prediction formulae. More specifically, the U.S. DOT Accident Prediction Formula does not account for quadrant sight distance, roadway approach characteristics, and puts a lot of emphasis on the accident history. The study also highlighted that certain important data are not available in the FRA highway-rail grade crossing inventory database (e.g., sight distance, number of buses, passenger trains, school buses, hazardous material transporters), and field inspections are required in order to obtain the necessary information for the accident and hazard prediction formulae and resource allocation. Table 9 presents a summary of the highway-rail grade crossing prioritization methods used by states from the survey. Note that Table 9 was prepared using the data reported by Bowman (1994) [page 38 of the report].

**Table 9** Summary of prioritization methods from the conducted survey.

| Prioritization Method | Number of States | States Satisfied with Method | States Not Satisfied with Method |
|---|---|---|---|
| Peabody Dimmick Formula | 2 | 2 | 0 |
| New Hampshire Hazard Index Formula | 6 | 5 | 1 |
| NCHRP Report 50 Accident Prediction Formula | 1 | 1 | 0 |
| U.S. DOT Accident Prediction Formula | 11 | 9 | 2 |
| Other quantitative | 15 | 12 | 3 |
| Non-quantitative | 5 | 2 | 3 |
| Totals | 40 | 31 | 9 |

Based on the collected responses, approximately 83% of states using the New Hampshire Hazard Index Formula were satisfied with its performance (see Table 9). About 82% of states using the U.S. DOT Accident Prediction Formula were also satisfied (see Table 9). In terms of the average project implementation time (i.e., the time from the highway-rail grade crossing identification to installation of the appropriate countermeasure), a total of 19 states indicated that the average project implementation time varied between one and two years. The average project implementation time of two to three years was reported by 17 states, while four states indicated that the average project implementation time was typically greater than four years. A total of 24% of responses indicated that the primary cause for delays consisted in the fact that the railroad companies required a significant amount of time to process necessary paperwork (i.e., project plans, cost estimates, and agreements). A significant number of states indicated that delays generally occurred throughout the process of obtaining funding obligations from the FHWA, state, and/or local agencies.

Many Highway-Rail Program coordinators highlighted a poor accuracy of the data in the FRA highway-rail grade crossing inventory database. It was indicated that the information should be updated in an appropriate manner. Otherwise, the adopted accident and hazard prediction formulae will return the erroneous results, and State DOTs will not be able to identify the most hazardous highway-rail grade crossings, which require upgrading. The study also mentioned that many states do not inspect the description of accidents from the FRA highway-rail grade crossing accident/incident database. Certain important factors regarding the accidents (e.g., struck-by or striking the train, time of day, action of a highway user) are not considered. The latter may result in failure to select an appropriate and less expensive countermeasure (i.e., adding illumination in case if a lot of accidents were reported during the night).

The report indicated that Alabama used a Quasi-Accident Frequency Method to identify and prioritize the highway-rail grade crossings for safety improvement projects (Bowman, 1994). According to the Quasi-Accident Frequency Method, the priority schedule is developed based on complaints and requests from local agencies. The study suggested that the State of Alabama should adopt the U.S. DOT Accident Prediction Formula based on the results, obtained from the conducted survey, and the fact that FRA supported the U.S. DOT Accident Prediction Formula. The U.S. DOT Accident Prediction Formula and the Quasi-Accident Frequency Method were both used to rank the top 40 locations of the highway-rail grade crossings in Alabama, which were on the FRA prioritized list. The U.S. DOT Accident Prediction Formula outperformed the Quasi-Accident Frequency Method. Specifically, the U.S. DOT Accident Prediction Formula identified more hazardous highway-rail grade crossings as compared to the Quasi-Accident Frequency Method (Bowman, 1994). The U.S. DOT Accident Prediction Formula was found to be effective in prioritizing crossings by their accident potential.

### *2.1.3. State of Illinois (2000)*

Illinois Transportation Research Center prepared a report in collaboration with Illinois DOT regarding the evaluation of various accident and hazard prediction formulae, including the Illinois Expected Accident Frequency Formula used by Illinois DOT at the moment (Elzohairy and Benekohal, 2000). A survey was conducted among 49 states in order to collect the data regarding the methodologies, used to prioritize highway-rail grade crossings for safety improvement projects. A total of 32 states responded to the survey. The factors considered in each accident and hazard prediction formula, identified under the study, were highlighted in the report. Furthermore, the report indicated that the threshold values, used by State DOTs to select highway-rail grade crossings for upgrading, significantly varied (e.g., one accident every 10 years, 3 accidents every five years, the highest hazard rating as funding allows, minimum AADT value). Other important factors, considered by State DOTs throughout accident and hazard prediction and prioritization of highway-rail grade crossings, were also discussed, including adjacent land development, heavily used truck/bus routes, political considerations, age/condition of the equipment at highway-rail grade crossings, and others. Table 10 summarizes findings regarding the factors, thresholds, and other criteria used throughout the resource allocation. Note that Table 10 was prepared using the data reported by Elzohairy and Benekohal (2000) [pages 19 and 20 of the report].

**Table 10** Factors, thresholds, and other criteria used throughout the resource allocation (2000).

| **Factors in Formulae** | **Thresholds Used by Other DOTs** | **Other Criteria in Addition to the Formula** |
|---|---|---|
| Daily average train movements by train type and length | Highest hazard rating as funding allows | Adjacent land use and development |
| Speed of each type of train | One accident every 10 years | Political considerations |
| Number of blind quadrants | No firm minimum but vehicular traffic > 1,000 vehicles per day | Near-miss reports from the railroad |
| Posted vehicle speed limit | Project must be in top 1/3 of the index list | Heavily used truck/bus route |
| Angle of intersection | New Hampshire Hazard Index > 4,000 | Age and condition of the equipment |
| Curvature of the roadway | U.S. DOT predicted accidents (PA) > 0.075 | Restricted sight distance |
| Approach grade | Three accidents within five years | |
| Driveways and street intersections near a highway-rail grade crossing | One accident every nine years | |
| Average daily school bus traffic | | |
| Number of school bus passengers | | |
| Surface type | | |
| Heavy truck traffic | | |
| Factor for hazardous materials material hauling on the roadway | | |
| Average daily traffic | | |
| Average daily train traffic (day/night, switch/through) | | |
| Number of tracks | | |
| Number of lanes | | |
| Type of warning device | | |
| Type of area (urban vs. rural) | | |
| Accident history (number of accidents in *n* years) | | |

The survey respondents from the 32 states reported the following criteria that are generally used for ranking safety improvement projects: (1) higher hazard index/predicted accidents; (2) benefit-cost analysis; (3) site review of vehicle types (school bus, mass transit); (4) engineering judgment and highway-rail grade crossing geometry; (5) public concerns/complaints; (6) service condition; and (7) sight distance (Elzohairy and Benekohal, 2000). Along with the survey, conducted among State DOTs, the study presented a detailed review of the literature, where a total of six accident prediction formulae and five hazard index formulae were described (Table 11).

**Table 11** Existing formulae for accident and hazard prediction (2000).

| Accident Prediction Formulae | Hazard Index Formulae |
|---|---|
| Peabody-Dimmick | Illinois Commerce Commission |
| Oregon Highway Commission | Mississippi Formula |
| NCHRP Report 50 | The Oregon Method |
| Coleman-Stewart Model | New Hampshire Hazard Index Formula |
| TSC Model | Contra Costa County (California) |
| DOT (U.S. DOT) | |

After identifying the predictors considered by different states and their formulae, the study performed a regression analysis to determine the factors that affect the accident frequency the most using the data, which were collected for the highway-rail grade crossings in the State of Illinois. The following predictors were found to be the most influential:

- Average daily traffic (ADT)
- Average number of accidents per year (ANA)
- Maximum timetable speed (MTS)
- Number of day switch trains (NDST)
- Number of day time trains (NDTT)
- Number of lanes (NOL)
- Number of main tracks (NMT)
- Number of night switch trains (NNST)
- Number of nighttime trains (NNTT)
- Number of other tracks (NOOT)
- Number of total trains (NTT)
- Other multiplicative variables: ADT x NTT, ADT x NDTT, NOL x NMT

Finally, the report recommended that the Illinois Expected Hazard Frequency Formula should be replaced with the model, developed within the scope of the report. It was suggested that the recommended formula (the Illinois Modified Expected Accident Frequency Formula or the Illinois Hazard Index Formula) could be applied to predict the number of accidents at the highway-rail grade crossings irrespective of the location (urban/rural) and the type of warning device.

***2.1.4. State of Missouri (2003)***

Missouri DOT, Research, Development, and Technology Division carried out a study in collaboration with the University of Missouri-Columbia/Rolla to evaluate seven accident and hazard prediction models (Qureshi et al., 2003). The considered models included: (1) the U.S. DOT Accident Prediction Formula; (2) the California Hazard Rating Formula; (3) the Connecticut Hazard Rating Formula; (4) the Modified New Hampshire Hazard Index Formula; (5) the Kansas Design Hazard Rating Formula; (6) the Missouri Exposure Index Formula; and (7) the Illinois Hazard Index Formula. A new Exposure Index Formula was also developed under the study, which was based on the Kansas Design Hazard Rating Formula, and its performance was evaluated. The performance of the models was assessed by the expert panel, which included the representatives from Missouri DOT, FRA, U.S. DOT, and railroad companies. A set of criteria was adopted in order to evaluate the candidate accident and hazard prediction models. Table 12 presents the list of attributes, which were considered by the expert panel, including the model objectives, key model variables, and criteria for evaluation of the models. Note that Table 12 was prepared using the data reported by Qureshi et al. (2003) [pages 15–17 of the report].

**Table 12** Attributes considered by the expert panel for model evaluation.

| **Model Objectives** | **Model Variables** | **Criteria for Model Evaluation** |
|---|---|---|
| Safety (should improve safety) | Annual Daily Traffic | Accuracy of the model |
| Rank crossings in order of relative priority | Approach sight distance vs. recommended sight distance | Number of difficult variables |
| Weighting factors (account for importance of factors in calculating the number of accidents or hazard index) | Stopping sight distance vs. recommended sight distance | Explanation ability |
| Accident rate = 0 | Speed of train | Number of key variables |
| Accurately predict accident frequency | Number of passenger trains | Inclusion of the highway-rail grade crossing type |
| Explainable and definable | Speed of highway traffic | Number of unavailable data variables |
| Data elements available in highway-rail grade crossing inventory databases | Total number of trains | Total number of variables |
| Should suggest highway-rail grade crossing treatments | Clearance time for the motorist (i.e., time to clear a highway-rail grade crossing) | Inclusion of weighting factors |
| Cover the FHWA requirements | | |

The evaluation of each model was performed by developing a baseline ranking of six highway-rail grade crossings for each crossing control category (passive and active) by the Missouri DOT staff. After that the considered accident and hazard prediction models were applied in order to rank the same highway-rail grade crossings. The predicted rankings were compared to the baseline rankings, which were suggested by the Missouri DOT staff. The Spearman rank correlation coefficient factor was used to assess the difference between the baseline rankings and the predicted rankings for each one of the considered accident and hazard prediction models (Qureshi et al., 2003). The evaluation results revealed that the California Hazard Rating Formula exhibited the best performance for the highway-rail grade crossings with passive controls, while the Illinois Hazard Index Formula outperformed the other models in case of active controls. More information regarding the evaluation results, obtained by the expert panel, is provided in Table 13. Note that Table 13 was prepared using the data reported by Qureshi et al. (2003) [page 30 of the report].

### *2.1.5. State of Tennessee (2012)*

Tennessee DOT in collaboration with the University of Memphis performed a study, which aimed to allocate the available monetary resources for safety improvement projects at the highway-rail grade crossings in the State of Tennessee, reduce the number of accidents and the accident severity at the highway-rail grade crossings (Dulebenets, 2012). Under the study, a review of the literature was conducted in order to identify and describe the existing accident and hazard prediction formulae used by various DOTs. Nationally recognized methods (e.g., the Peabody Dimmick Formula, the New Hampshire Hazard Index Formula, the NCHRP Report 50 Accident Prediction Formula, the U.S. DOT Accident Prediction Formula) and state-specific approaches (e.g., the California Hazard Rating Formula, the Connecticut Hazard Rating Formula, the Illinois Hazard Index Formula) for accident and hazard prediction were analyzed. The U.S. DOT procedures for accident prediction and resource allocation among the highway-rail grade crossings were discussed as well.

**Table 13** Summary of the evaluation results.

| Highway-Rail Grade Crossing Control Type | Model Ranking |
|---|---|
| Passive | 1. California Hazard Index<br>2. Illinois Hazard Index Formula<br>3. Modified New Hampshire Hazard Index Formula<br>4. U.S. DOT Accident Prediction Formula<br>5. Kansas Design Hazard Rating<br>6. Connecticut Hazard Index<br>7. Modified Exposure Index Formula<br>8. Missouri Exposure Index Formula |
| Active | 1. Illinois Hazard Index Formula<br>2. Kansas Design Hazard Rating<br>3. Connecticut Hazard Index<br>4. Missouri Exposure Index Formula<br>5. Modified Exposure Index Formula<br>6. U.S. DOT Accident Prediction Formula<br>7. Modified New Hampshire Hazard Index Formula<br>8. California Hazard Index |

The study also provided a detailed review of the Tennessee Roadway Information Management System (TRIMS) database, which contains the important information regarding the highway-rail grade crossings in the State of Tennessee (e.g., crossing location, train volume, AADT, roadway pavement type, number of travel lanes, posted roadway speed limit, type of roadway functional class, type of crossing surface, type of preemption if available, type of warning device). The TRIMS database also has the information regarding the number of predicted accidents, estimated based on the U.S. DOT Accident Prediction Formula, for each highway-rail grade crossing. However, the TRIMS database does not have certain information, which is used by other accident and hazard prediction formulae (e.g., sight distance).

Two optimization models were developed as a part of the study in order to assist TDOT with resource allocation for safety improvement projects at the highway-rail grade crossings in the

State of Tennessee. The objective of the first optimization model aimed to maximize the total accident reduction, while the second optimization model maximized the total weighted accident reduction by severity category. A total of three severity categories were considered, including the following: (1) fatality; (2) injury; and (3) property damage. Three basic countermeasure types, suggested by the canonical U.S. DOT resource allocation procedure (U.S. DOT, 2007), were considered: (1) passive to flashing lights; (2) passive to gates; and (3) flashing lights to gates. The effectiveness factors of countermeasures and associated costs were adopted from the Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007). A number of sorting algorithms were developed to solve the proposed optimization models. The sorting algorithms were based on the basic attributes, used throughout the resource allocation procedure and discussed in the Rail-Highway Grade Crossing Handbook (i.e., accident reduction, severity reduction, accident reduction/cost ratios, and accident severity reduction/cost ratios) (U.S. DOT, 2007).

### *2.1.6. State of Texas (2013)*

The University of Texas at San Antonio and Texas A&M Transportation Institute conducted a study in collaboration with Texas DOT and FHWA to develop a new methodology in order to prioritize public highway-rail grade crossings for safety improvement projects in the State of Texas (Weissmann et al., 2013). The study underlined that the State of Texas used the Texas Priority Index, which generally gave higher priority ranking to the high-volume highway-rail grade crossings based on the accident history. Once the high-volume highway-rail grade crossings had been upgraded, the challenge was to make modifications in the existing methodology; so, it could be applied for prioritization of the low-volume highway-rail grade crossings.

Throughout the study, some State DOTs were contacted with a request to provide the information regarding the variables, which are used in their accident and hazard prediction formulae. In addition, other accident and hazard prediction formulae were identified through the review of literature that was performed under the study. A summary of the collected information regarding the key variables, used by State DOTs in the accident and hazard prediction formulae, is presented in Table 14. Note that Table 14 was prepared using the data reported by Weissmann et al. (2013) [page 2-3 of the report]. It was found that the exposure variables (train volume and traffic volume), warning device type, and accident history were the most common variables used in the existing accident and hazard prediction formulae. Number of tracks and sight distance were also found to be fairly common variables among the considered accident and hazard prediction formulae. Train type (passenger/freight), bus or special vehicle use at the crossing, approach grade, crossing angle, train speed, pedestrian volume, crossing condition (e.g., surface type, humped/not humped), road/track alignment, road surface, and highway type were used less often in the considered accident and hazard prediction formulae (Weissmann et al., 2013).

The study proposed an alternative measure against the existing Texas Priority Index, which was referred to as the Revised Texas Priority Index. The Revised Texas Priority Index for a given highway-rail grade crossing is estimated based on the predicted number of accidents per year and the number of accidents observed over the last five years. The predicted number of accidents per year is calculated based on the following variables (Weissmann et al., 2013): (1) protection factor – $P\_f\_indicator\_T$ (= 0.5061 if flashing lights; = -0.2006 if gates; = 0 if passive); (2) highway pavement – $HwyPaved$ (= 1 is paved; = 2 if not paved); (3) $UrbanRural$ (= 1 if urban; = 2 if rural); (4) number of traffic lanes – $TrafLane$; (5) number of the main and other tracks – $TotalTrack$; (6) actual sight distance, approach 1 – $ActualSD1$; (7) maximum train speed (through trains) – $MaxSpeed$; (8) minimum train speed (switching trains) – $MinSpeed$; (9) daily train volume – $TotalTrn$; (10) vehicular AADT – $AADT$; (11) nearby roadway intersection – $NearbyInt$ (= 1 if present; = 2 if not present); and (12) higher roadway speed limit between approach 1 and approach 2 – $Higher\_SPD\_Lmt$. More details regarding the Revised Texas Priority Index Formula is provided in section 2.4.18 of this report.

**Table 14** Variables used in accident and hazard prediction formulae.

| Index | Traffic Volume | Train Volume | Warning Device | Accidents | Number of Tracks | Sight Distance | Train Type | Bus\Special Vehicle | Train Speed | Approach Grade | Crossing Angle | Pedestrian Volume | Crossing Condition | Road/Track Alignment | Road Surface | Highway Type\Lanes | Highway Speed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Texas | ✓ | ✓ | ✓* | ✓ | | | | ✓ | ✓ | | | | | | | | |
| USDOT | ✓* | ✓* | ✓* | ● | ✓* | | ✓* | | ✓* | | | | | | ✓* | ✓* | |
| Peabody Dimmick | ✓ | ✓ | ✓* | ● | | | | | | | | | | | | | |
| New Hampshire | ✓ | ✓ | ✓* | | | | | | | | | | | | | | |
| NCHRP | ✓* | ✓ | ✓* | ● | | | | | | | | | | | | | |
| Florida | ✓ | ✓ | ✓ | ●✓ | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| Ohio | | | | ✓* | ✓* | ✓* | | | ✓* | ✓* | ✓* | | | | | | |
| Mississippi | | | | ✓ | | ✓* | | | | | | | | | | | |
| Wisconsin | ✓ | ✓ | | ✓ | | ✓* | | | | | | ✓ | | | | | |
| North Dakota | ✓ | ✓* | ✓* | | ✓* | ✓* | | | | ✓* | ✓* | | ✓* | ✓* | | | |
| Missouri | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | | | | | | | | ✓ |
| City of Detroit | ✓ | ✓ | ✓* | ✓ | ✓* | ✓* | ✓ | | | ✓* | | | ✓* | | | | |
| Coleman-Stewart | ✓ | ✓ | ✓* | ✓ | ✓* | | | | | | | | | | | | |

✓ - variable present; ✓* - variable present as a factor or rating; ● - formula is an accident prediction equation

*Source: Weissmann et al. (2013). Integrated Prioritization Method for Active and Passive Highway-Rail Crossings*

The Revised Texas Priority Index Formula was validated against the existing Texas Priority Index Formula for 9,108 highway-rail grade crossings and 2011 accident data. It was found that the Revised Texas Priority Index Formula was able to identify the most hazardous highway-rail grade crossings that have to be considered for future safety improvement projects more effectively as compared to the original Texas Priority Index Formula. More specifically, the Revised Texas Priority Index Formula identified 13%, 21%, and 59% from the list of top 1%, top 2%, and top 25% most hazardous highway-rail grade crossings, respectively. On the other hand, the original Texas Priority Index Formula identified 10%, 15%, and 57% from the list of top 1%, top 2%, and top 25% most hazardous highway-rail grade crossings, respectively.

The study also reviewed different methodologies that are used to issue warrants for passive highway-rail grade crossings. The candidate methodologies were selected based on potential compatibility with Texas DOT's Rail Division practices, initial eligibility (i.e., the warrants are applicable to public passive highway-rail grade crossings that either had one or more accidents in the past five years or serve at least two trains per day), applicability as a highway-rail grade crossing management tool, and permanence. A total of four national guidelines were analyzed, including the following: (1) Idaho DOT; (2) Illinois DOT; (3) FHWA; and (4) FDOT. As a result of the conducted analysis, it was found that FDOT's methodology was stricter than other methods considered, as it selected 1,131 crossings for warrants. The methodologies, used by Illinois DOT and FHWA, selected 856 and 810 highway-rail grade crossings for warrants, respectively. It was concluded that the following factors should be considered in order to issue warrants for passive highway-rail grade crossings in Texas: AADT, train traffic, accident history, multiple tracks, school buses, parallel highway in conjunction with other risk factors, sight distance obstructions, vehicular and train speeds, and urban/rural designation.

**Table 15** The Texas Passive Crossing Index variables and weights.

| **Attribute** | **Normalized Weight** |
|---|---|
| Five-year crashes | 5.0000 |
| Daily trains | 4.7780 |
| Daily school buses | 4.7780 |
| Number of tracks | 3.8568 |
| Train speed | 3.8568 |
| AADT | 3.2922 |
| Nearby traffic signal | 3.0160 |
| Sight distance | 3.0160 |
| Trucks per day | 1.9300 |
| Nearby intersection | 1.8038 |
| Highway speed limit | 1.7132 |
| Approach angle | 1.5016 |
| Dip/hump | 1.0000 |

As a part of the study, a Texas Passive Crossing Index was proposed in order to prioritize passive highway-rail grade crossings, which received warrants, for safety improvement projects. The Texas Passive Crossing Index was estimated as a weighted average of certain variables. A total of 13 variables were selected for calculation of the Texas Passive Crossing Index. The weights of the selected variables were set using the data, collected throughout the workshop that was conducted during the study from a number of researchers. The responses from researchers were normalized, and the estimated weights are presented in Table 15 for each one of the variables, selected for calculation of the Texas Passive Crossing Index.

An adjustment factor for the Revised Texas Priority Index was developed in order to give a fair consideration to both passive and active highway-rail grade crossings in the priority list (since active highway-rail grade crossings are likely to receive higher priority rankings due to a higher number of accidents in the past five years). The adjustment factor was estimated for a given warranted passive highway-rail grade crossing based on the number of warrants met and the number of accidents in the most recent five-year time period. Therefore, application of the adjustment factor makes the Revised Texas Priority Index equally sensitive to the number of warrants, issued for passive highway-rail grade crossings, and the number of accidents over the recent five-year time period, which are generally observed at active highway-rail grade crossings. The following 10 warrants were suggested for passive highway-rail grade crossings (Weissmann et al., 2013):

- Warrant 1: Past Five-Year Crashes ≥ 1
- Warrant 2: Trains per Day ≥ 95% Cumulative Percentiles for Urban and Rural Areas
- Warrant 3: School Buses per Day ≥ 94% Cumulative Percentile of the Subset of Eligible Crossings that Serve School Buses
- Warrant 4: Total Number of Tracks ≥ 2
- Warrant 5: Train Speed ≥49 mph and AADT ≥ 75% Cumulative Percentile in Urban/Rural Areas
- Warrant 6: Either AADT or Exposure ≥ 95% Percentile for Rural Areas and ≥ 90% Percentile for Urban Areas
- Warrant 7: Average Number of Heavy Vehicles per Day ≥ 95% Percentile
- Warrant 8: Passenger Trains/Day ≥ 1
- Warrant 9: Presence of a Stopped Sight Distance Obstruction (0<Stopobs1<8 or 0<Stopobs2<8)
- Warrant 10: Highway Parallel to and less than 75 ft from Tracks when Other Factors Are Present

The study proposed an integrated methodology to prioritize the highway-rail grade crossings for safety improvement projects. The methodology starts with prioritizing separately passive and active highway-rail grade crossings. Active highway-rail grade crossings should be prioritized based on the Revised Texas Priority Index, while passive highway-rail grade crossings should be prioritized based on the Revised Texas Priority Index and the Texas Passive Crossing Index. The overall priority list should be developed by combining the top passive and the top active highway-rail grade crossings. After that, the highway-rail grade crossings from the overall priority list should be sorted based on the Revised Texas Priority Index with application of the adjustment factor for warranted passive highway-rail grade crossings. The remaining highway-rail grade crossings should be also sorted and added to the list. Upon development of the priority list and sorting the highway-rail grade crossings based on the adjusted Revised Texas Priority Index, the appropriate recommendations should be given regarding safety improvement projects.

### *2.1.7. State of Iowa (2015)*

Iowa DOT in collaboration with the Institute for Transportation at Iowa State University focused on development of a methodology to prioritize the highway-rail grade crossings for safety improvement projects in the State of Iowa (Iowa DOT, 2006; Hans et al., 2015). As a part of the literature review, the study discussed well-known accident and hazard formulae, which have been used by State DOTs, including the Kansas Design Hazard Rating Formula, the California Hazard Rating Formula, the U.S. DOT Accident Prediction Formula, the New Hampshire Hazard Index Formula, the Texas Priority Index Formula, and others (Hans et al., 2015). In 2002, Iowa DOT performed a corridor study of the Union Pacific West-East mainline across Iowa, aiming to investigate grade separation and consolidation of the highway-rail grade crossings (Hans et al., 2015). Some data inconsistences were pointed out, as the data had not been collected on a regular basis and were outdated. Also, it was mentioned that certain highway-rail grade crossings had a fairly low exposure rating, but the expected number of accidents was significant (Hans et al., 2015).

A safety action plan for the highway-rail grade crossings was developed by Iowa DOT in 2012. The purpose of the action plan is to reduce the number of accidents at the highway-rail grade crossings in the State of Iowa, identify the most hazardous highway-rail grade crossings, and determine specific engineering solutions for improving the highway-rail grade crossing safety. Iowa DOT has been using the benefit-cost analysis in order to allocate the available monetary resources among the highway-rail grade crossings that require safety improvement projects. The benefit-cost analysis is based on seven major steps, which include the following (Iowa DOT, 2006): (1) calculate exposure; (2) calculate the number of predicted accidents; (3) calculate the accident severity; (4) calculate the societal cost; (5) calculate benefits; (6) calculate costs; and (7) calculate the benefit-cost ratio.

The exposure of a highway-rail grade crossing is estimated based on the AADT, the number of daily trains, and the time-of-day exposure correlation factor. The number of predicted accidents is calculated using the exposure value, train-movement factors, roadway and highway-rail grade crossing characteristics, and type of the existing warning device. Similar to the U.S. DOT Accident Prediction Formula, the initial number of predicted accidents is adjusted based on the accident history over the last five years. The accident severity (i.e., fatality, injury, or property damage) is assessed based on the number of train movements and the environment factors associated with a highway-rail grade crossing. More details regarding estimation of the predicted accidents and accident severity is provided in section 2.4.7 of this report. The societal cost is calculated as a summation of the total costs associated with fatality, injury, and property damage accidents. The costs of each fatality, injury, and property damage accident are assumed to be $1,000,000, $320,000, and $26,000, respectively (Iowa DOT, 2006).

The benefits are estimated based on the effectiveness factors associated with the countermeasure that will be applied at a given highway-rail grade crossing. The effectiveness factor is the rate of reduction in the number of predicted accidents after implementation of a given countermeasure (U.S. DOT, 2014). The values of effectiveness factors for the common types of countermeasures (e.g., passive to flashing lights, passive to lights and gates, installation of a median at crossings with gates) are typically adopted from the GradeDec.NET Reference Manual (U.S. DOT, 2014) and the data available through Iowa DOT. Once the total cost associated with a given safety improvement project is estimated, the benefit-cost ratio can be further calculated for implementation of the selected countermeasure at a given highway-rail grade crossing.

The study, conducted by Hans et al. (2015), highlighted that the following factors should be considered throughout selection of the highway-rail grade crossings for safety improvement projects:

1) *Demand factors* (AADT, heavy-truck annual average daily traffic [TAADT], proximity to emergency medical services [EMSFRQ3 – within 3 miles, EMSFREQ6 – within 6 miles], distance to the nearest emergency medical service [EMSDIST], proximity to primary and secondary schools [SCHFRQ2 – within 2 miles, SCHFRQ6 – within 6 miles], distance to the nearest school [SCHDIST], roadway system [RDSYS] – capturing potential effects of the crossing closure on the Iowa transportation system);
2) *Alternate route factors* (out-of-distance travel [ALTDIST] – capturing potential effects of the crossing closure on motorists, alternate route accident rate [ALTRATE]);
3) *Other railroad- and roadway-related factors considered but not included in the analysis* (e.g., proximity of an intersection, humped crossings).

A weighted-index method and an accompanying Microsoft Excel spreadsheet-based tool were developed for prioritization of the highway-rail grade crossings based on the aforementioned factors. The factors were weighted based on the location of highway-rail grade crossings (e.g., urban vs. rural). Examples of factor weights for urban and rural areas, which were provided by the study, are presented in Table 16. Note that Table 16 was prepared using the data reported by Hans et al. (2015) [page 35 of the report]. The weight values were determined based on consultation with the Technical Advisory Committee members (Hans et al., 2015). The advantage of using such weighted-index method consists in the fact that the weight of different factors could be adjusted if the priorities of any factors change. The composite indexes were computed for both urban and rural highway-rail grade crossings using Microsoft Excel spreadsheets. The estimated index values were further used to rank urban and rural highway-rail grade crossings.

**Table 16** Examples of factor weights for urban and rural areas.

| Factor | Urban | Rural |
|---|---|---|
| AADT | 0.16185 | 0.16185 |
| ALTDIST | 0.17341 | 0.17341 |
| TAADT | 0.04624 | 0.04624 |
| RDSYS | 0.08671 | 0.12139 |
| EMSFRQ3 | 0.12717 | - |
| EMSFRQ6 | - | 0.12717 |
| EMSDIST | 0.12717 | 0.12717 |
| SCHFRQ2 | 0.08671 | - |
| SCHFRQ6 | - | 0.06936 |
| SCHDIST | 0.08671 | 0.06936 |
| ALTRATE | 0.10405 | 0.10405 |

*Source: Hans et al. (2015). Development of Railroad Highway Grade Highway-Rail Grade Crossing Consolidation Rating Formula*

***2.1.8. State of Nevada (2017)***

Ryan and Mielke (2017) investigated the traditional methods, which have been used to prioritize highway-rail grade crossings for safety improvement projects. The traditional methods reported in the study were: (1) the New Hampshire Hazard Index Formula; (2) the U.S. DOT Accident Prediction Formula; (3) the Peabody-Dimmick Accident Prediction Formula; (4) the NCHRP Report 50 Accident Prediction Formula; and (5) the Texas Priority Index Formula. The report referred to two major surveys that were previously conducted among State DOTs, aiming to collect the data regarding the accident and hazard prediction methods used for highway-rail grade crossings. The first survey was conducted in 1986 (the State of Virginia), while the second one was performed in 2000 (the State of Illinois). A total of 45 states participated in the first survey, while the second survey had 32 respondents. The results of both surveys are summarized in Figure 11. Note that Figure 11 was prepared using the data reported by Ryan and Mielke (2017) [page 7 of the report]. Based on both surveys, it can be observed that the majority of states use their own formulae for accident and hazard prediction methods at highway-rail grade crossings. A significant number of states use the U.S. DOT Accident Prediction Formula.

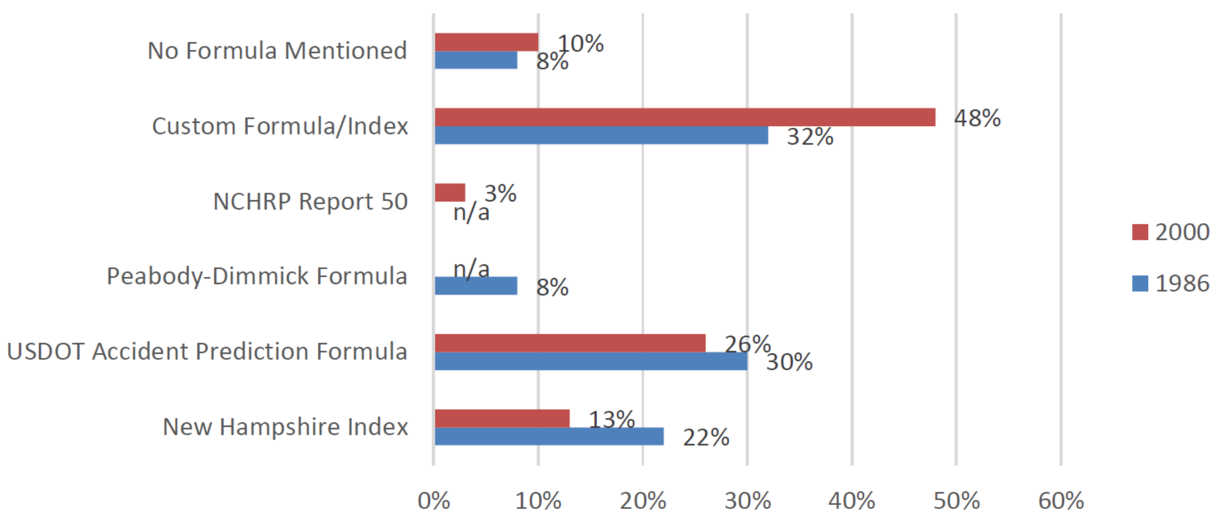


**Figure 11** Accident and hazard prediction formulae employed by State DOTs (2017).
*Source: Ryan and Mielke (2017). Development of Revised Grade Highway-Rail Grade Crossing Hazard Index Model*

Throughout the study, a set of peer interviews were conducted with the DOT representatives from the following states: (1) Arizona; (2) Oregon; and (3) Utah. The states were selected based on a number of similarities with Nevada, including location, large rural areas, and significant presence of trucking activities related to extraction of natural resources. The Arizona DOT representative indicated that they use the Texas Priority Index for prioritizing the highway-rail grade crossings. However, it was highlighted that the Texas Priority Index does not account for certain important factors, such as train speeds, school bus usage, transport of hazardous materials, urban/rural distinction, and others. Furthermore, stakeholders play an important role in selection of the highway-rail grade crossing safety improvement projects in Arizona. A custom accident prediction formula is used by Oregon DOT, which is called the “Jaqua model”. Some discretion can be applied by the Oregon DOT representatives throughout selection of the highway-rail grade crossing safety improvement projects. For example, a crossing with a lower priority can be upgraded first if the implementation project would not result in bus route changes, adjacent crossing closures, increased truck traffic, and/or other negative externalities.

The Utah DOT representative indicated that they use the FRA Web Based Accident Prediction System (WBAPS), which is based on the U.S. DOT Accident Prediction Formula. WBAPS is used to create a list of top 50 highway-rail grade crossings. However, the accident prediction is only a starting point throughout the decision making. Individual highway-rail grade crossing reviews are conducted to collect the additional data (e.g., site-specific safety issues, local weather conditions, highly skewed intersections) in order to select crossings for upgrading. Two important safety-related issues at the highway-rail grade crossings were pointed out by the Utah DOT representative during the conducted interview, including: (a) pedestrian safety; and (b) traffic signal preemption.

The study highlighted that apart from the traditional factors, which influence the occurrence of accidents and are commonly used in the existing accident and hazard prediction formulae (e.g., highway and train volumes, existing warning devices, and accident history), some other factors may significantly influence the number of accidents at highway-rail grade crossings. The report provided references to "Minnesota Crude-by-Rail Study" and "Minnesota DOT Rail Grade Crossing Safety Project Selection", listing the following factors (Ryan and Mielke, 2017):

***Minnesota Crude-by-Rail Study***

- Traffic and train volumes and speeds
- Population in hazmat evacuation zones (schools, senior communities, etc.)
- Makeup of vehicle traffic including heavy truck and school bus
- Physical conditions at a highway-rail grade crossing

***Minnesota DOT Rail Grade Crossing Safety Project Selection***

- Roadway and train volumes
- Roadway and railroad speed limits
- Number of mainline tracks
- Highway-rail grade crossing angle
- Distance to nearby intersections
- Distance to nearest highway-rail grade crossings
- Sight distance limitations

The highway-rail grade crossing characteristics that were most commonly used by the considered accident and hazard prediction methodologies are presented in Figure 12. Note that Figure 12 was prepared using the data reported by Ryan and Mielke (2017) [page 28 of the report]. Based on the collected data, it was found that the train volume and the highway traffic volume were the key components for each one of the considered accident and hazard prediction formulae. The latter finding can be considered as intuitive, as every additional train and every additional vehicle increase the likelihood of an accident at a given highway-rail grade crossing. The highway speed was considered only in the methodologies, used by the States of Oregon and Minnesota. However, train speed was included in five of the considered accident and hazard prediction formulae. Other fairly common model inputs included the following: information regarding the existing warning device, accident history, accident severity, number of tracks, distinction between urban and rural crossings, and sight distance restrictions. The highway-rail grade crossing geometric characteristics (e.g., crossing angle, approach curves/grades) and surrounding environment characteristics (e.g., population characteristics, presence of school buses) were taken into account only by a few accident and hazard prediction formulae.

| **Crossing Characteristic** | Nevada (Modified New Hampshire Index) | USDOT Accident Prediction Formula | Peabody-Dimmick Crash Prediction Formula | NCHRP Report 50 Accident Prediction Formula | Texas Priority Index | Oregon (Jaqua Model) | Minnesota Crude-by-Rail Study | Minnesota Suggested Risk Factors |
|---|---|---|---|---|---|---|---|---|
| Highway Traffic Volumes | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Highway Speed | | | | | | ■ | | ■ |
| Train Volumes | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Train Speed | | ■ | | | ■ | ■ | ■ | ■ |
| Existing Warning Devices | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| Crash History | ■ | ■ | | | ■ | ■ | ■ | |
| Crash Severity | ■ | ■ | | | | | ■ | |
| Number of Tracks | | ■ | | | | ■ | ■ | ■ |
| Number of Highway Lanes | | ■ | | | | | ■ | |
| Highway Pavement | | ■ | | | | | ■ | |
| Urban/Rural Classification | | ■ | | ■ | | ■ | | |
| Sight Distance Restrictions | | | | | | ■ | ■ | ■ |
| Crossing Angle | | | | | | ■ | | ■ |
| Highway Approach Geometry | | | | | | ■ | | |
| Rail Approach Geometry | | | | | | ■ | | |
| Proximity of Highway Accesses | | | | | | ■ | | |
| Proximity to Highway Intersections | | | | | | ■ | | ■ |
| Functional Classification | | ■ | | | | | ■ | |
| Hazardous Materials | | | | | | | | |
| Commercial/Heavy Vehicles | | | | | | | ■ | |
| School Buses | | | | | | | ■ | |
| Passenger Trains | | | | | | ■ | | |
| Nearest At-Grade Crossing | | | | | | | | ■ |
| Population Characteristics | | | | | | | ■ | |
| Physical Condition of Crossing | | | | | | | ■ | |
| Railroad Close Call/Near Miss List | | | | | | | ■ | |

**Figure 12** Factors used in accident and hazard prediction formulae (2017).
*Source: Ryan and Mielke (2017). Development of Revised Grade Highway-Rail Grade Crossing Hazard Index Model*

**Table 17** Summary of the potential hazard index inputs and reviewed factors.

| Characteristic | Description | Proposed Hazard Index Variable Options |
|---|---|---|
| Average Daily Traffic | This factor was found to have a clear correlation with accidents and near misses and should be the base input for the proposed hazard index. | Raw ADT Count |
| Average Daily Train Counts | This factor alone was found to have a small correlation with accidents. If used, an adjusted input value based on thresholds may be appropriate. | • Raw Train Count<br>• Multiplier based on threshold (0-10 trains, 11-20 trains, etc.) |
| Exposure Index (ADT x Train Counts) | This factor was found to have a stronger correlation to accidents and near misses than the use of each factor individually. In order to avoid overemphasis of high-volume highway-rail grade crossings, this factor may also be modified such as through the use of squaring the index value. | • Raw Exposure Index<br>• Modified Exposure Index (e.g., Squared Root of Index Value) |
| Highway Speed | The correlation between accident rates and highway speed tended to be grouped into similar rates for three distinct speed limit ranges. Highway speed could be factored based on these ranges or raw speed limit alone could be applied as an unmodified factor. | • Raw posted speed<br>• Speed Factors:<br>➢ $\leq$ 30 mph = 1.0<br>➢ 35-65 mph = 1.25<br>➢ 70 mph = 1.50 |
| Train Speed | Due to the lack of correlation between train speed and accidents or near misses, it is not recommended that the proposed hazard index include a variable for this characteristic. | No recommended variable |
| Urban/Rural | The granular distinctions between varying levels of urban and rural designation are better handled using highway ADT or Exposure Index. | No recommended variable |
| Current Warning Devices | The presence of existing warning devices will play a role in estimating levels of safety. The use of a protection factor will also aid in the determination of when the next level of improvement is warranted. While this review found no difference between gates with or without medians, the existing research suggests that a higher protection value is warranted for gates with medians. | Protection Factors:<br>➢ Passive or Flashing Lights Only = 1.0<br>➢ Gates = 0.5<br>➢ Gates with Medians = 0.2 |

**Table 17** Summary of the potential hazard index inputs and reviewed factors (cont'd).

| **Characteristic** | **Description** | **Proposed Hazard Index Variable Options** |
|---|---|---|
| Truck Percentage | The review found very slight correlations between truck percentage and accidents. However, the existing research shows that accidents involving heavy vehicles are much more likely to result in fatal or injury accidents. | • Multiplier based on percentage (e.g., 1.07 for 7 percent of trucks)<br>• Multiplier based on thresholds (0-5%, 6-10%, etc.) |

**Table 18** Summary of the Nevada Hazard Index Model evaluation analysis.

| Factor | Approach | Correlation with Expert Panel Ranking | Correlation with Crash/Near Miss Data | Data Availability | Complexity | Recommended |
|---|---|---|---|---|---|---|
| Exposure Index | Linear | Medium | Medium | High | High | No |
| | Squared Root | Medium | High | High | Medium | Yes |
| Crash History | Current | High | Medium | High | Low | No |
| | Texas Priority Index Approach | Medium | Medium | High | Medium | No |
| | Reducing Weight of Crash History | Low | Medium | High | High | No |
| Near Miss History | Texas Priority Index Approach | Low | Medium | Medium | Medium | No |
| | Combination of Crash and Near Miss Data | Low | Medium | Medium | Medium | Yes |
| Protection Factor | Current | Medium | Medium | High | High | No |
| | Crash Rate-Based | High | High | High | High | Yes |
| Highway Speed | Formula Approach | Medium | Medium | High | High | No |
| | Simple Factors | High | Medium | High | High | Yes |
| | Combination with Train Speed | High | Low | Medium | Medium | No |
| Rail Speed | Texas Priority Index Approach | Medium | Low | Medium | High | No |
| | Formula Approach | Medium | Low | Medium | High | No |
| Heavy Commercial Vehicles | Proportion | Medium | Low | Medium | High | No |
| | Heavy Commercial/Pass. Train Volumes | Medium | Low | Medium | Medium | No |
| Passenger Trains | Simple Factors | Medium | Low | High | High | No |
| Track Configuration | Simple Factors | Medium | High | High | High | Yes |
| Population Density | Simple Factors | Low | Low | Low | High | No |
| Crossing Angle | Simple Factors | Medium | High | High | High | Yes |

*Source: Ryan and Mielke (2017). Development of Revised Grade Highway-Rail Grade Crossing Hazard Index Model*

As a result of the analysis, conducted for Nevada's highway-rail grade crossings, some correlation between the crossing characteristics and accident/near miss data was identified. Table 17 provides more information regarding the potential hazard index inputs and reviewed factors. Note that Table 17 was prepared using the data reported by Ryan and Mielke (2017) [page 30 of the report]. The final recommendation for the hazard index model was based on individual assessments of each potential factor and a review of the effects of various factors. The following criteria were used throughout the evaluation: (1) correlation with expert panel ranking; (2) correlation with accident/near miss data; (3) data availability/ease of collection; and (4) complexity. The evaluation analysis summary is presented in Table 18. Note that Table 18 was prepared using the data reported by Ryan and Mielke (2017) [page 55 of the report].

### *2.1.9. State of Ohio (2017)*

Ohio DOT in collaboration with Ohio University and Texas A&M Transportation Institute performed a study, aiming to assist with selection of the highway-rail grade crossings for safety improvement projects (Sperry et al., 2017). The analysis of the highway-rail grade accident data for the State of Ohio revealed that an average of 110 accidents occurred annually between 2005 and 2010, while an average of 67 accidents was recorded per year between 2010 and 2015. It was indicated that two agencies are responsible for safety improvement projects at the highway-rail grade crossings in the State of Ohio, including the following (Sperry et al., 2017): (1) Ohio Rail Development Commission (ORDC), which administers the Federal Railway-Highway Crossings Program (Section 130) funds on behalf of Ohio DOT and coordinates other safety initiatives; and (2) Public Utilities Commission of Ohio (PUCO), which maintains the highway-rail grade crossing inventory database, conducts regulatory oversight, and performs the annual crossing inspection. Based on a detailed review of the 2010-2015 accident data, it was found that the highway-rail grade crossings, which experienced accident(s), generally had higher train volumes, train speeds, and more tracks, as well as higher AADT than the statewide average over all the highway-rail grade crossings. Although higher highway and train traffic volumes were recorded at the highway-rail grade crossings with active warning devices, one-third of accidents occurred at passive highway-rail grade crossings (Sperry et al., 2017).

The highway-rail grade crossing improvement program is administered in three steps in the State of Ohio, including the following: (1) develop the list of candidate grade crossing locations; (2) diagnostic review of the candidate grade crossing locations (the team includes ORDC, railroad, and local highway agency representatives); and (3) project implementation (typical project is approximately $250,000; 20 –30 projects are generally conducted per funding cycle). ORDC and PUCO have been using the U.S. DOT Accident Prediction Formula to develop the list of candidate highway-rail grade crossing locations, which should be considered for future upgrading. The estimated number of predicted accidents is used to assess the hazard of highway-rail grade crossings. It was highlighted that the mathematical models, which are used by State DOTs for prioritizing highway-rail grade crossings, are expected to provide a similar ranking of highway-rail grade crossings as the actual ranking of highway-rail grade crossings, obtained based on a recent accident data.

As a part of the study, a detailed review of the existing accident and hazard prediction formulae, which have been deployed by State DOTs to rank highway-rail grade crossings for safety improvement projects, was conducted. The latter task was achieved through a comprehensive literature review, telephone interviews with representatives from State DOTs/other relevant agencies, and a detailed evaluation of the selected accident and hazard prediction formulae. Some of the interviewed organizations included the following (Sperry et al., 2017): (1) California Public Utilities Commission; (2) Illinois DOT; (3) Kansas DOT; (4) Michigan DOT; (5) Missouri DOT; (6) New Mexico DOT; (7) North Carolina DOT; and (8) Texas DOT. Table 19 presents a distribution of accident and hazard prediction formulae by states, which was developed based on the collected data.

From Table 19, the majority of states (19 states or 38% of states) relied on the U.S. DOT Accident Prediction Formula. A total of 11 states (or 22% of states) adopted state-specific formulae or methods, while other 11 states (or 22% of states) either did not use a formula or did not mention the formula used. Moreover, five states (or 10% of states) adopted the New Hampshire Hazard Index Formula. Two states (or 4% of states) used more than one formula. The NCHRP Report 50 Accident Prediction Formula and Peabody-Dimmick Formula were each adopted by one state. According to the study, the typical factors that were considered in the models included train volume, train speed, number of tracks, existing warning device, AADT, accident history, and number of lanes (Sperry et al., 2017). The factors, which are not considered by the State of Ohio throughout prioritization of the highway-rail grade crossings but are used by other states, were listed, including the following: (1) stopping sight distance (considered by nine states and used in three formulae); (2) school bus/special vehicle volume (considered by four states and used in two formulae); (3) highway traffic speed (considered by five states and used in three formulae); (4) proximity of a highway-rail grade crossing to a nearby intersection (considered by three states and used in one formula); and (5) “Close Call” data.

**Table 19** Distribution of accident and hazard prediction formulae by states.

| **Formula/Method** | **Number of States** | **Percent of States** |
|---|---|---|
| U.S. DOT Accident Prediction Model | 19 | 38% |
| State-Specific Formula or Method | 11 | 22% |
| None/No Formula Mentioned | 11 | 22% |
| New Hampshire Hazard Index | 5 | 10% |
| Multiple Formulas | 2 | 4% |
| NCHRP 50 Accident Prediction Model | 1 | 2% |
| Peabody-Dimmick Formula | 1 | 2% |
| Total All States | 50 | 100% |

Some representatives from State DOTs/other relevant agencies expressed their concerns regarding the accuracy of data used in accident and hazard prediction formulae. Throughout the interviews, it was found that train counts and AADT were not updated on a regular basis in certain states. Field inspectors and local data sources should be used to verify the accuracy of data, provided in the highway-rail grade crossing inventory database. As a part of the study, the U.S. DOT Accident Prediction Formula was evaluated against the alternative formulae for the highway-rail grade crossings in the State of Ohio. The following formulae were considered: (1) the New Hampshire Hazard Index Formula; (2) the NCHRP Report 50 Accident Prediction Formula; (3) the Florida Accident Prediction and Safety Index Formula; (4) the Missouri Exposure Index Formula; (5) the North Carolina Investigative Index Formula; and (6) the Texas Priority Index Formula. The results indicated that the U.S. DOT Accident Prediction Formula was superior to other methods. However, the North Carolina Investigative Index Formula demonstrated a good performance.

The study recommended that the State of Ohio should continue using the U.S. DOT Accident Prediction Formula for resource allocation among the highway-rail grade crossings. The Missouri Exposure Index and the North Carolina Investigative Index should be considered in order to rank passive highway-rail grade crossings upon completion of the initial prioritization. The study also suggested that the diagnostic field review process should be updated and should focus on collecting the information regarding the sight distance at highway-rail grade crossings. ORDC should revise the existing warning device project development process to increase the number of highway-rail grade crossings on the preliminary list of project locations. ORDC and PUCO should develop a formal procedure for updating the highway-rail grade crossing inventory database. It was also recommended that additional factors (e.g., sight distance) should be included in the highway-rail grade crossing inventory database.

## 2.2. Nationally Recognized Accident and hazard Prediction Models for Highway-Rail Grade Crossings

Different State DOTs have been using a variety of accident and hazard prediction models to prioritize highway-rail grade crossings for safety improvement projects. Some of the models are recognized nationally, which include the Coleman-Stewart Model, the NCHRP Report 50 Accident Prediction Formula, the New Hampshire Hazard Index Formula, and the Peabody-Dimmick Formula (Chadwick et al., 2014; Ryan and Mielke, 2017). This section of the report describes the nationally recognized accident and hazard prediction models for highway-rail grade crossings.

### *2.2.1. Coleman-Stewart Model*

The Coleman-Stewart Model considers the highway-rail grade crossings to be similar if they have similar characteristics, such as location, number of tracks, warning device, and highway and traffic volumes. The highway-rail grade crossings with similar features are considered to be in a group. The accident prediction equation analyzes the relationship between the observed accident rates and the associated characteristics of the highway-rail grade crossings (i.e., daily vehicular movements, daily train movements). The Coleman-Stewart Accident Prediction Model can be expressed using the following equation (Elzohairy and Benekohal, 2000):

$$log_{10}A = B_0 + B_1 \cdot log_{10}C + B_2 \cdot log_{10}T + B_3 \cdot (log_{10}T)^2 \quad (2.1)$$

where:
$A$ = average number of accidents per highway-rail grade crossing per year;
$C$ = average daily vehicular movements (if $C$ = 0, use 0.5 instead);
$T$ = average daily train movements (if $T$ = 0, use 0.5 instead);
$B_0$, $B_1$, $B_2$, and $B_3$ = coefficients of the accident prediction equation.

The variance of individual highway-rail grade crossings within groups has a significant impact on the variability of accident prediction among highway-rail grade crossings. Nonetheless, the Coleman-Stewart Model does not consider such variance. The coefficients of the accident prediction equation (which is a multiple linear regression equation) and corresponding R-squared values were obtained by Coleman and Stewart and are presented in Table 20. Note that Table 20 was prepared using the data reported by Faghri and Demetsky (1986) [page 17 of the report].

**Table 20** The Coleman-Stewart Model coefficients and R-squared values.

| Item | $B_0$ | $B_1$ | $B_2$ | $B_3$ | $R^2$ | Item | $B_0$ | $B_1$ | $B_2$ | $B_3$ | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Single-track urban** | | | | | | **Multiple-track urban** | | | | | |
| Automatic gates | -2.17 | 0.16 | 0.96 | -0.35 | 0.186 | Automatic gates | -2.58 | 0.23 | 1.30 | -0.42 | 0.396 |
| Flashing lights | -2.85 | 0.37 | 1.16 | -0.42 | 0.729 | Flashing lights | -2.50 | 0.36 | 0.68 | -0.09 | 0.691 |
| Crossbucks | -2.38 | 0.26 | 0.78 | -0.18 | 0.684 | Crossbucks | -2.49 | 0.32 | 0.63 | -0.02 | 0.706 |
| Other active | -2.13 | 0.30 | 0.72 | -0.30 | 0.770 | Other active | -2.16 | 0.36 | 0.19 | 0.08 | 0.65 |
| Stop signs | -2.98 | 0.42 | 1.96 | -1.13 | 0.590 | Stop signs | -1.43 | 0.09 | 0.18 | 0.16 | 0.35 |
| None | -2.46 | 0.16 | 1.24 | -0.56 | 0.24 | None | -3.00 | 0.41 | 0.63 | -0.02 | 0.58 |
| **Item** | $B_0$ | $B_1$ | $B_2$ | $B_3$ | $R^2$ | **Item** | $B_0$ | $B_1$ | $B_2$ | $B_3$ | $R^2$ |
| **Single-track rural** | | | | | | **Multiple-track rural** | | | | | |
| Automatic gates | -1.42 | 0.08 | -0.15 | 0.25 | 0.200 | Automatic gates | -1.63 | 0.22 | -0.17 | 0.05 | 0.142 |
| Flashing Lights | -3.56 | 0.62 | 0.92 | -0.38 | 0.857 | Flashing Lights | -2.75 | 0.38 | 1.02 | -0.36 | 0.674 |
| Crossbucks | -2.77 | 0.40 | 0.89 | -0.29 | 0.698 | Crossbucks | -2.39 | 0.46 | -0.50 | 0.53 | 0.780 |
| Other active | -2.25 | 0.34 | 0.34 | -0.01 | 0.533 | Other active | -2.32 | 0.33 | 0.80 | -0.35 | 0.31 |
| Stop signs | -2.97 | 0.61 | -0.02 | 0.29 | 0.689 | Stop signs | -1.87 | 0.18 | 0.67 | -0.34 | 0.32 |
| None | -3.62 | 0.67 | 0.22 | 0.26 | 0.756 | None | - | - | - | - | - |

#### *2.2.2. NCHRP Report 50 Accident Prediction Formula*

The National Cooperative Highway Research Program (NCHRP) Report 50 presented an accident prediction formula for highway-rail grade crossings, which is based on the number of trains per day, the number of highway vehicles per day, the existing warning devices, and the urban/rural designation. The formula is relatively simple and does not explain significant variations in the number of accidents (Elzohairy and Benekohal, 2000). The NCHRP Report 50 Accident Prediction Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000; U.S. DOT, 2007; Chadwick et al., 2014; Ryan and Mielke, 2017):

$$Number\ of\ accidents\ per\ year = A \cdot B \cdot T \quad (2.2)$$

where:
$A$ = factor based on the number highway vehicles per day;
$B$ = factor based on the existing warning devices and urban/rural classification;
$T$ = current train volume per day.

**Table 21** The "A" factor values for highway vehicles per day based on 10-year AADT.

| Vehicles Per Day (10 yr. ADT) | "A" Factor | Vehicles Per Day (10 yr. ADT) | "A" Factor |
|---|---|---|---|
| 250 | 0.000347 | 9000 | 0.011435 |
| 500 | 0.000694 | 10000 | 0.012674 |
| 1000 | 0.001377 | 12000 | 0.015012 |
| 2000 | 0.002627 | 14000 | 0.017315 |
| 3000 | 0.003981 | 16000 | 0.019549 |
| 4000 | 0.005208 | 18000 | 0.021736 |
| 5000 | 0.006516 | 20000 | 0.023877 |
| 6000 | 0.007720 | 25000 | 0.029051 |
| 7000 | 0.009005 | 30000 | 0.034757 |
| 8000 | 0.010278 | | |

The values of factor "A" (based on the number of highway vehicles per day) and factor "B" (based on the existing warning devices and urban/rural classification), which are used in the NCHRP Report 50 Accident Prediction Formula, are presented in Table 21 and Table 22, respectively. Note that Table 21 and Table 22 were prepared using the data reported by U.S. DOT (2007) [page 250 of the report].

**Table 22** The "B" factor values for the existing warning devices and urban/rural classification.

| | | |
|---|---|---|
| A | Crossbucks, highway volume less than 500 per day | 3.89 |
| B | Crossbucks, urban | 3.06 |
| C | Crossbucks, rural | 3.08 |
| D | Stop signs, highways volume less than 500 per day | 4.51 |
| E | Stop signs | 1.15 |
| F | Wigwags | 0.61 |
| G | Flashing lights, urban | 0.23 |
| H | Flashing lights, rural | 0.93 |
| I | Gates, urban | 0.08 |
| J | Gates, rural | 0.19 |

### *2.2.3. New Hampshire Hazard Index Formula*

The New Hampshire Hazard Index Formula introduced a simple hazard index that can be used to rank highway-rail grade crossings by the likelihood of accidents. The highway-rail grade crossing with the highest hazard index should be given the highest priority. The formula states that the hazard index is proportional to the product of the average daily volume of vehicles and the average daily volume of trains. Also, the hazard index depends on the warning device type, installed at a given highway-rail grade crossing. The New Hampshire Hazard Index Formula can be expressed using the following equation (Chadwick et al., 2014; Ryan and Mielke, 2017):

$$NHHI = V \cdot T \cdot PF \quad (2.3)$$

where:
$NHHI$ = New Hampshire Hazard Index;
$V$ = annual average daily traffic;
$T$ = average daily volume of trains;
$PF$ = protection factor (see Table 23).

**Table 23** Protection factor values for the New Hampshire Hazard Index Formula.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Stop signs | 1.0 |
| Flashing lights | 0.6 |
| Gates | 0.1 |

Several State DOTs have used the New Hampshire Hazard Index Formula, while some states have modified the formula with the introduction of supplementary variables, such as train speed, vehicle speed, sight distance, highway-rail grade crossing angle, highway-rail grade crossing width, and type of train. Other variables include surface type, population, number of buses, number of school buses, number of tracks, surface condition, presence of the nearby intersection, functional class of highway, vertical alignment, horizontal alignment, number of hazardous material trucks, number of passengers, number of accidents, etc. The purpose of introducing new variables in the model is to improve the accuracy of a hazard prediction at highway-rail grade crossings.

### *2.2.4. Peabody-Dimmick Formula*

In 1941, U.S. Bureau of Public Roads developed the Peabody-Dimmick Formula based on the data, collected in the 1930s at 3,563 rural highway-rail grade crossings from 29 states. The Peabody-Dimmick Formula estimates the anticipated number of accidents for the next five years based on the annual average daily traffic, average daily train traffic, and protection coefficient (which depends on the warning device type) using the following equation (U.S. DOT, 2007; Chadwick et al., 2014; Ryan and Mielke, 2017):

$$A_5 = K + \frac{1.28 \cdot V^{0.170} \cdot T^{0.151}}{P^{0.171}} \tag{2.4}$$

where:

$A_5$ = expected number of accidents in five years;
$V$ = annual average daily traffic factor;
$T$ = average daily train traffic factor;
$P$ = protection coefficient;
$K$ = additional parameter.

The expected number of accidents in five years ($A_5$) can be determined from the set of curves presented in Figure 13, Figure 14, Figure 15, and Figure 16. Note that Figure 13, Figure 14, Figure 15, and Figure 16 were prepared using the data reported by U.S. DOT (2007) [page 251 of the report].

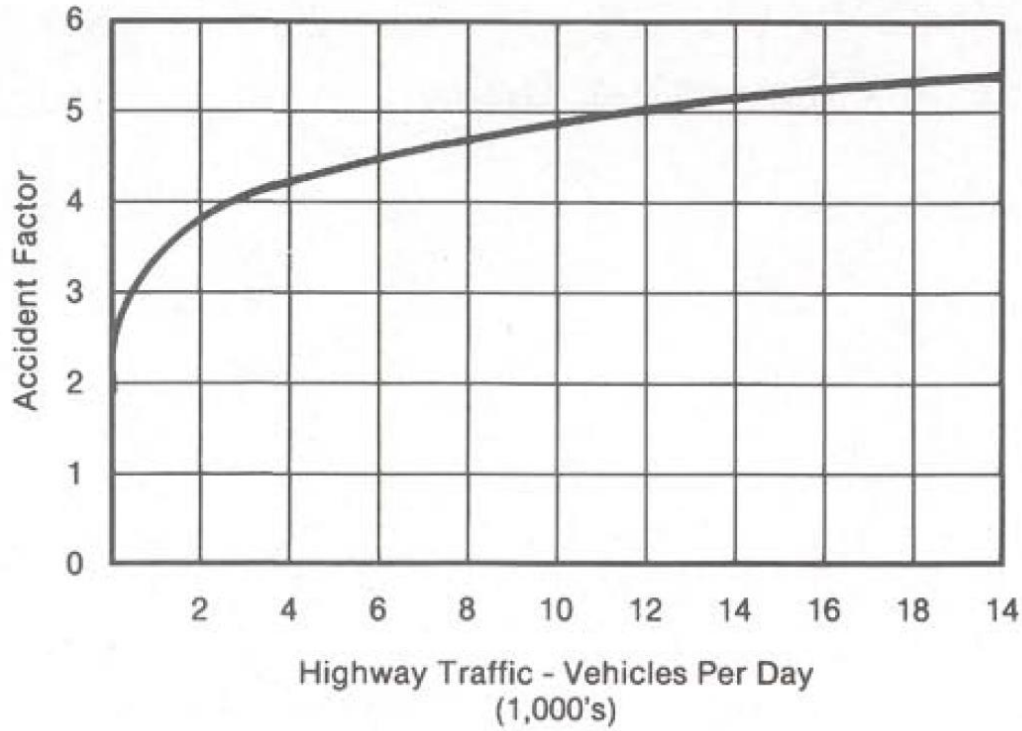


**Figure 13** Relationship between highway traffic and accident factor, $V^a$.
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

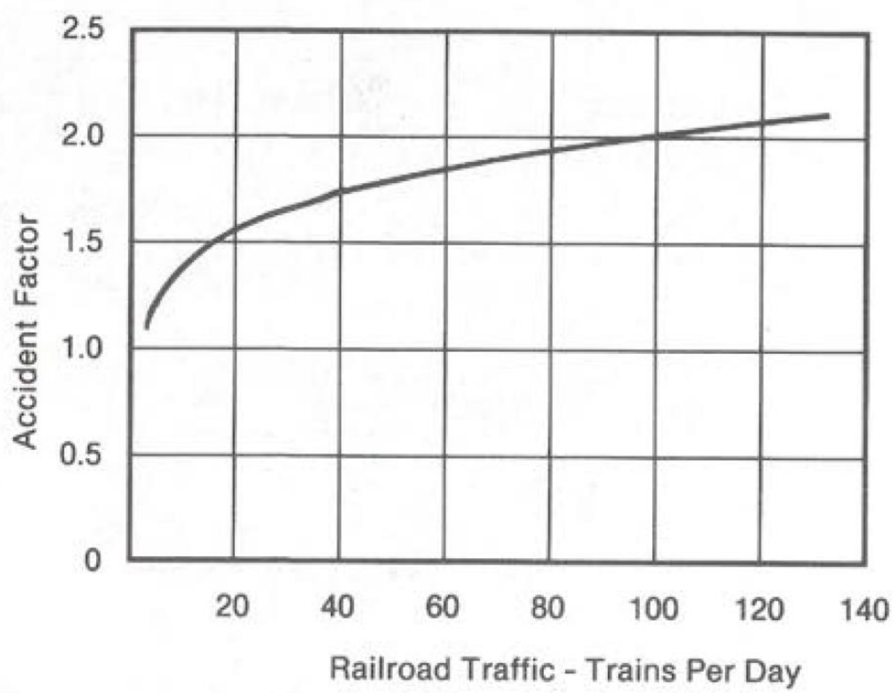


**Figure 14** Relationship between railroad traffic and accident factor, $T^b$.
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

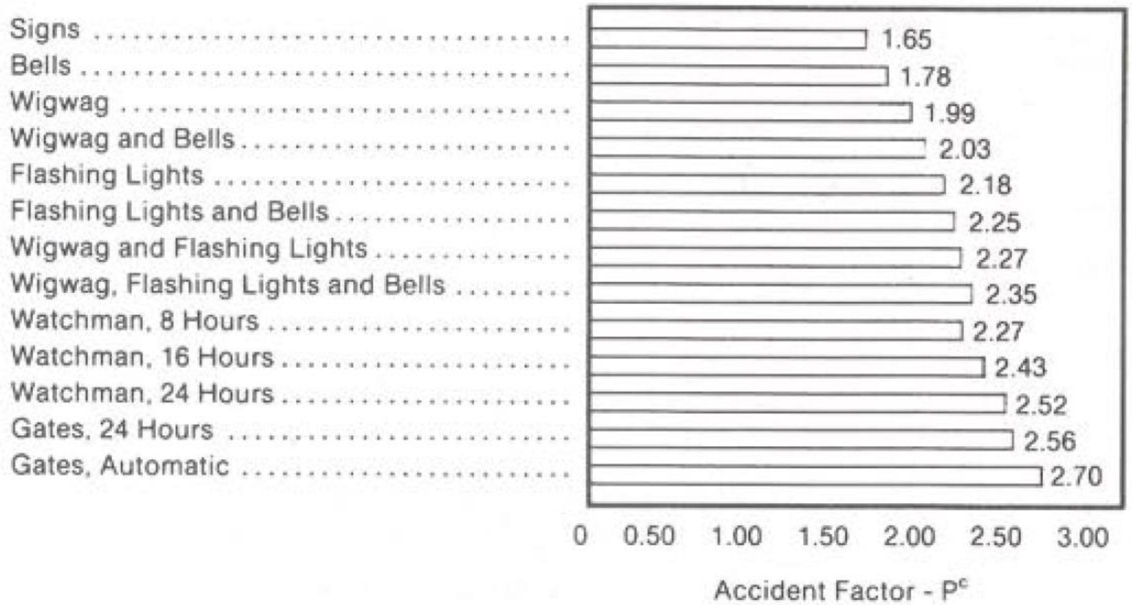


**Figure 15** Relationship between warning device and accident factor, $P^c$.
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

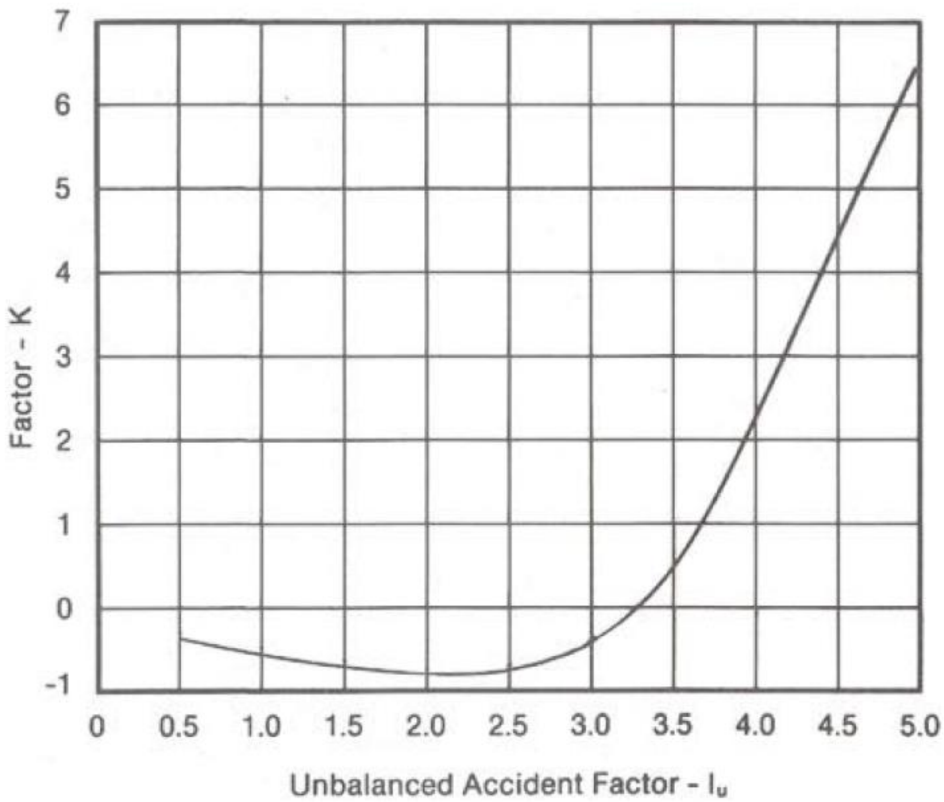


**Figure 16** Relationship between K-factor and unbalanced accident factor, $l^u$.
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

The unbalanced accident factor ($l_u$), which is used for calculating additional parameter $K$ in the Peabody-Dimmick Formula, can be estimated using the following equation (U.S. DOT, 2007):

$$l_u = 1.28 \cdot \frac{V^a \cdot T^b}{P^c} \tag{2.5}$$

In order to develop a mathematical relationship between the variables that are used in the Peabody-Dimmick Formula, the corresponding trendlines have been developed; so, that the process can be simplified. The approximations of the curves are presented in Figure 17, Figure 18, and Figure 19. Note that Figure 17, Figure 18, and Figure 19 were prepared using the data reported by Dulebenets (2012) [pages 45–46 of the thesis].

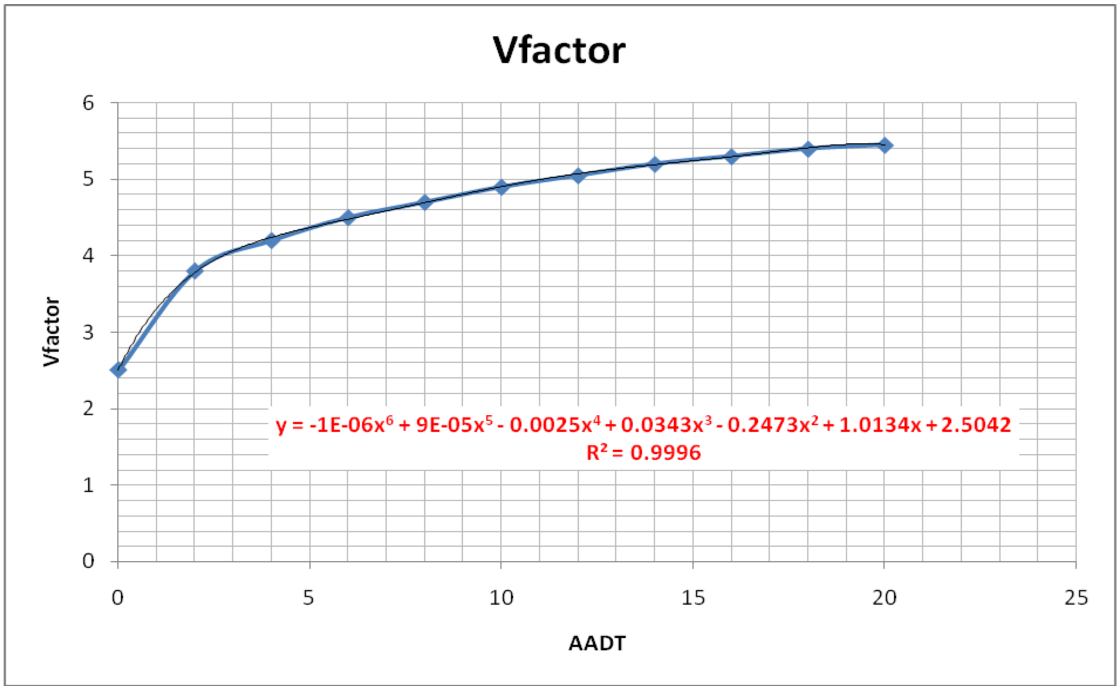


**Figure 17** Relationship between highway traffic and V-factor.

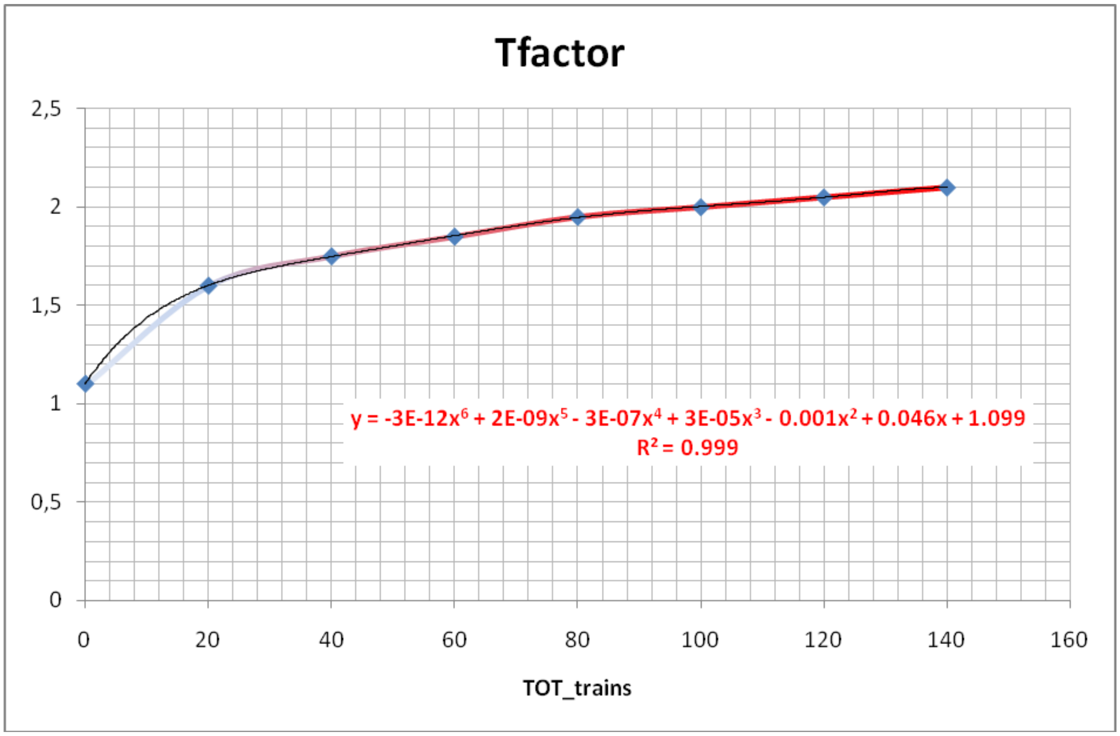


**Figure 18** Relationship between railroad traffic and T-factor.

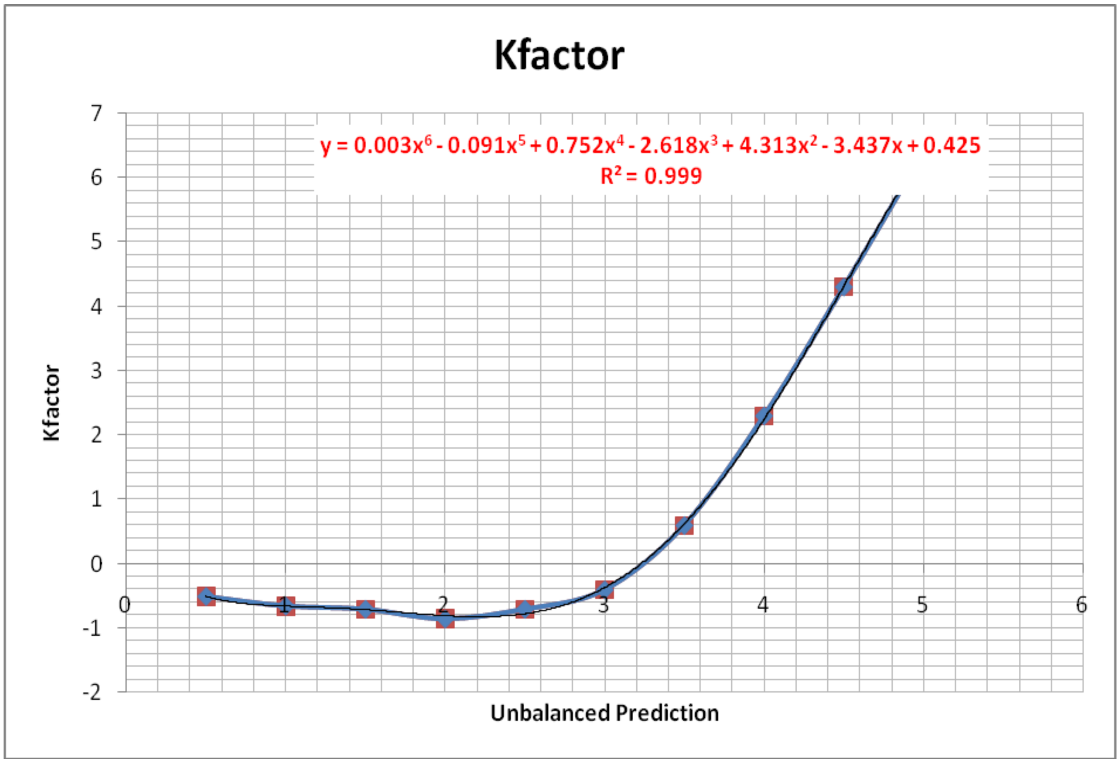


**Figure 19** Relationship between K-factor and unbalanced accident prediction.

### 2.3. U.S. DOT Procedure for Accident Prediction and Resource Allocation

An accident prediction model forecasts the expected number of accidents at a highway-rail grade crossing over a given time period based on the existing physical and operational characteristics of that highway-rail grade crossing. U.S. DOT formulated the accident prediction model in order to assist the states to maintain the requirements under the Federal-Aid Policy Guidelines (FAPG) (U.S. DOT, 1991). The model includes three equations to generate an accident prediction value for a highway-rail grade crossing. The first equation determines an initial accident prediction for a highway-rail grade crossing based on the existing physical and operational characteristics. The second equation calculates an accident prediction value, taking into account the average historical accident rates over a given time period. The equation assumes that the future accidents will occur at the same rate as the past accidents. The third equation applies a normalizing constant, which shifts the procedure from the past accident trends to the current accident trends. The normalizing constant is updated periodically. The three equations altogether determine an accident prediction value, which can be further used for ranking of highway-rail grade crossings in order to allocate resources based on the potential risk reduction, taking into account the highway-rail grade crossing characteristics, historical accident data, and current accident trends. The three equations are discussed further in detail in the following sections of this report.

#### *2.3.1. Prediction of Accidents at Highway-Rail Grade Crossings*

The first equation, which is also called the initial accident prediction formula, predicts the number of accidents per year at a highway-rail grade crossing. The formula is essentially represented with a series of factors that characterize the highway-rail grade crossing, described in the national highway-rail grade crossing inventory database, and are multiplied together. The initial accident prediction can be estimated using the following equation (Qureshi et al., 2003; U.S. DOT, 2007; Chadwick et al., 2014; Ryan and Mielke, 2017):

$$a = K \cdot EI \cdot MT \cdot DT \cdot HP \cdot MS \cdot HT \cdot HL \tag{2.6}$$

where:

$a$ = initial accident prediction, accidents per year at a highway-rail grade crossing;
$K$ = formula constant;
$EI$ = factor for exposure index based on the product of highway and train traffic;
$MT$ = factor for the number of main tracks;
$DT$ = factor for the number of through trains per day during daylight;
$HP$ = factor for highway paved (yes or no);
$MS$ = factor for maximum timetable speed;
$HT$ = factor for highway type;
$HL$ = factor for the number of highway lanes.

The values of the highway-rail grade crossing characteristic factors for three highway-rail grade crossing categories are presented in Table 24. Note that Table 24 was prepared using the data reported by U.S. DOT (2007) [page 56 of the report]. The highway-rail grade crossing categories are based on the traffic control devices, installed at a given highway-rail grade crossing, namely: (a) passive; (b) flashing lights; and (c) gates. The highway-rail grade crossing characteristic factors can be equated and tabulated based on the highway-rail grade crossing characteristics known. The tabulated values of these factors for the three highway-rail grade crossing categories are shown in Appendix A.

**Table 24** Highway-rail grade crossing characteristic factors for the Initial U.S. DOT Accident Prediction Formula.

**Crossing Characteristic Factors**

| Crossing Category | Formula Constant K | Exposure Index Factor EI | Main Tracks Factor MT | Day Thru Trains Factor DT | Highway Paved Factor HP | Maximum Speed Factor MS | Highway Type Factor HT | Highway Lanes Factor HL |
|---|---|---|---|---|---|---|---|---|
| Passive | 0.002268 | $\left(\frac{c \times t + 0.2}{0.2}\right)^{0.3334}$ | $e^{0.2094mt}$ | $\left(\frac{d + 0.2}{0.2}\right)^{0.1336}$ | $e^{-0.6160(hp-1)}$ | $e^{0.0077ms}$ | $e^{-0.1000(ht-1)}$ | 1.0 |
| Flashing Lights | 0.003646 | $\left(\frac{c \times t + 0.2}{0.2}\right)^{0.2953}$ | $e^{0.1088mt}$ | $\left(\frac{d + 0.2}{0.2}\right)^{0.0470}$ | 1.0 | 1.0 | 1.0 | $e^{0.1380(hl-1)}$ |
| Gates | 0.001088 | $\left(\frac{c \times t + 0.2}{0.2}\right)^{0.3116}$ | $e^{0.2912mt}$ | 1.0 | 1.0 | 1.0 | 1.0 | $e^{0.1036(hl-1)}$ |

c = annual average number of highway vehicles per day (total both directions)

t = average total train movements per day

mt = number of main tracks

d = average number of thru trains per day during daylight

hp = highway paved, yes = 1.0, no = 2.0

ms = maximum timetable speed, mph

ht = highway type factor value

hl = number of highway lanes

| Highway Type | Inventory Code | ht Value |
|---|---|---|
| **Rural** | | |
| Interstate | 01 | I |
| Other principal arterial | 02 | 2 |
| Minor arterial | 06 | 3 |
| Major collector | 07 | 4 |
| Minor collector | 08 | 5 |
| Local | 09 | 6 |
| **Urban** | | |
| Interstate | 11 | 1 |
| Other freeway and expressway | 12 | 2 |
| Other principal arterial | 14 | 3 |
| Minor arterial | 16 | 4 |
| Collector | 17 | 5 |
| Local | 19 | 6 |

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

The second accident prediction can be determined using the following equation (Qureshi et al., 2003; U.S. DOT, 2007; Chadwick et al., 2014; Ryan and Mielke, 2017):

$$B = \frac{T_0}{T_0 + T}(a) + \frac{T_0}{T_0 + T}\left(\frac{N}{T}\right) \tag{2.7}$$

where:

$B$ = second accident prediction, accidents per year at a highway-rail grade crossing;

$a$ = initial accident prediction, accidents per year at a highway-rail grade crossing;

$\frac{N}{T}$ = accident history prediction, accidents per year, where $N$ is the number of observed accidents in $T$ years at a highway-rail grade crossing;

$T_0$ = formula weighting factor = $\frac{1}{0.05+a}$.

The values of the second accident prediction ($B$) can be determined and tabulated based on the known highway-rail grade crossing characteristic factors, the values of the initial accident prediction ($a$), and number of reported accidents in the past years, as presented in Appendix B. If all the available accident history is used, the formula will produce the most accurate results. Note that accident history for more than five years may be misleading due to the changes that occur in the highway-rail grade crossing characteristics over time. Furthermore, if significant changes in the highway-rail grade crossing characteristics have occurred within the past five years (e.g., installation of flashing lights at a passive highway-rail grade crossing), only the accident data after that change should be used.

The final accident prediction ($A$) is determined with the application of a normalizing constant, so that the procedure can be updated for the current accident trends. The normalizing constant is determined for each category of highway-rail grade crossings separately by setting the sum of the predicted accidents multiplied by the corresponding normalizing constant equal to the number of accidents, which occurred in a recent period (U.S. DOT, 2007; FRA, 2010). For example, the accident history data between 2005 and 2009 will be used to predict the number of accidents at highway-rail grade crossings with stop signs, flashing lights, and gates in 2010. The normalizing constants for each one of the aforementioned three categories of highway-rail grade crossings (distinguished by the type of warning device installed) will be set, so the number of predicted accidents for the year of 2010 multiplied by the corresponding normalizing constant will be equal to the number of observed accidents for the year of 2010 (U.S. DOT, 2007; FRA, 2010). The periodic updates of the accident prediction and resource allocation procedure normalizing constants are shown in Table 25. Note that Table 25 was prepared using the data reported by FRA (2010) [page 1 of the report]. A downward trend in the recent values of the normalizing constants can be observed. These values represent the current accident trends at the highway-rail grade crossings.

**Table 25** Accident prediction and resource allocation procedure normalizing constants.

| WARNING DEVICE | NEW | PRIOR YEAR CONSTANTS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| GROUPS | 2010 | 2007 | 2005 | 2003 | 1998 | 1992 | 1990 | 1988 | 1986 |
| (1) Passive | **.4613** | .6768 | .6407 | .6500 | .7159 | .8239 | .9417 | .8778 | .8644 |
| (2) Flashing Lights | **.2918** | .4605 | .5233 | .5001 | .5292 | .6935 | .8345 | .8013 | .8887 |
| (3) Gates | **.4614** | .6039 | .6513 | .5725 | .4921 | .6714 | .8901 | .8911 | .8131 |

*Source: FRA (2010). Accident Prediction and Resource Allocation Procedure Normalizing Constants 2010*

The final normalized accident prediction values can be used for the accident severity calculations and the resource allocation procedure, so that the proper initiatives can be undertaken in order to improve safety at highway-rail grade crossings.

### *2.3.2. Assessment of Accident Severity*

U.S. DOT provides additional equations for determining the probabilities of fatalities and injuries. The probability of a fatal accident given an accident can be determined using the following equation (U.S. DOT, 2007; Chadwick et al., 2014):

$$P(FA|A) = \frac{1}{1 + CF \cdot MS \cdot TT \cdot TS \cdot UR} \tag{2.8}$$

where:
$P(FA|A)$ = probability of a fatal accident given an accident;
$CF$ = formula constant ($CF = 695$);

$MS$ = factor for maximum timetable train speed;
$TT$ = factor for through trains per day;
$TS$ = factor for switch trains per day;
$UR$ = factor for urban or rural highway-rail grade crossing.

The probability of an injury accident given an accident can be determined using the following equation (U.S. DOT, 2007; Chadwick et al., 2014):

$$P(IA|A) = \frac{1 - P(FA|A)}{1 + CI \cdot MS \cdot TK \cdot UR} \tag{2.9}$$

where:
$P(IA|A)$ = probability of an injury accident given an accident;
$P(FA|A)$ = probability of a fatal accident given an accident;
$CI$ = formula constant ($CI = 4.280$);
$MS$ = factor for maximum timetable train speed;
$TK$ = factor for the number of tracks;
$UR$ = factor for urban or rural highway-rail grade crossing.

The equations, required to calculate the highway-rail grade crossing characteristic factors of the fatal accident probability formula and the injury accident probability formula, are listed in Table 26 and Table 27. Note that Table 26 and Table 27 were prepared using the data reported by U.S. DOT (2007) [page 61 of the report]. For ease of use, the values of the factors, adopted in the fatality and injury probability formulae, are also presented in Table 28 and Table 29 for typical highway-rail grade crossing characteristics. Note that Table 28 and Table 29 were prepared using the data reported by U.S. DOT (2007) [pages 61–62 of the report].

**Table 26** Equations for highway-rail grade crossing characteristic factors for the U.S. DOT Fatal Accident Probability Formula.

Fatal Accident Probability Formula:

$$P(FA \mid A) = \frac{1}{(1 + CF \times MS \times TT \times TS \times UR)}$$

| Crossing Characteristic Factor | Equation for Crossing Characteristic Factor |
|---|---|
| Formula constant | $CF = 695$ |
| Maximum timetable train speed factor | $MS = ms^{-1.074}$ |
| Thru trains per day | $TT = (tt + 1)^{-0.1025}$ |
| Switch train per day factor | $TS = (tt + 1)^{0.1025}$ |
| Urban-Rural crossing factor | $UR = e^{0.1880ur}$ |

where: ms = maximum timetable train speed, mph
tt = number of thru trains per day
ts = number of switch trains per day
ur = 1, urban crossing
= 0, rural crossing

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

**Table 27** Equations for highway-rail grade crossing characteristic factors for the U.S. DOT Injury Accident Probability Formula.

$$P(IA \mid A) = \frac{1 - P(FA \mid A)}{(1 + CI \times MS \times TK \times UR)}$$

| Crossing Characteristic Factor | Equation for Crossing Characteristic Factor |
|---|---|
| Fatal accident probability | P(FA\|A) - See Table 25 |
| Formula constant | $CI = 4.280$ |
| Maximum timetable train speed factor | $MS = ma^{-0.2334}$ |
| Number of tracks factor | $TK = e^{0.1176tk}$ |
| Urban-Rural crossing factor | $UR = e^{0.1844ur}$ |

where: ms = maximum timetable train speed, mph
tk = total number of tracks at crossing
ur = 1, urban crossing
0, rural crossing

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

**Table 28** Factor values for the U.S. DOT Fatal Accident Probability Formula.

Fatal Accident Probability Formula:

$$P(FA \mid A) = \frac{1}{(1 + CF \times MS \times TT \times TS \times UR)}$$

where: CF = 695.0, formula constant
UR = 1.207, urban crossing
= 1.000, rural crossing, and

| Maximum Timetable Train Speed | MS | Thru Trains Per Day | TT | Switch Trains Per Day | TS |
|---|---|---|---|---|---|
| 1 | 1.000 | 0 | 1.000 | 0 | 1.000 |
| 5 | 0.178 | 1 | 0.931 | 1 | 1.074 |
| 10 | 0.084 | 2 | 0.894 | 2 | 1.119 |
| 15 | 0.055 | 3 | 0.868 | 3 | 1.152 |
| 20 | 0.040 | 4 | 0.848 | 4 | 1.179 |
| 25 | 0.032 | 5 | 0.832 | 5 | 1.202 |
| 30 | 0.026 | 6 | 0.819 | 6 | 2.221 |
| 40 | 0.019 | 7 | 0.808 | 7 | 1.238 |
| 50 | 0.015 | 9 | 0.790 | 9 | 1.266 |
| 60 | 0.012 | 10 | 0.782 | 10 | 1.279 |
| 70 | 0.010 | 20 | 0.732 | 20 | 1.366 |
| 80 | 0.009 | 30 | 0.703 | 30 | 1.422 |
| 90 | 0.008 | 40 | 0.683 | 40 | 1.464 |
| 100 | 0.007 | 50 | 0.668 | 50 | 1.497 |

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

**Table 29** Factor values for the U.S. DOT Injury Accident Probability Formula.

Injury Accident Probability Formula:

$$P(IA \mid A) = \frac{1 - P(FA \mid A)}{(1 + CI \times MS \times TK \times UR)}$$

where: P(FA|A) = Fatal accident probability, See Tables 25 and 27
CI = 4.280, formula constant
UR = 1.202, urban crossing
= 1.000, rural crossing, and

| Maximum Timetable Train Speed | MS | Total Number Of Tracks | TK |
|---|---|---|---|
| 1 | 1.000 | 0 | 1.000 |
| 5 | 0.687 | 1 | 1.125 |
| 10 | 0.584 | 2 | 1.265 |
| 15 | 0.531 | 3 | 1.423 |
| 20 | 0.497 | 5 | 1.800 |
| 25 | 0.472 | 6 | 2.025 |
| 30 | 0.452 | 7 | 2.278 |
| 40 | 0.423 | 8 | 2.562 |
| 50 | 0.401 | 9 | 2.882 |
| 60 | 0.385 | 10 | 3.241 |
| 70 | 0.371 | 15 | 5.836 |
| 80 | 0.360 | 20 | 10.507 |
| 90 | 0.350 | | |
| 100 | 0.341 | | |

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

### *2.3.3. Resource Allocation among Highway-Rail Grade Crossings*

In addition to various economic analysis procedures, U.S. DOT developed a resource allocation procedure for highway-rail grade crossing improvements. The procedure has a potential to assist

State DOTs with identification of the highway-rail grade crossings that need to be prioritized for upgrading in case of limited Federal funds for safety improvements. The U.S. DOT resource allocation procedure provides a number of highway-rail grade crossing improvement alternatives, which can result in certain accident reduction benefits. Based on the canonical U.S. DOT resource allocation procedure, the following alternatives for upgrading highway-rail grade crossings are considered:

- For passive single-track highway-rail grade crossings, there are two upgrade options: installation of flashing lights or gates.
- For passive multiple-track highway-rail grade crossings, there is only one upgrade option: installation of gates.
- For flashing light highway-rail grade crossings, there is only one upgrade option: installation of gates.

Note that the resource allocation procedure considers only traffic control improvement alternatives. The improvement alternatives, such as illumination, highway-rail grade crossing surface improvements, removal of visual obstructions, train detection circuitry improvements, and others, are not considered throughout the canonical resource allocation procedure (U.S. DOT, 2007). The required input data for the resource allocation procedure includes the number of predicted accidents, the safety effectiveness achieved from flashing lights and automatic gates (a.k.a., effectiveness factors or effectiveness multipliers), the cost of improvements, and the available funding information. William J. Hedley, California Public Utilities Commission, and U.S. DOT carried out the safety effectiveness studies for the equipment (i.e., warning devices at highway-rail grade crossings) used throughout the resource allocation procedure in 1952, 1974, and 1980, respectively. The effectiveness factors, which represent the percent reduction in terms of accidents that occurred after the implementation of improvements, are shown in Table 30. Note that Table 30 was prepared using the data reported by U.S. DOT (2007) [page 99 of the report].

**Table 30** Effectiveness factors for active highway-rail grade crossing warning devices.

| | **Effectiveness Factors (Percent)** | | |
|---|---|---|---|
| **Category** | **1980 U.S. DOT** | **1974 California** | **1952 Hedley** |
| Passive to Flashing Lights | 70 | 64 | 63 |
| Passive to Automatic Gates | 83 | 88 | 96 |
| Flashing Lights to Automatic Gates | 69 | 66 | 68 |

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

The resource allocation procedure also requires the data regarding the costs (i.e., installation and maintenance costs) associated with the highway-rail grade crossing safety improvement alternatives. The costs should be estimated for the following alternatives (U.S. DOT, 2007):

- Passive devices to flashing lights;
- Passive devices to automatic gates;
- Flashing lights to gates.

There is a need to take an adequate caution in developing the countermeasure costs for selected projects, while assuming the average costs for the other projects. Without a proper caution, there is a risk of generating biased decisions throughout the resource allocation procedure. The hierarchy of the resource allocation procedure, which requires the inputs discussed above, is outlined in Figure 20. Note that Figure 20 was prepared using the data reported by U.S. DOT (2007) [page 162 of the report]. Denote $X$ as a set of highway-rail grade crossings, considered for safety improvement projects; and $C$ as a set of available countermeasures. As indicated earlier, the resource allocation procedure requires the information for the following critical parameters that are related to the considered countermeasures: (1) the effectiveness of installing a proposed warning device at a highway-rail grade crossing with a lower-class warning device ($EF_c, c \in C$); and (2) the corresponding cost of the proposed warning device ($CA_c, c \in C$). Table 31 shows the effectiveness/cost symbol matrix ($c$ = 1, 2, and 3) for flashing lights installed at a passive highway-rail grade crossing, gates installed at a passive highway-rail grade crossing, and gates installed at a highway-rail grade crossing with flashing lights, respectively. Note that Table 31 was prepared using the data reported by U.S. DOT (2007) [page 162 of the report].

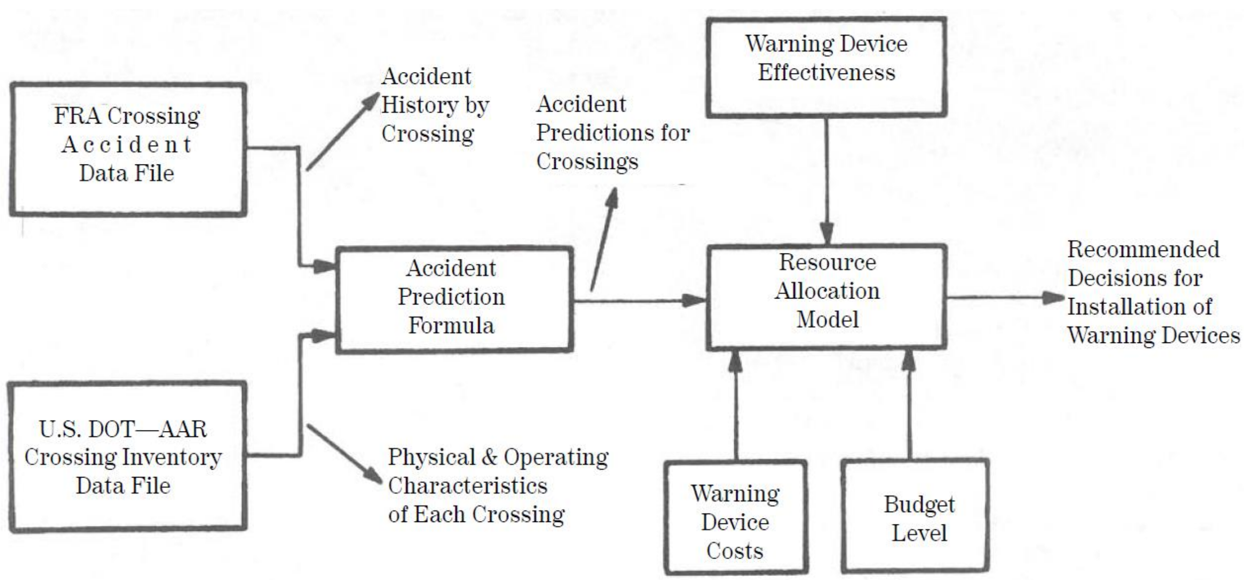


**Figure 20** Highway-rail grade crossing resource allocation procedure.
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

**Table 31** Effectiveness/cost symbol matrix.

| | Existing warning device | |
|---|---|---|
| **Proposed warning device** | **Passive** | **Flashing lights** |
| Flashing lights | | |
| Effectiveness | $E_1$ | — |
| Cost | $C_1$ | — |
| Automatic gates | | |
| Effectiveness | $E_2$ | $E_3$ |
| Cost | $C_2$ | $C_3$ |

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

The resource allocation procedure evaluates signal improvements for all highway-rail grade crossings with either passive or flashing light traffic control devices. For instance, if a single-track passive crossing $x$ is chosen for upgrading, flashing lights with effectiveness $EF_1$ or gates with effectiveness $EF_2$ can be selected for this highway-rail grade crossing. If the number of predicted accidents at highway-rail grade crossing $x$ is $TNA_x, x \in X$, the number of reduced accidents at this highway-rail grade crossing after installation of flashing lights and gates will be $TNA_x EF_1$ and $TNA_x EF_2$, respectively. The accident reduction/cost ratios are $TNA_x EF_1/CA_1$ for flashing lights and $TNA_x EF_2/CA_2$ for gates, respectively. The rate of increase in accident reduction versus costs that result from changing an initial decision to install flashing lights to a new decision to install gates at highway-rail grade crossing $x$ is referred to as the incremental accident reduction/cost ratio and is equal to $TNA_x(EF_2 - EF_1)/(CA_2 - CA_1)$. In case of a passive multiple-track crossing $x$, the only improvement option that would be allowable is the installation of gates with effectiveness $EF_2$, cost $CA_2$, and an accident reduction/cost ratio of $TNA_x EF_2/CA_2$.

If a flashing-light crossing is considered, the only allowable improvement option would be the installation of gates with effectiveness $EF_3$, cost $CA_3$, and an accident reduction/cost ratio of $TNA_x EF_3/CA_3$. The individual accident reduction/cost ratios, associated with these improvements, are selected by the resource allocation procedure to produce the maximum accident reduction that can be obtained for the pre-determined total available budget. The total cost is a sum of all the costs, associated with the selected countermeasures ($CA_1$, $CA_2$, and $CA_3$). The total maximum accident reduction is the sum of the individual accident reductions of the form $TNA_x EF_c$. Based on the canonical U.S. DOT resource allocation procedure, a field diagnostic team should be dispatched to investigate the selected highway-rail grade crossings in order to collect the required data and check for the accuracy of the input data, which have been used in the calculations. Appendix C presents a field verification worksheet that is typically adopted throughout field reviews of the highway-rail grade crossings. The field verification worksheet can be further used to update the values of certain parameters for the resource allocation procedure (if necessary).

### *2.3.4. GradeDec Software for Resource Allocation*

In order to assist local and state authorities with highway-rail grade crossing investment decision making, FRA developed a web-based highway-rail grade crossing investment analysis tool GradeDec.NET (GradeDec) (U.S. DOT, 2014). GradeDec allows state railway authorities to assess the impacts of a variety of highway-rail grade crossing safety improvements and provides a detailed benefit-cost analysis for each alternative. Based on the latter evaluations, decision-makers at the state and local levels can select appropriate safety improvement measures to implement at prioritized highway-rail grade crossings. Some benefits of highway-rail grade crossing improvements, considered throughout the analysis, include: (1) reduction in highway-rail grade crossing accident risk (safety); (2) reduction in delay and queuing on roadways located closer to the crossing (time savings); (3) improvement in air quality (reduced emissions); (4) reduction in vehicle operating costs; (5) improvement in highway network traffic flow; and other benefits (U.S. DOT, 2014). Local authorities can use GradeDec to investigate the safety improvement measures, which can benefit the local communities when implemented. For example, a highway-rail grade crossing that has a high accident record and is considered unsafe can be upgraded using one of the available countermeasures, which will mitigate highway-rail grade crossing accident risk and improve safety for local roadway travelers.

The GradeDec application can be accessed via the FRA website (https://gradedec.fra.dot.gov/). GradeDec has a graphical user interface (GUI) that supports data entry and visualization of probability distributions. The software is also equipped with an investment analysis feature, which estimates the economic rate of return (ROR) for highway-rail grade crossing safety improvement alternatives at the corridor level or at the regional level. The economic ROR effectively quantifies the overall benefits of a safety improvement measure to the public (users of the transportation facility), including accident reduction, reduction in emissions, time and vehicle operating cost savings (U.S. DOT, 2014). GradeDec computes the economic ROR by taking into account the safety improvements, as well as operating and maintenance costs over a given time period. The benefits of an investment over a time given period are monetized, and the discounts are estimated to reflect the opportunity cost of the initial investment capital. The latter capability allows state and local authorities to compare the benefits and costs of a safety improvement measure in different time periods. The benefit-cost analysis method, which has been used by the U.S. DOT agencies (such as FRA, FHWA, Federal Transit Administration, and Federal Aviation Administration) to allocate Federal infrastructure investments, is adopted by GradeDec. Furthermore, the basic assumptions and default model inputs, used by the software, are provided to the users by FRA. GradeDec application allows the users changing the input parameter values to emulate local conditions (U.S. DOT, 2014).

The analysis of highway-rail grade crossing safety improvements can be conducted separately for a corridor (single rail alignment) or an entire region (such as a county or several counties) using GradeDec. The corridor analysis feature of the software assesses the effects of each safety improvement measure at the selected highway-rail grade crossings of a single rail alignment on the adjacent roadway traffic, while the regional analysis mode evaluates the effects of each highway-rail grade crossing improvement measure on single and multiple rail alignments in a region. Moreover, the corridor and regional analysis components of the GradeDec software are based on the U.S. DOT Accident Prediction and Severity Models (see sections 2.3.1 and 2.3.2 of this report for a detailed description of the U.S. DOT Accident Prediction and Severity Models, respectively). In addition, the corridor analysis component of the application adopts the highway-rail grade crossing mitigation model which was developed by the Volpe National Transportation Systems Center. The GradeDec corridor analysis can be selected to effectively reduce the overall capital cost required to construct facilities for high-speed passenger rail services (with operating speeds ranging between 111 mph and 125 mph) where the highway-rail grade crossing hazards and mitigation measures can be the major cost factors. A risk analysis can be modeled more accurately using a certain range of the model inputs in the software instead of making assumptions which may substantially affect the results. The range of the inputs, defined in the software, is set based on historical data, empirical evidence, and expert recommendations. The results highlight the difference in the considered safety improvement alternatives and assist decision-makers with selection of the most advantageous alternative.

GradeDec provides users with several highway-rail grade crossing safety investment options for both corridor and regional analysis, which include (U.S. DOT, 2014) (1) highway-rail grade crossing device type change (options available under this category are passive, lights, gates, new technology, and closure or grade separation), (2) additions of supplementary measures to gated crossings (options available under this category are four-quadrant gates without detection, four-quadrant gates with detection, four-quadrant gates with 60-foot medians, mountable curbs, barrier curbs, one-way streets, and photo enforcement), and (3) changes to highway traffic flows in a corridor (traffic is re-routed away from crossings during the time periods with the highest accident risk using signage or signals). The safety improvement measure, which is selected in the model, will influence the outcomes of the accident prediction and severity analysis. State and local authorities may specify a one-time investment or consider the implementation of safety improvement measures in two phases, based on a number of factors, including the available funds as well as the anticipated increase in the highway and rail traffic volumes. GradeDec models two scenarios, namely (a) Base Case and (b) Alternate Case. The Base Case analysis is conducted to assess the benefits and costs over a time period when minor safety improvements are made to a highway-rail grade crossing (i.e., the "no major investment" scenario). Conversely, the Alternate Case analysis assesses the benefits and costs based on the assumption that the planned safety improvement measures have been implemented at a highway-rail grade crossing.

Some of the parameters required to conduct the Base and Alternate Case analyses include the following: (1) type of a highway-rail grade crossing; (2) supplementary measures at gated crossings; (3) AADT at highway-rail grade crossings (a consistent value is used for both cases, except an improvement program that specifically requires traffic management measures for re-assigning traffic); (4) characteristics of rail operations at highway-rail grade crossings; (5) operational and maintenance costs; and (6) capital investment (applicable to the alternate case analysis only). The corridor analysis mode in GradeDec offers a more detailed analysis, compared to the regional analysis mode. Some of options available in the corridor analysis mode, but not available in the regional analysis mode, include: (1) choice of the high-speed rail model or the U.S. DOT model for the accident and severity prediction (while the regional model solely relies on the U.S. DOT model for the accident and severity prediction); (2) traffic re-assignment at grade-separated or closed crossings; and (3) estimation of benefits from a reduction in delay on the adjacent highway network (U.S. DOT, 2014). The software characterizes rail corridors using certain parameters, such as the average daily number of trains, time-of-day distribution of rail traffic, coordination between traffic signaling system and rail signals in the corridor, and type of warning device(s) installed at crossings. In addition, the information regarding the reduction in delay, time savings, traffic re-assignment options, as well as the impacts of reduced queuing at the adjacent roadways, is provided in the corridor analysis. The information regarding highway traffic re-assignment due to highway-rail grade crossing closure or grade separation is not provided by the software, when the regional analysis mode is selected. Using GradeDec, state and local authorities can evaluate safety improvements for up to 600 highway-rail grade crossings at the same time for both corridor and regional analysis modes.

The time period, considered by the software, is based on the "start" and "end" year values that are used for a given scenario. GradeDec assumes that the safety investments will be implemented in the base year (i.e., year "0"). The benefits are estimated from the start of the first year. For example, if the start and end year values are defined in a scenario as 2018 and 2050, respectively, the software assumes that the safety investments have been completed in 2017; thus, the benefits are estimated from the beginning of the year 2018. Since the benefit-cost values are calculated annually, it is assumed that the benefits and costs are applied at the end of each year within the analysis time period. The U.S. dollar is adopted as the currency in the model. GradeDec applies the "discount rate", which is a constant dollar rate, in order to account for the price inflation. It is also assumed that the commodities have fixed relative prices over the time horizon of the investment (i.e., the ratios of the prices for two goods/services), except gasoline and oil. Moreover, GradeDec allows the user to evaluate the possible benefit and cost growth path. To achieve the latter objective, the user can split the time period into "near term" and "far term." This feature of the software shows whether the growth in benefits is sustainable over a long-time period.

***Assessment of Accident Severity – U.S. DOT Formulae within GradeDec***

The U.S. DOT Accident Severity Formulae, which are used in the canonical U.S. DOT resource allocation procedure, allow predicting the expected number of fatal and injury accidents at highway-rail grade crossings (see section 2.3.2 of this report). On the other hand, the GradeDec software allows assessing the following types of accident severity (U.S. DOT, 2014): (1) fatal accidents (i.e., accidents with at least one fatality); (2) casualty accidents (i.e., accidents with at least one fatality or injury); (3) injury accidents (i.e., accidents with at least one injury, but no fatality); and (4) property damage only accidents. The GradeDec software calculates the number of accidents by severity category using the following equations (U.S. DOT, 2014):

$$KF = 440.9 \tag{2.10}$$
$$MS = ms^{-0.9981} \tag{2.11}$$
$$TT = (thru + 1)^{-0.0872} \tag{2.12}$$
$$TS = (switch + 1)^{0.0872} \tag{2.13}$$
$$UR = e^{0.3571 \cdot urban} \tag{2.14}$$
$$KC = 4.481 \tag{2.15}$$
$$MS_{CA} = ms^{-0.343} \tag{2.16}$$
$$TK = e^{0.1153 \cdot tracks} \tag{2.17}$$
$$UR_{CA} = e^{0.2960 \cdot urban} \tag{2.18}$$
$$FA = \frac{NA}{1 + KF \cdot MS \cdot TT \cdot TS \cdot UR} \tag{2.19}$$

$$CA = \frac{NA}{1 + KC \cdot MS_{CA} \cdot TK \cdot UR_{CA}} \tag{2.20}$$
$$IA = CA - FA \tag{2.21}$$
$$PA = NA - FA - IA \tag{2.22}$$
where:
$ms$ = maximum timetable train speed, miles per hour;
$thru$ = number of through trains per day;
$switch$ = switch trains per day;
$urban$ = if a highway-rail grade crossing is urban, $urban$ =1, else $urban$ =0;
$tracks$ = number of railroad tracks;
$NA$ = predicted number of accidents per year at a highway-rail grade crossing;
$FA$ = predicted number of fatal accidents per year at a highway-rail grade crossing;
$CA$ = predicted number of casualty accidents per year at a highway-rail grade crossing;
$IA$ = predicted number of injury accidents per year at a highway-rail grade crossing;
$PA$ = predicted number of property damage only accidents per year at a highway-rail grade crossing.

***Number of Accidents by Severity Category – High Speed Rail (HSR) Formulae***

Unlike the U.S. DOT Accident Prediction Formulae, which estimate the severity of predicted accidents, the HSR formulae compute the number of fatalities among highway vehicle and train occupants. The HSR model considers several factors in the estimation of the number of fatalities, including the accident type (a train strikes a vehicle or a vehicle strikes a train), vehicle type (automobile, truck, or truck trailer), as well as occupants by mode (i.e., train and highway vehicle). The predicted number of fatalities, if a train strikes a highway vehicle, can be estimated using the following equation (U.S. DOT, 2014):

$$Ftsv_{occ} = \sum_{ttype} \left[ \alpha_{ttype} \cdot \overline{sp}^2_{ttype} \cdot \sum_{vtype} \beta_{vtype} \cdot \left( \gamma_{atype,vtype,occ} + P(sd)_{vtype} \cdot s_{vtype,occ} \right) \right] \tag{2.23}$$

$$\overline{sp}_{ttype} = \begin{cases} sp_{ttype}, & sp_{ttype} \leq sp^{max} \\ sp^{max}, & sp_{ttype} > sp^{max} \end{cases}, for\ occ = Highway\ vehicle\ occupants \tag{2.24}$$

$$\overline{sp}_{ttype} = sp_{ttype}, for\ occ = Train\ occupants \tag{2.25}$$

The predicted number of fatalities, if a highway vehicle strikes a train, can be estimated using the following equation (U.S. DOT, 2014):

$$Fvst_{occ} = \sum_{ttype} \alpha_{ttype} \cdot \sum_{vtype} \beta_{vtype} \cdot \gamma_{atype,vtype,occ} \tag{2.26}$$
where:
$Ftsv_{occ}$ = predicted fatalities when a train strikes a vehicle by occupancy mode;

$Fvst_{occ}$ = predicted fatalities when a vehicle strikes a train by occupancy mode;
$occ$ = occupancy mode of fatality (e.g., train occupants, highway vehicle occupants);
$atype$ = accident type (e.g., a train strikes a vehicle, a vehicle strikes a train);
$vtype$ = vehicle type (e.g., auto, truck, truck trailer);
$ttype$ = train type (passenger, freight, switch);
$\gamma_{atype,vtype,occ}$ = model coefficient by accident type, highway vehicle type, and occupancy mode of casualties;
$\beta_{vtype}$ = share of a vehicle type in the highway traffic;
$\alpha_{ttype}$ = share of a train type in the total rail traffic;
$sp_{ttype}$ = average train speed for a train type;
$sp^{max}$ = train speed of maximum impact on highway fatalities;
$P(sd)_{vtype}$ = probability of severe derailment;
$sd$ = added severity with severe derailment (model coefficient).

The total predicted fatalities can be estimated using the following equation (U.S. DOT, 2014):

$$F = Ptsv \cdot \sum_{occ} Ftsv_{occ} + (1 - Ptsv) \cdot \sum_{occ} Fvst_{occ} \quad (2.27)$$

where:
F = total predicted fatalities;
$Ftsv_{occ}$ = predicted fatalities when a train strikes a vehicle by occupancy mode;
$Fvst_{occ}$ = predicted fatalities when a vehicle strikes a train by occupancy mode;
$Ptsv$ = probability that an accident is of a type, where a train strikes a highway vehicle.

The total number of predicted injuries can be estimated using the following equation (U.S. DOT, 2014):

$$I = u \cdot F \quad (2.28)$$

where:
$I$ = total predicted injuries;
$F$ = total predicted fatalities;
$u$ = ratio of predicted injuries to fatalities.

***Effectiveness Multipliers***

In order to estimate the safety risk at highway-rail grade crossings after implementing the proposed improvements for the base case, the U.S. DOT resource allocation procedure recommends that the predicted number of accidents should be multiplied by a certain effectiveness multiplier (a.k.a., effectiveness factor), which is set based on the type of the safety improvement measure applied. For alternate case scenario, the predicted number of accidents is estimated by multiplying the number of predicted accidents in the base case by one minus the effectiveness multiplier. If the highway-rail grade crossing signal device is upgraded to a newer technology, the effectiveness factor is calculated by subtracting the "upgrade to gates" effectiveness factor from one and multiplying the resulting value by one minus the corresponding technology effectiveness factor (U.S. DOT, 2014). Table 32 presents the effectiveness values for various safety improvement alternatives. Note that Table 32 was prepared using the data reported by the GradeDec.NET Reference Manual (U.S. DOT, 2014) [page 25 of the report].

**Table 32** Effectiveness values for crossing warning devices.

| | **Total Number of Trains Per Day** | | | |
|---|---|---|---|---|
| | 10 or less | | More than 10 | |
| Improvement Action | Single Track | Multiple Track | Single Track | Multiple Track |
| Passive to Flashing Lights | 0.75 | 0.65 | 0.61 | 0.57 |
| Passive to Lights and Gates | 0.9 | 0.86 | 0.8 | 0.78 |
| Flashing Lights to Gates | 0.89 | 0.65 | 0.69 | 0.63 |

***Supplementary Safety Measures***

The use of locomotive horns at highway-rail grade crossings is guided by regulations. However, there are some areas that are designated as "quiet zones", where locomotive horns cannot be used based on certain provisions of the law. In an effort to prevent accidents at highway-rail grade crossings within the areas, designated as "quiet zones," jurisdictions are allowed to apply specific countermeasures, which are expected to have an equivalent effect of using horns on the predicted accidents. Table 33 shows the estimated effectiveness factors for various supplementary measures at gated highway-rail grade crossings. Note that Table 33 was prepared using the data reported by the GradeDec.NET Reference Manual (U.S. DOT, 2014) [page 26 of the report]. The effectiveness factor is the rate of reduction in the number of predicted accidents after implementation of a given countermeasure (U.S. DOT, 2014). Note that supplementary measures can be applied to gated crossings only. Moreover, if an improvement measure upgrades the crossing from a non-gated to a gated highway-rail grade crossing, the effectiveness factors are applied consecutively.

**Table 33** Effectiveness factors for supplementary safety measures at gated highway-rail grade crossings.

| **Supplemental Safety Measures** | **Effectiveness Factor** |
|---|---|
| 4 quadrant – no detection | 0.82 |
| 4 quadrant – with detection | 0.77 |
| 4 quadrant – with 60' medians | 0.92 |
| Mountable curbs-with channelized devices | 0.75 |
| Barrier curbs-with or without channelized devices | 0.80 |
| One-way street with gate | 0.82 |
| Photo enforcement | 0.78 |

***Cost of Supplementary Safety Measures***

The GradeDec software uses some parameters and default values to estimate the initial capital costs, operational and maintenance (O&M) costs, and other life-cycle costs for highway-rail grade crossings with various types of countermeasures. The types of highway-rail grade crossings include the following (U.S. DOT, 2014): (1) passive grade crossings; (2) crossings with flashing lights; (3) crossings with flashing lights and gates; (4) grade closure; (5) grade separation; and (6) crossings with new technology. The project costs for different highway-rail grade crossing types are presented in Table 34. Furthermore, Table 35 shows the costs for implementing supplementary safety measures at gated highway-rail grade crossings, which are available in the GradeDec software. Note that Table 34 and Table 35 were prepared using the data reported by the GradeDec.NET Reference Manual (U.S. DOT, 2014) [pages 59–60 of the report].

**Table 34** Project cost data.

| Crossing Type | Initial Capital Cost (thous. of $) | O and M Costs (thous. of $) | Other Life Cycle Costs (thous. of $) |
|---|---|---|---|
| Passive | 1.60 | 0.20 | 0.00 |
| Lights | 74.80 | 1.80 | 0.00 |
| Gates | 106.10 | 2.50 | 0.00 |
| Closure | 20.00 | 0.00 | 0.00 |
| Separation | 1,500.00 | 0.50 | 0.00 |
| New Technology | 180.00 | 0.50 | 0.00 |

**Table 35** Costs of supplementary safety measures.

| Measure Type | Initial Capital Cost (thous. of $) | O and M Costs (thous. of $) | Other Life Cycle Costs (thous. of $) |
|---|---|---|---|
| 4-quadarnt gates without detection | 244.00 | 3.50 | 0.00 |
| 4-quadarnt gates with detection | 260.00 | 5.00 | 0.00 |
| 4-quadarnt gates with 60' medians | 255.00 | 25.00 | 0.00 |
| Mountable curbs | 15.00 | 3.50 | 0.00 |
| Barrier curbs | 15.00 | 3.50 | 0.00 |
| One-way street | 5.00 | 3.50 | 0.00 |
| Photo enforcement | 65.00 | 25.00 | 0.00 |

### 2.4. Other Models and Resource Allocation Procedures Used by State DOTs

Apart from the nationally recognized accident and hazard prediction models and resource allocation procedures, some State DOTs developed their own accident and hazard prediction formulae for estimating the number of accidents, assessing the highway-rail grade crossing hazard, and prioritizing highway-rail grade crossings for safety improvement projects. The state-specific models, identified throughout the literature search, include the following:

- Arkansas Hazard Rating Formula
- California Hazard Rating Formula

- Connecticut Hazard Rating Formula
- Florida Accident Prediction and Safety Index Formula
- Illinois Hazard Index Formula
- Iowa Accident Prediction Formula
- Kansas Design Hazard Rating Formula
- Michigan Hazard Index Formula
- Missouri Exposure Index Formula
- Nevada Hazard Index Formula
- New Mexico Hazard Index Formula
- North Carolina Investigative Index Formula
- The Jaqua Formula (used by the State of Oregon)
- South Dakota Hazard Index Formula
- Texas Priority Index Formula
- Revised Texas Priority Index Formula

The formulae and procedures, which have been used by the States of Alaska, North Dakota, and Washington for accident and hazard prediction and resource allocation among highway-rail grade crossings, were also found as a result of a detailed literature review. The identified formulae and resource allocation procedures are presented in the following sections of this report.

**Table 36** Alaska policy on highway-rail grade crossings: changes in level of protection.

| Existing Traffic Control Device | Hazard Index | Recommended Action for Improvement |
|---|---|---|
| Passive | 0.08 – 0.12 | *Note |
| | 0.12 – 0.15 | Flashing lights |
| | 0.15 – 0.23 | Flashing lights or gates and flashing lights |
| | 0.23 – 12.4 | Gates and flashing lights |
| | 12.4 – 18.5 | Gates and flashing lights or grade separation |
| | > 18.5 | Grade separation |
| Flashing lights | 0.12 – 0.18 | *Note |
| | 0.18 – 3.7 | Gates and flashing lights |
| | 3.7 – 5.6 | Gates and flashing lights or grade separation |
| | > 5.6 | Grade separation |
| Gates | 1.32 – 1.98 | *Note |
| | > 1.98 | Grade separation |

*Note: For hazard indexes within this range, the decision may be to do nothing, improve the existing traffic control system, install a different type of traffic control system, or make some other improvement at a highway-rail grade crossing.

### *2.4.1. Alaska*

The Alaska Department of Transportation and Public Facilities has been using the Accident Prediction Value (APV) computational procedures from the Railroad-Highway Grade Crossing Handbook, Second Edition (1986). To change the protection type for a highway-rail grade crossing from passive to active protection, a threshold value of 0.10 (one accident every 10 years) is selected. A hazard index is compared with the threshold values (presented Table 36) to choose the upgrades of the traffic control system at a given highway-rail grade crossing. Note that Table 36 was prepared using the data reported by Elzohairy and Benekohal (2000) [pages 16–17 of the report].

### *2.4.2. Arkansas Hazard Rating Formula*

Arkansas Highway and Transportation Department (AHTD) has been using a hazard rating index along with field diagnostic team reviews to detect the highway-rail grade crossings that require safety improvements. ATHD does not have any thresholds for resource allocation. It tries to improve as many highway-rail grade crossings as the available budget allows (based on hazard ratings). The Hazard Rating Formula, deployed by ATHD to prioritize the highway-rail grade crossings for safety improvement projects, can be expressed using the following equation (Elzohairy and Benekohal, 2000):

Hazard rating of a highway-rail grade crossing = (Highway traffic points) · (Railway traffic points) · (Accident record points) (2.29)

where:

Highway traffic points = 5 points maximum, depending on ADT;

Railway traffic points = 5 points maximum. Up to 75% of the railway traffic points are dependent on the number of trains. The rest depend on the number of side and main tracks at a highway-rail grade crossing;

Accident record points = 4 points maximum, depending on the number of accidents over the past 15 years.

### *2.4.3. California Hazard Rating Formula*

The California Hazard Rating Formula calculates the hazard index of a highway-rail grade crossing as a surrogate to the number of accidents. The hazard index can be used to rank highway-rail grade crossings based on the likelihood of accidents. The highway-rail grade crossing with the highest value of the hazard index is the most likely to experience accidents and should be given the highest priority throughout resource allocation. The formula requires four inputs, including the number of vehicles, number of trains, highway-rail grade crossing protection type, and accident history. Unlike the U.S. DOT Accident Prediction Formula (which requires only 5-year accident history records), the California Hazard Rating Formula uses the accident history over the last ten years. The California Hazard Rating Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000; Qureshi et al., 2003):

$$CaHI = \frac{V \cdot T \cdot PF}{1{,}000} + AH \tag{2.30}$$

where:

$CaHI$ = the California Hazard Index;

$V$ = number of vehicles;

$T$ = number of trains;

$PF$ = protection factor (see Table 37);

$AH$ = accident history (the total number of accidents in the last ten years multiplied by a factor of “3”).

**Table 37** Protection factor values for the California Hazard Rating Formula.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Stop sign or crossbuck | 1.00 |
| Wigwag | 0.67 |
| Flashing lights | 0.33 |
| Gates | 0.13 |

### *2.4.4. Connecticut Hazard Rating Formula*

The State of Connecticut has been using a Hazard Rating Formula, which is similar to the one used by the State of California (i.e., the State of Connecticut's formula determines the hazard index, not the predicted number of accidents). Four determinants of the hazard index are required for the formula, including annual average daily traffic, number of trains per day, highway-rail grade crossing protection type, and accident history. The main difference between the two hazard rating formulae is that the Connecticut Hazard Rating Formula considers the accident history for the last five years, while the California Hazard Rating Formula uses the accident history over the last ten years. The Connecticut Hazard Rating Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000; Qureshi et al., 2003):

$$CoHI = \frac{(T+1)\cdot(A+1)\cdot AADT \cdot PF}{100} \qquad (2.31)$$

where:
$CoHI$ = the Connecticut Hazard Index;
$AADT$ = annual average daily traffic;
$T$ = number of trains per day;
$PF$ = protection factor (see Table 38);
$A$ = accident history (the total number of accidents in the last five years).

**Table 38** Protection factor values for the Connecticut Hazard Rating Formula.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Passive Warning Devices | 1.25 |
| Stop Sign Control | 1.00 |
| Stop Sign and Protect Control | 0.75 |
| Manually Activated Traffic Signal | 0.75 |
| Railroad Flashing Lights | 0.25 |
| Traffic Signal Control with Preemption | 0.25 |
| Gates with Railroad Flashing Lights | 0.01 |
| Inactive Rail Line | 0.001 |

### *2.4.5. Florida Accident Prediction and Safety Index Formula*

Under Florida's Highway-Railroad Improvement Program, which is sponsored by FHWA, an accident prediction model was developed to prioritize the highway-rail grade crossings for safety improvement projects in the State of Florida. The proposed accident prediction model was based on a stepwise regression analysis, data transformation, dummy variables, and transformation of the accident prediction model to its original scale. The accident prediction is further used for estimating the safety index for a given highway-rail grade crossing. The Florida Accident Prediction and Safety Index Formula can be expressed using the following equations (U.S. DOT, 2007):

$$t_p = -8.075 + 0.318 \cdot \ln S_t + 0.484 \cdot \ln T + 0.437 \cdot \ln A + 0.387 \cdot \ln V_V + \\ + \left(0.28 - 0.28 \cdot \frac{MASD}{RSSD}\right) + \left(0.33 - 1.23 \cdot \frac{MCSD}{RSSD}\right) + 0.15 \cdot (no\ crossbucks) \quad (2.32)$$

$$y = e^{(0.968 \cdot t_p + 1.109)}/4 \quad (2.33)$$

$$t_a = -8.075 + 0.318 \cdot \ln S_t + 0.166 \cdot \ln T + 0.293 \cdot \ln A + 0.387 \cdot \ln V_V + \\ + \left(0.28 - 0.28 \cdot \frac{MASD}{RSSD}\right) + 0.225 \cdot (L - 2) - 0.233 \cdot (gates) \quad (2.34)$$

$$y = e^{(0.938 \cdot t_a + 1.109)}/4 \quad (2.35)$$

where:
$A$ = vehicles per day or annual average daily traffic;
$L$ = number of lanes;
ln = logarithm to the base $e$;
$MASD$ = actual minimum stopping sight distance along a highway;
$MCSD$ = clear sight distance (ability to see approaching train along a highway, recorded for the four quadrants established by the intersection of the railroad tracks and road);
$RSSD$ = required stopping sight distance on wet pavement;
$S_t$ = maximum speed of a train;
$T$ = yearly average of the number of trains per day;
$t_a$ = ln of predicted number of accidents in four-year period at highway-rail grade crossings with active traffic control devices;
$t_p$ = ln of predicted number of accidents in four-year period at highway-rail grade crossings with passive traffic control devices;
$V_V$ = posted vehicle speed limit unless geometrics dictates a lower speed;
$no\ crossbucks$ = total number of crossbucks at a highway-rail grade crossing;
$gates$ = gate presence indicator (=1 if gated; =0 if not);
$y$ = predicted number of accidents per year at a highway-rail grade crossing.

The number of accidents predicted at a highway-rail grade crossing per year ($y$) is adjusted to account for the accident history as follows:

$$Y = y\sqrt{\frac{H}{(y)(P)}} \quad (2.36)$$

where:
$Y$ = accident prediction adjusted for the accident history;
$y$ = accident prediction based on the regression model;
$H$ = number of accidents for the six-year history or since the year of last improvement;

$P$ = number of years of the accident history period.

Based on the accident prediction formula, a safety/hazard index method was developed to rank the highway-rail grade crossings in the State of Florida. A highway-rail grade crossing with a safety index value of 70 is considered safe; thus, there is no need to implement any safety improvements at that highway-rail grade crossing. Moreover, a safety index value of 60, which represents one accident in nine years, is considered as marginal. The safety index is calculated based on the predicted number of accidents per year, adjusted for the accident history, using the following equation (U.S. DOT, 2007):

$$R = X\left(1 - \sqrt{Y}\right) \tag{2.37}$$

where:
$R$ = safety index;
$Y$ = adjusted accident prediction value;
$X$ = 90 when less than 10 school buses per day traverse a highway-rail grade crossing; = 85 when 10 or more school buses per day traverse a highway-rail grade crossing with active traffic control devices without gates; = 80 when 10 or more school buses per day traverse a highway-rail grade crossing with passive traffic control devices.

***2.4.6. Illinois Hazard Index Formula***

The State of Illinois conducted an evaluation of the existing accident and hazard prediction models, used by different DOTs (Elzohairy & Benekohal, 2000). The study performed multiple non-linear regression analyses to determine the factors, which influence the occurrence of accidents at the highway-rail grade crossings the most in the State of Illinois. The results of the conducted regression analyses demonstrated the best fit of the Illinois Hazard Index Formula (Elzohairy & Benekohal, 2000). The Illinois Hazard Index Formula can be expressed using the following equation (Elzohairy & Benekohal, 2000; Qureshi et al., 2003):

$$IHI = 10^{-6} \cdot A^{2.59088} \cdot B^{0.09673} \cdot C^{0.40227} \cdot D^{0.59262} \cdot (15.59 \cdot N^{5.60977} + PF) \tag{2.38}$$

where:
$IHI$ = the Illinois Hazard Index;
$A$ = $\ln(ADT \cdot NTT)$;
$ADT$ = average daily traffic;
$NTT$ = number of total trains per day;
$B$ = maximum timetable speed, mph;
$C$ = number of main and other tracks;
$D$ = number of highway lanes;
$N$ = average number of accidents per year (typically, over a 5-year period);
$PF$ = protection factor (see Table 39);

**Table 39** Protection factor values for the Illinois Hazard Index Formula.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Crossbucks | 86.39 |
| Flashing lights | 68.97 |
| Gates | 37.57 |

### *2.4.7. Iowa Accident Prediction Formula*

Iowa DOT developed an Accident Prediction Formula, which is based on the U.S. DOT Accident Prediction Formula (Iowa DOT, 2006). The estimations for accident prediction and severity are divided into the following steps: (1) estimation of exposure (exposure is a variable used in the accident prediction calculation); (2) estimation of predicted accidents; and (3) estimation of accident severity. The estimation of exposure is based on the AADT, the number of daily trains, and the time-of-day exposure correlation factor. The Exposure Factor ($EF$) can be calculated using the following equation (Iowa DOT, 2006):

$$\begin{aligned} EF = {} & [(\%\ of\ AADT\ between\ 12{:}00\ AM\ and\ 6{:}00\ AM) \\ & \cdot (\%\ of\ TRAINS\ between\ 12{:}00\ AM\ and\ 6{:}00\ AM)] \\ & + [(\%\ of\ AADT\ between\ 6{:}00\ AM\ and\ 12{:}00\ PM) \\ & \cdot (\%\ of\ TRAINS\ between\ 6{:}00\ AM\ and\ 12{:}00\ PM)] \\ & + [(\%\ of\ AADT\ between\ 12{:}00\ PM\ and\ 6{:}00\ PM) \\ & \cdot (\%\ of\ TRAINS\ between\ 12{:}00\ PM\ and\ 6{:}00\ PM)] \\ & + [(\%\ of\ AADT\ between\ 6{:}00\ PM\ and\ 12{:}00\ AM) \\ & \cdot (\%\ of\ TRAINS\ between\ 6{:}00\ PM\ and\ 12{:}00\ AM)] \end{aligned}$$

**divided by the GREATER of**

$$\begin{aligned} & [(\%\ of\ AADT\ between\ 12{:}00\ AM\ and\ 6{:}00\ AM)^2 \\ & + (\%\ of\ AADT\ between\ 6{:}00\ AM\ and\ 12{:}00\ PM)^2 \\ & + (\%\ of\ AADT\ between\ 12{:}00\ PM\ and\ 6{:}00\ PM)^2 \\ & + (\%\ of\ AADT\ between\ 6{:}00\ PM\ and\ 12{:}00\ AM)^2] \end{aligned} \tag{2.39}$$

**OR**

$$\begin{aligned} & [(\%\ of\ TRAINS\ between\ 12{:}00\ AM\ and\ 6{:}00\ AM)^2 \\ & + (\%\ of\ TRAINS\ between\ 6{:}00\ AM\ and\ 12{:}00\ PM)^2 \\ & + (\%\ of\ TRAINS\ between\ 12{:}00\ PM\ and\ 6{:}00\ PM)^2 \\ & + (\%\ of\ TRAINS\ between\ 6{:}00\ PM\ and\ 12{:}00\ AM)^2] \end{aligned}$$

$$Exposure = (1.35 \cdot EF) \cdot AADT \cdot Total\ Trains \tag{2.40}$$

The estimation of predicted accidents depends on the existing highway-rail grade crossing warning devices. Similar to the U.S. DOT Accident Prediction Formula, the initial number of predicted accidents is adjusted based on the accident history over the last five years. The following equation is used to estimate the number of predicted accidents at the highway-rail grade crossings equipped with passive devices (Iowa DOT, 2006):

$$\begin{aligned} Predicted\ Accidents\ (PA) = {} & 0.0006938 \cdot [(Exposure + 0.2)/0.2]^{0.37} \cdot \\ & \cdot [(DayThruTrains + 0.2)/0.2]^{0.1781} \cdot e^{(0.0077 \cdot MaxTimeTable)} \cdot e^{[-0.5966 \cdot (Paved - 1)]} \end{aligned} \tag{2.41}$$

where:

$Paved$ = 2 if the crossing is on a dirt or gravel road; = 1 if on a paved road.

$$Adjustment\ of\ Predicted\ Accidents = \frac{(\{PA \cdot [1/(0.05 + Predicted\ Accidents)]\} + Number\ of\ Accidents\ in\ 5\ Years)}{\{[1/(0.05 + Predicted\ Accidents)] + 5\}} \cdot 0.65 \quad (2.42)$$

The following equation is used to estimate the number of predicted accidents at the highway-rail grade crossings equipped with flashing lights (Iowa DOT, 2006):

$$Predicted\ Accidents\ (PA) = 0.0003351 \cdot [(Exposure + 0.2)/0.2]^{0.4106} \cdot [(DayThruTrains + 0.2)/0.2]^{0.1131} \cdot e^{(0.1917 \cdot NumberofTracks)} \cdot e^{[0.1826 \cdot (Lanes - 1)]} \quad (2.43)$$

$$Adjustment\ of\ Predicted\ Accidents = \frac{(\{PA \cdot [1/(0.05 + Predicted\ Accidents)]\} + Number\ of\ Accidents\ in\ 5\ Years)}{\{[1/(0.05 + Predicted\ Accidents)] + 5\}} \cdot 0.5001 \quad (2.44)$$

The following equation is used to predict the number of accidents at the highway-rail grade crossings equipped with lights and gates (Iowa DOT, 2006):

$$Predicted\ Accidents\ (PA) = 0.0005745 \cdot [(Exposure + 0.2)/0.2]^{0.2942} \cdot [(DayThruTrains + 0.2)/0.2]^{0.1781} \cdot e^{(0.1512 \cdot NumberofTracks)} \cdot e^{[0.142 \cdot (Lanes - 1)]} \quad (2.45)$$

$$Adjustment\ of\ Predicted\ Accidents = \frac{(\{PA \cdot [1/(0.05 + Predicted\ Accidents)]\} + Number\ of\ Accidents\ in\ 5\ Years\ )}{\{[1/(0.05 + Predicted\ Accidents)] + 5\}} \cdot 0.5725 \quad (2.46)$$

The severity of accidents can be assessed based on a set of factors, such as train speed, number of tracks, number of through trains, number of switching trains, and type of location (rural or urban). Since the number of predicted accidents is the same, the probability of an injury accident will be equal to the probability of a casualty accident minus the probability of a fatal accident, while the probability of a property-damage-only accident will be equal to the probability of an accident minus the probability of a casualty accident (Iowa DOT, 2006). The following equations are used to predict the number of accidents by severity category:

$$Predicted\ Fatal\ Accidents = \frac{Adjusted\ Predicted\ Accidents}{1 + \left[\begin{matrix} 440.9 \cdot (MaxTimeTable^{-0.9931}) \cdot (ThruTrains + 1)^{-0.0873} \cdot \\ (Switches + 1)^{0.0872} \cdot e^{(0.3571 \cdot Urban)} \end{matrix}\right]} \quad (2.47)$$

$$Predicted\ Casualty\ Accidents = \frac{Adjusted\ Predicted\ Accidents}{1 + [4.481 \cdot (MaxTimeTable^{-0.343}) \cdot (e^{(0.1153 \cdot NumberofTracks)}) \cdot (e^{(0.2960 \cdot Urban)})]} \quad (2.48)$$

$$Predicted\ Injury\ Accidents = Predicted\ Casualty\ Accidents - Predicted\ Fatal\ Accidents \quad (2.49)$$

$$Predicted\ Property\ Accidents = Adjusted\ Predicted\ Accidents - Predicted\ Casualty\ Accidents \quad (2.50)$$

### *2.4.8. Kansas Design Hazard Rating Formula*

The Kansas Design Hazard Rating Formula determines a hazard index instead of the number of accidents. If the hazard rating is estimated to be negative, then it is set to zero. Six factors, influencing the occurrence of accidents, are used in the formula, including the number of highway vehicles, number of fast trains, number of slow trains, angle of the intersection between the road and the track, the sight distances for all four quadrants, and number of main tracks. The Kansas Design Hazard Rating Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000; Qureshi et al., 2003):

$$KDHR = \frac{A \cdot (B + C + D)}{4} \quad (2.51)$$

where:

$KDHR$ = the Kansas Design Hazard Rating;

$A = \frac{HT \cdot (2 \cdot NFT + NST)}{400}$;

$HT$ = highway traffic;

$NFT$ = number of fast trains;

$NST$ = number of slow trains (switch trains are not included);

$B = 2 \cdot \sqrt[3]{\frac{8{,}000}{sum\ of\ maximum\ sight\ distance\ 4\ ways}}$;

$C = \sqrt{\frac{90}{angle\ of\ intersection}}$;

$D$ = main track factor (see Table 40).

**Table 40** Protection factor values for the Kansas Design Hazard Rating Formula.

| Number of Main Tracks | Factor (D) |
|---|---|
| 1 | 1.0 |
| 2 | 1.5 |
| 3 | 1.8 |
| 4 | 2.0 |

### *2.4.9. Michigan Hazard Index Formula*

Michigan DOT has been using the New Hampshire Hazard Index Formula, described in section 2.2.3 of this report, for prioritization of the highway-rail grade crossings (Elzohairy and Benekohal, 2000). However, the values of the protection factor ($PF$), used in the original New Hampshire Hazard Index Formula, have been modified by the State of Michigan for their Hazard Index Formula. The values of the protection factor, used by Michigan DOT, are shown in Table 41 for different types of countermeasures. Note that Table 41 was prepared using the data reported by Elzohairy and Benekohal (2000) [page 8 of the report].

**Table 41** Protection factor values used by Michigan DOT.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Reflectorized crossbuck with or without a yield sign | 1.00 |
| Stop sign | 0.80 |
| Stop and flag procedures | 0.75 |
| Flashing-light signals | 0.30 |
| Flashing-light signals with cantilever arms | 0.27 |
| Flashing-light signals with cantilever arms and traffic signal interconnect | 0.24 |
| Flashing-light signals with half-roadway gates | 0.11 |
| Flashing-light signals with cantilever arms and half-roadway gates | 0.08 |
| Flashing-light signals with cantilever arms, half-roadway gates, and traffic signal interconnection | 0.05 |
| The addition of warranted motion sensor or predictor circuitry further reduces PF by 0.02. | |

In case if the Michigan Hazard Index exceeds 4,000, a system of flashing lights can be issued for a given highway-rail grade crossing, which may already have crossbuck signs, stop signs, wig-wag signals, yield signs, bell, or manual warning (Elzohairy and Benekohal, 2000).

### *2.4.10. Missouri Exposure Index Formula*

Missouri DOT has been using an exposure index based on the type of existing protection at the highway-rail grade crossings. The factors that are used to estimate the exposure index include the following: number and speed of vehicles, number of passenger and freight trains, speed of passenger and freight trains, switching movements, required and actual sight distance. The Missouri Exposure Index Formula can be expressed using the following equations (Elzohairy and Benekohal, 2000; Qureshi et al., 2003):

For passive to active upgrade:

$$MEI = TI + SDO \cdot TI \tag{2.52}$$

For active upgrade:

$$MEI = TI \tag{2.53}$$

where:

$MEI$ = the Missouri Exposure Index;

$SDO$ = sight distance obstruction factor; $SDO = \frac{\text{required sight distance} - \text{actual sight distance}}{\text{required sight distance}}$;

$TI$ = traffic index; $TI = \frac{(VM \cdot VS)(FM \cdot FS + PM \cdot PS + 10 \cdot SM)}{10{,}000}$;

$VM$ = vehicle movements;

$VS$ = vehicle speed;

$PM$ = passenger train movements;

$PS$ = passenger train speed;

$FM$ = freight train movements;

$FS$ = freight train speed;

$SM$ = switching movements.

***2.4.11. Nevada Hazard Index Formula***

In 2017, Ryan and Mielke (2017) recommended a revised hazard index model to prioritize the highway-rail grade crossings for safety improvement projects in the State of Nevada. Several factors were considered in the model, including average daily highway traffic, daily train volume, accidents within the past five years, near misses within the past three years, protection factor, highway speed factor, rail speed factor, track configuration factor, and highway-rail grade crossing angle factor. The Nevada Hazard Index Formula can be expressed using the following equation (Ryan and Mielke, 2017):

$$NHI = \sqrt{EI} \cdot ANMF \cdot PF \cdot HSF \cdot RSF \cdot TCF \cdot CAF \tag{2.54}$$

where:

$NHI$ = Nevada Hazard Index;

$EI$ = exposure index; $EI$ = (average daily highway traffic) · (daily train volume);

$ANMF$ = accident and near miss factor; $ANMF = 1.3^{\left(A+\frac{N}{3}\right)}$;

$A$ = accidents within the past five years;

$N$ = near misses within the past three years;

$PF$ = protection factor; 0.15 for 4 quad gate or gates with medians; 0.30 for gates only; and 1.00 for flashing lights or passive;

$HSF$ = highway speed factor; 0.50 for 0 to 15 mph; 1.00 for 20 to 35 mph; 1.50 for 40 to 65 mph; and 2.00 for 70 mph or above;

$RSF$ = rail speed factor; 1.00 for 0 to 59 mph; and 1.50 for 60 mph and above;

$TCF$ = track configuration factor; 1.25 for 1 siding/other track; 1.50 for 2 siding/other tracks; and 2.00 for 3 or more siding/other tracks;

$CAF$ = highway-rail grade crossing angle factor; 2.00 for 0 to 30 degrees; 1.50 for 30 to 60 degrees; and 1.00 for 60 to 90 degrees).

***2.4.12. New Mexico Hazard Index Formula***

New Mexico State Highway and Transportation Department has been using a Hazard Index Formula, which is based on the Modified New Hampshire Hazard Index Formula, to determine a hazard index and rank the highway-rail grade crossings. The New Mexico Hazard Index Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000):

$$NMHI = \frac{Train\ ADT \cdot Hwy\ ADT \cdot PF}{100} \cdot SD_f \cdot T_s \cdot AH_f \tag{2.55}$$

where:

$NMHI$ = the New Mexico Hazard Index;

$PF$ = protection factor; 0.11 for gates; 0.20 for lights; 0.34 for wigwags; 0.58 for signs; 1.00 for crossbucks; and 2.00 for no protection;

$SD_f$ = sight distance factor; 1.0 for no restrictions; 1.2 for restrictions at one quadrant; and 1.5 for restrictions at more than one quadrant;

$T_s$ = train speed in mph;

$AH_f$ = accident history factor; $AH_f$ = $A + B + C$;

$A$ = 0.10 for each property damage only accident;

$B$ = 0.20 for each injury accident;

$C$ = 0.30 for each fatal accident.

### *2.4.13. North Carolina Investigative Index Formula*

The Investigative Index Formula, used by North Carolina DOT, includes three terms related to exposure, accident history, and sight distance. The North Carolina Investigative Index Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000):

$$NCII = \frac{PF \cdot ADT \cdot TV \cdot TSF \cdot TF}{160} + (70 \cdot A/Y)^2 + SDF \tag{2.56}$$

where:
$NCII$ = the North Carolina Investigative Index;
$PF$ = protection factor; 1.0 for no warning devices or crossbucks; 0.50 for traffic signals; 0.20 for flashing lights; and 0.10 for gates;
$ADT$ = average daily traffic. When school buses use a highway-rail grade crossing, add (No. of school bus passengers/1.2) to $ADT$. When passenger trains use a highway-rail grade crossing, multiply $ADT$ by the average vehicle occupancy, which is 1.2;
$TV$ = train volume;
$TSF$ = train speed factor; $TSF$ = (maximum allowable train speed)/50 + 0.8;
$TF$ = track factor, depending on the number of through tracks and the number of total tracks;
$A/Y$ = train-vehicle accidents per year. A 10-year accident history is required for the model;
$SDF$ = sight distance factor; $SDF = 16 \cdot \sum(SDF_n/4)$;
$SDF_n$ = sight distance factor for quadrant $n$; 0 for clear sight; 2 for average sight; and 4 for poor sight.

The highway-rail grade crossings are selected for safety improvement projects based on the estimated investigative indexes and the amount of funding available for a given fiscal year (Elzohairy and Benekohal, 2000).

### *2.4.14. North Dakota PAR Rating*

North Dakota DOT has been using a sufficiency rating system to prioritize the highway-rail grade crossings for safety improvement projects. A Performance Appearance Rating of PAR rating of 100 is defined under the system. Points from the total (100) are deducted for different negative conditions. The highway-rail grade crossing with the lowest rating is given the highest priority for safety improvements and additional funding. The rating system is shown in Table 42. Note that Table 42 was prepared using the data reported by Elzohairy and Benekohal (2000) [page 12 of the report].

**Table 42** North Dakota PAR rating.

| **Criteria** | **PAR Rating** |
|---|---|
| Railroad Conditions | 20 |
| Highway Conditions | 14 |
| Exposure Factor | 30 |
| Visibility Factor | 36 |
| Total | 100 |

### *2.4.15. Oregon*

Oregon DOT has been using the "Jaqua Formula" to prioritize the highway-rail grade crossing for safety improvement projects. The Jaqua Formula can be expressed using the following equations (Elzohairy and Benekohal, 2000):

$$ACC5 = \frac{A \cdot B \cdot C}{1610} \tag{2.57}$$

$$A = \sum_{i=1}^{n} T_i \left( \left( \frac{C_i \cdot V}{3 \cdot S_i} \right) + V \right) \tag{2.58}$$

where:
$ACC5$ = accident prediction for the next five years;
$A$ = exposure factor;
$n$ = number of train types;
$T_i$ = number of trains of type $i$;
$C_i$ = number of cars in a train of type $i$;
$S_i$ = speed of a train of type $i$;
$V$ = AADT;
$B$ = hazard rating, which depends on the number of tracks, number of blind quadrants, speed of vehicles and trains, number of lanes, angle of intersection, curvature of the roadway, approach grade, existence of entrances and exits to streets and street intersections near a highway-rail grade crossing;
$C$ = protection factor, which depends on the type of existing warning devices at the highway-rail grade crossings and type of area (urban vs. rural).

### *2.4.16. South Dakota Hazard Index Formula*

The State of South Dakota has been using the Hazard Index Formula to rank the highway-rail grade crossings for safety improvement projects. Four factors are used to determine the hazard index of a given highway-rail grade crossing, including train traffic, average daily highway traffic, highway-rail grade crossing protection factor, and obstruction factor. The South Dakota Hazard Index Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000):

$$SDHI = \frac{TV \cdot ADT \cdot PF \cdot OF}{5} \tag{2.59}$$

where:
$SDHI$ = the South Dakota Hazard Index;
$TV$ = number of trains per day;
$ADT$ = average daily highway traffic;
$PF$ = highway-rail grade crossing protection factor;
$OF$ = obstruction factor.

### *2.4.17. Texas Priority Index Formula*

The Texas Priority Index Formula has been used by several states. The formula is very similar to the New Hampshire Hazard Index Formula; however, a number of additional factors, including train speed and accident history, are considered in the Texas Priority Index Formula.

Furthermore, the formula differentiates between the cantilever and mast-mounted flashing lights. Although the number of accidents over the past five years is considered, it can only affect the priority index when the value is greater than one. A record of one or no accidents over a period of five years produces the same result. The Texas Priority Index Formula can be expressed using the following equation (Elzohairy and Benekohal, 2000; Ryan and Mielke, 2017):

$$TPI = V \cdot T \cdot (0.1 \cdot S) \cdot PF \cdot (0.01 \cdot A^{1.15}) \quad (2.60)$$

where:
$TPI$ = the Texas Priority Index;
$V$ = average daily traffic volume;
$T$ = average daily train volume;
$S$ = train speed;
$PF$ = protection factor (see Table 43);
$A$ = train accidents in the past five years (default = 1).

**Table 43** Protection factor values for the Texas Priority Index Formula.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Passive | 1.00 |
| Mast-mounted flashing lights | 0.70 |
| Cantilever flashing lights | 0.15 |
| Gates | 0.10 |

### *2.4.18. Revised Texas Priority Index Formula*

In 2013, the University of Texas at San Antonio and Texas A&M Transportation Institute conducted a study in collaboration with Texas DOT in order to revise the original Texas Priority Index Formula, which generally gave higher priority ranking to the high-volume highway-rail grade crossings based on the accident history (see section 2.1.6 of this report for more details). The study proposed a Revised Texas Priority Index Formula, which can be expressed using the following equations (Weissmann et al., 2013):

$$TPI_{rev} = 1{,}000 \cdot \hat{\mu} \cdot (A_5 + 0.1) \quad (2.61)$$

$$\begin{aligned}\hat{\mu} = exp[&-6.9240 + P\_f\_indicator\_T + 0.2587 \cdot HwyPaved - 0.3722 \\ &\cdot UrbanRural + 0.0706 \cdot TrafLane + 0.0656 \cdot TotalTrack \\ &+ 0.0022 \cdot ActualSD1 + 0.0143 \cdot MaxSpeed + 0.0126 \cdot MinSpeed \\ &+ 1.0024 \cdot log_{10}(TotalTrn + 0.5) + 0.4653 \cdot log_{10}(AADT) - 0.2160 \\ &\cdot NearbyInt + 0.0092 \cdot Higher\_SPD\_Lmt]\end{aligned} \quad (2.62)$$

where:
$TPI_{rev}$ = the Revised Texas Priority Index;
$\hat{\mu}$ = predicted number of accidents per year at a highway-rail grade crossing;
$P\_f\_indicator\_T$ = protection factor; 0.5061 for flashing lights; -0.2006 for gates; 0 for passive;
$HwyPaved$ = highway pavement; 1 for paved; 2 for unpaved;
$UrbanRural$ = urban/rural designation; 1 for urban; 2 for rural;
$TrafLane$ = number of traffic lanes;
$TotalTrack$ = number of the main and other tracks;

$ActualSD1$ = actual sight distance, approach 1;
$MaxSpeed$ = maximum train speed (through trains);
$MinSpeed$ = minimum train speed (switching trains);
$TotalTrn$ = daily train volume;
$AADT$ = vehicular AADT;
$NearbyInt$ = nearby roadway intersection; 1 if present; 2 if not present;
$Higher\_SPD\_Lmt$ = higher roadway speed limit between approach 1 and approach 2;
$A_5$ = number of accidents in the last five years at a highway-rail grade crossing.

An adjustment factor for the Revised Texas Priority Index was developed in order to give a fair consideration to both passive and active highway-rail grade crossings in the priority list (since active highway-rail grade crossings are likely to receive higher priority rankings due to a higher number of accidents in the past five years). The adjustment factor for a given warranted passive highway-rail grade crossing can be estimated as follows (Weissmann et al., 2013):

$$AF_{pas} = 1.5 \cdot (nw + c) \qquad (2.63)$$

where:
$AF_{pas}$ = the adjustment factor for warranted passive highway-rail grade crossings;
$nw$ = number of warrants met;
$c$ = number of accidents in the most recent five-year period.

As discussed in section 2.1.6 of this report, warranted passive and active highway-rail grade crossings should be prioritized separately first. Active highway-rail grade crossings should be prioritized based on the Revised Texas Priority Index, while warranted passive highway-rail grade crossings should be prioritized based on the Revised Texas Priority Index and the Texas Passive Crossing Index. After that, the overall priority list should be developed by combining the top passive and the top active highway-rail grade crossings. Then, the highway-rail grade crossings from the overall priority list should be sorted using the Revised Texas Priority Index with application of the adjustment factor for warranted passive highway-rail grade crossings. The remaining highway-rail grade crossings must be also sorted and appended to the priority list.

### *2.4.19. Washington*

The State of Washington has been using a priority matrix and a field review matrix to prioritize the highway-rail grade crossings for safety improvement projects under the Railroad Crossing Improvements Program (Elzohairy and Benekohal, 2000).

#### *The Priority Matrix*

The priority matrix consists of different criteria with corresponding scores. The scores are summed up for a first-order ranking of projects. After conducting an initial ranking with the priority matrix (see Table 44), the top-ranked projects are selected for a field review. Note that Table 44 was prepared using the data reported by Elzohairy and Benekohal (2000) [pages 10–11 of the report].

**Table 44** Washington State priority matrix.

| **Criteria** | **Deficiency Rating (Points)** |
|---|---|
| *Accidents* | |
| Any accident occurrence within the past five years | 10 |
| Lack of accident history | 0 |
| | |
| *Sight Distance* | |
| Sight distance less than the required design distance | 9 |
| Adequate sight distance | 0 |
| | |
| *ADT* | |
| ADT > 5,000 | 8 |
| 1,500 < ADT < 5,000 | 4 |
| ADT < 1,500 | 0 |
| | |
| *Highway-Rail Grade Crossing Angle and Number of Tracks* | |
| A. Highway-rail grade crossing angle 00 to 60 degrees (measured from a parallel to the rail line) | |
| Single track | 6 |
| Multiple tracks | 8 |
| B. Highway-rail grade crossing angle 61 to 80 degrees (measured from parallel to the rail line) | |
| Single track | 5 |
| Multiple tracks | 7 |

***The Field Review Matrix***

After a field review of the top-ranked projects (see Table 45), the priority points and the field review points are added together for the final ranking of projects. Note that Table 45 was prepared using the data reported by Elzohairy and Benekohal (2000) [page 11 of the report].

### *2.4.20. Other States*

A significant number of states have been using the U.S. DOT Accident Prediction Formula, including Alabama, Idaho, Indiana, Maine, Maryland, Ohio, South Carolina, Utah, Virginia, and Wisconsin (Elzohairy and Benekohal, 2000; Sperry et al., 2017). Based on an interview, which was conducted with the Arizona DOT representative (Ryan and Mielke, 2017), the State of Arizona adopted the Texas Priority Index for prioritizing the highway-rail grade crossings. The State of Indiana has been using the U.S. DOT Accident Prediction Formula to estimate the expected number of accidents at the highway-rail grade crossings. A 5-year highway-rail accident record is required to estimate the number of predicted accidents. However, Indiana DOT has not been using any threshold values for prioritization of the highway-rail grade crossings for safety improvement projects. Indiana DOT has been using a benefit-cost analysis to rank all the projects within the state (Elzohairy and Benekohal, 2000).

**Table 45** Washington State field review matrix.

| Criteria | Deficiency Rating (Points) |
|---|---|
| *Routes* | |
| Designated bike/pedestrian route | 5 |
| Hazardous material rail/truck | 10 |
| Heavy truck traffic (15% or more) | 5 |
| Heavily used bus route | 10 |
| | |
| *Roadway Items* | |
| Traffic signal within 200' of a highway-rail grade crossing | 5 |
| Hump crossing and/or poor roadway grade | 5 |
| Poor vehicle storage area in vicinity | 5 |
| | |
| *Railroad Safety Items* | |
| Railroad engineer recorded | -5 |
| Train speed 0-25 mph | 5 |
| | |
| *Highway-Rail Grade Crossing Safety Items* | |
| Closure of the existing highway-rail grade crossing included in proposal | 10 |

The State of Louisiana has been using a Modified New Hampshire Hazard Index Formula to rank the highway-rail grade crossings for safety improvements. No specific threshold values were reported for the Modified New Hampshire Hazard Index Formula (Elzohairy and Benekohal, 2000). New Jersey DOT considers the accident history to determine the appropriate devices for safety improvements at the highway-rail grade crossings (Elzohairy and Benekohal, 2000). However, there is no specific formula used to predict the expected number of accidents or hazard index at the highway-rail grade crossings. The Railroad-Highway Grade Crossing Handbook is used as a guide for safety improvements. A given highway-rail grade crossing with the existing warning devices will be considered for a potential upgrading in the State of New Jersey if requested by the operator or municipality or if it is located within the project limits of a state roadway project. South Carolina DOT considers different criteria for prioritization of the highway-rail grade crossings along with using the U.S. DOT Accident Prediction Formula. The criteria include the following: hazardous material hauling on the roadway, school bus crossings, passenger rail service, sight distance, and implementation feasibility (Elzohairy and Benekohal, 2000).

Previously, Virginia DOT used the Expected Accident Rate methodology, presented in the NCHRP Report 50. The latter methodology was replaced with the U.S. DOT Accident Prediction Formula to rank the existing highway-rail grade crossings for safety improvement projects. Additional factors are also considered throughout an engineering review, including vehicle type, sight distance, roadway geometrics, and adjacent land use development. The final priority index is determined considering both office and site reviews (Elzohairy and Benekohal, 2000). Once the indexes are calculated, the highway-rail grade crossings are sorted in the order of their priority. The top-priority highway-rail grade crossings are selected for safety improvement projects until all the allocated Federal funds are exhausted for a given fiscal year.

Wisconsin DOT has been using the FHWA Rail-Highway Crossing Resource Allocation procedure (Elzohairy and Benekohal, 2000), where the required inputs are the number of predicted accidents, effectiveness factors for flashing lights and automatic gates, improvement costs, and amount of the available funding (see section 2.3.3 of this report). The U.S. DOT Accident Prediction Formula has been used to predict the expected number of accidents. Improvement costs include both installation and maintenance costs. Serious consideration is given to the highway-rail grade crossings that have an expected accident frequency of more than one in ten years (Elzohairy and Benekohal, 2000).

## 3. COMPREHENSIVE ANALYSIS OF THE EXISTING METHODS FOR ACCIDENT AND HAZARD PREDICTION AT HIGHWAY-RAIL GRADE CROSSINGS

This section of the report presents a comprehensive analysis of the accident and hazard prediction formulae found throughout the review of the literature. A classification of the formulae, which have been used by different states, is presented in this section. Furthermore, this section provides a discussion regarding the predictors used in the existing accident and hazard prediction models along with the reported performance and implementation challenges of the models.

### 3.1. Accident Prediction vs. Hazard Prediction

A total of 21 accident and hazard prediction formulae were identified from the review of the available literature. The existing accident and hazard prediction formulae were divided into two categories, namely: (1) accident prediction formulae; and (2) hazard prediction formulae. The accident prediction formulae estimate the expected number of accidents at highway-rail grade crossings over a given time period. The hazard prediction formulae, on the other hand, provide a hazard or safety index value that is used to rank the highway-rail grade crossings for safety improvements/resource allocation. Figure 21 presents a distribution of the identified formulae. It can be observed that 29% (or 6 out of 21 formulae) of the formulae are the accident prediction formulae, while 71% (or 15 out of 21 formulae) are the hazard prediction formulae. The latter finding can be explained by the fact that it is quite challenging to accurately predict the number of accidents at highway-rail grade crossings, as there are lot of factors influencing the accident occurrence at highway-rail grade crossings (including human factors that are difficult to model). Therefore, a substantial portion of the identified formulae aim to estimate the hazard index for highway-rail grade crossings rather than the expected number of accidents.

The accident prediction formulae include the following:

- Coleman-Stewart Model
- NCHRP Report 50 Accident Prediction Formula
- Peabody-Dimmick Formula
- U.S. DOT Accident Prediction Formula
- Iowa Accident Prediction Formula
- The Jaqua Formula (used by the State of Oregon)

The reviewed hazard prediction formulae include the following:

- New Hampshire Hazard Index Formula
- Arkansas Hazard Rating Formula
- California Hazard Rating Formula
- Connecticut Hazard Rating Formula
- Florida Accident Prediction and Safety Index Formula
- Illinois Hazard Index Formula
- Kansas Design Hazard Rating Formula
- Michigan Hazard Index Formula
- Missouri Exposure Index Formula
- Nevada Hazard Index Formula

- New Mexico Hazard Index Formula
- North Carolina Investigative Index Formula
- South Dakota Hazard Index Formula
- Texas Priority Index Formula
- Revised Texas Priority Index Formula

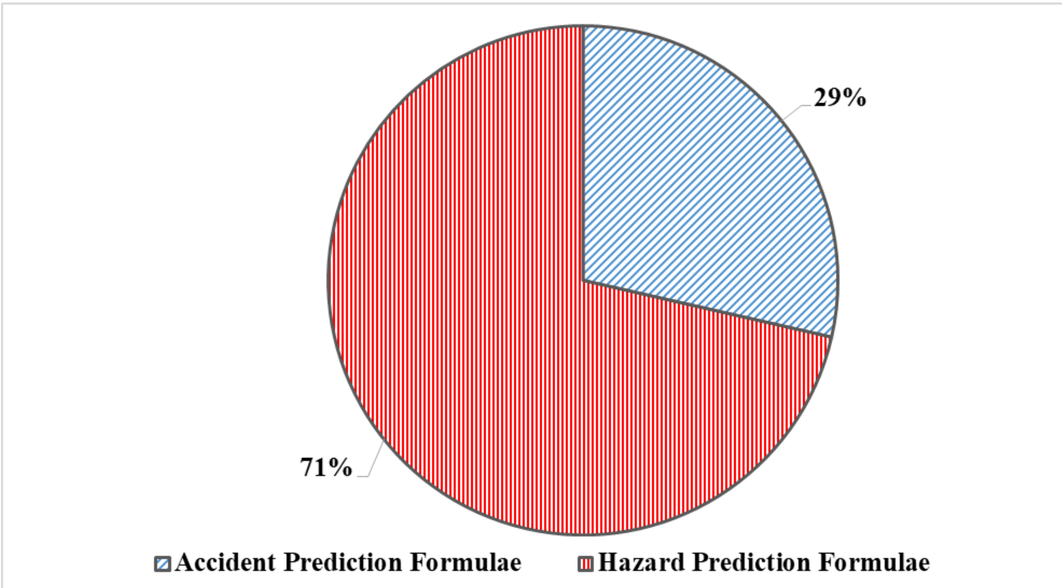


**Figure 21** Accident prediction formulae versus hazard prediction formulae.

A number of states (i.e., Alaska, North Dakota, and Washington) have been using certain spreadsheets, which allowed raking highway-rail grade crossings for safety improvement projects based on specific criteria without using any of the aforementioned accident and hazard prediction formulae. The Florida Accident Prediction and Safety Index Formula estimates the number of predicted accidents per year (see section 2.4.5 of this report); however, the calculated number of predicted accidents is further used for estimation of the safety index. Since the latter measure if directly used for raking the highway-rail grade crossings, the Florida Accident Prediction and Safety Index Formula was classified as a hazard prediction formula (i.e., the second category of formulae). Certain hazard prediction formulae (e.g., the Connecticut Hazard Rating Formula, the New Mexico Hazard Index Formula, the Texas Priority Index Formula) have been inspired by the nationally recognized New Hampshire Hazard Index Formula. A substantial number of states have been using the U.S. DOT Accident Prediction Formula (e.g., Alabama, Idaho, Indiana, Maine, Maryland, Ohio, South Carolina, Utah, Virginia, and Wisconsin).

### 3.2. Factors Considered in the Existing Models

The list of factors (or predictors), considered by each one of the discovered accident and hazard prediction formulae, is provided in Table 46. A total of 20 unique predictors, affecting the expected number of accidents at highway-rail grade crossings, have been identified from the 21 accident and hazard prediction formulae reviewed. These factors include the following:

- Accident history

- Angle of crossing
- Approach gradient
- Daylight thru trains per day
- Existing protection
- Highway pavement type
- Highway vehicular speed
- Location (i.e., urban vs. rural)
- Number of cars in a train
- Number of tracks
- Number of traffic lanes
- Other roadway geometrics
- Presence of a nearby highway intersection
- School buses
- Sight distance
- Time of day
- Train speed
- Trains per day
- Type of train
- Vehicles per day

**Table 46** Factors considered by the discovered accident and hazard prediction formulae.

| **Accident and hazard Prediction Formulae** | **Factors** |
|---|---|
| Arkansas Hazard Rating Formula | Vehicles per day; Trains per day; Number of tracks; Accident history |
| California Hazard Rating Formula | Vehicles per day; Trains per day; Existing protection; Accident history |
| Coleman-Stewart Model | Vehicles per day; Trains per day; Location; Number of tracks; Existing protection |
| Connecticut Hazard Rating Formula | Vehicles per day; Trains per day; Existing protection; Accident history |
| Florida Accident Prediction and Safety Index Formula | Vehicles per day; Trains per day; Number of traffic lanes; Sight distance; Train speed; Highway vehicular speed; Accident history; School buses; Existing protection |
| Illinois Hazard Index Formula | Vehicles per day; Trains per day; Train speed; Number of tracks; Number of traffic lanes; Accident history; Existing protection |

**Table 46** Factors considered by the discovered accident and hazard prediction formulae (cont'd).

| **Accident and hazard Prediction Formulae** | **Factors** |
|---|---|
| Iowa Accident Prediction Formula | Vehicles per day; Trains per day; Time of day; Existing protection; Daylight thru trains per day; Train speed; Highway pavement type; Number of tracks; Number of traffic lanes; Accident history |
| Jaqua Formula | Trains per day; Type of train; Number of cars in a train; Train speed; Vehicles per day; Number of tracks; Sight distance; Highway vehicular speed; Number of traffic lanes; Angle of crossing; Approach gradient; Other roadway geometrics; Existing protection; Location |
| Kansas Design Hazard Rating Formula | Vehicles per day; Trains per day; Type of train; Angle of crossing; Sight Distance; Number of tracks |
| Michigan Hazard Index Formula | Vehicles per day; Trains per day; Existing protection |
| Missouri Exposure Index Formula | Existing protection; Sight distance; Vehicles per day; Highway vehicular speed; Trains per day; Type of train; Train speed |
| NCHRP Report 50 Accident Prediction Formula | Vehicles per day; Trains per day; Existing protection; Location |
| Nevada Hazard Index Model | Vehicles per day; Trains per day; Accident history; Existing protection; Highway vehicular speed; Train speed; Number of tracks; Angle of crossing |
| New Hampshire Formula | Vehicles per day; Trains per day; Existing protection |
| New Mexico Hazard Index Formula | Vehicles per day; Trains per day; Existing protection; Sight distance; Train speed; Accident history |
| North Carolina Investigative Index Formula | Existing protection; Vehicles per day; School buses; Trains per day; Type of train; Train speed; Number of tracks; Accident history; Sight distance |
| Peabody-Dimmick Formula | Vehicles per day; Trains per day; Existing protection |
| South Dakota Hazard Index Formula | Vehicles per day; Trains per day; Existing protection; Sight distance |
| Texas Priority Index Formula | Vehicles per day; Trains per day; Existing protection; Train speed; Accident history |
| Revised Texas Priority Index Formula | Existing protection; Highway pavement type; Location; Number of traffic lanes; Number of tracks; Sight distance; Train speed; Vehicles per day; Trains per day; Presence of a nearby highway intersection; Highway vehicular speed; Accident history |
| U.S. DOT Accident Prediction Formula | Existing protection; Vehicles per day; Trains per day; Daylight thru trains per day; Number of tracks; Highway pavement type; Train speed; Location; Number of traffic lanes; Accident history |

Table 47 presents a distribution of factors considered by the discovered accident and hazard prediction formulae. It can be observed that all the discovered accident and hazard prediction formulae consider the number of trains per day and the number of vehicles per day. The latter finding can be explained by the fact that the number of trains per day and the number of vehicles per day are the basic factors, which are required to assess the "exposure" of a given highway-rail grade crossing. The existing protection (i.e., presence of specific types of warning devices) has been accounted for in 19 accident and hazard prediction formulae. Some other factors, which are fairly frequently used in the existing accident and hazard prediction formulae, include the following: (1) accident history (considered in 12 formulae); (2) train speed (considered in 11 formulae); (3) number of tracks (considered in ten formulae); (4) sight distance (considered in eight formulae); (5) number of traffic lanes (considered in six formulae); (6) highway vehicular speed (considered in five formulae); and (7) location (considered in five formulae).

**Table 47** Distribution of factors considered by accident and hazard prediction formulae.

| **Factors** | **Number of Formulae Containing the Factor (n=21)** |
|---|---|
| Trains per day | 21 |
| Vehicles per day | 21 |
| Existing protection | 19 |
| Accident history | 12 |
| Train speed | 11 |
| Number of tracks | 10 |
| Sight distance | 8 |
| Number of traffic lanes | 6 |
| Highway vehicular speed | 5 |
| Location | 5 |
| Type of train | 4 |
| Angle of crossing | 3 |
| Highway pavement type | 3 |
| Daylight thru trains per day | 2 |
| School buses | 2 |
| Approach gradient | 1 |
| Number of cars in a train | 1 |
| Other roadway geometrics | 1 |
| Presence of a nearby highway intersection | 1 |
| Time of day | 1 |

Certain factors have been considered only by a few accident and hazard prediction formulae. For example, the North Carolina Investigative Index Formula and the Florida Accident Prediction and Safety Index Formula are the only hazard index formulae, which explicitly account for the number of school buses traversing highway-rail grade crossings. Also, only the Jaqua Formula, used in the State of Oregon, considers for the approach gradient, number of cars in a train, and a large variety of roadway geometric characteristics (e.g., curvature of the roadway, existence of entrances and exits to streets and street intersections near a highway-rail grade crossing). Only the Revised Texas Priority Index Formula explicitly models the effects of a nearby highway intersection presence on a potential hazard at a given highway-rail grade crossing. Although consideration of the aforementioned factors (i.e., traversing school buses, approach gradient, number of cars in a train, other roadway geometrics, and presence of a nearby highway intersection) may improve accuracy of the accident and hazard prediction formulae, it can be challenging to collect the information regarding these predictors. As the information regarding the aforementioned factors may not be readily available in the existing highway-rail grade crossing inventory databases (e.g., the FRA highway-rail grade crossing inventory database, the state highway-rail grade crossing accident/incident database), the State DOT representatives will be required to conduct additional field reviews or contact railroad companies in order to gather necessary data.

### 3.3. Performance and Implementation Challenges of the Existing Accident and hazard Prediction Models

As indicated in section 3.1 of this report, several accident and hazard prediction models have been developed to prioritize highway-rail grade crossings for safety improvement projects and mitigate the risk posed to highway and rail users. The accident and hazard prediction methodologies are classified into two groups based on the formula adopted. The first group is comprised of the methodologies that use the absolute formulae to predict the number of accidents that may occur at a highway-rail grade crossing over a given time period. The second group of methodologies uses the relative formulae, which assess the susceptibility of a highway-rail grade crossing to highway-rail accidents. Both groups of methodologies are used by decision-makers to determine the most hazardous highway-rail grade crossings and select the appropriate types of countermeasures for these highway-rail grade crossings. A total of 21 accident and hazard prediction models have been reviewed in detail under this project, five of which are considered as nationally recognized (i.e., the Coleman-Stewart Model, the NCHRP Report 50 Accident Prediction Formula, the New Hampshire Hazard Index Formula, the Peabody-Dimmick Formula, and the U.S. DOT Accident Prediction Formula), while the rest can be considered as state-specific.

A number of previously conducted studies evaluated performance of the existing accident and hazard prediction models and discussed challenges, associated with implementation of these models. Chadwick et al. (2014) discussed the highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S. The following nationally recognized formulae, used to rank highway-rail grade crossings for safety improvement projects, were listed: (1) the NCHRP Report 50 Accident Prediction Formula; (2) the Peabody-Dimmick Formula; (3) the New Hampshire Hazard Index Formula; and (4) the U.S. DOT Accident Prediction Formula. The authors indicated that the aforementioned formulae are still widely used by State DOTs in their present forms or with certain modifications. However, the U.S. DOT Accident Prediction Formula was found to be the most common model used for resource allocation among highway-rail grade crossings by State DOTs.

Faghri and Demetsky (1986) evaluated performance of the Coleman-Stewart Model, the NCHRP Report 50 Accident Prediction Formula, the Peabody-Dimmick Formula, the New Hampshire Hazard Index Formula, and the U.S. DOT Accident Prediction Formula using the data, collected from the highway-rail grade crossings in the State of Virginia. The power factor analysis was used to compare the models. The power factor analysis aimed to determine the percentage of accidents that were observed at the most hazardous highway-rail grade crossings (as identified by the candidate accident and hazard prediction models). The results from the conducted numerical experiments demonstrated superiority of the U.S. DOT Accident Prediction Formula. Furthermore, the U.S. DOT Accident Prediction Formula outperformed the other absolute formulae (i.e., the Coleman-Stewart Model, the NCHRP Report 50 Accident Prediction Formula, the Peabody-Dimmick Formula) in terms of the number of predicted accidents, as it yielded lower chi-square values throughout the analysis for the available data.

Bowman (1994) performed a comprehensive survey among Highway-Rail Program coordinators in each state of the U.S. (except Hawaii). Certain states, which used the New Hampshire Hazard Index Formula, highlighted that some modifications were made to the original formula in order to account for the important operational features and ensure the ranking accuracy of highway-rail grade crossings. A number of State Highway-Rail Program coordinators indicated that the U.S. DOT Accident Prediction Formula does not consider certain critical factors (i.e., quadrant sight distance, roadway approach characteristics) and puts a lot of emphasis on the accident history. It was also mentioned that certain important information is not available in the FRA highway-rail grade crossing inventory database (e.g., sight distance, number of buses, passenger trains, school buses, hazardous material transporters). In order to gather such information, the State DOT representatives are required to conduct field inspections. Furthermore, the issue of the data accuracy and data updating in the FRA highway-rail grade crossing inventory database was raised as well. As a part of the study, the U.S. DOT Accident Prediction Formula was compared to the Quasi-Accident Frequency Method, which was used for resource allocation among the highway-rail grade crossings in the State of Alabama at the moment (see section 2.1.2 of this report for more details). It was found that the U.S. DOT Accident Prediction Formula outperformed the Quasi-Accident Frequency Method and was able to identify more hazardous highway-rail grade crossings.

Elzohairy and Benekohal (2000) developed the hazard index formula for the highway-rail grade crossings in the State of Illinois. The model was named as the Illinois Hazard Index Formula and was compared with some nationally recognized and State DOT accident and hazard prediction models in terms of the ability to identify and rank the crossings, which require safety improvements. The authors stated that some models could not be evaluated for the State of Illinois due to the lack of data. It was reported that the highway-rail grade crossing accident prediction formula, used by Oregon DOT (also known as the Jaqua Formula), could not be evaluated due to the lack of additional information regarding the daily average train movements by type, speed of each type of train, number of blind quadrants, angle of the intersection of a track and a roadway, approach grade, and speed of vehicles. Moreover, the North Carolina Investigative Index Model could not be evaluated, as it requires the information regarding the number of school bus passengers, using each crossing, and the sight distances in the four quadrants of each crossing. The latter data were not available through the Illinois' highway-rail grade crossing inventory and accident database.

The performance of the developed Illinois Hazard Index Formula was evaluated against the following models using the data, collected for the highway-rail grade crossings in the State of Illinois: (1) the Expected Accident Frequency (EAF) Formula deployed by Illinois DOT; (2) the

Michigan Hazard Index Formula; (3) the Connecticut Hazard Rating Formula; (4) the California Hazard Index Formula; and (5) the U.S. DOT Accident Prediction Formula. The EAF Formula, deployed by Illinois DOT at the moment, was found to be more accurate in identification of the most hazardous highway-rail grade crossings as compared to the Connecticut Hazard Rating Formula. The authors pointed out challenges in implementation of the California Hazard Index Formula, since it required the 10-year accident history data. The EAF Formula demonstrated a similar performance as compared to the Michigan Hazard Index Formula, but was outperformed by the U.S. DOT Accident Prediction Formula and the Illinois Hazard Index Formula. The Illinois Hazard Index Formula primarily selected locations that had higher accident rates. The study pointed out that the Illinois Hazard Index Formula could be used in both rural and urban areas and was not dependent on the type of existing warning devices at a given highway-rail grade crossing.

Austin and Carson (2002) pointed out drawbacks of the NCHRP Report 50 Accident Prediction Formula, the Peabody-Dimmick Formula, and the New Hampshire Hazard Index Formula. The study highlighted the lack of descriptive capabilities of the latter formulae due to their limited number of explanatory variables. On the other hand, the U.S. DOT Accident Prediction Formula addresses the explanatory characteristics of highway-rail grade crossings in a comprehensive manner, but some of its parameters (i.e., normalizing constants) have to be adjusted over time in order to ensure the accuracy in terms of the accident prediction. The accuracy of the U.S. DOT Accident Prediction Formula is substantially affected with the normalizing constant values. The study also underlined that the U.S. DOT Accident Prediction Formula does not include certain important factors (e.g., sight distance) due to lack of the data, provided by the FRA highway-rail grade crossing inventory database.

As indicated in section 2.1.4 of this report, Qureshi et al. (2003) evaluated a number of accident and hazard prediction models using the data, collected from the highway-rail grade crossings in the State of Missouri. Performance of the following models was assessed: (1) the U.S. DOT Accident Prediction Formula; (2) the California Hazard Rating Formula; (3) the Connecticut Hazard Rating Formula; (4) the Modified New Hampshire Hazard Index Formula; (5) the Kansas Design Hazard Rating Formula; (6) the Missouri Exposure Index Formula; and (7) the Illinois Hazard Index Formula. A new Exposure Index Formula was developed under that study, which was based on the Kansas Design Hazard Rating Formula. The performance of the models was assessed by the expert panel, which included the representatives from Missouri DOT, FRA, U.S. DOT, and railroad companies. It was found that the California's Hazard Rating Formula demonstrated the best performance for the highway-rail grade crossings with passive controls, while the Illinois Hazard Index Formula outperformed the other models for the highway-rail grade crossings with active controls. The study also indicated that some variables, used in certain accident and hazard prediction models, were not available in the Missouri's highway-rail grade crossing inventory database; and, therefore, site visits were required for data collection.

Weissmann et al. (2013) conducted a study, aiming to develop a new methodology, which could be used to accurately prioritize the highway-rail grade crossings for safety improvement projects in the State of Texas. It was underlined that the State of Texas had been using the Texas Priority Index Formula, which typically gave higher priority ranking to the high-volume highway-rail grade crossings based on the number of accidents occurred in the past. Once the high-volume highway-rail grade crossings had been upgraded, the challenge was to update the existing methodology; so, it can be used to prioritize the low-volume highway-rail grade crossings. The study proposed the Revised Texas Priority Index Formula, which accounted for a wide range of factors as compared to the original Texas Priority Index Formula. More specifically, the Revised Texas Priority Index Formula captured the existing protection, highway pavement type, highway-rail grade crossing location, number of traffic lanes, number of tracks, sight distance, train speed, vehicles per day, trains per day, presence of a nearby highway intersection, highway vehicular speed, and accident history (see sections 2.1.6 and 2.4.18 of this report for more details).

Throughout the study, an adjustment factor was developed for the Revised Texas Priority Index in order to give a fair consideration to both passive and active highway-rail grade crossings in the priority list. The adjustment factor was calculated for a given warranted passive highway-rail grade crossing using the number of warrants met and the number of accidents in the most recent five-year time period. Furthermore, the Texas Passive Crossing Index was proposed in order to prioritize the warranted passive highway-rail grade crossings for safety improvement projects. The Texas Passive Crossing Index was estimated as a weighted average of certain variables, including five-year accident history, daily trains, daily school buses, number of tracks, train speed, AADT, and others (see section 2.1.6 of this report for more details). Weissmann et al. (2013) also presented an integrated methodology to prioritize the highway-rail grade crossings for safety improvement projects. Based on the proposed methodology, warranted passive and active highway-rail grade crossings were prioritized separately, where active crossings were prioritized using the Revised Texas Priority Index, while passive crossings were prioritized based on the Texas Passive Crossing Index and the Revised Texas Priority Index. After that, both passive and active crossing priority lists were combined, and the highway-rail grade crossings were sorted based on the Revised Texas Priority Index with application of the adjustment factor for warranted passive highway-rail grade crossings.

Hans et al. (2015) reported a number of challenges, associated with prioritization of the highway-rail grade crossings for safety improvement projects in the State of Iowa. More specifically, throughout the Union Pacific West-East mainline study in 2002, some data inconsistences were identified. The latter was caused due to the fact that the highway-rail grade crossing information was not updated on a regular basis. Furthermore, the study highlighted that a number of highway-rail grade crossings had a fairly low exposure rating; however, the expected number of accidents was significant (Hans et al., 2015). A weighted-index method and an accompanying Microsoft Excel spreadsheet-based tool were developed in order to prioritize the highway-rail grade crossings for safety improvement projects in the State of Iowa. The factors (e.g., AADT, heavy-truck annual average daily traffic, proximity to emergency medical services, proximity to primary and secondary schools, alternate route accident rate, etc.) were weighted based on the location of highway-rail grade crossings (e.g., urban vs. rural) – see section 2.1.7 of this report for more details.

Historically, Nevada DOT has been using the Modified New Hampshire Hazard Index Formula to rank the highway-rail grade crossings for safety improvement projects. However, as pointed out in the technical report by Ryan and Mielke (2017), the New Hampshire Hazard Index Formula assigns “too much weight” to the train and highway traffic volumes. Due to the latter fact, many urban highway-rail grade crossings with higher traffic volumes are prioritized over lower-volume rural highway-rail grade crossings. In order to address the latter drawbacks, Ryan and Mielke (2017) developed an alternative Hazard Index Formula, which captured the average daily highway traffic, daily train volume, accidents within the past five years, near misses within the past 3 years, protection factor, highway speed factor, rail speed factor, track configuration factor, and highway-rail grade crossing angle factor (see section 2.4.11 of this report for more details).

Some drawbacks of other accident and hazard prediction formulae were highlighted as well. More specifically, the U.S. DOT Accident Prediction Formula relies on the past data in order to calculate the number of predicted accidents. The Texas Priority Index does not allow distinguishing two highway-rail grade crossings with the same physical and operational characteristics, which have no accidents and one accident over five years, respectively (i.e., both crossings will have exactly the same Texas Priority Index value despite differences in terms of the number of accidents occurred - see section 2.4.17 of this report for more details). Moreover, based on an interview with the Arizona DOT representative, which was conducted as a part of that study, it was highlighted that the Texas Priority Index does not account for certain important factors, such as highway vehicle speeds, school bus usage, transport of hazardous materials, and urban/rural distinction.

Sperry et al. (2017) compared performance of the U.S. DOT Accident Prediction Formula against the alternative accident and hazard prediction formulae, including the following: (1) the New Hampshire Hazard Index Formula; (2) the NCHRP Report 50 Accident Prediction Formula; (3) the Florida Accident Prediction and Safety Index Formula; (4) the Missouri Exposure Index Formula; (5) the North Carolina Investigative Index Formula; and (6) the Texas Priority Index Formula. The U.S. DOT Accident Prediction Formula was found to be superior to other formulae based on the data, collected for the highway-rail grade crossings in the State of Ohio. The study also recommended that the Missouri Exposure Index and the North Carolina Investigative Index should be taken into account when ranking passive highway-rail grade crossings upon completion of the initial prioritization. Moreover, the study pointed out that train counts and AADT were not updated on a regular basis in certain states, which may negatively affect the accuracy of results, returned by accident and hazard prediction formulae.

### 3.4. Summary

Throughout the literature review, a total of 21 accident and hazard prediction formulae have been discovered. A number of formulae are considered as nationally recognized (i.e., the Coleman-Stewart Model, the NCHRP Report 50 Accident Prediction Formula, the New Hampshire Hazard Index Formula, the Peabody-Dimmick Formula, and the U.S. DOT Accident Prediction Formula), while the other formulae are state-specific. Certain state-specific formulae are inspired by the nationally recognized accident and hazard prediction formulae. For example, several formulae are based on the New Hampshire Hazard Index Formula (e.g., the Michigan Hazard Index Formula, the New Mexico Hazard Index Formula, the Texas Priority Index Formula). The formulae, identified in the literature, were classified into two categories, including the following: (1) accident prediction formulae; and (2) hazard prediction formulae. The accident prediction formulae are used to calculate the expected number of accidents at highway-rail grade crossings, while the hazard prediction formulae are used to assess the hazard/susceptibility of highway-rail grade crossings to accidents. A total of 29% of the identified formulae were accident prediction formulae, while the remaining 71% were hazard prediction formulae.

The discovered accident and hazard prediction formulae were analyzed in detail. A total of 20 unique predictors were identified in the existing accident and hazard prediction formulae. It was found that all of the considered accident and hazard prediction formulae used the number of trains per day and the number of vehicles per day in order to estimate the expected number of accidents or assess the hazard of a given highway-rail grade crossing. The number of trains per day and the number of vehicles per day can be considered as the basic predictors, which are required to assess the "exposure" of a given highway-rail grade crossing. The existing protection (i.e., presence of specific types of warning devices), accident history, train speed, number of tracks, sight distance, number of traffic lanes, highway vehicular speed, and location (i.e., urban vs. rural) are also frequently used by the existing accident and hazard prediction formulae. Certain factors have been considered only by a very limited number of formulae (e.g., traversing school buses, approach gradient, number of cars in a train, other roadway geometrics, and presence of a nearby highway intersection).

The scope of this study also included a critical performance assessment for the identified accident and hazard prediction formulae and review of the challenges, associated with implementation of the existing accident and hazard prediction formulae. One of the major challenges with implementation of certain accident and hazard prediction formulae was reported to be the data availability (Bowman, 1994; Elzohairy and Benekohal, 2000; Qureshi et al., 2003; Sperry et al., 2017). The information regarding specific factors (e.g., daily average train movements by type of train, speed of each type of train, number of blind quadrants, and number of school bus passengers) may not be readily available in the existing highway-rail grade crossing inventory databases (e.g., the FRA highway-rail grade crossing inventory database or the state highway-rail grade crossing accident/incident database), and the State DOT representatives will be required to perform additional field reviews or contact railroad companies in order to obtain necessary data. Bowman (1994) conducted a survey among the Highway-Rail Program coordinators in the U.S. and found that a number of states had to modify the New Hampshire Hazard Index Formula in order to capture the important operational features and ensure the ranking accuracy of highway-rail grade crossings. Also, many Highway-Rail Program coordinators expressed some concerns regarding the U.S. DOT Accident Prediction Formula because it does not consider quadrant sight distance and roadway approach characteristics and puts a lot of emphasis on the accident history.

Another issue which was highlighted in the literature consists in the fact that several accident and hazard prediction formulae (e.g., the NCHRP Report 50 Accident Prediction Formula, the Peabody-Dimmick Formula, and the New Hampshire Hazard Index Formula) have a limited number of explanatory variables, which further causes the lack of descriptive capabilities (Austin and Carson, 2002). On the other hand, certain formulae (e.g., the U.S. DOT Accident Prediction Formula) have a substantial number of explanatory variables; however, some parameters of such formulae have to be updated periodically because otherwise the accuracy of results would be negatively affected (Austin and Carson, 2002). The issue of insufficient descriptive capabilities was also pointed out by Ryan and Mielke (2017). For example, the Texas Priority Index does not account for certain important factors, such as train speeds, school bus usage, transport of hazardous materials, and urban/rural distinction (Ryan and Mielke, 2017).

Weissmann et al. (2013) underlined the drawbacks of the accident and hazard prediction formulae, which rely on the accident history. More specifically, the latter group of accident and hazard prediction formulae yields higher priority values for the high-volume highway-rail grade crossings based on the number of accidents occurred in the past. Therefore, such formulae may not be able to return adequate results, when applied for the analysis of the low-volume highway-rail grade crossings. Hans et al. (2015) pointed out the challenges, which are associated with prioritization of the highway-rail grade crossings for safety improvement projects in the State of Iowa. Throughout the Union Pacific West-East mainline study in 2002, some inconsistences in the highway-rail grade crossing inventory database were identified. The inconsistences were caused by the fact that the highway-rail grade crossing inventory database was not regularly updated. Furthermore, the study indicated that a number of highway-rail grade crossings had a low exposure rating, but the expected number of accidents was substantial (Hans et al., 2015).

Ryan and Mielke (2017) highlighted that the New Hampshire Hazard Index Formula assigns "too much weight" to the train and highway traffic volumes and, therefore, will generally give higher priority ranking to urban highway-rail grade crossings with higher traffic volumes as compared lower-volume rural highway-rail grade crossings. Ryan and Mielke (2017) also indicated that certain accident and hazard prediction formulae rely on the accident history; however, the tendencies in accident occurrence at highway-rail grade crossings may change over time, which will negatively affect the accuracy of such accident and hazard prediction formulae. Moreover, it was indicated that the Texas Priority Index does not allow distinguishing two highway-rail grade crossings with the same physical and operational characteristics, which have no accidents and one accident over five years, respectively (i.e., both crossings will be assigned exactly the same Texas Priority Index value despite differences in terms of the number of accidents occurred) - Ryan and Mielke (2017). Sperry et al. (2017) pointed out that train counts and AADT were not regularly updated in certain states, which may negatively affect the accuracy of results, provided by accident and hazard prediction formulae.

A number of states attempted to compare performance of the proposed/currently adopted accident and hazard prediction formulae against the alternative formulae. For example, Faghri and Demetsky (1986) found that the U.S. DOT Accident Prediction Formula had the best performance in terms of its ability to identify and rank the highway-rail grade crossings, which require safety improvements, based on the data, collected for the highway-rail grade crossings in the State of Virginia. The U.S. DOT Accident Prediction Formula outperformed the Quasi-Accident Frequency Method and was able to identify more hazardous highway-rail grade crossings in the State of Alabama (Bowman, 1994). The Illinois Hazard Index Formula was found to be superior to the Expected Accident Frequency Formula, which had been deployed by Illinois DOT, as well as the Michigan Hazard Index Formula, the Connecticut Hazard Rating Formula, the California Hazard Index Formula, and the U.S. DOT Accident Prediction Formula, for the highway-rail grade crossings in the State of Illinois (Elzohairy and Benekohal, 2000). Qureshi et al. (2003) found that the California's Hazard Rating Formula and the Illinois Hazard Index Formula were the most appropriate formulae for prioritizing passive and active highway-rail grade crossings in the State of Missouri, respectively.

Weissmann et al. (2013) developed the Revised Texas Priority Index Formula and demonstrated its superiority against the original Texas Priority Index Formula for 9,108 highway-rail grade crossings in the State of Texas and 2011 accident data. Sperry et al. (2017) evaluated performance of the U.S. DOT Accident Prediction Formula against alternative six accident and hazard prediction formulae for the highway-rail grade crossings in the State of Ohio. It was recommended that the State of Ohio should continue using the U.S. DOT Accident Prediction Formula; however, the Missouri Exposure Index Formula and the North Carolina Investigative Index Formula can be applied to rank passive highway-rail grade crossings upon completion of the initial prioritization.

# 4. DESCRIPTION OF THE RELEVANT FEDERAL RAILROAD ADMINISTRATION DATABASES

This section of the report provides a detailed description of the FRA crossing inventory database and the FRA highway-rail grade crossing accident database, which will be further used throughout this project.

## 4.1. The Federal Railroad Administration's Crossing Inventory Database Description

The Federal-Aid Policy Guide (FAPG 924.9(a) (1)) (U.S. DOT, 1991) stipulates that each state should maintain "a process for collecting and maintaining a record of accident, traffic, and highway data, including, for railroad-highway grade crossings, the characteristics of both highway and train traffic". In 1973, the Federal Highway Administration (FHWA) instructed the State of Florida to implement a Highway-Railroad Improvement Program (FDOT, 2011). As part of the program, the Florida Department of Transportation (FDOT) is required to perform inventory of all the crossings in the State of Florida. FDOT's Central Utility/Rail Office assisted the Department's Safety Office and assigned a District Railroad Coordinator for each geographic area of the state in order to conduct inventory of the highway-rail grade crossings within their District boundaries (FDOT, 2011). The information, provided by the District Railroad Coordinators, is collated and presented to FRA. FRA collects the data from each state, which are further transferred to a database of highway-rail grade crossings for the United States (U.S.) (FDOT, 2011).

Class I Railroads are required to submit the crossing inventory data electronically to Federal Railroad Administration (FRA) (FRA, 2015). To facilitate the process, FRA has set up a Grade Crossing Inventory System (GCIS), which replaced the GX 32 system, a PC-based crossing data maintenance system software used by different data providers, including railroad, transit, and state authorities. The users can submit their U.S. DOT Crossing Inventory data (Form FRA F 6180.71) as electronic files in Microsoft (MS) Excel (.xlsx) format. In the latter case, the users have to submit multiple crossing records at the same time using a preformatted Excel file template. Alternatively, the users can submit their U.S. DOT Crossing Inventory data via Application Programming Interface (API) in one of the following formats (FRA, 2015): (1) Extensible Markup Language (.xml); (2) JavaScript Object Notification (.json); and (3) ATOM (.atom).

The authorized users of the GCIS Web Application are required to have a registered username and password. The highway-rail grade crossing inventory data, submitted using the FRA-approved file formats, must conform to the field names, valid values, and other rules, provided in the GCIS Inventory Data Field File Specification (FRA, 2015). In order to update the highway-rail grade crossing data, the users are required to enter the new values in the appropriate fields to be updated. The number of GCIS fields may vary from one year to another (depending on the system updates/modifications conducted by FRA and/or other appropriate agencies). A detailed description of the FRA crossing inventory database fields (specifically, field name, field description, and potential values [if any]) is provided in Appendix D, which accompanies this report. The database fields provide the information regarding different aspects of the existing crossings.

Once a reporting agency (e.g., railroad authority, transit authority, state authority) initiates an update of the highway-rail grade crossing inventory database, the update form must be completed. It is recommended that the agency notify the other appropriate agencies regarding any updates and forward the completed update form (Bowman, 1994). After the agencies agree on the changes to the highway-rail grade crossing inventory database, the state is required to provide the original copy of the file with the updates to FRA for processing. This procedure ensures that all the parties that are being involved in the process are informed of any changes made in the database (Bowman, 1994). Note that the FRA procedure for reporting the highway-rail grade crossing inventory data allows states or railroads to report the inventory data without verification from the other reporting agency. Although there is a procedure for updating the highway-rail grade crossing inventory database, some data elements, including average daily highway traffic and train volumes, might not be updated on a regular basis. Outdated values of the average daily highway traffic and train volumes may cause erroneous prediction of accidents at highway-rail grade crossings, which may further lead to inaccurate resource allocation (Bowman, 1994). Results from surveys show that states and railroads often complain about the poor accuracy of the data available in the FRA crossing inventory database (Bowman, 1994). The latter finding implicates states and railroads, since they are responsible for providing the information and updates regarding the highway-rail grade crossings, which are used in preparing the database.

The geographic location of a given crossing is denoted by various fields, such as state, county, city, in or near a city, type of land development (e.g., open space, residential, commercial, industrial, etc.), position of a crossing (e.g., at grade, railroad under, railroad over), latitude, longitude, etc. The FRA crossing inventory database also contains a lot of highway-related information, including highway functional classification, street or road name, highway traffic signals, highway system, AADT, percentage of trucks, existing pavement, number of traffic lanes, posted highway speed, average number of school buses passing over the crossing on a school day, and other. The extent of warning and types of warning devices used at crossings is described in a number of fields, specifically: count of advance warning signs, wayside horn, number of bells, flashing lights, channelization devices/medians, gate configuration, number of STOP signs, number of YIELD signs, number of crossbuck assemblies, illumination, etc. Relevant information regarding the trains, passing through a given crossing, is specified in certain fields, including the following: total daylight thru trains, total night time thru trains, total transit trains, total switching trains, maximum timetable speed, number of main tracks, number of siding tracks, number of transit tracks, number of yard tracks, average passenger train count per day, etc.

The FRA Data Dictionary for External Use Grade Crossing Inventory System (FRA, 2016), prepared by the U.S. DOT, FRA, and Office of Railroad Safety, classifies the fields of the FRA crossing inventory database available via the GCIS system into the following groups: (1) “Crossing Header” – the fields of that group contain the information regarding the crossing and the ownership data; (2) “Highway Traffic Control Device” – the fields of that group contain the information regarding the highway or pathway traffic control devices; (3) “Location and Classification” – the fields of that group contain the information regarding crossing location and classification; (4) “Operating Railroad” – the fields of that group contain the information regarding the operating railroad; (5) “Physical Characteristics” – the fields of that group contain the information regarding the crossing physical characteristics; (6) "Public Highway" – the fields of that group contain the information regarding the public highway, associated with a given crossing; (7) "Report Base" – the fields of that group store the header information and the crossing records, where the primary operating railroad chose the value of "Yes" for field "I.7 Do Other Railroads Operate a Separate Track at Crossing"; (8) "Errors" – the fields of that group contain the information regarding the validation error messages, which were generated by the inventory system; (9) "Lookups" – the fields of that group contain all the valid values available upon completion of a crossing record; and (10) "Reason" – the fields of that group contain all the available values, associated with the reason to update the crossing inventory form.

## 4.2. The Federal Railroad Administration's Highway-Rail Grade Crossing Accident Database

### *4.2.1. Purpose of the Database*

The primary function of the FRA Office of Safety Analysis is to promote and regulate safety throughout the U.S. railroad industry. The procedure for reporting railroad accidents/incidents is guided by the FRA regulations, which are available in Title 49 Code of Federal Regulations (CFR) Part 225 provided by the U.S. Government Publishing Office (GPO) (U.S. GPO, 2006). FRA needs the accurate information to conduct its regulatory and enforcement responsibilities. The accurate information is also required to estimate comparative trends in railroad safety, so that hazard elimination and risk reduction programs can be administered to prevent railroad injuries and accidents (FRA, 2011a). For these reasons, FRA developed several safety databases, including the following (FRA, 2018b): (1) train accident database; (2) trespasser accident database; (3) rail equipment accident database; (4) highway-rail grade crossing accident database (also referred to as "highway-rail grade crossing accident/incident database"); (5) railroad casualty database; and others. The highway-rail grade crossing accident database consists of accident records for various highway-rail grade crossings in the U.S. The FRA highway-rail grade crossing accident database is an open source, aiming to provide the public with the up-to-date railroad safety information for the highway-rail grade crossings across the nation (FRA, 2018b).

### *4.2.2. Collection of the Data for the Database*

FRA requires railroads to report any accident that involves the impact of a train with a roadway user (including pedestrians). Moreover, FRA collects the data regarding railroad safety from the railroads in the U.S. and analyzes the data to provide useful statistics in the database. FRA uses the accident data, reported by railroads, and the highway-rail grade crossing inventory data to develop accident summaries each year by state and highway-rail grade crossing characteristics (Bowman, 1994). Railroads are required to submit an annual report of total work hours and casualties by state using the Form FRA F 6180.56 (FRA, 2011a). The annual report should be accompanied with monthly reports regarding the recorded accidents, which have to be submitted to FRA by railroad companies as well (the annual report should be included with the monthly report for December). Railroad authorities report the following primary groups of accidents/incidents to FRA on a monthly basis (FRA, 2011a):

> *Group I - Highway-Rail Grade Crossing Accident/Incident:* Railroads must report highway-rail grade crossing accidents/incidents to FRA using the Highway-Rail Grade

Crossing Accident/Incident Form (Form FRA F 6180.57). It is required that potentially injured highway users are contacted by railroads via mail using a Highway User Injury Inquiry Form record (FRA F 6180.150) or by phone if unsuccessful. Railroads are required to use the information, obtained from the individuals who were involved in the highway-rail grade crossing accident, in order to satisfy the FRA accident/incident reporting and recording requirements.

*Group II – Rail Equipment Accident/Incident:* These accidents/incidents involve the operation of on-track equipment that causes damages higher than the current threshold for reporting. They are reported using the Rail Equipment Accident/Incident Form (Form FRA F 6180.54). If an employee factor is cited as the cause of the accident, railroads are required to complete and submit an Employee Human Factor Attachment (Form FRA F 6180.81). Railroads are required to provide the employee concerned with a Notice to Railroad Employee Involved in Rail Equipment Accident/Incident Attributed to Employee Human Factor (Form FRA F 6180.78). In addition, railroads are required to investigate the possible use of alcohol/drug or impairment and submit the report to FRA.

*Group III – Death, Injury, or Occupational Illness:* All the deaths, fatal, and non-fatal injuries must be reported to FRA using Form FRA F 6180.55a. These accidents include occupational illnesses to railroad employees. If a fatality involves a trespasser, railroads are required to provide supplemental information about the cause of death and include their findings in the Form FRA F 6180.55a.

Furthermore, railroads are required to provide immediate telephonic notifications to FRA regarding certain kinds of accidents/incidents, including the following: (1) accidents related to railroad locomotive safety standards (i.e., accidents due to failure of a locomotive or a part of a locomotive, causing serious injury of people); (2) accidents related to signal failure (i.e., accidents due to failure of a signal system that may cause a potential hazard to the train movement); (3) accidents related to grade crossing signal failure (i.e., accidents due to impact between on-track railroad equipment and an automobile, truck, bus, motorcycle, bicycle, other types of vehicles, or pedestrian); and (4) accidents related to control of alcohol and drug use. More information regarding the procedures for telephonic notifications that are used to report the data regarding highway-rail grade crossing accidents/incidents is provided in Appendix E, which accompanies this report.

In some cases, railroads may have to complete multiple accident/incident forms. For instance, if a highway-rail grade crossing accident results in reportable injuries, the railroad would be required to complete the Form FRA F 6180.55a for each FRA reportable injury sustained by individuals, along with the Form FRA F 6180.57. Furthermore, the Form FRA F 6180.54 must be completed in case if a given accident caused the damage of track and on-track equipment, which exceeds an established monetary threshold. FRA requires arranging reports in the following order (FRA, 2011a):

1) Form FRA F 6180.55 (Injury/Illness Summary);
2) Form FRA F 6180.55a (Injury/Illness Continuation Sheet);

3) Form FRA F 6180.54 (Rail Equipment Accident/Incident), which can be accompanied with Form FRA F 6180.81 (Employee Human Factor) when applicable;
4) Form FRA F 6180.57 (Highway-Rail Accident/Incident);
5) Form FRA F 6180.56 (Annual Report of Hours & Casualties) - December report only.

#### *4.2.3. Description of Fields for the FRA Highway-Rail Grade Crossing Accident Database*

The FRA highway-rail grade crossing accident database (i.e., the Form FRA F 6180.57) consists of a wide range of fields. These fields can be divided into eight categories. The first category comprises a number of fields, which provide the information regarding the time of incident, including year of incident, month of incident, day of incident, hour of incident, AM or PM, and others. The second category comprises the information regarding the region or location, where a given highway-rail grade crossing is situated. The latter information is provided in several fields, including names of state, county, city, Federal Information Processing Standards (FIPS) State code, FIPS designated region, etc. The third category includes a number of fields, which comprise of several codes, associated with the railroads (and the highway-rail grade crossing where the accident occurred), such as railroad code, railroad assigned identification number, highway-rail grade crossing ID number, number of tracks, type of warning, location of warning, etc. The fourth category consists of the information regarding the highway and the highway user, which are outlined in the fields, including type of a highway user, a highway user direction, position of a highway user, action of a highway user, highway vehicular speed, etc.

The fifth category includes the fields, which describe the environmental conditions at the time of an incident, including temperature, weather conditions, and visibility. The sixth category is composed of several fields, which provide the information regarding the train involved in the accident. Some of the fields include a train type, speed of a train, a train speed type, number of locomotive units, number of cars, total number of people in a train, etc. The seventh category provides the information regarding the fatalities and injuries reported, such as number of highway-rail grade crossing user fatalities/injuries, number of railroad employee fatalities/injuries, number of train passenger fatalities/injuries, etc. Finally, several other details are reported, including name and quantity of hazardous materials released, entity releasing hazardous materials, whether a video was recorded or not, and others. A detailed description of the FRA highway-rail grade crossing accident database fields (specifically, field name, field description, potential values [if any], and notes/conversion [if any]) is provided in Appendix F, which accompanies this report.

# 5. IDENTIFICATION OF THE CANDIDATE ACCIDENT AND HAZARD PREDICTION MODELS AND THE ADOPTED EVALUATION APPROACHES

This section of the report presents the candidate accident and hazard prediction models, which were selected for a detailed analysis using the FRA crossing inventory database and the FRA highway-rail grade crossing accident database for the highway-rail grade crossings in the State of Florida. Furthermore, the methodology and criteria that were used to evaluate the candidate accident and hazard prediction models are described as well.

## 5.1. Identification of the Candidate Accident and hazard Prediction Models

A detailed review of the literature, performed under this project, revealed that some State DOTs developed custom accident and hazard prediction models for estimating the number of accidents, assessing the highway-rail grade crossing hazard, and prioritizing highway-rail grade crossings for safety improvement projects, while other State DOTs used nationally recognized formulae and procedures. The accident and hazard prediction formulae, identified from the conducted literature review, were divided into two groups: (1) accident prediction formulae; and (2) hazard prediction formulae. The latter two groups of formulae are primarily differentiated based on the performance measure, which is used in ranking highway-rail grade crossings. Specifically, the accident prediction formulae compute the forecasted number of accidents at highway-rail grade crossings over a given time period, while the hazard prediction formulae estimate a hazard or safety index value that is used to rank highway-rail grade crossings for safety improvements/resource allocation.

Based on a comprehensive review of the literature, a total of 21 accident and hazard prediction formulae have been identified (6 formulae or 29% of the identified formulae can be classified as accident prediction formulae, while the remainder or 71% of the identified formulae can be classified as hazard prediction formulae). The accident prediction formulae include the following:

- Coleman-Stewart Model
- NCHRP Report 50 Accident Prediction Formula
- Peabody-Dimmick Formula
- U.S. DOT Accident Prediction Formula
- Iowa Accident Prediction Formula (the State of Iowa)
- The Jaqua Formula (the State of Oregon)

The hazard prediction formulae include the following:

- New Hampshire Hazard Index Formula
- Arkansas Hazard Rating Formula (the State of Arkansas)
- California Hazard Rating Formula (the State of California)
- Connecticut Hazard Rating Formula (the State of Connecticut)
- Florida Accident Prediction and Safety Index Formula (the State of Florida)
- Illinois Hazard Index Formula (the State of Illinois)
- Kansas Design Hazard Rating Formula (the State of Kansas)
- Michigan Hazard Index Formula (the State of Michigan)

- Missouri Exposure Index Formula (the State of Missouri)
- Nevada Hazard Index Formula (the State of Nevada)
- New Mexico Hazard Index Formula (the State of New Mexico)
- North Carolina Investigative Index Formula (the State of North Carolina)
- South Dakota Hazard Index Formula (the State of South Dakota)
- Texas Priority Index Formula (the State of Texas)
- Revised Texas Priority Index Formula (the State of Texas)

### *5.1.1. Selection of the Candidate Accident Prediction Formulae*

The predictors of the candidate accident prediction models, identified based on the existing literature, were extracted to determine if sufficient information regarding these predictors is available in the FRA crossing inventory database and the FRA highway-rail grade crossing accident database for the model implementation. Note that the information, provided in the FRA crossing inventory database, was combined with the information, provided in the FRA highway-rail grade crossing accident database, to generate the input data for a given accident prediction model. Table 48 presents the predictors that are considered in the candidate accident prediction models and identifies the predictors, which are not available in the FRA crossing inventory database and the FRA highway-rail grade crossing accident database.

**Table 48** The information regarding predictors of the candidate accident prediction models.

| Accident Prediction Model | Predictors in the Accident Prediction Model | Predictor Information Not Reported in the FRA Databases |
|---|---|---|
| Coleman-Stewart Model | Vehicles per day; Trains per day; Location; Number of tracks; Existing protection | |
| NCHRP Report 50 Accident Prediction Formula | Vehicles per day; Trains per day; Existing protection; Location | |
| Peabody-Dimmick Formula | Vehicles per day; Trains per day; Existing protection | |
| U.S. DOT Accident Prediction Formula | Existing protection; Vehicles per day; Trains per day; Daylight thru trains per day; Number of tracks; Highway pavement type; Train speed; Location; Number of traffic lanes; Accident history (the total number of accidents in the last five years or since the year of last improvement) | |

**Table 48** The information regarding predictors of the candidate accident prediction models (cont'd).

| Accident Prediction Model | Predictors in the Accident Prediction Model | Predictor Information Not Reported in the FRA Databases |
|---|---|---|
| Iowa Accident Prediction Formula | Vehicles per day; Trains per day; Time of day; Existing protection; Daylight thru trains per day; Train speed; Highway pavement type; Number of tracks; Number of traffic lanes; Accident history (the total number of accidents in the last five years) | Time of day (AADT and number of trains by time of day) |
| Jaqua Formula | Trains per day; Type of train; Number of cars in a train; Train speed; Vehicles per day; Number of tracks; Sight distance; Highway vehicular speed; Number of traffic lanes; Angle of crossing; Approach gradient; Other roadway geometrics (such as curvature of the roadway, existence of entrances and exits to streets and street intersections near a highway-rail grade crossing); Existing protection; Location | Number of cars in a train; Sight distance; Approach gradient; Other roadway geometrics (such as curvature of the roadway, existence of entrances and exits to streets and street intersections near a highway-rail grade crossing) |

Based on the information, presented in Table 48 and a detailed analysis of the identified accident prediction models, all the accident prediction models, except the Iowa Accident Prediction Formula and the Jaqua Formula, can be evaluated using the data available through the FRA crossing inventory database and the FRA highway-rail grade crossing accident database. The Iowa Accident Prediction Formula cannot be evaluated throughout this study, as it relies on the exposure factor, which is estimated based on AADT and number of trains by time of day (i.e., between 12:00 AM and 6:00 AM, between 6:00 AM and 12:00 PM, between 12:00 PM and 6:00 PM, and between 6:00 PM and 12:00 AM) (Iowa DOT, 2006). The latter information is not available neither in the FRA crossing inventory database nor the FRA highway-rail grade crossing accident database.

The Jaqua Formula also cannot be analyzed throughout this study, as values for certain predictors of the Jaqua Formula are not provided in the FRA crossing inventory database and the FRA highway-rail grade crossing accident database. More specifically, the information regarding the following predictors of the Jaqua Formula is not available through the FRA crossing inventory database and the FRA highway-rail grade crossing accident database: (1) number of cars in a train; (2) sight distance; (3) approach gradient; (4) curvature of the roadway; and (5) existence of entrances and exits to streets and street intersections near a highway-rail grade crossing. Although the number of cars in the train, involved in the accident, is provided in the

FRA highway-rail grade crossing accident database, the information regarding the number of cars in a train is required for all the types of trains passing a given highway-rail grade crossing on a daily basis. Moreover, the protection factor for the Jaqua Formula is determined based on the type of warning devices, currently installed at a given highway-rail grade crossing, and location (i.e., urban vs. rural) (Elzohairy and Benekohal, 2000). The study, conducted by Elzohairy and Benekohal (2000), provides a detailed description of the Jaqua Formula (unlike the other studies which have been reviewed as a part of this project). However, it does not elaborate how the protection factor value is set for a given highway-rail grade crossing based on the type of warning devices and its location.

Based on the aforementioned facts, the following candidate accident prediction models will be evaluated in this study for the highway-rail grade crossings in the State of Florida using the FRA crossing inventory database and the FRA highway-rail grade crossing accident database:

- Coleman-Stewart Model
- NCHRP Report 50 Accident Prediction Formula
- Peabody-Dimmick Formula
- U.S. DOT Accident Prediction Formula

### *5.1.2. Selection of the Candidate Hazard Prediction Formulae*

The predictors of the candidate hazard prediction models, identified based on the existing literature, were extracted to determine if sufficient information regarding these predictors is available in the FRA crossing inventory database and the FRA highway-rail grade crossing accident database for the model implementation. Note that the information, provided in the FRA crossing inventory database, was combined with the information, provided in the FRA highway-rail grade crossing accident database, to generate the input data for a given hazard prediction model. Table 49 presents the predictors that are considered in the candidate hazard prediction models and identifies the predictors, which are not available in the FRA crossing inventory database and the FRA highway-rail grade crossing accident database.

Based on the information, presented in Table 49, and a detailed analysis of the identified hazard prediction models, a total of six hazard prediction models out of 15 hazard prediction models, which were identified from the review of the literature, can be evaluated using the FRA crossing inventory database and the FRA highway-rail grade crossing accident database. The latter can be explained by the fact that the FRA crossing inventory database and the FRA highway-rail grade crossing accident database provide sufficient information regarding the predictors, which can be used for implementation of only six hazard prediction models, including the following: (1) the New Hampshire Formula; (2) the California Hazard Rating Formula; (3) the Connecticut Hazard Rating Formula; (4) the Illinois Hazard Index Formula; (5) the Michigan Hazard Index Formula; and (6) the Texas Priority Index Formula.

**Table 49** The information regarding predictors of the candidate hazard prediction models.

| Hazard Prediction Model | Predictors in the Hazard Prediction Model | Predictor Information Not Reported in the FRA Databases |
|---|---|---|
| New Hampshire Formula | Vehicles per day; Trains per day; Existing protection | |
| Arkansas Hazard Rating Formula | Vehicles per day; Trains per day; Number of tracks; Accident history (the total number of accidents in the last 15 years) | |
| California Hazard Rating Formula | Vehicles per day; Trains per day; Existing protection; Accident history (the total number of accidents in the last ten years) | |
| Connecticut Hazard Rating Formula | Vehicles per day; Trains per day; Existing protection; Accident history (the total number of accidents in the last five years) | |
| Florida Accident and Safety Index Prediction Model | Vehicles per day; Trains per day; Number of traffic lanes; Sight distance; Train speed; Highway vehicular speed; Accident history (the total number of accidents in the last six years or since the year of last improvement); School buses; Existing protection | Sight distance |
| Illinois Hazard Index Formula | Vehicles per day; Trains per day; Train speed; Number of tracks; Number of traffic lanes; Accident history (average number of accidents per year over a 5-year period); Existing protection | |
| Kansas Design Hazard Rating Formula | Vehicles per day; Trains per day; Type of train; Angle of crossing; Sight Distance; Number of tracks | Type of train (fast trains vs. slow trains); Sight distance |
| Michigan Hazard Index Formula | Vehicles per day; Trains per day; Existing protection | |

**Table 49** The information regarding predictors of the candidate hazard prediction models (cont'd).

| Hazard Prediction Model | Predictors in the Hazard Prediction Model | Predictor Information Not Reported in the FRA Databases |
|---|---|---|
| Missouri Exposure Index Formula | Existing protection; Sight distance; Vehicles per day; Highway vehicular speed; Trains per day; Type of train; Train speed | Sight distance |
| Nevada Hazard Index Model | Vehicles per day; Trains per day; Accident history (the total number of accidents in the last five years); Near misses (the total number of near misses in the last three years); Existing protection; Highway vehicular speed; Train speed; Number of tracks; Angle of crossing | Near misses (the total number of near misses in the last three years) |
| New Mexico Hazard Index Formula | Vehicles per day; Trains per day; Existing protection; Sight distance; Train speed; Accident history (custom formula based on the accident severity) | Sight distance |
| North Carolina Investigative Index Model | Existing protection; Vehicles per day; School buses (average number of passengers); Trains per day; Type of train; Train speed; Number of tracks; Accident history (average number of accidents per year over a 10-year period); Sight distance | School buses (average number of passengers); Sight distance |
| South Dakota Hazard Index Formula | Vehicles per day; Trains per day; Existing protection; Sight distance | Sight distance |
| Texas Priority Index Formula | Vehicles per day; Trains per day; Existing protection; Train speed; Accident history (the total number of accidents in the last five years) | |

**Table 49** The information regarding predictors of the candidate hazard prediction models (cont'd).

| Hazard Prediction Model | Predictors in the Hazard Prediction Model | Predictor Information Not Reported in the FRA Databases |
|---|---|---|
| Revised Texas Priority Index Formula | Existing protection; Highway pavement type; Location; Number of traffic lanes; Number of tracks; Sight distance; Train speed; Vehicles per day; Trains per day; Presence of a nearby highway intersection; Highway vehicular speed; Accident history (the total number of accidents in the last five years) | Sight distance |

The Arkansas Hazard Rating Formula cannot be evaluated throughout this study, as it requires points that are assigned based on the highway traffic, railway traffic, number of side and main tracks, and accident records (Elzohairy and Benekohal, 2000). The methodology, which has been used by Arkansas Highway and Transportation Department (AHTD) for assigning points to the highway-rail grade crossings based on the aforementioned factors, was not reported in any of the studies that have been reviewed as a part of this project. In addition, the Arkansas Hazard Rating Formula requires the accident records over a period of 15 years. A fairly long accident history, required to evaluate the Arkansas Hazard Rating Formula, might affect performance of the model (i.e., significant changes may occur in the physical and operational characteristics of a given highway-rail grade crossing over a 15-year time period).

Since the FRA crossing inventory database and the FRA highway-rail grade crossing accident database do not provide the information regarding sight distance at highway-rail grade crossings, a number of hazard prediction models cannot be evaluated, including the following: (1) Florida Accident and Safety Index Prediction Model; (2) Kansas Design Hazard Rating Formula; (3) Missouri Exposure Index Formula; (4) New Mexico Hazard Index Formula; (5) North Carolina Investigative Index Model; (6) South Dakota Hazard Index Formula; and (7) Revised Texas Priority Index Formula. It is more likely that the sight distance data are available for the highway-rail grade crossings in the State of Florida; however, it was not provided by FDOT throughout this project (most likely due to the fact that the data were outdated at the moment and could negatively affect accuracy of the hazard prediction models that rely on sight distance).

Furthermore, a number of hazard prediction models require certain additional information (along with sight distance), which is not available neither in the FRA crossing inventory database nor in the FRA highway-rail grade crossing accident database. For example, the Kansas Design Hazard Rating Formula requires the information regarding the number of fast trains and the number of slow trains (excluding switching trains), along with the sum of the maximum sight distance 4-ways (Elzohairy and Benekohal, 2000; Qureshi et al., 2003). The average number of school bus passengers is one of the predictors, which is used by the North Carolina Investigative Index (Elzohairy and Benekohal, 2000). The South Dakota Hazard Index Formula assesses a potential hazard of a given highway-rail grade crossing based on the protection factor and the obstruction factor (Elzohairy and Benekohal, 2000). The study, conducted by Elzohairy and Benekohal (2000), provides a detailed description of the South Dakota Hazard Index Formula (unlike the other studies which have been reviewed as a part of this project). However, it does not elaborate how both protection and obstruction factors are determined.

The Nevada Hazard Index Model does not use the sight distance information; however, it requires the total number of near misses within the past three years in order to estimate a hazard index for a given highway-rail grade crossing (Ryan and Mielke, 2017). Since the information regarding the total number of near misses within the past three years at the highway-rail grade crossings in the State of Florida is not available, the Nevada Hazard Index Model cannot be evaluated throughout this study. Based on the aforementioned facts, the following candidate hazard prediction models will be evaluated in this study for the highway-rail grade crossings in the State of Florida using the FRA crossing inventory database and the FRA highway-rail grade crossing accident database:

- New Hampshire Formula
- California Hazard Rating Formula
- Connecticut Hazard Rating Formula
- Illinois Hazard Index Formula
- Michigan Hazard Index Formula
- Texas Priority Index Formula

## 5.2. Adopted Evaluation Approaches for the Candidate Accident and hazard Prediction Models

The following approaches were adopted for comparison of the candidate accident and hazard prediction models: (1) chi-square formula; (2) grouping of crossings based on the actual accident data; and (3) Spearman rank correlation coefficient. Note that the chi-square formula will be applied to evaluate the absolute formulae (i.e., accident prediction models) only, while the other approaches will be used to evaluate both absolute and relative formulae (i.e., accident and hazard prediction models). The following sections of this report provide a detailed description of the required input data, the key assumptions, which were adopted throughout evaluation of the candidate accident and hazard prediction models, and the descriptive statistics for the highway-rail grade crossings, which were selected for evaluation of the candidate accident and hazard prediction models. Moreover, the aforementioned approaches, adopted to assess performance of the candidate accident and hazard prediction models, and the analysis software, which was used under this project, are discussed in this section of the report as well.

### *5.2.1. Input Data and Key Assumptions*

As indicated earlier in this report, the FRA crossing inventory database and the FRA highway-rail grade crossing accident database will serve as the primary data sources in order to evaluate the considered accident and hazard prediction models. The following fields of the databases will be used throughout the analysis:

***The FRA Crossing Inventory Database***

- Field "CrossingID" – crossing inventory number;
- Field "WdCode" – warning device code;
- Field "Aadt" – annual average daily traffic (AADT) count;
- Field "DayThru" – total daylight through trains;
- Field "NghtThru" – total night time through trains;
- Field "TotalSwt" – total switching trains;
- Field "MaxTtSpd" – maximum timetable speed;
- Field "MainTrk" – number of main tracks;
- Field "OthrTrk" – number of other tracks;
- Field "HwyPved" – is roadway/pathway paved? (1 = yes; 2 = no)
- Field "TraficLn" – number of traffic lanes crossing railroad;
- Field "HwyClassCD" – functional classification of road at crossing (0 = rural; 1 = urban);
- Field "HwyClassrdtpID" – functional classification of road at crossing: type of highway/roadway (11 = interstate; 12 = other freeways and expressways; 13 = other principal arterial; 16 = minor arterial; 17 = major collector; 18 = minor collector; 19 = local);
- Field "AwdIDate" – installation date of current active warning devices;
- Field "PosXing" – crossing position (1 = at grade; 2 = railroad under; 3 = railroad over).

***The FRA Highway-Rail Grade Crossing Accident Database***

- Field "GXID" – grade crossing ID number.

A number of assumptions were made throughout evaluation of the considered accident and hazard prediction models for the highway-rail grade crossings in the State of Florida. The list of the key assumptions includes the following:

1) A set of the most hazardous highway-rail grade crossings in the State of Florida were selected for evaluation of the candidate accident and hazard prediction models. The most hazardous highway-rail grade crossings included the following types of highway-rail grade crossings: (a) the highway-rail grade crossings that experienced at least one accident between the year of 2007 and the year of 2017; (b) 50 active highway-rail grade crossings with the highest exposure value but without accidents between the year of 2007 and the year of 2017; and (c) 50 passive highway-rail grade crossings with the highest exposure value but without accidents between the year of 2007 and the year of 2017. Note that the exposure was estimated as a product of the number of vehicles per day and the number of trains per day. The latter approach (i.e., selection of certain highway-rail grade crossings from all the existing highway-rail grade crossings in a given state for evaluation of the candidate accident and hazard prediction models) has been previously used in the highway-rail grade crossing safety literature (Bowman, 1994; Elzohairy and Benekohal, 2000; Qureshi et al., 2003).
2) If there is a missing value in a dataset (i.e., the FRA crossing inventory database and/or the FRA highway-rail grade crossing accident database) for a predictor used by a given accident and hazard prediction model for a given highway-rail grade crossing, this highway-rail grade crossing will be excluded from the analysis.

3) The values of certain predictors in the FRA crossing inventory database were assumed to be "1" for the cases when "zero" values were recorded. These predictors include the following: (1) AADT; (2) total number of trains per day; (3) maximum train time table speed; (4) number of main tracks; (5) number of main and other tracks; and (6) number of traffic lanes. The latter assumption was necessary to ensure that the candidate accident and hazard prediction will not return abnormal accident or hazard prediction values (e.g., "$-\infty$","$+\infty$").
4) If the protection factor is not provided by a given accident and hazard prediction model for a highway-rail grade crossing with a specific protection type, the worst case protection factor value will be used in the analysis. For example, the New Hampshire Hazard Index Formula does not suggest any specific protection factors for the highway-rail grade crossings with crossbucks. Therefore, the worst case protection factor value, which corresponds to the protection factor of "1.00" (used for stop signs in the New Hampshire Hazard Index Formula), will be adopted in the analysis. The latter approach will allow avoiding significant elimination of highway-rail grade crossings from the analysis due to lack of the protection factor values for specific protection types.
5) The accident data that are used to develop a given candidate accident and hazard prediction model, will be excluded from the analysis throughout the validation process. For example, if 2012-2016 accident data were used to develop a given candidate accident and hazard prediction model; then, the accident data from 2017 will be adopted to validate the model.
6) The baseline ranking of highway-rail grade crossings will be obtained based on the actual accident data for the year of 2017. If two highway-rail grade crossings have the same number of accidents over the considered time horizon, a higher rank will be given to the highway-rail grade crossing with a higher exposure value. The exposure value will be also used as a secondary factor to rank the highway-rail grade crossings, which have the same accident and hazard prediction values (as suggested by the considered accident and hazard prediction models).
7) In order to accentuate the degree of correlation between the baseline rankings and the predicted rankings, the estimated Spearman rank correlation coefficient values will be multiplied by a factor of "5" for each one of the considered accident and hazard prediction models. The latter approach has been previously used by Qureshi et al. (2003) throughout evaluation of various accident and hazard prediction models for the highway-rail grade crossings in the State of Missouri.

#### *5.2.2. Descriptive Statistics for the Considered Highway-Rail Grade Crossings*

The analysis of the highway-rail grade accident data showed that a total of 586 highway-rail grade crossings in the State of Florida experienced at least one accident between the year of 2007 and the year of 2017. However, only 489 highway-rail grade crossings were used throughout evaluation of the candidate accident and hazard prediction models, as some of the information, required for implementation of the candidate accident and hazard prediction models, was not available for certain crossings in the FRA crossing inventory database and the FRA highway-rail grade crossing accident database. Moreover, 50 active highway-rail grade crossings and 50 passive highway-rail grade crossings with the highest exposure values but without accidents between the year of 2007 and the year of 2017 were considered as well. Therefore, the total number of highway-rail grade crossings that were analyzed using the candidate accident and hazard prediction models is 589: (489 highway-rail grade crossings that experienced at least one accident between the year of 2007 and the year of 2017) + (50 active highway-rail grade crossings with the highest exposure values but without accidents between the year of 2007 and the year of 2017) + (50 passive highway-rail grade crossings with the highest exposure values but without accidents between the year of 2007 and the year of 2017).

A descriptive statistics of the predictors used throughout evaluation of the candidate accident and hazard prediction models was obtained to quantitatively describe the features of the Florida's highway-rail grade crossings used in the analysis. The analysis of the protection type data revealed that a total of 494 highway-rail grade crossings considered (or 83.9% of highway-rail grade crossings) were equipped with active protection devices (such as gates, flashing lights, highway traffic signals, wigwags, bells, or other active devices). On the other hand, 79 highway-rail grade crossings (or 13.4% of highway-rail grade crossings) were equipped with passive protection devices (such as stop signs, crossbucks, or other passive signs or signals). A total of 16 highway-rail grade crossings (or 2.7% of highway-rail grade crossings) had no signs or signals. Figure 22 presents a distribution of the selected highway-rail grade crossings by protection type.

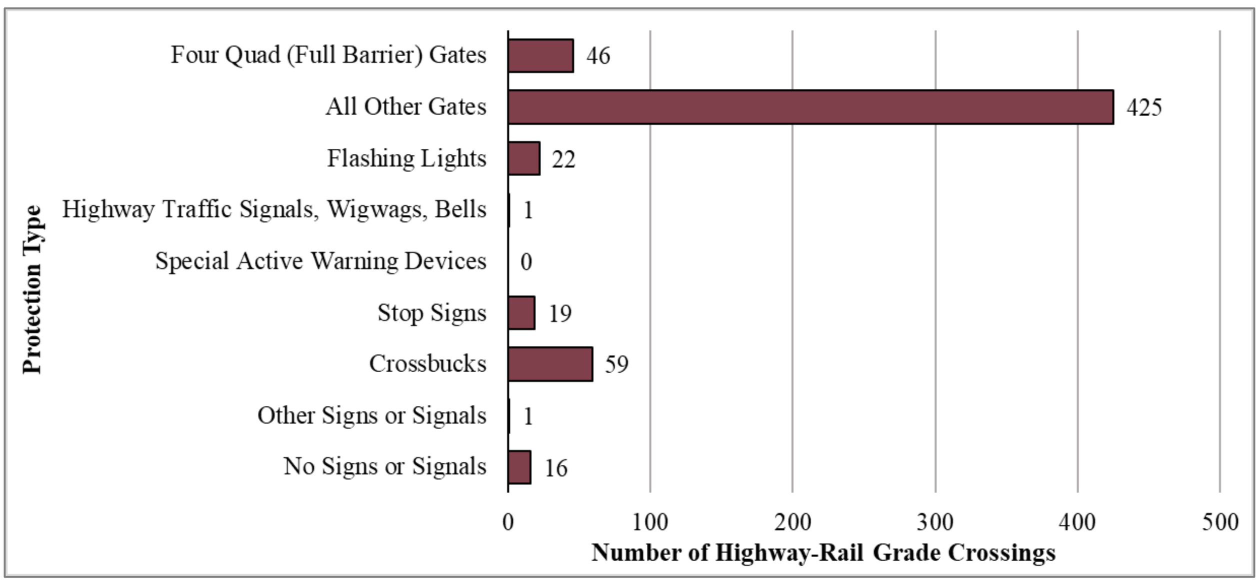


**Figure 22** Distribution of the selected highway-rail grade crossings by protection type.

Figure 23 shows a distribution of the selected highway-rail grade crossings by AADT. Based on the information presented in Figure 23, it can be observed that the maximum and the minimum AADT at the considered highway-rail grade crossings are 99,999 vehicles per day and 1 vehicle per day, respectively. The average AADT at the selected highway-rail grade crossings is approximately 13,267.71 vehicles per day.

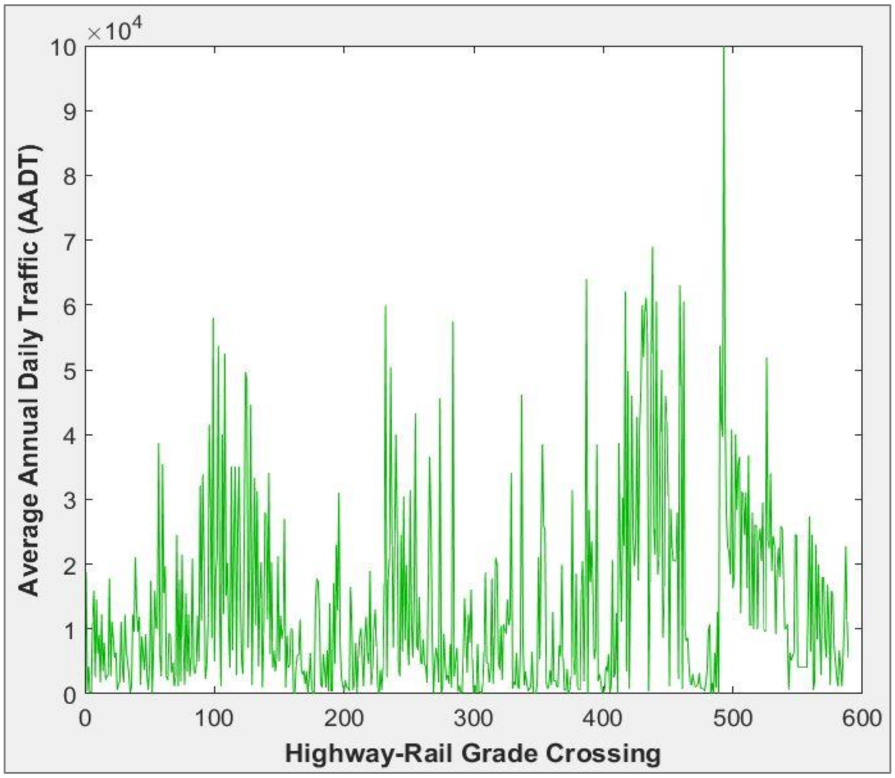

**Figure 23** Distribution of the selected highway-rail grade crossings by AADT.

A statistical analysis for the number of trains per day at the considered highway-rail grade crossings was conducted, and the results are presented in Figure 24 and Figure 25. Figure 24 illustrates the number of trains that uses the selected highway-rail grade crossings per day (over a 24-hour period), while Figure 25 shows the number of through trains that pass the selected highway-rail grade crossings in the State of Florida during daylight (between 6 AM and 6 PM). Based on the statistical analysis, the maximum and the minimum number of trains per day at the considered highway-rail grade crossings are 241 trains per day and 1 train per day, respectively. The average number of trains per day that pass the selected highway-rail grade crossings is approximately 19.01 trains per day. Furthermore, the maximum and the minimum number of trains per day during daylight at the considered highway-rail grade crossings are 62 trains per day and 1 train per day, respectively. The average number of trains per day that pass the selected highway-rail grade crossings during daylight is approximately 9.66 trains per day.

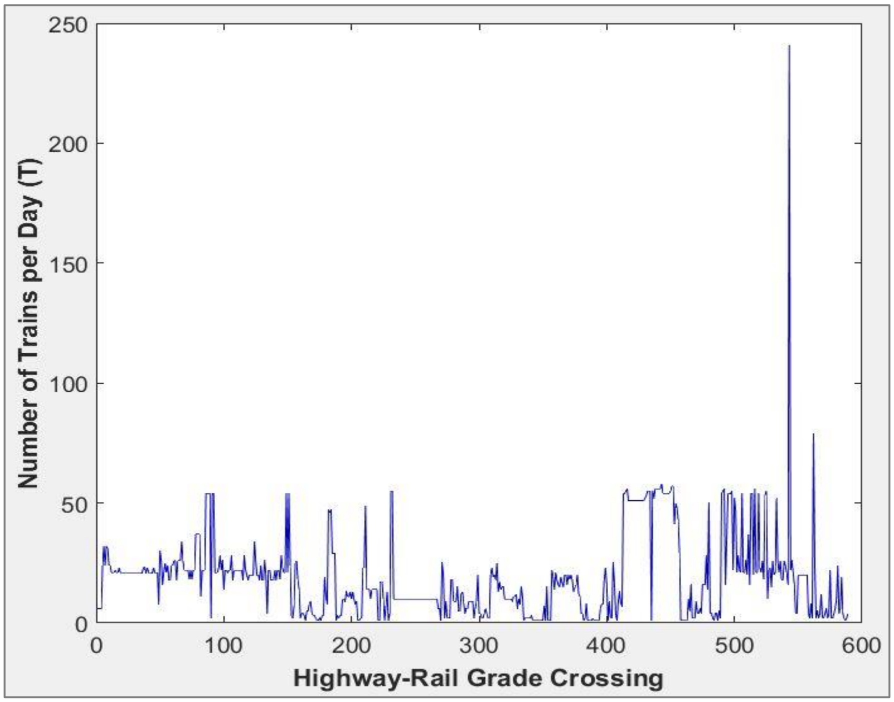

**Figure 24** Distribution of the selected highway-rail grade crossings by number of trains per day.

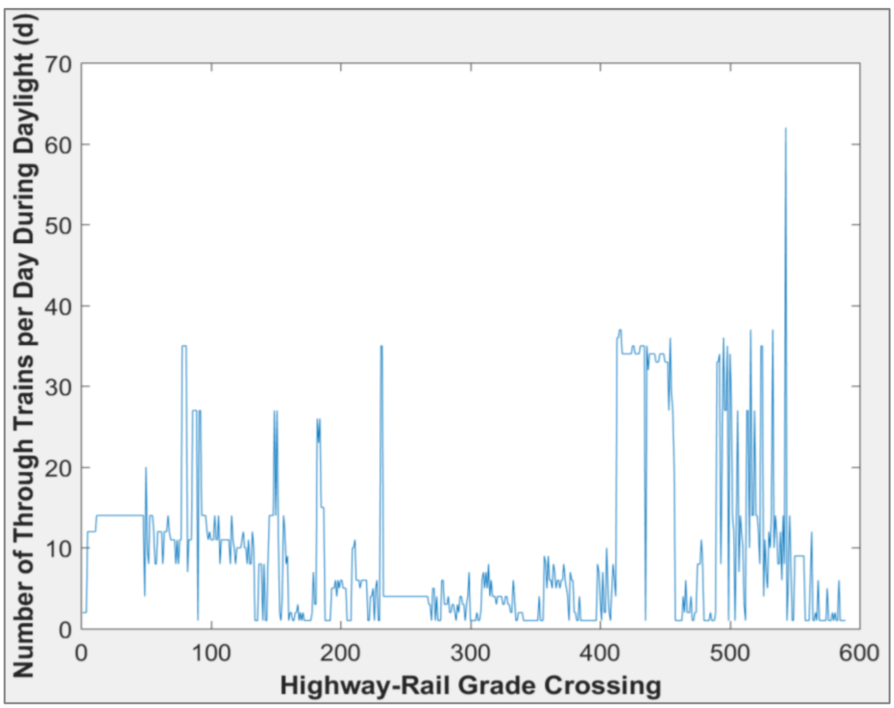

**Figure 25** Distribution of the selected highway-rail grade crossings by number of through trains per day during daylight.

A distribution of the considered highway-rail grade crossings by highway classification is presented in Figure 26. The analysis of the highway classification data revealed that a total of 447 roadways at the selected highway-rail grade crossings (or 75.9 % of roadways) were classified as urban roadways, while 142 roadways at the selected highway-rail grade crossings (or 24.1 % of roadways) were classified as rural roadways. It was found that the highway-rail grade crossings in urban areas experienced more accidents as compared to the highway-rail grade crossings in rural areas. Specifically, the accidents were recorded at 323 highway-rail grade crossings (or 54.8% of the considered highway-rail grade crossings) in urban areas between the year of 2007 and the year of 2016, while 115 highway-rail grade crossings (or 19.5% of the considered highway-rail grade crossings) experienced the accidents in rural areas between the year of 2007 and the year of 2016.

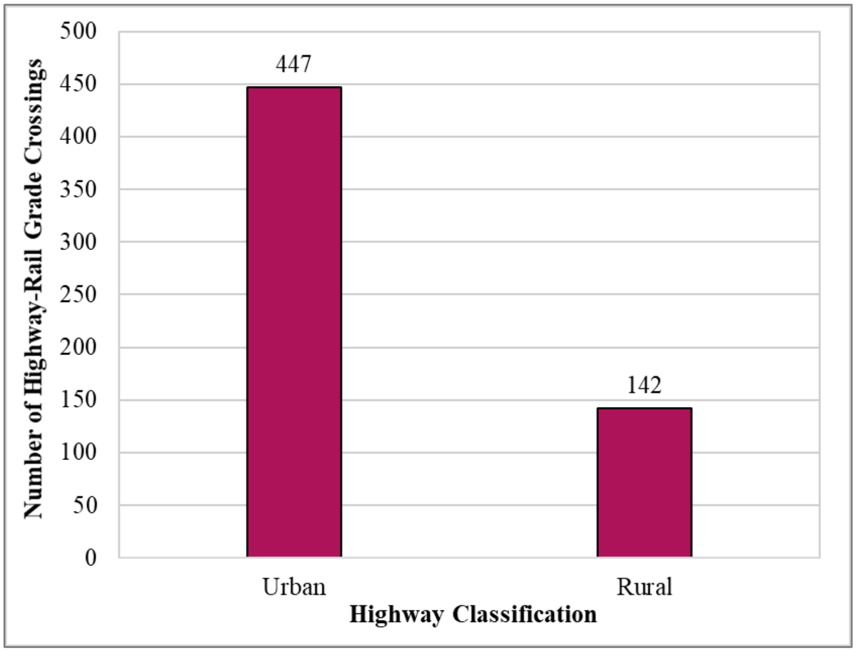


**Figure 26** Distribution of the selected highway-rail grade crossings by highway classification.

Based the Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007) [page 56 of the report], rural roadways are further classified into the following types: (1) interstate; (2) other principal arterial; (3) minor arterial; (4) major collector; (5) minor collector; and (6) local roadway. A distribution of rural roadways at the selected highway-rail grade crossings by highway type is presented in Figure 27. Based on the information provided in Figure 27, it can be observed that the considered highway-rail grade crossings are located on 82 local roadways, 28 interstates, 17 minor collector roadways, and 15 major collector roadways. Based the Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007) [page 56 of the report], urban roadways are further classified into the following types: (1) interstate; (2) other freeway and expressway; (3) other principal arterial; (4) minor arterial; (5) collector; and (6) local roadway. A distribution of urban roadways at the selected highway-rail grade crossings by highway type is presented in Figure 28. Based on the information provided in Figure 28, it can be observed that the considered highway-rail grade crossings are located on 173 local roadways, 114 collector roadways, 87 minor arterial roadways, and 73 interstates.

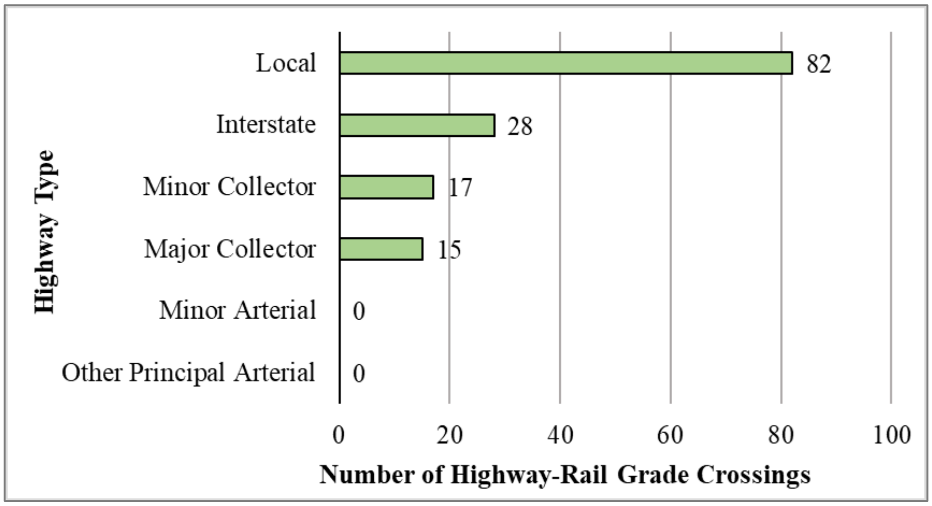


**Figure 27** Distribution of rural roadways at the selected highway-rail grade crossings by highway type.

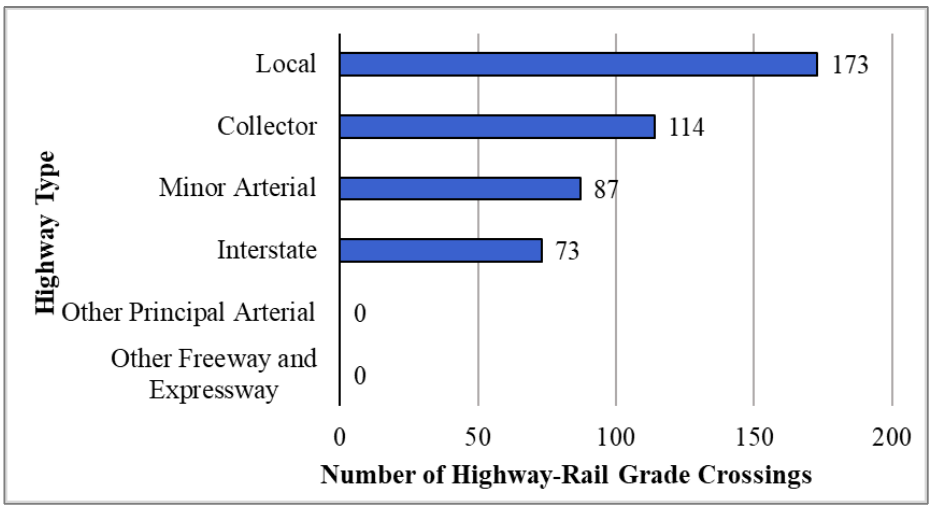


**Figure 28** Distribution of urban roadways at the selected highway-rail grade crossings by highway type.

A distribution of the selected highway-rail grade crossings by highway pavement condition is presented in Figure 29. Figure 29 shows that a total of 537 roadways at the considered highway-rail grade crossings (or 91.2% of roadways) are paved, while 52 roadways at the considered highway-rail grade crossings (or 8.8% of roadways) are unpaved. Figure 30 illustrates a distribution of the selected highway-rail grade crossings by number of main and other tracks. Based on the conducted statistical analysis, it was revealed that the minimum number of main and other tracks at the highway-rail grade crossings is 1, while the maximum number of main and other tracks is 8. Moreover, the average number of main and other tracks at the selected highway-rail grade crossings is approximately 1.65 tracks. A distribution of highway-rail grade crossings by number of main and other tracks shows that 308 highway-rail grade crossings have a single track, 217 highway-rail grade crossings have 2 tracks, while 43 highway-rail grade crossings have 3 tracks. A total of 21 highway-rail grade crossings have 4 tracks or more.

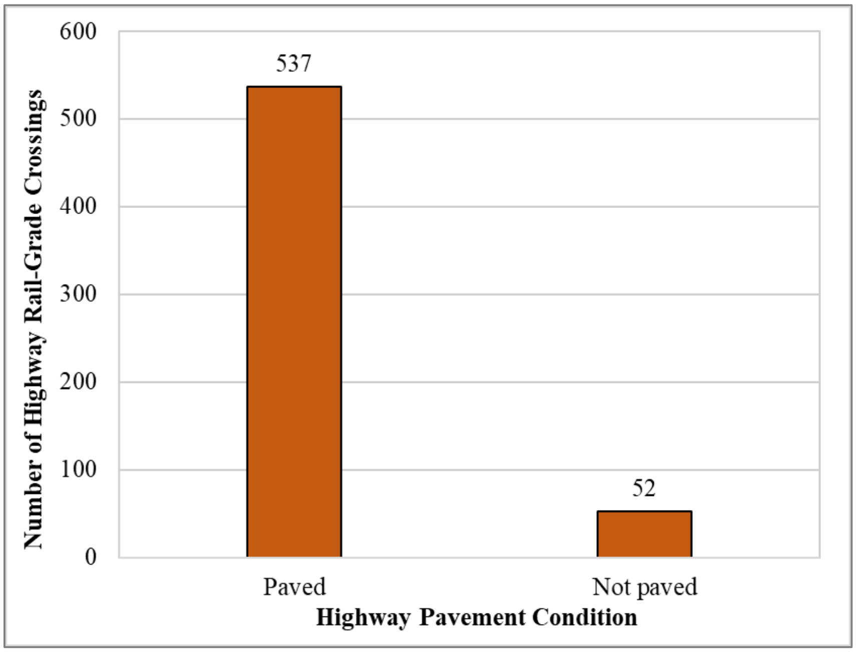


**Figure 29** Distribution of the selected highway-rail grade crossings by highway pavement condition.

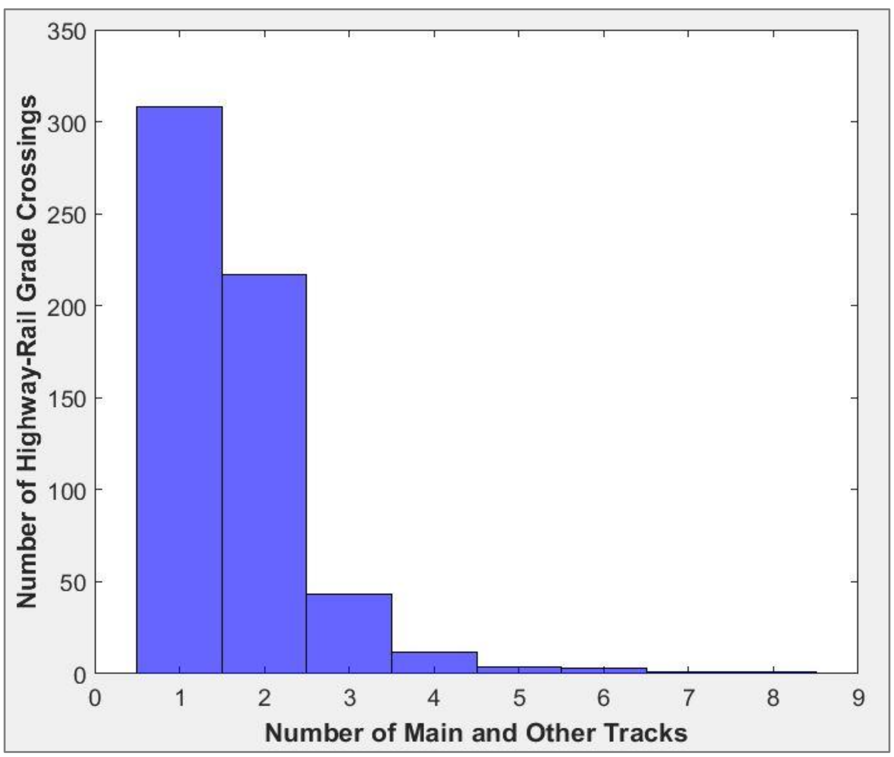


**Figure 30** Distribution of the selected highway-rail grade crossings by number of main and other tracks.

Figure 31 presents a distribution of the selected highway-rail grade crossings by number of traffic lanes. Based on the information provided in Figure 31, it can be observed that the minimum number of traffic lanes at the considered highway-rail grade crossings is 1 lane, while the maximum number of traffic lanes is 9 lanes. The average number of traffic lanes at the selected highway-rail grade crossings is approximately 3.05 lanes. A distribution of the selected highway-rail grade crossings by number of traffic lanes indicates that 10 highway-rail grade crossings have a single traffic lane, 334 highway-rail grade crossings have 2 traffic lanes, 30 highway-rail grade crossings have 3 traffic lanes, while 126 highway-rail grade crossings have 4 traffic lanes. A total of 89 highway-rail grade crossings have 5 traffic lanes or more. A statistical analysis was conducted for the maximum timetable speed data at the considered highway-rail grade crossings. Figure 32 shows a distribution of the selected highway-rail grade crossings by maximum timetable speed. The results from the statistical analysis indicate that the maximum and the minimum timetable speeds at the considered highway-rail grade crossings are 79 mph and 5 mph, respectively. Furthermore, the average timetable speed at the selected highway-rail grade crossings is approximately 46.23 mph.

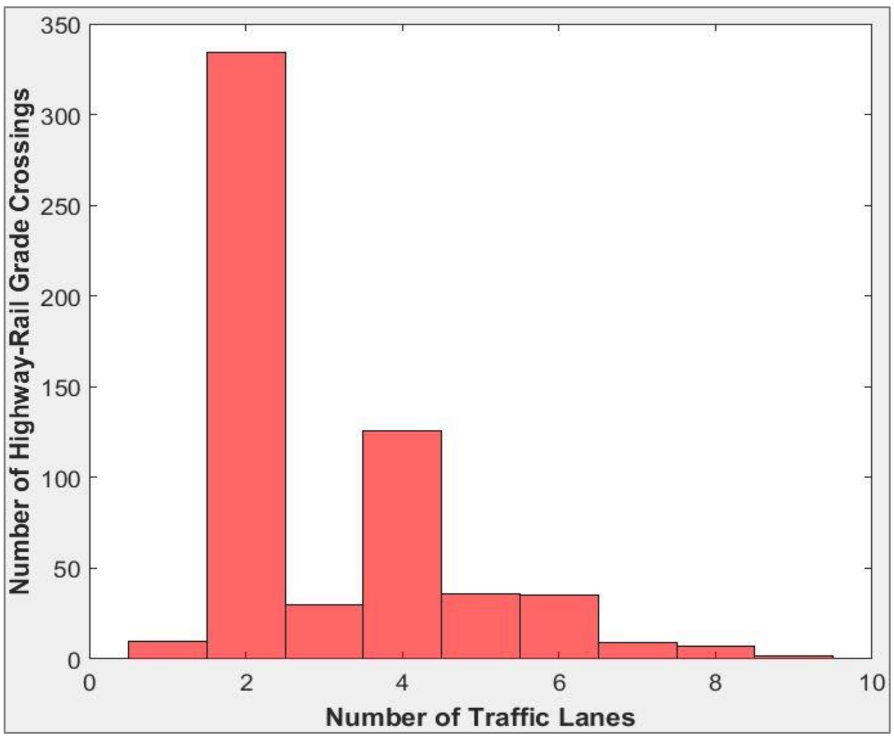


**Figure 31** Distribution of the selected highway-rail grade crossings by number of traffic lanes.

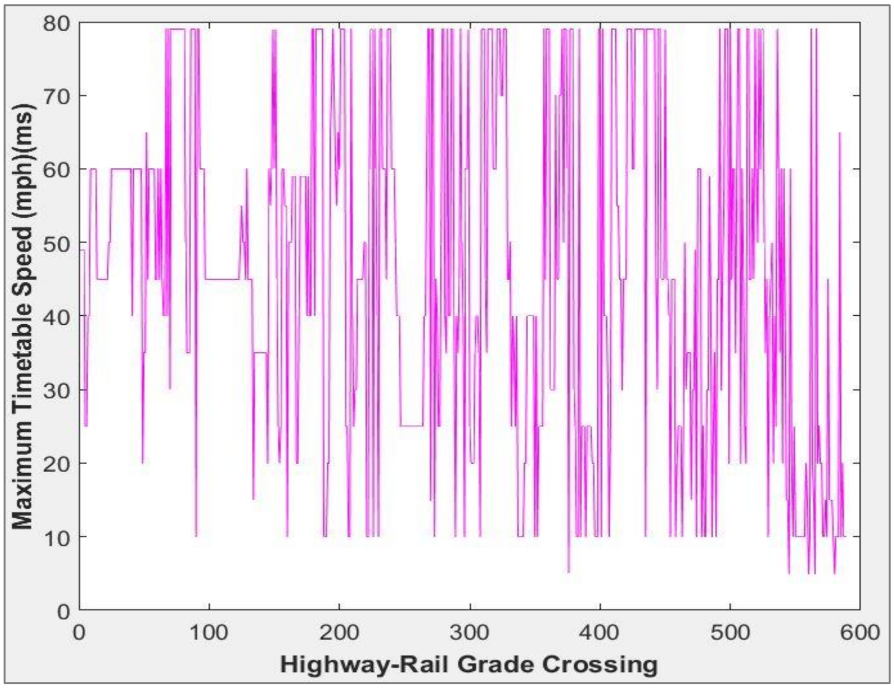


**Figure 32** Distribution of the selected highway-rail grade crossings by maximum timetable speed.

A distribution of the selected highway-rail grade crossings by total number of accidents over a 5-year period (2012-2016) is illustrated in Figure 33, while a distribution of the selected highway-rail grade crossings by average number of accidents per year over a 5-year period (2012-2016) is presented in Figure 34. The maximum and the minimum number of accidents recorded at the considered highway-rail grade crossings between 2012 and 2016 are four accidents and zero accidents, respectively (see Figure 33). The minimum number of accidents is zero due to the fact that 50 passive and 50 active highway-rail grade crossings with the highest exposure but without accidents between the year of 2007 and the year of 2017 were evaluated throughout the analysis (while more than 100 highway-rail grade crossings did not experience accidents between 2012 and 2016, which is a shorter period of time as compared to 2007-2017). Based on the information presented in Figure 34, the highest average number of accidents per year at the selected highway-rail grade crossings over a 5-year period (2012-2016) is 0.8 accidents per year.

A distribution of the selected highway-rail grade crossings by total number of accidents over a 10-year period (2007-2016) is illustrated in Figure 35, while a distribution of the selected highway-rail grade crossings by average number of accidents per year over a 10-year period (2007-2016) is presented in Figure 36. The maximum and the minimum number of accidents recorded at the considered highway-rail grade crossings between 2007 and 2016 are seven accidents and zero accidents, respectively (see Figure 35). The minimum number of accidents is zero due to the fact that 50 passive and 50 active highway-rail grade crossings with the highest exposure but without accidents between the year of 2007 and the year of 2017 were evaluated throughout the analysis (while more than 100 highway-rail grade crossings did not experience accidents between 2007 and 2016, which is a shorter period of time as compared to 2007-2017). Based on the information presented in Figure 36, the highest average number of accidents per year at the selected highway-rail grade crossings over a 10-year period (2007-2016) is 0.7 accidents per year.

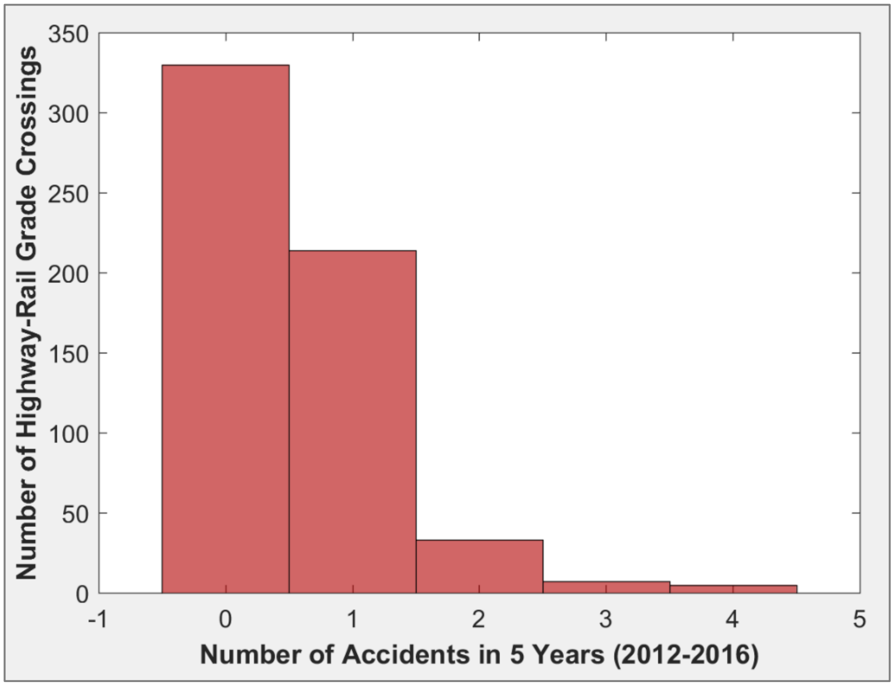


**Figure 33** Distribution of the selected highway-rail grade crossings by total number of accidents over a 5-year period (2012-2016).

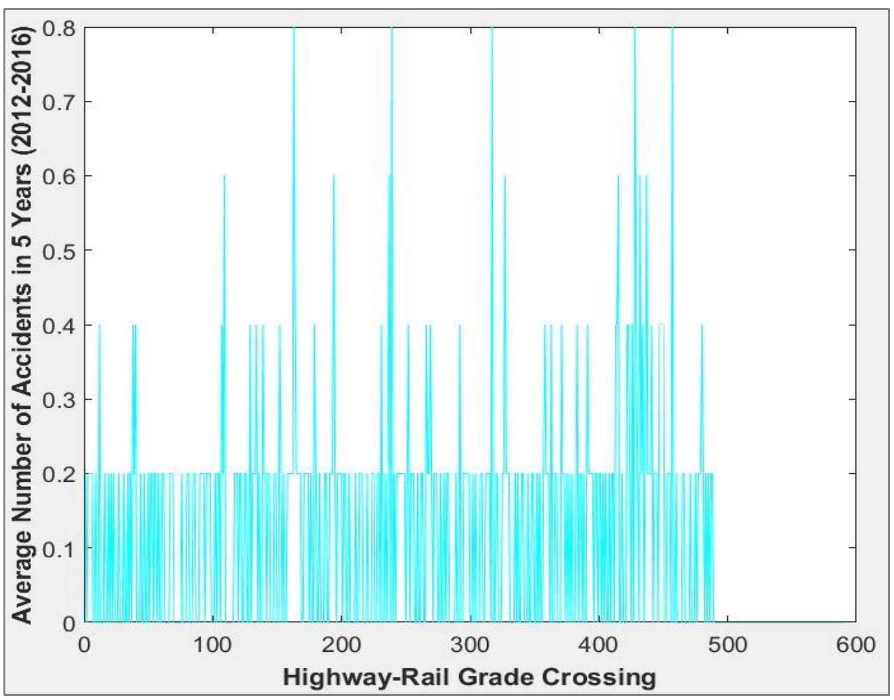


**Figure 34** Distribution of the selected highway-rail grade crossings by average number of accidents per year over a 5-year period (2012-2016).

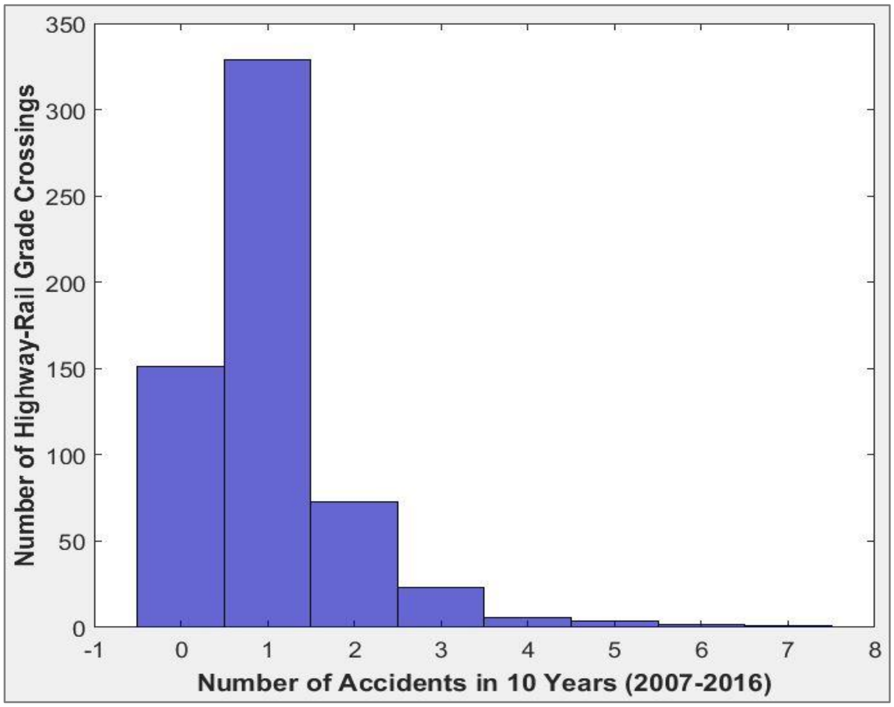


**Figure 35** Distribution of the selected highway-rail grade crossings by total number of accidents over a 10-year period (2007-2016).

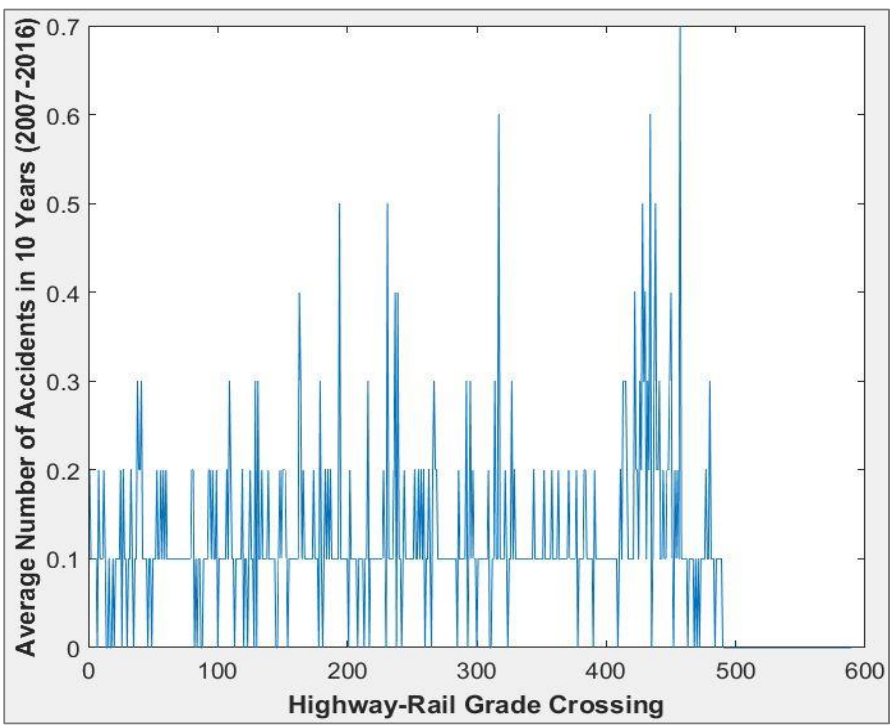


**Figure 36** Distribution of the selected highway-rail grade crossings by average number of accidents per year over a 10-year period (2007-2016).

### *5.2.3. Approaches for Evaluation of the Candidate Accident and hazard Prediction Models*

As discussed earlier, the candidate accident and hazard prediction models will be evaluated using the following approaches: (1) chi-square formula; (2) grouping of crossings based on the actual accident data; and (3) Spearman rank correlation coefficient. A detailed description of the adopted approaches is provided in the following sections of the report.

#### *Chi-Square Formula*

The first approach relies on the statistical chi-square formula for evaluation of the candidate accident prediction models. The chi-square statistic has been commonly used for assessing the relationships between categorical variables. The test can be performed using a cross-tabulation that presents the values/distributions of two categorical variables concurrently. Comparison between the two variables in the cross-tabulation will determine if there is an association between the variables, i.e. the variables are not independent (Statistics Solutions, 2018). The value of the test statistic ($\chi^2$) implies the goodness of fit or correlation between the observed data and the theoretical/computed data. A low value of the chi-square statistic indicates that the observed data (i.e., the actual number of accidents, observed at a highway-rail grade crossing) fit well the expected data (i.e., the accident prediction value, proposed by a given candidate accident prediction model for a highway-rail grade crossing) (Statistics How To, 2018a). On the other hand, a large value of the chi-square statistic indicates that the observed data do not fit well the expected data.

Note that the chi-square statistic has been previously used in the highway-rail grade crossing safety literature. More specifically, Faghri and Demetsky (1986) adopted the chi-square statistic for evaluation of certain accident prediction models (i.e., the NCHRP Report 50 Accident Prediction Formula, the Peabody-Dimmick Formula, the Coleman-Stewart Model, and the U.S. DOT Accident Prediction Formula) for the highway-rail grade crossings in the State of Virginia. The following chi-square formula will be used to determine the goodness of fit of the candidate accident prediction models (Faghri and Demetsky, 1986; Franke et al., 2012; McHugh, 2013):

$$\chi^2 = \sum_{x=1}^{n} \frac{(AO_x - AC_x)^2}{AC_x} \tag{5.1}$$

where:
$\chi^2$ = the chi-square statistic;
$AO_x$ = the number of accidents observed at highway-rail grade crossing $x$;
$AC_x$ = the number of accidents estimated using a given candidate accident prediction model for highway-rail grade crossing $x$;
$n$ = the number of highway-rail grade crossings.

The chi-square statistic will be estimated over the selected highway-rail grade crossings in the State of Florida, listed in the FRA crossing inventory database, for each one of the candidate accident prediction models. Similar to the procedure adopted by Faghri and Demetsky (1986), the chi-square formula will be applied only for the absolute formulae (i.e., accident prediction models), not for the relative formulae (i.e., hazard prediction models). The computed chi-square statistic values will be further utilized to assess accuracy of the candidate accident prediction models in terms of forecasting the number of accidents at highway-rail grade crossings.

***Grouping of Crossings based on the Actual Accident Data***

The second approach aims to validate the accident and hazard prediction models in terms of their ability to rank highway-rail grade crossings for safety improvement projects, based on the actual or real-world accident data. Such an approach has been previously used by a number of states (e.g., State of Alabama - Bowman, 1994; State of Illinois - Elzohairy and Benekohal, 2000; State of Texas - Weissmann et al., 2013; State of Ohio - Sperry et al., 2017). In this project, the actual accident data will be adopted from the FRA highway-rail grade crossing accident database. The highway-rail grade crossings will be categorized into the top 15%, 20%, 25%, 30%, 40%, and 50% of the most hazardous highway-rail grade crossings, based on the actual accident data. Then, the candidate accident and hazard prediction models will be applied to rank the highway-rail grade crossings, using the data available through the FRA crossing inventory database and the FRA highway-rail grade crossing accident database. The candidate accident prediction models will be used to rank the highway-rail grade crossings in the State of Florida based on the predicted number of accidents. On the other hand, the candidate hazard prediction models will be used to rank the highway-rail grade crossings in the State of Florida based on the estimated hazard values.

The number and percentage of highway-rail grade crossings, captured by a given candidate accident and hazard prediction model for the top 15%, 20%, 25%, 30%, 40%, and 50% of the most hazardous highway-rail grade crossings, will be used as the performance indicators for the model evaluation. The accident and hazard prediction model that captures the highest number and percentage of highway-rail grade crossings for these hazardous highway-rail grade crossing categories will be considered as the most effective or accurate model. This approach also has similarities with the power factor method, employed by Faghri and Demetsky (1986) for the highway-rail grade crossings in the State of Virginia. The power factor analysis aims to determine the percentage of accidents that were observed at the most hazardous highway-rail grade crossings, which were identified by the candidate accident and hazard prediction models (Faghri and Demetsky, 1986). Note that if any accident dataset is used to develop any candidate accident and hazard prediction model, it cannot be used for the validation process. For example, if 2012-2016 accident data are used to develop the candidate accident and hazard prediction model; then, the accident data from 2017 or any other following year should be used to validate the model. In addition, if there is a missing value in a dataset (i.e., the FRA crossing inventory database and/or the FRA highway-rail grade crossing accident database) for a predictor used by a given accident and hazard prediction model for a given highway-rail grade crossing, this highway-rail grade crossing will be excluded from the analysis.

***Spearman Rank Correlation Coefficient***

The third approach relies on the Spearman rank correlation coefficient for evaluation of the candidate accident and hazard prediction models. The Spearman rank correlation coefficient represents a nonparametric measure of rank correlation. The Spearman rank correlation coefficient is also considered as a nonparametric version of the Pearson correlation coefficient (Statistics How To, 2018b). The data should be ordinal, interval, or ratio. The correlation coefficient ($r_s$) can range between the values of "-1" to "+1". A value of "+1" indicates a perfect positive correlation between the baseline ranking set and the predicted ranking set proposed by the candidate model. On the other hand, a value of "-1" implies a perfect negative correlation, while a value of "0" indicates that there is no correlation between the two datasets (Statistics How To, 2018b).

The Spearman rank correlation coefficient has been previously used in the highway-rail grade crossing safety literature. More specifically, Qureshi et al. (2003) adopted the Spearman rank correlation coefficient for evaluation of certain accident and hazard prediction models (i.e., the U.S. DOT Accident Prediction Formula, the California Hazard Rating Formula, the Connecticut Hazard Rating Formula, the Modified New Hampshire Hazard Index Formula, the Kansas Design Hazard Rating Formula, the Missouri Exposure Index Formula, and the Illinois Hazard Index Formula) for the highway-rail grade crossings in the State of Missouri. The evaluation of each accident and hazard prediction model was performed by developing a baseline ranking of six highway-rail grade crossings for each crossing control category (passive and active) by the Missouri DOT representatives. After that, the candidate accident and hazard prediction models were applied in order to rank the same highway-rail grade crossings. The predicted rankings were compared to the baseline rankings, which were developed by the Missouri DOT representatives. The difference between the baseline rankings and the predicted rankings was assessed using the Spearman rank correlation coefficient for each one of the considered accident and hazard prediction models (Qureshi et al., 2003). The Spearman rank correlation coefficient can be calculated using the following equation (Laerd Statistics, 2018; Statistics How To, 2018b):

$$r_s = \frac{(\frac{1}{n})\sum_{x=1}^{n}[(P_x - \bar{P}) \cdot (B_x - \bar{B})]}{\sqrt{[\left(\frac{1}{n}\right)\sum_{x=1}^{n}(P_x - \bar{P})^2] \cdot [\left(\frac{1}{n}\right)\sum_{x=1}^{n}(B_x - \bar{B})^2]}} \tag{5.2}$$

where:
$r_s$ = the Spearman rank correlation coefficient;
$P_x$ = the ranking of highway-rail grade crossing $x$, proposed by a given candidate accident and hazard prediction model;
$\bar{P}$ = the average ranking value of highway-rail grade crossings, proposed by a given candidate/hazard accident prediction model;
$B_x$ = the baseline ranking of highway-rail grade crossing $x$;
$\bar{B}$ = the average baseline ranking value;
$n$ = the number of highway-rail grade crossings.

In order to accentuate the degree of correlation between the baseline rankings and the predicted rankings, Qureshi et al. (2003) multiplied the estimated Spearman rank correlation coefficient values by a factor of "5" for each one of the considered accident and hazard prediction models. The latter approach will be adopted in this study as well. The baseline rankings of the highway-rail grade crossings in the State of Florida will be derived based on the actual accident data, provided in the FRA highway-rail grade crossing accident database.

### *5.2.4. Analysis Software*

MATLAB (Matrix Laboratory) software will be used in this study to evaluate the candidate accident and hazard prediction formulae, which have been identified in section 5.1 of this report. MATLAB is a high-level fourth-generation programming language equipped with an interactive environment, which allows its users (primarily engineers and scientists) to perform complex numerical computing tasks (such as matrix manipulations, data and function plotting, algorithm design, development of graphical user interfaces, and other purposes) in an efficient manner. (MathWorks, 2019a). The MATLAB software relies on the MATLAB scripting language, a matrix-based language that facilitates computational mathematics (MathWorks, 2019a). Throughout this project, MATLAB will be used to encode the candidate accident and hazard prediction models and apply the aforementioned evaluation approaches.

# 6. ANALYSIS RESULTS FOR THE CANDIDATE ACCIDENT AND HAZARD PREDICTION MODELS

This section of the report exhibits the results obtained from analysis of the candidate accident prediction models (i.e., the Coleman-Stewart Model, the NCHRP Report 50 Accident Prediction Formula, the Peabody-Dimmick Formula, and the U.S. DOT Accident Prediction Formula) and the candidate hazard prediction models (i.e., the New Hampshire Formula, the California Hazard Rating Formula, the Connecticut Hazard Rating Formula, the Illinois Hazard Index Formula, the Michigan Hazard Index Formula, and the Texas Priority Index Formula). Along with the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, and the canonical Texas Priority Index Formula, the modified versions of the aforementioned formulae will be evaluated under this project (which will be referred to as the Modified California Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the Modified Texas Priority Index Formula). The key difference between the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, the canonical Texas Priority Index Formula, and their modified versions consists in the approach for estimating the accident history.

Specifically, the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, and the canonical Texas Priority Index Formula simply account for the total number of accidents in the last ten years, the last five years, and the last five years, respectively. Since the upgrades can cause significant changes in the operational characteristics of a given highway-rail grade crossing, performance of the aforementioned models can be negatively affected. On the other hand, the Modified California Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the Modified Texas Priority Index Formula consider the total number of accidents in the last years (the last ten years, the last five years, and the last five years, respectively) or since the year of last improvement (in case there was an upgrade). Such an approach for estimating the accident history is expected to be methodologically more advantageous and has been recommended in the canonical U.S. DOT resource allocation procedure, outlined in the Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007).

Three analytical approaches that were discussed in section 5.2 of this report, including the chi-square formula, grouping of crossings based on the actual accident data, and Spearman rank correlation coefficient, were undertaken to evaluate accuracy of the candidate accident and hazard prediction models. The accident data for the year of 2017 were used to assess performance of the candidate accident and hazard prediction models. The rankings of highway-rail grade crossings based on the predicted number of accidents or the predicted hazard, suggested by the candidate models, was compared with the baseline rankings of highway-rail grade crossings based on the actual accident data for the year of 2017. The observed number of accidents in 2017 was used to examine performance of the models based on the fact that none of the candidate accident and hazard prediction models relied on the 2017 accident data to rank the highway-rail grade crossings. Therefore, there was no scope of bias due to the use of the 2017 accident data. The accident data between 2007 and 2016 were used throughout development and evaluation of the candidate accident and hazard prediction models. The following sections of this report present the results, which were obtained from the three analytical approaches and elaborate on accuracy of the candidate accident and hazard prediction models for the selected highway-rail grade crossings in the State of Florida.

### 6.1. Analysis of the Accident Prediction Models based on the Chi-Square Statistic

The chi-square statistic was the first performance metric used to assess the goodness of fit of the accident prediction models based on the data collected for the 589 highway-rail grade crossings in the State of Florida, which were selected for the analysis. The chi-square test, which was performed using the predicted and observed number of accidents in the year of 2017, demonstrated that the Peabody-Dimmick Formula had the closest fit to the observed number of accidents at the 589 highway-rail grade crossings. Specifically, the Peabody-Dimmick Formula had a chi-square statistic of 482.74, which was the lowest among the chi-square statistics of all the accident prediction models (see Figure 37). The summation of chi-square values of the 589 highway-rail grade crossings derived for the Coleman-Stewart Model, the U.S. DOT Accident Prediction Formula, and the NCHRP Report 50 Accident Prediction Formula were 1341.68, 1800.79, and 17099.01, respectively (see Figure 37). Since lower values of the chi-square statistic indicate a closer fit to the actual accident data, the Coleman-Stewart Model, the U.S. DOT Accident Prediction Formula, and the NCHRP Report 50 Accident Prediction Formula were ranked as 2nd, 3rd, and 4th, respectively. Table 50 shows the ranking of the candidate accident prediction models based on the chi-square statistic. As discussed in section 5.2.3 of this report, the chi-square test was not conducted for the hazard prediction models, as the predicted number of accidents is required in order to determine the chi-square statistic.

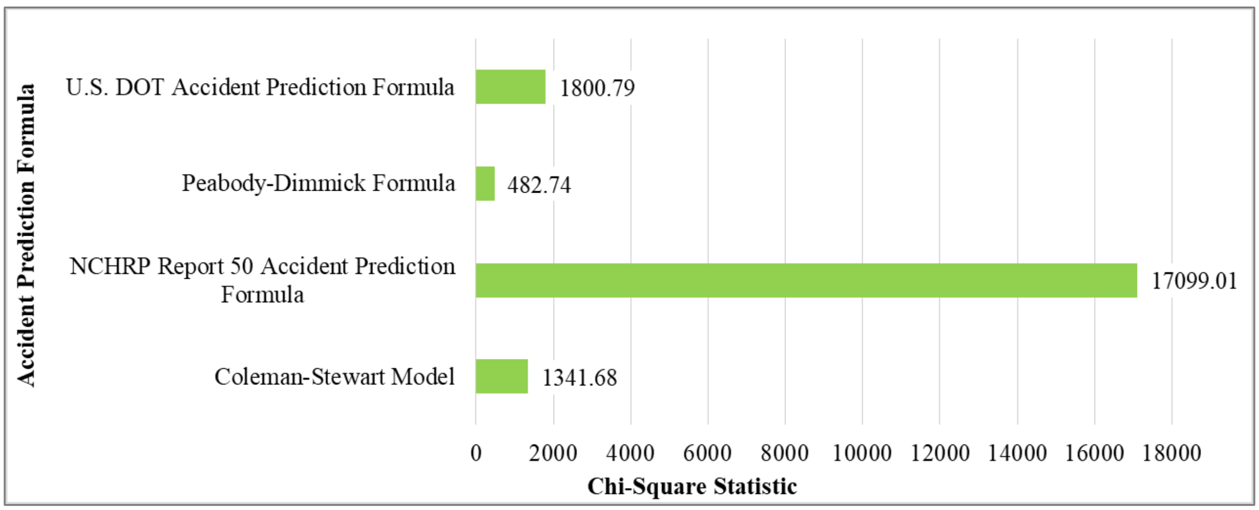


**Figure 37** Chi-square statistic values for the candidate accident prediction models.

**Table 50** Ranking of the candidate accident prediction models based on the chi-square statistic.

| Accident Prediction Model | Rank |
|---|---|
| Peabody-Dimmick Formula | 1 |
| Coleman-Stewart Model | 2 |
| U.S. DOT Accident Prediction Formula | 3 |
| NCHRP Report 50 Accident Prediction Formula | 4 |

### 6.2. Analysis of the Accident and hazard Prediction Models based on the Crossing Groups

The percentage of the most hazardous highway-rail grade crossings, captured by the candidate accident and hazard prediction models, was retrieved throughout the data analysis. The dataset, which consisted of the accident history for the 589 highway-rail grade crossings, was sorted according to the observed number of accidents in 2017 and was divided into the top 15%, 20%, 25%, 30%, 40%, and 50% of the most hazardous highway-rail grade crossings. These groups included 89, 118, 148, 177, 236, and 295 highway-rail grade crossings, respectively. The percentage and number of the most hazardous highway-rail grade crossings, captured by the accident and hazard prediction candidate models, are presented in Table 51 and Table 52, respectively.

Among the top 15% of the most hazardous highway-rail grade crossings (or 89 highway-rail grade crossings), the U.S. DOT Accident Prediction Formula, the Michigan Hazard Index Formula, the California Hazard Rating Formula, the Modified California Hazard Rating Formula, the Illinois Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula captured the largest portion of highway-rail grade crossings. Specifically, the U.S. DOT Accident Prediction Formula and the Michigan Hazard Index Formula captured 23.6% (or 21 out of 89 highway-rail grade crossings) from the top 15% of the most hazardous highway-rail grade crossings, while the California Hazard Rating Formula, the Modified California Hazard Rating Formula, the Illinois Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula captured 21.3% (or 19 out of 89 highway-rail grade crossings) from the top 15% of the most hazardous highway-rail grade crossings. The least accurate models in this group were found to be the NCHRP Report 50 Accident Prediction Formula, the Connecticut Hazard Rating Formula, and the Modified Connecticut Hazard Rating Formula, which captured only 15.7% (or 14 out of 89 highway-rail grade crossings) from the top 15% of the most hazardous highway-rail grade crossings.

Furthermore, the Texas Priority Index Formula, the Modified Texas Priority Index Formula, the Illinois Hazard Index Formula, and the Michigan Hazard Index Formula achieved the closest fit to the actual accident data for the 20% of the most hazardous highway-rail grade crossings. The Texas Priority Index Formula and the Modified Texas Priority Index Formula captured 44.9% (53 out of 118 highway-rail grade crossings) from the top 20% of the most hazardous highway-rail grade crossings, while the Illinois Hazard Index Formula and the Michigan Hazard Index Formula captured 43.2% (51 out of 118 highway-rail grade crossings) from the top 20% of the most hazardous highway-rail grade crossings. On the other hand, the Connecticut Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the U.S. DOT Accident Prediction Formula were found to be the least accurate for this group. Specifically, the Connecticut Hazard Rating Formula and the Modified Connecticut Hazard Rating Formula captured only 35.6% (42 out of 118 highway-rail grade crossings) from the top 20% of the most hazardous highway-rail grade crossings, while the U.S. DOT Accident Prediction Formula captured only 32.2% (38 out of 118 highway-rail grade crossings) from the top 20% of the most hazardous highway-rail grade crossings.

As for the top 25% of the most hazardous highway-rail grade crossings, the best performance was demonstrated by the Texas Priority Index Formula, the Modified Texas Priority Index Formula, and the Michigan Hazard Index Formula. The Texas Priority Index Formula and the

Modified Texas Priority Index Formula captured 56.8% (or 84 out of 148 highway-rail grade crossings) from the top 25% of the most hazardous highway-rail grade crossings, while the Michigan Hazard Index Formula captured 56.1% (or 83 out of 148 highway-rail grade crossings) from the top 25% of the most hazardous highway-rail grade crossings. The worst performance was recorded for the Connecticut Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the U.S. DOT Accident Prediction Formula. Specifically, the Connecticut Hazard Rating Formula and the Modified Connecticut Hazard Rating Formula captured only 45.9% (68 out of 148 highway-rail grade crossings) from the top 25% of the most hazardous highway-rail grade crossings, while the U.S. DOT Accident Prediction Formula captured only 33.1% (49 out of 148 highway-rail grade crossings) from the top 25% of the most hazardous highway-rail grade crossings.

As for the top 30% of the most hazardous highway-rail grade crossings, the Michigan Hazard Index Formula, the Modified California Hazard Rating Formula, the California Hazard Rating Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula had the most satisfactory goodness of fit. The Michigan Hazard Index Formula captured 66.1% (117 out of 177 highway-rail grade crossings), the Modified California Hazard Rating Formula captured 65.0% (115 out of 177 highway-rail grade crossings), while the California Hazard Rating Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula captured 64.4% (114 out of 177 highway-rail grade crossings) from the top 30% of the most hazardous highway-rail grade crossings. On the other hand, the Modified Connecticut Hazard Rating Formula, the Connecticut Hazard Rating Formula, and the U.S. DOT Accident Prediction Formula were found to be the least accurate for this group. Specifically, the Modified Connecticut Hazard Rating Formula captured only 52.5% (93 out of 177 highway-rail grade crossings), the Connecticut Hazard Rating Formula captured only 51.4% (91 out of 177 highway-rail grade crossings), while the U.S. DOT Accident Prediction Formula captured only 31.1% (55 out of 177 highway-rail grade crossings) from the top 30% of the most hazardous highway-rail grade crossings.

The Michigan Hazard Index Formula, the Texas Priority Index Formula, the Modified Texas Priority Index Formula, the California Hazard Rating Formula, and the Modified California Hazard Rating Formula were the most successful in capturing the top 40% of the most hazardous highway-rail grade crossings. The Michigan Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula captured 77.1% (or 182 out of 236 highway-rail grade crossings) from the top 40% of the most hazardous highway-rail grade crossings, while the California Hazard Rating Formula and the Modified California Hazard Rating Formula captured 76.7% (or 181 out of 236 highway-rail grade crossings) from the top 40% of the most hazardous highway-rail grade crossings. The worst performance was recorded for the Connecticut Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the U.S. DOT Accident Prediction Formula. Specifically, the Connecticut Hazard Rating Formula and the Modified Connecticut Hazard Rating Formula captured only 67.4% (159 out of 236 highway-rail grade crossings) from the top 40% of the most hazardous highway-rail grade crossings, while the U.S. DOT Accident Prediction Formula captured only 40.3% (95 out of 236 highway-rail grade crossings) from the top 40% of the most hazardous highway-rail grade crossings.

**Table 51** Percentage of highway-rail grade crossings captured by the candidate accident and hazard prediction models.

| **Accident and hazard Prediction Model** | **Percentage of Highway-Rail Grade Crossings Captured** | | | | | |
|---|---|---|---|---|---|---|
| | Top 15% (89 crossings) | Top 20% (118 crossings) | Top 25% (148 crossings) | Top 30% (177 crossings) | Top 40% (236 crossings) | Top 50% (295 crossings) |
| Coleman-Stewart Model | 19.1% | 39.0% | 50.0% | 57.1% | 69.5% | 77.3% |
| NCHRP Report 50 Accident Prediction Formula | 15.7% | 36.4% | 52.7% | 61.6% | 72.5% | 78.3% |
| Peabody-Dimmick Formula | 18.0% | 39.0% | 52.0% | 59.3% | 70.3% | 81.4% |
| U.S. DOT Accident Prediction Formula | 23.6% | 32.2% | 33.1% | 31.1% | 40.3% | 59.3% |
| New Hampshire Formula | 19.1% | 42.4% | 55.4% | 63.8% | 76.3% | 82.4% |
| California Hazard Rating Formula | 21.3% | 42.4% | 55.4% | 64.4% | 76.7% | 82.7% |
| Modified California Hazard Rating Formula | 21.3% | 42.4% | 55.4% | 65.0% | 76.7% | 82.7% |
| Connecticut Hazard Rating Formula | 15.7% | 35.6% | 45.9% | 51.4% | 67.4% | 76.6% |
| Modified Connecticut Hazard Rating Formula | 15.7% | 35.6% | 45.9% | 52.5% | 67.4% | 76.6% |
| Illinois Hazard Index Formula | 21.3% | 43.2% | 54.7% | 58.2% | 70.3% | 77.6% |
| Michigan Hazard Index Formula | 23.6% | 43.2% | 56.1% | 66.1% | 77.1% | 85.1% |
| Texas Priority Index Formula | 21.3% | 44.9% | 56.8% | 64.4% | 77.1% | 83.1% |
| Modified Texas Priority Index Formula | 21.3% | 44.9% | 56.8% | 64.4% | 77.1% | 83.1% |

**Table 52** Number of highway-rail grade crossings captured by the candidate accident and hazard prediction models.

| **Accident and hazard Prediction Model** | **Number of Highway-Rail Grade Crossings Captured** | | | | | |
|---|---|---|---|---|---|---|
| | Top 15% (89 crossings) | Top 20% (118 crossings) | Top 25% (148 crossings) | Top 30% (177 crossings) | Top 40% (236 crossings) | Top 50% (295 crossings) |
| Coleman-Stewart Model | 17 crossings | 46 crossings | 74 crossings | 101 crossings | 164 crossings | 228 crossings |
| NCHRP Report 50 Accident Prediction Formula | 14 crossings | 43 crossings | 78 crossings | 109 crossings | 171 crossings | 231 crossings |
| Peabody-Dimmick Formula | 16 crossings | 46 crossings | 77 crossings | 105 crossings | 166 crossings | 240 crossings |
| U.S. DOT Accident Prediction Formula | 21 crossings | 38 crossings | 49 crossings | 55 crossings | 95 crossings | 175 crossings |
| New Hampshire Formula | 17 crossings | 50 crossings | 82 crossings | 113 crossings | 180 crossings | 243 crossings |
| California Hazard Rating Formula | 19 crossings | 50 crossings | 82 crossings | 114 crossings | 181 crossings | 244 crossings |
| Modified California Hazard Rating Formula | 19 crossings | 50 crossings | 82 crossings | 115 crossings | 181 crossings | 244 crossings |
| Connecticut Hazard Rating Formula | 14 crossings | 42 crossings | 68 crossings | 91 crossings | 159 crossings | 226 crossings |
| Modified Connecticut Hazard Rating Formula | 14 crossings | 42 crossings | 68 crossings | 93 crossings | 159 crossings | 226 crossings |
| Illinois Hazard Index Formula | 19 crossings | 51 crossings | 81 crossings | 103 crossings | 166 crossings | 229 crossings |
| Michigan Hazard Index Formula | 21 crossings | 51 crossings | 83 crossings | 117 crossings | 182 crossings | 251 crossings |
| Texas Priority Index Formula | 19 crossings | 53 crossings | 84 crossings | 114 crossings | 182 crossings | 245 crossings |
| Modified Texas Priority Index Formula | 19 crossings | 53 crossings | 84 crossings | 114 crossings | 182 crossings | 245 crossings |

The last and also the largest group of the most hazardous highway-rail grade crossings includes the top 50% of the most hazardous highway-rail grade crossings. The Michigan Hazard Index Formula had the best fit for this group, capturing 85.1% (251 out of 295 highway-rail grade crossings) from the top 50% of the most hazardous highway-rail grade crossings. Moreover, the Texas Priority Index Formula and the Modified Texas Priority Index Formula captured 83.1% (245 out of 295 highway-rail grade crossings) from the top 50% of the most hazardous highway-rail grade crossings. On the other hand, the Connecticut Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the U.S. DOT Accident Prediction Formula were found to be the least accurate for this group. Specifically, the Connecticut Hazard Rating Formula and the Modified Connecticut Hazard Rating Formula captured only 76.6% (226 out of 295 highway-rail grade crossings), while the U.S. DOT Accident Prediction Formula captured only 59.3% (175 out of 295 highway-rail grade crossings) from the top 50% of the most hazardous highway-rail grade crossings.

Based on the conducted analysis, it can be observed that the Michigan Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula generally performed better than other candidate accident and hazard prediction models and were able to capture more highway-rail grade crossings in the groups, representing the top 15%, 20%, 25%, 30%, 40%, and 50% of the most hazardous highway-rail grade crossings. The candidate hazard prediction models were found to be superior to the candidate accident prediction models for the selected highway-rail grade crossings in the State of Florida. The latter finding can be explained by the fact that the accident prediction models include a significant number of coefficients, which were calibrated based on the historical data regarding the physical and operational characteristics collected for a large sample of the highway-rail grade crossings across the country. Over time, changes in the physical and operational characteristics of highway-rail grade crossings are inevitable. Therefore, many coefficients are becoming outdated in the accident prediction models. Furthermore, the coefficients, which were calibrated based on the historical data collected for a large sample of the highway-rail grade crossings across the country, may not be appropriate for the highway-rail grade crossings in the State of Florida.

On the other hand, the hazard prediction models are more generic and do not rely on a large number of coefficients, which have to be calibrated based on a large sample of data. A highway-rail grade crossing hazard is assessed using basic physical and operational characteristics (e.g., number of vehicles per day, number of trains per day, existing protection, accident history, train speed, number of tracks, number of traffic lanes, etc.). Among the candidate accident and hazard prediction models, the U.S. DOT Accident Prediction Formula typically captured less highway-rail grade crossings in the groups, representing the top 15%, 20%, 25%, 30%, 40%, and 50% of the most hazardous highway-rail grade crossings. A fairly weak performance was also demonstrated by the Connecticut Hazard Rating Formula and the Modified Connecticut Hazard Rating Formula as compared to other candidate accident and hazard prediction models.

Another important finding consists in the fact that the Modified California Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the Modified Texas Priority Index Formula generally outperformed the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, and the canonical Texas Priority Index Formula, respectively. The latter finding can be supported by the fact that the Modified California Hazard

Rating Formula, the Modified Connecticut Hazard Rating Formula, and the Modified Texas Priority Index Formula consider the total number of accidents in the last years (the last ten years, the last five years, and the last five years, respectively) or since the year of last improvement (in case there was an upgrade), while the canonical versions of the aforementioned formulae ignore the upgrades at highway-rail grade crossings. However, the upgrades may cause significant changes in the operational characteristics of highway-rail grade crossings, which further negatively affect performance of the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, and the canonical Texas Priority Index Formula.

### 6.3. Analysis of the Accident and hazard Prediction Models based on the Spearman Rank Correlation Coefficient

The Spearman rank correlation coefficient, which is a performance metric showing the difference between the baseline rankings of highway-rail grade crossings (i.e., the ones that were obtained based on the actual accident data for the year of 2017) against the predicted baseline rankings of highway-rail grade crossings (i.e., the ones that were suggested by the given candidate accident and hazard prediction model), was estimated for each one of the candidate accident and hazard prediction models. The calculated Spearman rank correlation coefficient values are presented in Figure 38.

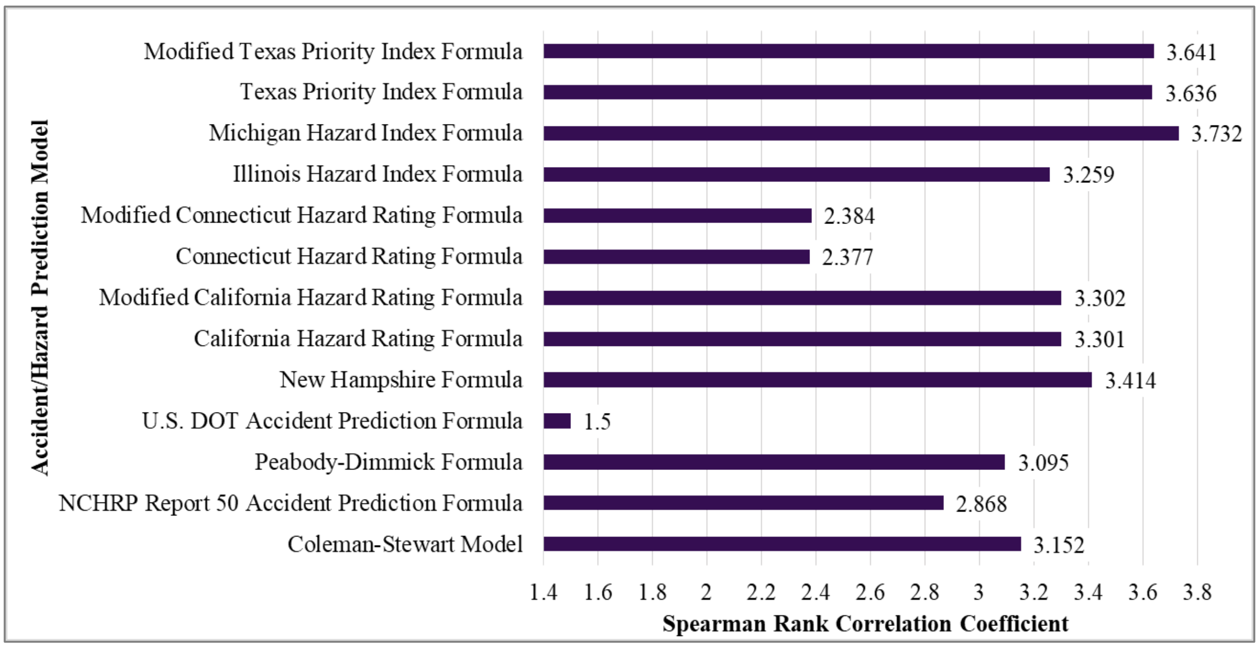


**Figure 38** The Spearman rank correlation coefficient values for the candidate accident and hazard prediction models.

Based on the methodology proposed by Qureshi et al. (2003), the Spearman rank correlation coefficients were multiplied by a factor of “5” for all the candidate accident and hazard prediction models in order to accentuate the degree of correlation between the baseline rankings and the predicted rankings. For instance, if three decimal places are considered, the Spearman rank correlation coefficient of the California Hazard Rating Formula and the Modified California Hazard Rating Formula would be 0.660. However, after multiplying the correlation coefficient by a factor of “5,” the corresponding coefficients for the California Hazard Rating Formula and the Modified California Hazard Rating Formula would be 3.301 and 3.302, respectively. The latter highlights that the ranks, proposed by the Modified California Hazard Rating Formula, are more accurate as compared to the ones, proposed by the canonical California Hazard Rating Formula.

Table 53 illustrates the ranking of the candidate accident and hazard prediction models based on the Spearman rank correlation coefficient values (the highest rank was given to the models with the highest values of the Spearman rank correlation coefficient). The Spearman rank correlation analysis revealed that the ranking of highway-rail grade crossings based on the Michigan Hazard Index Formula had the closest match with the rankings of highway-rail grade crossings based on the actual accident data. The Spearman rank correlation coefficient value for this model was calculated to be 3.732 when multiplied by "5" (see Figure 38). Note that a coefficient value of "5" indicates a perfect positive correlation between the baseline rankings and the predicted rankings, while a coefficient value of "-5" implies a perfect negative correlation between the baseline rankings and the predicted rankings. Therefore, the Spearman rank correlation coefficient of the Michigan Hazard Index Formula shows a highly positive relationship between the baseline rankings and the predicted rankings. Throughout the conducted analysis, it was found that none of the Spearman rank correlation coefficients of the candidate accident and hazard prediction models were negative; thus, higher values of the coefficient denote closer goodness of fit.

**Table 53** Ranking of the candidate accident and hazard prediction models based on the Spearman rank correlation coefficient.

| Accident and hazard Prediction Model | Spearman Rank Correlation Coefficient | Rank |
|---|---|---|
| Michigan Hazard Index Formula | 3.732 | 1 |
| Modified Texas Priority Index Formula | 3.641 | 2 |
| Texas Priority Index Formula | 3.636 | 3 |
| New Hampshire Formula | 3.414 | 4 |
| Modified California Hazard Rating Formula | 3.302 | 5 |
| California Hazard Rating Formula | 3.301 | 6 |
| Illinois Hazard Index Formula | 3.259 | 7 |
| Coleman-Stewart Model | 3.152 | 8 |
| Peabody-Dimmick Formula | 3.095 | 9 |
| NCHRP Report 50 Accident Prediction Formula | 2.868 | 10 |
| Modified Connecticut Hazard Rating Formula | 2.384 | 11 |
| Connecticut Hazard Rating Formula | 2.377 | 12 |
| U.S. DOT Accident Prediction Formula | 1.500 | 13 |

The second most accurate model in terms of the Spearman rank correlation coefficient values was found to be the Modified Texas Priority Index Formula, which had a coefficient value of 3.641, indicating a strong positive relationship between the baseline rankings and the predicted rankings (see Figure 38). The predicted rankings of highway-rail grade crossings, obtained by the Texas Priority Index Formula, were also found to be close to the baseline rankings of highway-rail grade crossings (the Spearman rank correlation coefficient for the Texas Priority Index Formula comprised 3.636). Similar to the findings, revealed from analysis of the accident and hazard prediction models based on the crossing groups (see section 6.2 of this report for more details), the candidate hazard prediction models were generally found to be superior to the candidate accident prediction models in terms of the Spearman rank correlation coefficient values for the selected highway-rail grade crossings in the State of Florida. The latter finding can be supported by the fact that the accident prediction models include a significant number of coefficients that become outdated over time due to changes in the physical and operational characteristics of highway-rail grade crossings, which negatively affect accuracy of the accident prediction models. Therefore, the difference between the baseline rankings and the predicted rankings, obtained by the candidate accident prediction models, was generally higher as compared to the difference between the baseline rankings and the predicted rankings, obtained by the candidate hazard prediction models.

The U.S. DOT Accident Prediction Formula had the lowest Spearman rank correlation coefficient of 1.500, which indicates that the associated rankings of the selected highway-rail grade crossings had a weak positive relationship with the baseline rankings. Relatively low values of the Spearman rank correlation coefficient were recorded for the Connecticut Hazard Rating Formula and the Modified Connecticut Hazard Rating Formula (2.377 and 2.384, respectively). Based on the conducted analysis, it can be observed that the Modified California Hazard Rating Formula, the Modified Connecticut Hazard Rating Formula, and the Modified Texas Priority Index Formula typically had higher Spearman rank correlation coefficient values as compared to the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, and the canonical Texas Priority Index Formula, respectively. Similar to the findings, revealed from analysis of the accident and hazard prediction models based on the crossing groups (see section 6.2 of this report for more details), worse performance of the canonical California Hazard Rating Formula, the canonical Connecticut Hazard Rating Formula, and the canonical Texas Priority Index Formula can be explained by the fact that these formulae do not consider upgrades at highway-rail grade crossings throughout estimation of the accident history.

### 6.4. Final Model Recommendation

As a result of a detailed evaluation of 13 candidate accident and hazard prediction models, it was observed that the Michigan Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula were found to be superior to the other models for the highway-rail grade crossings in the State of Florida in terms of the considered performance indicators. Specifically, the Michigan Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula were able to capture more highway-rail grade crossings in the groups, representing the top 15%, 20%, 25%, 30%, 40%, and 50% of the most hazardous highway-rail grade crossings in the State of Florida. Furthermore, the Michigan Hazard Index Formula, the Texas Priority Index Formula, and the Modified Texas Priority Index Formula had the highest values of the Spearman rank correlation coefficient (i.e., greater than 3.600). However, the Michigan Hazard Index Formula has a major drawback as compared to the Texas Priority Index Formula and the Modified Texas Priority Index Formula, since it does consider the accident history at highway-rail grade crossings.

Moreover, the Modified Texas Priority Index Formula is methodologically more advantageous as compared to the canonical Texas Priority Index Formula, since it considers the total number of accidents in the last five years or since the year of last improvement (in case there was an upgrade), while the canonical Texas Priority Index Formula simply accounts for the total number of accidents in the last five years. Since the upgrades can cause significant changes in the operational characteristics of a given highway-rail grade crossing, the Modified Texas Priority Index Formula returned higher values of the Spearman rank correlation coefficient as compared to the canonical Texas Priority Index Formula. Therefore, the Modified Texas Priority Index Formula, which will be further referred to as "***the Florida Priority Index Formula***", is recommended to rank the highway-rail grade crossings in the State of Florida for safety improvement projects. The Florida Priority Index Formula can be expressed using the following equation:

$$FPI = V \cdot T \cdot (0.1 \cdot S) \cdot PF \cdot (0.01 \cdot A^{1.15}) \qquad (5.3)$$

where:
$FPI$ = the Florida Priority Index;
$V$ = average daily traffic volume;
$T$ = average daily train volume;
$S$ = train speed;
$PF$ = protection factor;
$A$ = accident history parameter.

Based on the analysis results, it was found that the protection factor values, proposed in the canonical Texas Priority Index Formula (see Table 54 – Ryan and Mielke, 2017), demonstrated a good performance for the highway-rail grade crossings in the State of Florida; therefore, these protection factor values will be further used within the Florida Priority Index Formula. Note that the field "WdCode" of the FRA crossing inventory database was used to identify the protection type at the highway-rail grade crossings. However, the field "WdCode" does not differentiate between mast-mounted flashing lights and cantilever flashing lights. The field "WdCode" provides a value "7" in case if a given highway-rail grade crossing is equipped with flashing lights (without specifying whether the flashing lights are mast-mounted or cantilever). In order to be on the conservative side, the worst case protection factor value of "0.70" (which corresponds to mast-mounted flashing lights) was assumed for the highway-rail grade crossings, which are equipped with flashing lights. The latter approach was found to be efficient, considering the fact that the Texas Priority Index Formula and the Florida Priority Index Formula demonstrated a competitive performance throughout evaluation of the highway-rail grade crossings in the State of Florida.

**Table 54** Protection factor values for the Texas Priority Index Formula.

| **Traffic Control Devices** | **Protection Factor (PF)** |
|---|---|
| Passive | 1.00 |
| Mast-mounted flashing lights | 0.70 |
| Cantilever flashing lights | 0.15 |
| Gates | 0.10 |

The procedure for estimating the accident history parameter ($A$), which is used by the Florida Priority Index Formula, is outlined in **Algorithm 1**. In step 0, a data structure for storing the values of accident history parameter for the considered highway-rail grade crossings is initialized. Then, the algorithm enters the main loop (steps 1-15). If the last upgrade was performed more than four years ago for a given highway-rail grade crossing, the accident history parameter will be set based on a 5-year accident history (steps 2 and 3). If the last upgrade was performed four years ago for a given highway-rail grade crossing, the accident history parameter will be set based on a 4-year accident history (steps 4 and 5). If the last upgrade was performed three years ago for a given highway-rail grade crossing, the accident history parameter will be set based on a 3-year accident history (steps 6 and 7). If the last upgrade was performed two years ago for a given highway-rail grade crossing, the accident history parameter will be set based on a 2-year accident history (steps 8 and 9). If the last upgrade was performed one year ago for a given highway-rail grade crossing, the accident history parameter will be set based on the current year accident history (steps 10 and 11). If the last upgrade was performed in the current year for a given highway-rail grade crossing, the accident history parameter will be set to a default value of one accident (steps 12 and 13). The algorithm exits the main loop, once the accident history parameter has been estimated for each one of the considered highway-rail grade crossings.

**Algorithm 1:** Accident History Parameter Estimation (AHPE)

$\boldsymbol{AHPE}(X, Y, y^{cur}, AH, LU)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $Y = \{1, \dots, q\}$ - set of years; $y^{cur}$ - current year; $AH$ - accident history for the considered crossings (by year); $LU$ - year of the last upgrade for the considered crossings.

**out:** $A$ - accident history parameter

0: $|A| \leftarrow n$ ⊲ Initialization
1: **for all** $x \in X$ **do**
2: **if** $LU_x < (y^{cur} - 4)$ **do** ⊲ If the last upgrade was performed more than 4 years ago
3: $A_x \leftarrow max(1, AH_{x[(y^{cur}-4):y^{cur}]})$ ⊲ Consider a 5-year accident history
4: **else if** $LU_x = (y^{cur} - 4)$ **do** ⊲ If the last upgrade was performed 4 years ago
5: $A_x \leftarrow max(1, AH_{x[(y^{cur}-3):y^{cur}]})$ ⊲ Consider a 4-year accident history
6: **else if** $LU_x = (y^{cur} - 3)$ **do** ⊲ If the last upgrade was performed 3 years ago
7: $A_x \leftarrow max(1, AH_{x[(y^{cur}-2):y^{cur}]})$ ⊲ Consider a 3-year accident history
8: **else if** $LU_x = (y^{cur} - 2)$ **do** ⊲ If the last upgrade was performed 2 years ago
9: $A_x \leftarrow max(1, AH_{x[(y^{cur}-1):y^{cur}]})$ ⊲ Consider a 2-year accident history
10: **else if** $LU_x = (y^{cur} - 1)$ **do** ⊲ If the last upgrade was performed 1 year ago
11: $A_x \leftarrow max(1, AH_{x[y^{cur}]})$ ⊲ Consider the accident history from the current year
12: **else if** $LU_x = y^{cur}$ **do** ⊲ If the last upgrade was performed in the current year
13: $A_x \leftarrow 1$ ⊲ Assume a default value of 1 accident
14: **end if**
15: **end for**
16: **return** $A$ ⊲ Return the accident history parameter

Note that the accident history parameter cannot be less than “1”. Even for the highway-rail grade crossings, which did not experience any accidents over the last five years, the accident history parameter will be assumed to be equal to “1” (which is in line with the common assumption used in the canonical Texas Priority Index Formula – see Ryan and Mielke, 2017). Note that **Algorithm 1** can be modified depending on the accident data availability (e.g., if the accident data are not available for the current year, the accident history can be shifted by one year in the past).

# 7. DEVELOPMENT OF THE OPTIMIZATION MODELS FOR RESOURCE ALLOCATION AMONG THE HIGHWAY-RAIL GRADE CROSSINGS IN FLORIDA

This section of the report provides a detailed description of all the components/notations, which will be used throughout development of the mathematical models for resource allocation among the highway-rail grade crossings in the State of Florida. Furthermore, integer programming mathematical formulations are presented for two optimization models, where the first model aims to minimize the overall hazard at the highway-rail grade crossings, while the second model aims to minimize the overall hazard severity at the highway-rail grade crossings. The input data, required by both models, as well as the computational complexity of the models are also discussed in this section of the report.

## 7.1. Nomenclature

The nomenclature, used throughout the mathematical model development, is explained in this section of the report. Table 55 provides a description of all the components of the integer programming mathematical formulations, which were adopted for the proposed optimization models.

**Table 55** Description of the mathematical model components.

| Model Component<br>Type | <br>Nomenclature | Description |
|---|---|---|
| Sets | $X = \{1, \dots, n\}$ | set of highway-rail grade crossings (highway-rail grade crossings) |
| | $C = \{1, \dots, m\}$ | set of countermeasures (countermeasures) |
| | $S = \{1, \dots, k\}$ | set of severity categories (severity categories) |
| Decision Variables | $\boldsymbol{z}_{xc} \in \mathbb{B}\ \forall x \in X, c \in C$ | =1 if countermeasure $c$ is applied at highway-rail grade crossing $x$ (=0 otherwise) |
| Parameters | $n \in \mathbb{N}$ | number of highway-rail grade crossings (highway-rail grade crossings) |
| | $m \in \mathbb{N}$ | number of considered countermeasures (countermeasures) |
| | $k \in \mathbb{N}$ | number of severity categories (severity categories) |
| | $OH_x \in \mathbb{R}^+\ \forall x \in X$ | overall hazard at highway-rail grade crossing $x$ (no units) |
| | $HS_{xs} \in \mathbb{R}^+\ \forall x \in X, s \in S$ | hazard of severity $s$ at highway-rail grade crossing $x$ (no units) |
| | $W_s \in \mathbb{R}^+\ \forall s \in S$ | weight associated with severity $s$ (varies from 0.0 to 1.0) |
| | $p_{xc} \in \mathbb{B}\ \forall x \in X, c \in C$ | =1 if countermeasure $c$ can be potentially applied at highway-rail grade crossing $x$ (=0 otherwise) |
| | $EF_{xc} \in \mathbb{R}^+\ \forall x \in X, c \in C$ | effectiveness factor for countermeasure $c$ when applied at highway-rail grade crossing $x$ |
| | $CA_{xc} \in \mathbb{R}^+\ \forall x \in X, c \in C$ | cost of applying countermeasure $c$ at highway-rail grade crossing $x$ (USD) |
| | $TAB \in \mathbb{R}^+$ | total available budget (USD) |

The appropriate values for the parameters of the mathematical models will be set based on the available literature and consultation with the FDOT representatives. A detailed description of the parameters, which are used in the proposed mathematical models, is provided in section 7.4 of this report.

### 7.2. Minimizing the Overall Hazard

This section of the report presents an integer programming model for the resource allocation problem (RAP) among the existing highway-rail grade crossings, aiming to minimize the overall hazard at the highway-rail grade crossings. The latter mathematical model will be referred to as **RAP-1** and is presented next.

**RAP-1:**

$$min \sum_{x \in X} [1 - \sum_{c \in C} (EF_{xc} \cdot \boldsymbol{z}_{xc})] \cdot OH_x \tag{7.1}$$

**Subject to:**

$$\sum_{c \in C} \boldsymbol{z}_{xc} \leq 1 \ \forall x \in X \tag{7.2}$$

$$\boldsymbol{z}_{xc} \leq p_{xc} \ \forall x \in X, c \in C \tag{7.3}$$

$$\sum_{x \in X} \sum_{c \in C} CA_{xc} \cdot \boldsymbol{z}_{xc} \leq TAB \tag{7.4}$$

$$\boldsymbol{z}_{xc}, p_{xc} \in \mathbb{B} \ \forall x \in X, c \in C \tag{7.5}$$

$$OH_x, EF_{xc}, CA_{xc}, TAB \in \mathbb{R}^+ \ \forall x \in X, c \in C \tag{7.6}$$

The objective function (7.1) aims to minimize the overall hazard at the highway-rail grade crossings. Constraint set (7.2) indicates that no more than one countermeasure can be applied at each one of the considered highway-rail grade crossings. Constraint set (7.3) guarantees that a given countermeasure can be applied only at the highway-rail grade crossings that are eligible for such countermeasure. Constraint set (7.4) ensures that the total cost of upgrading the selected highway-rail grade crossings will not exceed the total available budget. Constraint sets (7.5) and (7.6) define the nature of decision variables and parameters of the **RAP-1** mathematical model (note that "$\mathbb{B}$" refers to a set of binary integers, while "$\mathbb{R}^+$" refers to a set of positive real numbers).

### 7.3. Minimizing the Overall Hazard Severity

This section of the report presents an integer programming model for the resource allocation problem (RAP) among the existing highway-rail grade crossings, aiming to minimize the overall hazard severity at the highway-rail grade crossings. The latter mathematical model will be referred to as **RAP-2** and is presented next.

**RAP-2:**

$$min \sum_{x\in X}\sum_{s\in S}[1-\sum_{c\in C}(EF_{xc}\cdot \boldsymbol{z}_{xc})]\cdot W_s\cdot HS_{xs} \quad (7.7)$$

**Subject to:**

$$\sum_{c\in C}\boldsymbol{z}_{xc}\leq 1\ \forall x\in X \quad (7.8)$$

$$\boldsymbol{z}_{xc}\leq p_{xc}\ \forall x\in X, c\in C \quad (7.9)$$

$$\sum_{x\in X}\sum_{c\in C}CA_{xc}\cdot \boldsymbol{z}_{xc}\leq TAB \quad (7.10)$$

$$\boldsymbol{z}_{xc}, p_{xc}\in\{0,1\}\ \forall x\in X, c\in C \quad (7.11)$$

$$HS_{xs}, W_s, EF_{xc}, CA_{xc}, TAB\in\mathbb{R}^+\ \forall x\in X, c\in C, s\in S \quad (7.12)$$

The objective function (7.7) aims to minimize the overall hazard severity at the highway-rail grade crossings. Constraint set (7.8) indicates that no more than one countermeasure can be applied at each one of the considered highway-rail grade crossings. Constraint set (7.9) guarantees that a given countermeasure can be applied only at the highway-rail grade crossings that are eligible for such countermeasure. Constraint set (7.10) ensures that the total cost of upgrading the selected highway-rail grade crossings will not exceed the total available budget. Constraint sets (7.11) and (7.12) define the nature of decision variables and parameters of the **RAP-2** mathematical model (note that "$\mathbb{B}$" refers to a set of binary integers, while "$\mathbb{R}^+$" refers to a set of positive real numbers).

### 7.4. Required Input Data

This section of the report focuses on a detailed description of the input data, which are necessary in order to execute the developed optimization models and perform resource allocation among the highway-rail grade crossings in the State of Florida. The **RAP-1** mathematical model requires the following inputs: (1) $X=\{1,\dots,n\}$ – set of highway-rail grade crossings (highway-rail grade crossings); (2) $C=\{1,\dots,m\}$ – set of countermeasures (countermeasures); (3) $OH_x, x\in X$ – overall hazard at highway-rail grade crossing $x$ (no units); (4) $p_{xc}, x\in X, c\in C$ =1 if countermeasure $c$ can be potentially applied at highway-rail grade crossing $x$ (=0 otherwise); (5) $EF_{xc}, x\in X, c\in C$ – effectiveness factor for countermeasure $c$ when applied at highway-rail grade crossing $x$; (6) $CA_{xc}, x\in X, c\in C$ – cost of applying countermeasure $c$ at highway-rail grade crossing $x$ (USD); and (7) $TAB$ – total available budget (USD).

On the other hand, the **RAP-2** mathematical model requires the following inputs: (1) $X=\{1,\dots,n\}$ – set of highway-rail grade crossings (highway-rail grade crossings); (2) $C=\{1,\dots,m\}$ – set of countermeasures (countermeasures); (3) $S=\{1,\dots,k\}$ – set of severity categories (severity categories); (4) $HS_{xs}, x\in X, c\in C$ – hazard of severity $s$ at highway-rail grade crossing $x$ (no units); (5) $W_s, s\in S$ – weight associated with severity $s$ (varies from 0.0 to 1.0); (6) $p_{xc}, x\in X, c\in C$ =1 if countermeasure $c$ can be potentially applied at highway-rail grade crossing $x$ (=0 otherwise); (7) $EF_{xc}, x\in X, c\in C$ – effectiveness factor for countermeasure $c$ when applied at highway-rail grade crossing $x$; (8) $CA_{xc}, x\in X, c\in C$ – cost of applying countermeasure $c$ at highway-rail grade crossing $x$ (USD); and (9) $TAB$ – total available budget

(USD). Sections 7.4.1-7.4.3 of this report elaborate on the adopted values for the aforementioned parameters of the **RAP-1** and **RAP-2** mathematical models.

### *7.4.1. Set of Highway-Rail Grade Crossings*

Federal Railroad Administration (FRA) maintains a publicly available crossing inventory database, which provides a detailed information regarding basic characteristics of different crossing types (i.e., at grade, railroad under, railroad over) across the nation. Specifically, the FRA crossing inventory database provides the information regarding the following aspects (FRA, 2016): (1) existing highway or pathway traffic control devices; (2) crossing location and classification; (3) the operating railroad information; (4) crossing physical characteristics; (5) the information regarding the public highway that is associated with a given crossing; and others (see section 4 of this report for more details). This project will primarily rely on the information, which is available in the FRA crossing inventory database for all the highway-rail grade crossings located in the State of Florida. A set of the considered highway-rail grade crossings will be denoted as $X = \{1, \dots, n\}$ in the **RAP-1** and **RAP-2** mathematical models.

Furthermore, the **RAP-1** mathematical model requires the data regarding the overall hazard at highway-rail grade crossings ($OH_x, x \in X$). The latter information will be obtained using the most promising accident and hazard prediction model, which was identified earlier under this project for the highway-rail grade crossings in the State of Florida – the Florida Priority Index Formula. The Florida Priority Index Formula can be estimated for highway-rail grade crossing $x$ using the following equation:

$$FPI_x = V_x \cdot T_x \cdot (0.1 \cdot S_x) \cdot PF_x \cdot \left(0.01 \cdot {A_x}^{1.15}\right) \quad (7.13)$$

where:

$FPI_x$ = the Florida Priority Index at highway-rail grade crossing $x$ (no units);
$V_x$ = average daily traffic volume at highway-rail grade crossing $x$ (vehicles per day);
$T_x$ = average daily train volume at highway-rail grade crossing $x$ (trains per day);
$S_x$ = train speed at highway-rail grade crossing $x$ (mph);
$PF_x$ = protection factor at highway-rail grade crossing $x$ (PF = 1.00 for passive; PF = 0.70 for flashing lights; PF = 0.10 for gates);
$A_x$ = accident history parameter at highway-rail grade crossing $x$ (accidents) - the total number of accidents in the last five years or since the year of last improvement (in case there was an upgrade).

The FRA highway-rail grade crossing accident database (FRA, 2018a) will be used in order to calculate the accident history parameter ($A_x, x \in X$). The estimated Florida Priority Index value will represent a potential hazard of a given highway-rail grade crossing (i.e., $FPI_x = OH_x \ \forall x \in X$) in the **RAP-1** mathematical model. One the other hand, the **RAP-2** mathematical model requires the data regarding a potential hazard at each highway-rail grade crossing by severity category ($HS_{xs}, x \in X, s \in S$). A set of severity categories will be further referred to as $S = \{1, \dots, k\}$ in the **RAP-2** mathematical model. The GradeDec methodology will be used to assess a potential hazard of each highway-rail grade crossing in the State of Florida of by severity category (see section 7.4.3 for more details).

### *7.4.2. Set of Countermeasures*

Different countermeasures are used at highway-rail grade crossings in order to reduce the number of accidents and improve the overall safety. These countermeasures include, but are not limited to, installation of flashing lights at passive highway-rail grade crossings, installation of flashing lights and gates at passive highway-rail grade crossings, installation of mountable curbs with channelized devices at gated highway-rail grade crossings, installation of barrier curbs with or without channelized devices at gated highway-rail grade crossings, installation of photo enforcement at gated highway-rail grade crossings, and others (U.S. DOT, 2007; U.S. DOT, 2014). A set of considered countermeasures will be denoted as $C = \{1, \dots, m\}$ in the **RAP-1** and **RAP-2** mathematical models. An effectiveness factor (or effectiveness multiplier) is associated with each countermeasure and represents the percent reduction in terms of accidents that occurred after the implementation of improvements at a given highway-rail grade crossing (U.S. DOT, 2007; U.S. DOT, 2014). Installation of the most effective countermeasures at the most hazardous highway-rail grade crossings may not be feasible, taking into account the fact that the countermeasures with higher effectiveness factors generally have higher installation costs as compared to the countermeasures with lower effectiveness factors. The effectiveness factors and the installation costs will be further referred to as $EF_{xc}, x \in X, c \in C$ and $CA_{xc}, x \in X, c \in C$, respectively, within the developed mathematical models. The total budget available for safety improvement projects at the considered highway-rail grade crossings will be denoted as $TAB$ in the **RAP-1** and **RAP-2** mathematical models.

Note that some specific types of countermeasures cannot be implemented at certain highway-rail grade crossings. For example, based on the canonical resource allocation procedure, there are two upgrade options at passive single-track highway-rail grade crossings, which include installation of flashing lights or installation of gates (U.S. DOT, 2007). On the other hand, there is only one upgrade option at passive multiple-track highway-rail grade crossings – installation of gates (U.S. DOT, 2007). The latter operational feature is captured by parameter $p_{xc}, x \in X, c \in C$ within the developed mathematical models. The value of parameter $p_{xc}, x \in X, c \in C$ is equal to "1" if countermeasure $c$ can be potentially applied at highway-rail grade crossing $x$ (equal to "0" otherwise).

A large number of traffic control devices have been designed over the years in order to improve safety at highway-rail grade crossings. Generally, traffic control devices can be classified in two groups, including the following: (1) active traffic control devices; and (2) passive traffic control devices. Active traffic control devices make a reaction and give advance notifications in case of an approaching train (U.S. DOT, 2007). Flashing light signals (both mast-mounted and cantilevered), bells, automatic gates, active advance warning devices, and highway traffic signals are the most well-known active traffic control devices. Unlike active traffic control devices, passive traffic control devices are typically located at or behind a highway-rail grade crossing and just indicate the presence of a crossing. The status of passive traffic control devices does not change in case of an approaching train (U.S. DOT, 2007). Regulatory signs, warning signs, guide signs, and supplemental pavement markings are some examples of passive traffic control devices. A description of certain basic countermeasures (including highway-rail grade crossing signs, flashing light signals, automatic gates, and pavement markings) is provided in the following sections of this report. Furthermore, a set of countermeasures that will be considered under this project throughout evaluation of the solution algorithms for the **RAP-1** and **RAP-2** mathematical models will be described as well.

***Highway-Rail Grade Crossing Signs***

Typical signs, which have been commonly utilized at highway-rail grade crossings, are illustrated in Figure 39. Some basic information for typical highway-rail grade crossing signs is provided in Table 56. Note that Figure 39 and Table 56 were prepared using the data reported by U.S. DOT (2007) [pages 84-86 of the report]. More details regarding these signs can be obtained from the Manual on Uniform Traffic Control Devices (MUTCD), which was developed by Federal Highway Administration (FHWA) (FHWA, 2003; U.S. DOT, 2007). Figure 39 presents two categories of highway-rail grade crossing signs, including the following: (1) warning signs; and (2) regulatory signs. Warning signs call attention to unexpected conditions on a highway or on a street or in the vicinity of a highway/street and to situations, which might not be readily apparent to road users. On the other hand, regulatory signs are used to inform road users regarding the existing traffic laws or regulations and indicate the applicability of certain legal requirements. Warning signs generally have a yellow background, while regulatory signs typically have black and white color coding. Moreover, labels of warning signs start with the letter "W", while labels of regulatory signs start with the letter "R" (see Table 56) (FHWA, 2003; U.S. DOT, 2007).

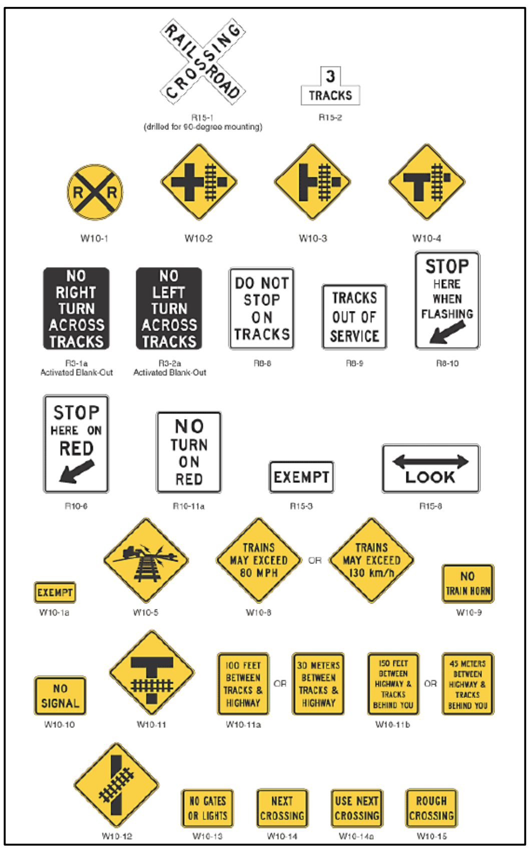


**Figure 39** Typical signs utilized at highway-rail grade crossings.

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

Table 56 includes the following information: (1) the label of a given highway-rail grade crossing sign; (2) section of MUTCD containing the related information regarding a given highway-rail grade crossing sign; (3) name of a given highway-rail grade crossing sign; and (4) application or indication of need for a given highway-rail grade crossing sign. MUTCD provides some basic tips for installing signs, including the following (U.S. DOT, 2007):

- In general, signs should be installed on the right-hand side of the road;
- Signs should be placed in order to optimize visibility;
- Signs should not be located beyond the crest of a hill or in a highway dip;
- Signs should not be covered by a parked car, foliage, snow accumulation, or any other obstructions that may impact sign visibility.

The distance between the location of the installed sign and a highway-rail grade crossing primarily depends on the vehicle speed and traffic conditions. The information regarding the advance placement distances for warning signs is presented in Table 57 for different posted speed limits (or 85$^{th}$ percentile speeds) and different traffic conditions (FHWA, 2003; U.S. DOT, 2007). Note that Table 57 was prepared using the data reported by U.S. DOT (2007) [page 89 of the report].

**Table 56** Basic information regarding highway-rail grade crossing signs.

| MUTCD no. | Section | Traffic control device | Application or indication of need |
|---|---|---|---|
| R3-1a | 8B.06, 10C.09 | No Right Turn Across Tracks | Used to prohibit turning movements toward the highway-rail grade crossing during preemption. |
| R3-2a | 8B.06, 10C.09 | No Left Turn Across Tracks | Used to prohibit turning movements toward the highway-rail grade crossing during preemption. |
| R8-8 | 8B.07, 10C.05 | Do Not Stop on Tracks | Where queuing occurs or where storage space is limited between a nearby highway intersection and the tracks; may be supplemented with a flashing light activated by queuing traffic in the exit lane(s) from the crossing. (See discussion on queue cutter signals.) |
| R8-9 | 8B.09, 10C.06 | Tracks Out of Service | Applicable when there is some physical disconnection along the railroad tracks to prevent trains from using those tracks. |
| R8-10 | 8B.10, 10C.08 | Stop Here When Flashing | May be used at a highway-rail grade crossing to inform drivers of the location of the stop line or the point at which to stop when the flashing light signals (Section 8D.02) are activated. |
| R10-6 | 8B.11, 10C.07 | Stop Here on Red | May be used at locations where vehicles frequently violate the stop line or where it is not obvious to road users where to stop. |
| R10-11a | 8D.07, 10C.09 | No Turn on Red | If there is a nearby signalized intersection with insufficient clear storage distance for a design vehicle or the highway-rail grade crossing does not have gates. |
| R15-1 | 8B.03, 10C.02 | Highway-Rail Grade Crossing (crossbuck) | Required device. |
| R15-2 | 8B.03, 10C.02 | Number of Tracks | Standard required device, with two or more tracks and no gate; optional with gate. |
| R15-3 | 8B.05, 10C.10 | Exempt | School buses and commercial vehicles that are usually required to stop at crossings are not required to do so where authorized by ordinance. |
| R15-4a | 10C.13 | Light Rail Only Right Lane | For multilane operations where roadway users might need additional guidance on lane use and/or restrictions. |
| R15-4b | 10C.13 | Light Rail Only Left Lane | For multilane operations where roadway users might need additional guidance on lane use and/or restrictions. |
| R15-4c | 10C.13 | Light Rail Only Center Lane | For multilane operations where roadway users might need additional guidance on lane use and/or restrictions. |
| R15-5 | 10C.14 | Light Rail Do Not Pass | Where vehicles are not allowed to pass LRT vehicles loading or unloading passengers where no raised platform physically separates the lanes. |
| R15-5a | 10C.14 | Do Not Pass Stopped Train | Where vehicles are not allowed to pass LRT vehicles loading or unloading passengers where no raised platform physically separates the lanes. |
| R15-6 | 10C.12 | Do Not Drive On Tracks Light Rail Symbol | Used where there are adjacent vehicle lanes separated from the LRT lane by a curb or pavement markings. |
| R15-6a | 10C.12 | Do Not Drive On Tracks | Used where there are adjacent vehicle lanes separated from the LRT lane by a curb or pavement markings. |
| R15-7 | 10C.11 | Light Rail Divided Highway Symbol | Use with appropriate geometric conditions. |
| R15-7a | 10C.11 | Light Rail Divided Highway Symbol (T-intersection) | Use with appropriate geometric conditions. |
| R15-8 | 8B.16, 10C.03 | Look | • Multiple tracks<br>• Collision experience<br>• Pedestrian presence |
| W10-1 | 8B.04, 10C.15 | Highway-Rail Grade Crossing Advance Warning | Required device, with MUTCD exceptions (Section 8B.04); school buses and commercial vehicles that are usually required to stop at crossings are not required to do so where authorized by ordinance. |
| W10-1a | 8B.05, 10C.10 | Exempt | |

**Table 56** Basic information regarding highway-rail grade crossing signs (cont'd).

| MUTCD no. | Section | Traffic control device | Application or indication of need |
|---|---|---|---|
| W10-2,3,4 | 8B.04, 10C.15 | Highway-Rail Grade Crossing Advance Warning | Based upon specific situations with a nearby parallel highway. |
| W10-5 | 8B.17, 10C.16 | Low Ground Clearance Highway-Rail Grade Crossing | As indicated by MUTCD guidelines, incident history, or local knowledge. |
| W10-7 | 10C.17 | Light Rail Activated Blank-Out Symbol | Supplements the traffic control signal to warn road users turning across the tracks of an approaching parallel LRT vehicle. |
| W10-8 | 8B.13 | Trains May Exceed 130 km/h (80 mph) | Where train speed is 80 mph (130 km/hr.) or faster. |
| W10-9 | 8B.14 | No Train Horn | Shall be used only for crossings in FRA-authorized quiet zones. |
| W10-10 | 8B.15 | No Signal | May be used at passive controlled crossings. |
| W10-11 | 8B.18, 10C.18 | Storage Space Symbol | Where the parallel highway is close to the crossing, particularly with limited storage space between the highway intersection and tracks. |
| W10-11a | 8B.18, 10C.18 | Storage Space XX Meters (Feet) Between Tracks & Highway | Where the parallel highway is close to the crossing, particularly with limited storage space between the highway intersection and tracks. |
| W10-11b | 8B.18, 10C.18 | Storage Space XX Meters (Feet) Between Highway & Tracks Behind You | Used where there is a highway intersection in close proximity to the highway-rail grade crossing and an engineering study determines that adequate space is not available to store a design vehicle(s) between the highway intersection and the train dynamic envelope. |
| W10-12 | 8B.19, 10C.19 | Skewed Crossing | May be used at a skewed highway-rail grade crossing to warn drivers that the railroad tracks are not perpendicular to the highway. |
| W10-13 | 8B.15 | No Gates or Lights | May be installed at highway-rail grade crossings that are not equipped with automated signals. |
| W10-14 | 8B.17 | Next Crossing | Placed below the W10-5 sign at the nearest intersecting highway where a vehicle can detour or at a point on the highway wide enough to permit a U-turn. |
| W10-14a | 8B.17 | Use Next Crossing | Placed below the W10-5 sign at the nearest intersecting highway where a vehicle can detour or at a point on the highway wide enough to permit a U-turn. |
| W10-15 | 8B.17 | Rough Crossing | If the highway-rail grade crossing is rough. |
| I-12 | 10C.20 | Light Rail Station Symbol | Used to direct road users to a light rail station or boarding location. |
| I-13 | 8B.12, 10C.21 | Emergency Notification | Post at all crossings to provide for emergency notification. |
| I-13a | 8B.12, 10C.21 | Emergency Notification | Post at all crossings to provide for emergency notification. |

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

Table 57 provides the placement distances for advance warning signs, considering two base traffic conditions: (1) speed reduction and lane changing in heavy traffic – typical conditions where the user should use extra time in order to adjust speed and change lanes in heavy traffic due to a complex driving situation; and (2) typical conditions where the user should reduce the vehicle speed in order to maneuver through the warned condition (various deceleration values are provided for the listed advisory speed in Table 57). For example, the suggested placement distance for advance warning signs is 850 ft for the scenario with the posted speed limit of 50 mph and the first traffic condition (see Table 57). However, in case of the second traffic condition and deceleration to 10 mph, the suggested placement distance for advance warning signs is 200 ft for the scenario with the posted speed limit of 50 mph. Based on the data available in Table 57, it can be observed that the placement distances for advance warning signs generally increase with an increasing posted speed limit (or 85th percentile speed).

**Table 57** Placement distances for advance warning signs.

| Posted or 85th-Percentile Speed | Advance Placement Distance [1] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Condition A: Speed Reduction and Lane Changing in Heavy Traffic[2] | Condition B: Deceleration to the listed advisory speed (mph) for the condition[4] | | | | | | | |
| | | 0[3] | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
| 20 mph | 225 ft. | N/A[5] | N/A[5] | — | — | — | — | — | — |
| 25 mph | 325 ft. | N/A[5] | N/A[5] | N/A[5] | — | — | — | — | — |
| 30 mph | 450 ft. | N/A[5] | N/A[5] | N/A[5] | — | — | — | — | — |
| 35 mph | 550 ft. | N/A[5] | N/A[5] | N/A[5] | N/A[5] | — | — | — | — |
| 40 mph | 650 ft. | 125 ft. | N/A[5] | N/A[5] | N/A[5] | — | — | — | — |
| 45 mph | 750 ft. | 175 ft. | 125 ft. | N/A[5] | N/A[5] | N/A[5] | — | — | — |
| 50 mph | 850 ft. | 250 ft. | 200 ft. | 150 ft. | 100 ft. | N/A[5] | — | — | — |
| 55 mph | 950 ft. | 325 ft. | 275 ft. | 225 ft. | 175 ft. | 100 ft. | N/A[5] | — | — |
| 60 mph | 1100 ft. | 400 ft. | 350 ft. | 300 ft. | 250 ft. | 175 ft. | N/A[5] | — | — |
| 65 mph | 1200 ft. | 475 ft. | 425 ft. | 400 ft. | 350 ft. | 275 ft. | 175 ft. | N/A[5] | — |
| 70 mph | 1250 ft. | 550 ft. | 525 ft. | 500 ft. | 425 ft. | 350 ft. | 250 ft. | 150 ft. | — |
| 75 mph | 1350 ft. | 650 ft. | 625 ft. | 600 ft. | 525 ft. | 450 ft. | 350 ft. | 250 ft. | 100 ft. |

*Notes:*
*[1] The distances are adjusted for a sign legibility distance of 175 ft. for Condition A. The distances for Condition B have been adjusted for a sign legibility distance of 250 ft., which is appropriate for an alignment warning symbol sign.*
*[2] Typical conditions are locations where the road user must use extra time to adjust speed and change lanes in heavy traffic because of a complex driving situation. Typical signs are Merge and Right Lane Ends. The distances are determined by providing the driver a PIEV (Perception-Identification-Emotion-Volition) time of 14.0 to 14.5 seconds for vehicle maneuvers (2001 AASHTO Policy, Exhibit 3-3, Decision Sight Distance, Avoidance Maneuver E) minus the legibility distance of 175 ft. for the appropriate sign.*
*[3] Typical condition is the warning of a potential stop situation. Typical signs are Stop Ahead, Yield Ahead, Signal Ahead, and Intersection Warning signs. The distances are based on the 2001 AASHTO Policy, Stopping Sight Distance, Exhibit 3-1, providing a PIEV time of 2.5 seconds, a deceleration rate of 11.2 ft./second$^2$, minus the sign legibility distance of 175 ft.*
*[4] Typical conditions are locations where the road user must decrease speed to maneuver through the warned condition. Typical signs are Turn, Curve, Reverse Turn, or Reverse Curve. The distance is determined by providing a 2.5 second PIEV time, a vehicle deceleration rate of 10 ft./second, minus the sign legibility distance of 250 ft.*
*[5] No suggested distances are provided for these speeds, as the placement location is dependent on site conditions and other signing to provide an adequate advance warning for the driver.*
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

***Flashing Light Signals***
A flashing light signal is generally composed of two light units, which flash alternately at a rate of approximately 45 to 65 times per minute (see Figure 40). A typical flashing light signal includes a number of the key components, including background, hood, roundel, lamp, lampholder, reflector, and housing (U.S. DOT, 2007). The background has a diameter of approximately 20-24 inches and is painted in a nonreflecting black color, which is able to provide a contrast to the red light. The hood of a flashing light signal is also typically colored in black. Based on the Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007), the standard diameter of flashing light signal heads is 12 inches.

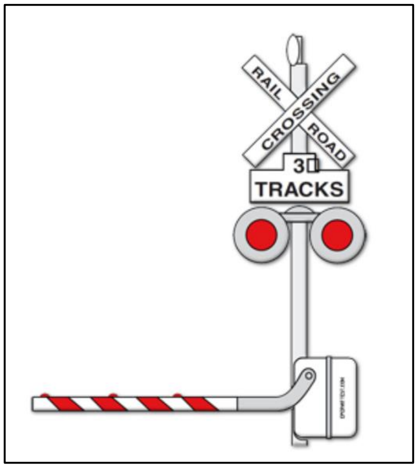


**Figure 40** A typical flashing light signal.
*Source: ePermitTest (2018). Railroad Crossing Gate*

Low-wattage bulbs are commonly used in flashing light signals to ensure operation on stand-by battery power in case of commercial power failures. The wattage is typically either 18 watts or 25 watts. A proper light alignment is critical from the operational standpoint. The lamp of a flashing light signal should be precisely aligned in order to direct the narrow intense beam towards the approaching motorist (U.S. DOT, 2007). The flashing light unit, located on the right-hand side of a highway, is generally aligned to cover a distance far from a given highway-rail grade crossing. Typical alignment patterns for two-lane two-way highways and for multilane highways are provided in Figure 41 and Figure 42, respectively. Note that Figure 41 and Figure 42 were prepared using the data reported by U.S. DOT (2007) [pages 99-100 of the report].

Two general layouts are presented in Figure 41, where the top layout illustrates the top view of a given highway-rail grade crossing, while the bottom layout illustrates the side view of a given highway-rail grade crossing. In the considered example, two flashing light signals are installed at the highway-rail grade crossing with two-lane two-way highway: one is located before the crossing, while another one is placed after the crossing. Similar to Figure 41, Figure 42 presents the top view and the side view of a given highway-rail grade crossing. However, the considered highway-rail grade crossing has four-lane one-way highway, and two flashing light signals are installed before the highway-rail grade crossing. The flashing light signals are installed on both sides of the highway in order to cover the whole width of the highway by beams (see Figure 42).

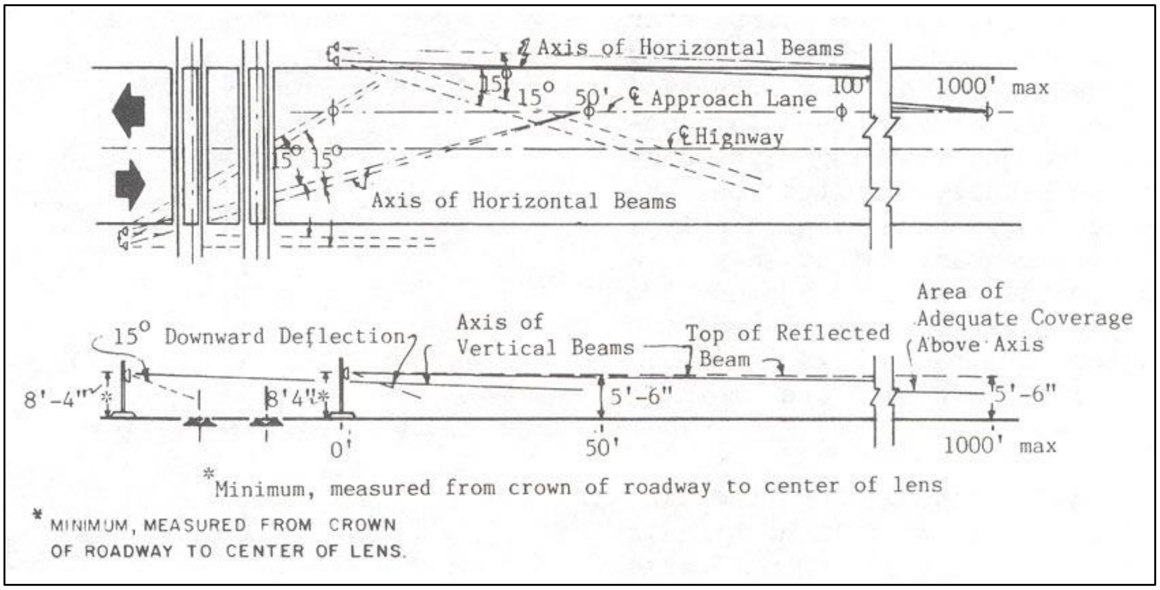


**Figure 41** Typical alignment pattern for flashing light signals with 30-15 degree roundel, two-lane two-way highway.

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

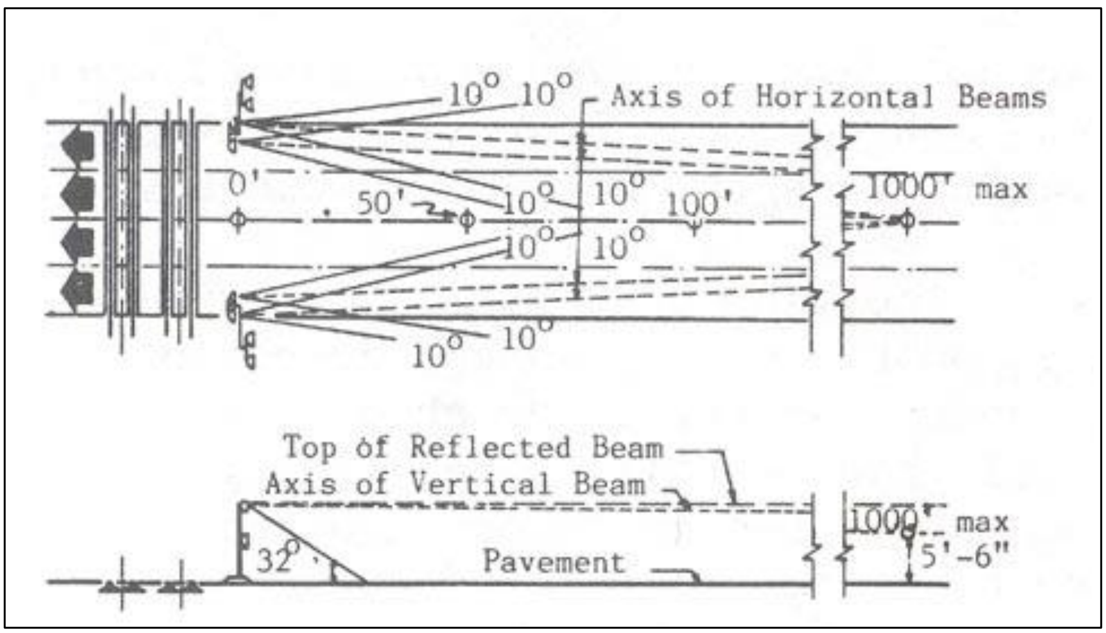


**Figure 42** Typical alignment pattern for flashing light signals with 20-32 degree roundel, multilane highway.

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

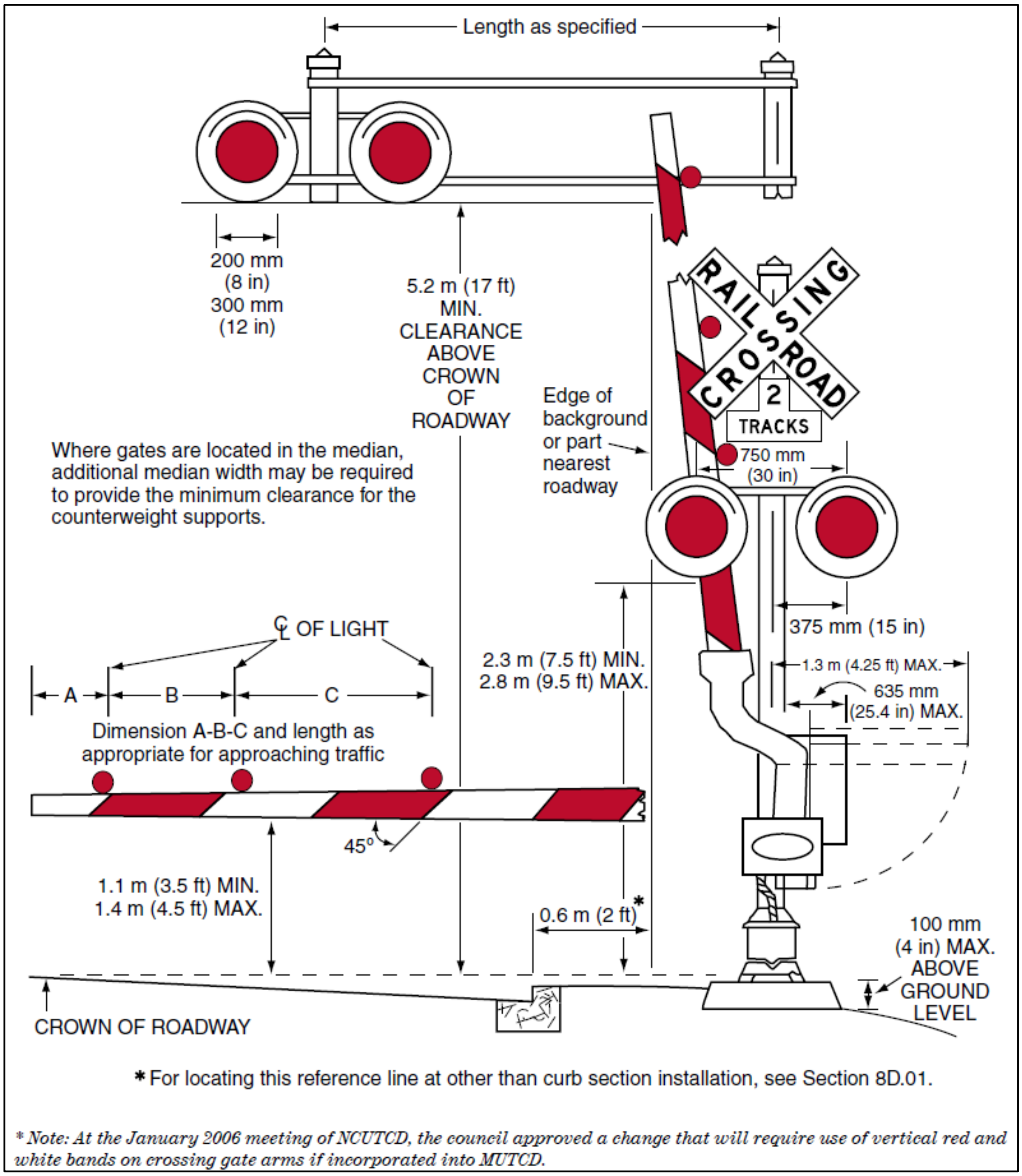


**Figure 43** Typical clearances for flashing light signals with automatic gates.
*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

Flashing light signals are often installed with automatic gates in order to achieve a higher level of safety at a given highway-rail grade crossing. Some basic dimensions for a system with flashing light signals and automatic gates are provided in Figure 43. Note that Figure 43 was prepared using the data reported by U.S. DOT (2007) [page 101 of the report]. Two sets of flashing light signals are presented in Figure 43, including a typical post-mounted flashing light signal and a cantilevered flashing light signal. A cantilevered flashing light signal improves the visibility as compared to the post-mounted flashing light signals (i.e., the ones which are generally installed on a vertical post). The Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007) recommends installing cantilevered flashing light signals if one of the following conditions is met:

- Multilane highways, where there are more than two lanes in one direction.
- If a post-mounted flashing light signal should be installed 10 feet farther than the edge of the travel lane (due to paved shoulders or parking lane).
- There is foliage alongside the highway obstructing the view of the post-mounted flashing light signal.
- Presence of roadside obstacles (e.g., utility poles).
- There is a distracting background reducing visibility of the post-mounted flashing light signal.
- Where the extension of the flashing light signals over the travel lanes provides the highway users with sufficient visibility for the required stopping sight distance at the horizontal or vertical curves.

***Automatic Gates***

When a train is approaching or occupying a highway-rail grade crossing, an automatic gate is utilized as a barrier to prevent highway users from passing through the crossing. As it is illustrated in Figure 44, alternating 16-inch diagonal red lights and white stripe are used to cover the gate arm. Generally, three red lights are placed on the gate arm in order to enhance visibility during darkness. The light nearest to the tip of the gate arm burns steadily, while the other two lights flash alternately. The automatic gate is typically combined with a standard flashing light signal to provide additional warning before the gate arm starts descending (U.S. DOT, 2007).

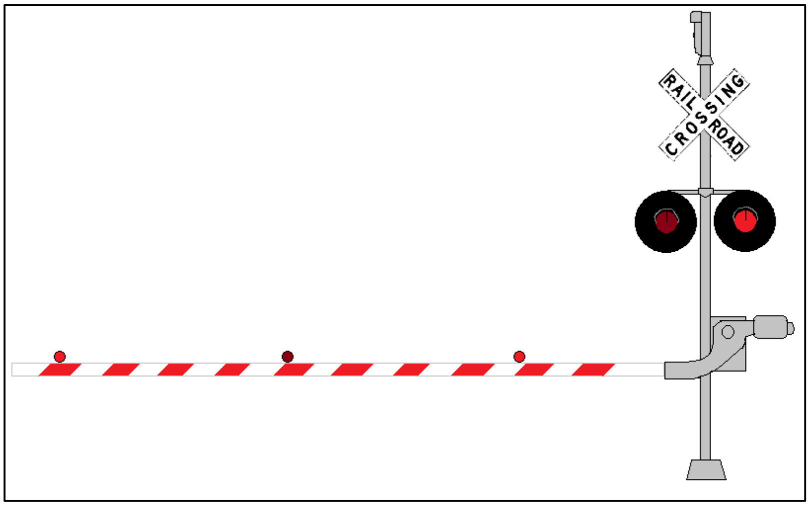


**Figure 44** A typical automatic gate.
*Source: DeviantArt (2018). Railroad Crossing Gate*

When a train is approaching a highway-rail grade crossing, the flashing light signal starts operating, while the gate should start its downward motion not less than three seconds afterwards (i.e., at least three seconds after the flashing light signal starts operating). The gate arm should reach its horizontal position before the train arrival at the highway-rail grade crossing and remain horizontal, while the train is occupying the crossing. Once the train leaves the highway-rail grade crossing and there are no other trains approaching, the gate arm starts ascending to its upright position. Generally, both flashing light signal and automatic gate stop operating not more than 12 seconds after the train passes the highway-rail grade crossing (U.S. DOT, 2007). The Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007) recommends installing automatic gates if one of the following conditions is met:

- Multiple mainline railroad tracks.
- Multiple tracks where a train on or near a highway-rail grade crossing can obscure the movement of another train, which is approaching the crossing.
- A combination of high-speed train operation and limited sight distance.
- A combination of high-speed train operation, moderately high-volume highway, and moderately high-volume railroad traffic.
- Presence of school buses, farm vehicles, and/or transit buses in the traffic flow, passing a highway-rail grade crossing.
- Presence of trucks with hazardous materials, especially if the view down the track from a stopped vehicle is obstructed (e.g., curve in track).
- Continuing accident occurrence after installation of flashing light signals.
- Presence of passenger trains.

The placement of flashing light signal and automatic gate assemblies should meet certain requirements. The lateral location of flashing light and automatic gate assemblies should provide an adequate clearance from the track and also have a sufficient space for construction of the foundations (U.S. DOT, 2007). Basic location requirements for the foundations of flashing lights and cantilevered flashing lights with automatic gates are presented in Figure 45. Note that Figure 45 was prepared using the data reported by U.S. DOT (2007) [page 105 of the report].

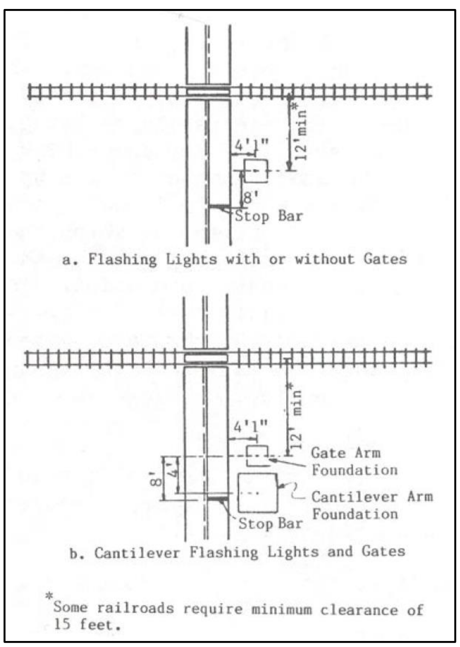


**Figure 45** Basic location requirements for flashing lights and cantilevered flashing lights with automatic gates.

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

***Pavement Markings***

Along with supplementary traffic control devices, pavement markings play an important role to ensure safety at highway-rail grade crossings. However, pavement markings may not be visible in case of inclement weather conditions (e.g., snow, rain) and many not be very durable for the highways that are subject to heavy traffic loads. Figure 46 illustrates some of the typical pavement markings including: an "X", the letters "RR", a "NO PASSING" marking for two-lane roads and certain transverse lines. Note that Figure 46 was prepared using the data reported by U.S. DOT (2007) [page 96 of the report]. The latter pavement markings are commonly placed on each approach lane of all the paved approaches to the highway-rail grade crossings, which are equipped with signals and/or automatic gates, and the highway-rail grade crossings, where the prevailing speed of highway traffic is at least 40 mph. Furthermore, the aforementioned pavement marking types are used at the highway-rail grade crossings, where there is a potential conflict between trains and vehicles based on the conducted engineering studies (U.S. DOT, 2007). On the other hand, the pavement markings are not required for minor highway-rail grade crossings in urban areas, where the other traffic control devices provide an adequate control based on the conducted engineering studies.

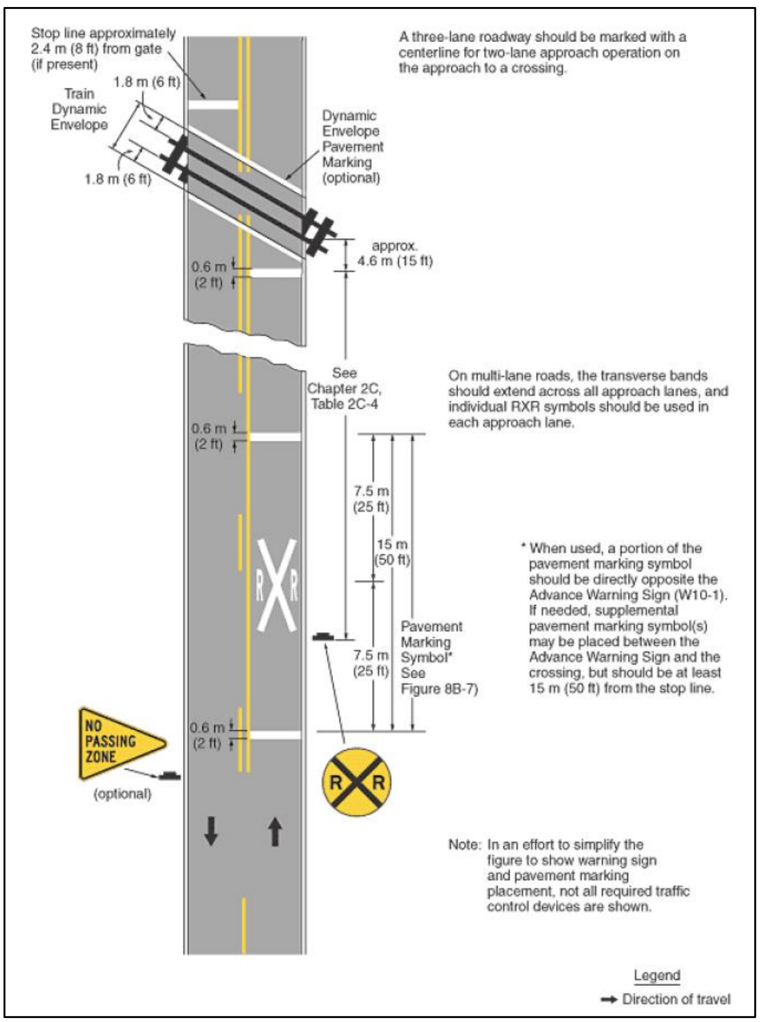


**Figure 46** Regular pavement markings, the codes, and placements.

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

All the pavement markings generally have white color, except the “NO PASSING” markings, which are colored in yellow. The stop line should be 2 ft wide and extend across the approach lanes. The stop line must be placed perpendicular to the highway centerline at a given highway-rail grade crossing and approximately 15 ft before the nearest rail. At the highway-rail grade crossings with automatic gates, the stop line must be placed approximately 8 ft before the line, where the gate arm crosses the highway surface. Figure 47 presents alternate pavement markings, where the paint is placed out of the wheel path. Note that Figure 47 was prepared using the data reported by U.S. DOT (2007) [page 97 of the report]. Along with “NO PASSING” pavement markings, a supplementary “No Passing Zone” sign (W14-3) can be installed at a given highway-rail grade crossing. The latter sign is typically placed at the beginning of the no passing zone on the left side of the highway (U.S. DOT, 2007).

***Countermeasures Considered for Evaluation of the Solution Algorithms***

A set of countermeasures, discussed in the GradeDec.NET Reference Manual (U.S. DOT, 2014), will be used under this project throughout evaluation of the solution algorithms for the **RAP-1** and **RAP-2** mathematical models. Basic information for the considered countermeasures is presented in Table 58, including the effectiveness factors ($EF_{xc}, x \in X, c \in C$) and the installation costs ($CA_{xc}, x \in X, c \in C$). Moreover, Table 59 provides feasible countermeasure types for different protection classes of highway-rail grade crossings. Note that the protection classes were adopted based on the FRA crossing inventory database (field “WdCode” – warning device code) – FRA (2016).

**Table 58** Basic information for the considered countermeasures.

| a/a | Countermeasure | Effectiveness | Installation Cost |
|---|---|---|---|
| 1 | passive to flashing lights | 0.57 | $74,800 |
| 2 | passive to flashing lights and gates | 0.78 | $180,900 |
| 3 | flashing lights to gates | 0.63 | $106,100 |
| 4 | 4 quadrant (no detection) - for gated crossings | 0.82 | $244,000 |
| 5 | 4 quadrant (with detection) - for gated crossings | 0.77 | $260,000 |
| 6 | 4 quadrant (with 60' medians) - for gated crossings | 0.92 | $255,000 |
| 7 | mountable curbs (with channelized devices) - for gated crossings | 0.75 | $15,000 |
| 8 | barrier curbs (with or without channelized devices) - for gated crossings | 0.80 | $15,000 |
| 9 | one-way street with gate - for gated crossings | 0.82 | $5,000 |
| 10 | photo enforcement - for gated crossings | 0.78 | $65,000 |
| 11 | grade separation | 1.00 | $1,500,000 |

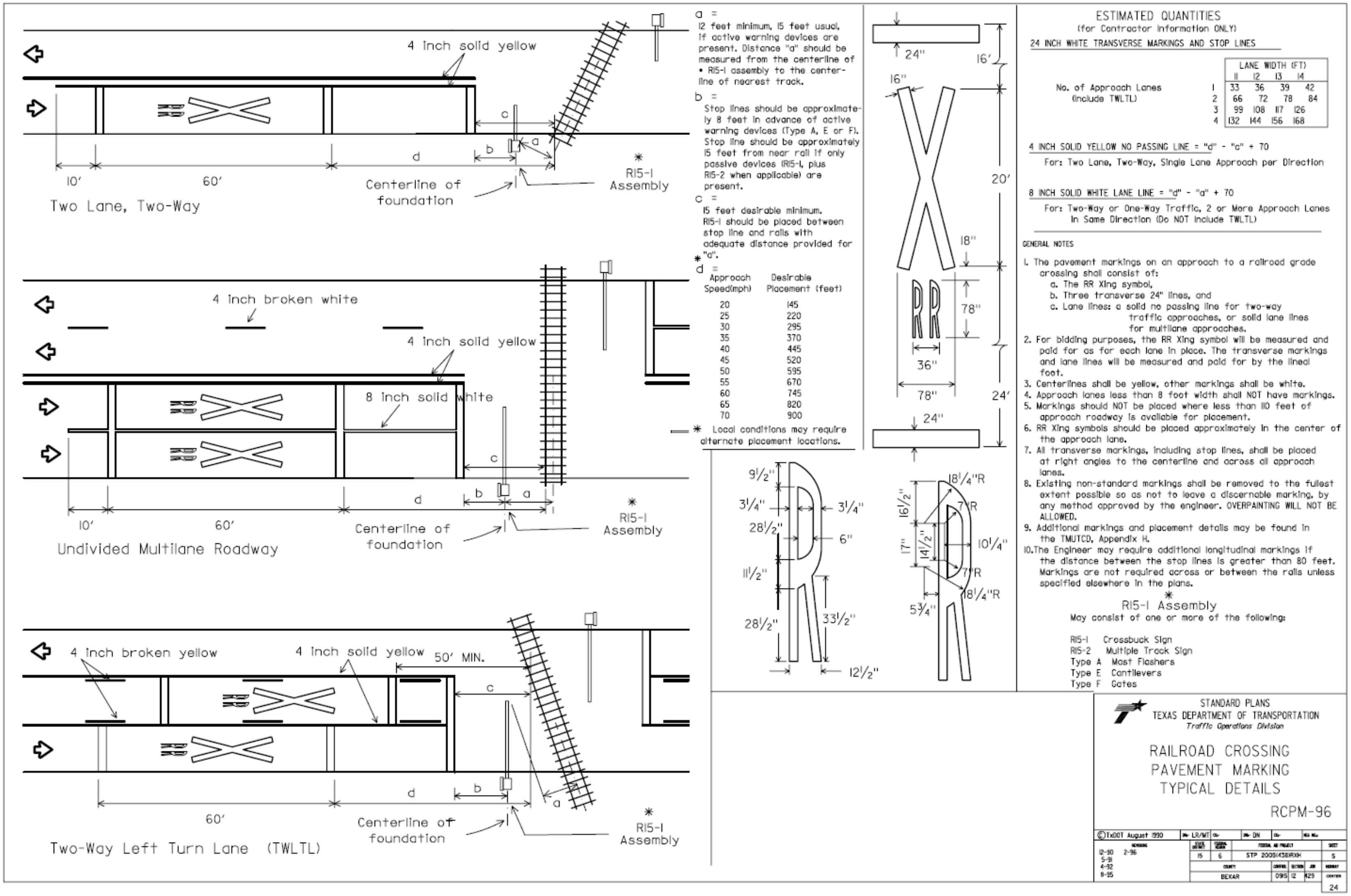


**Figure 47** Alternate pavement markings at highway-rail grade crossings.

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

**Table 59** Feasibility of countermeasure implementation by protection class.

| a/a | Protection Class | Feasible Countermeasures |
|---|---|---|
| 1 | No signs or signals (WdCode = 1) | 1, 2 |
| 2 | Other signs or signals (WdCode = 2) | 1, 2 |
| 3 | Crossbucks (WdCode = 3) | 1, 2 |
| 4 | Stop signs (WdCode = 4) | 1, 2 |
| 5 | Special active warning devices (WdCode = 5) | 1, 2 |
| 6 | Highway traffic signals, wigwags, bells, or other activated (WdCode = 6) | 1, 2 |
| 7 | Flashing lights (WdCode = 7) | 3 |
| 8 | All other gates (WdCode = 8) | 4, 5, 6, 7, 8, 9, 10, 11 |
| 9 | Four quad (full barrier) gates (WdCode = 9) | 5, 6, 7, 8, 9, 10, 11 |

Note that 11 countermeasures, described in the GradeDec.NET Reference Manual (see Table 58), have been commonly used for safety improvement projects at highway-rail grade crossings nationwide. Therefore, these countermeasures will be used to assess performance of the solution algorithms for the **RAP-1** and **RAP-2** mathematical models. However, without loss of generality, the **RAP-1** and **RAP-2** mathematical models still can be applied for resource allocation among highway-rail grade crossings with a different set of the available countermeasures.

### *7.4.3. Set of Severity Categories*

Accidents at highway-rail grade crossings can be classified into different groups based on their severity. The U.S. DOT Accident Severity Formulae, which are employed in the canonical U.S. DOT resource allocation procedure, predict the expected number of fatal and injury accidents at highway-rail grade crossings (U.S. DOT, 2007). On the other hand, the GradeDec.NET Reference Manual (U.S. DOT, 2014) provides a methodology for predicting the following types of accident severity: (1) fatal accidents – accidents with at least one fatality; (2) casualty accidents – accidents with at least one fatality or injury; (3) injury accidents – accidents with at least one injury, but no fatality; and (4) property damage only accidents. The accident severity prediction methodology, provided by the GradeDec.NET Reference Manual, will be further used under this project. The following formulae will be adopted for assessing the highway-rail grade crossing hazard by severity category:

$$KF = 440.9 \tag{7.14}$$
$$MS_x^{FH} = {ms_x}^{-0.9981}\ \forall x \in X \tag{7.15}$$
$$TT_x = (thru_x + 1)^{-0.0872}\ \forall x \in X \tag{7.16}$$
$$TS_x = (switch_x + 1)^{0.0872}\ \forall x \in X \tag{7.17}$$
$$UR_x^{FH} = e^{0.3571 \cdot urban_x}\ \forall x \in X \tag{7.18}$$
$$KC = 4.481 \tag{7.19}$$
$$MS_x^{CH} = {ms_x}^{-0.3430}\ \forall x \in X \tag{7.20}$$
$$TK_x = e^{0.1153 \cdot tracks_x}\ \forall x \in X \tag{7.21}$$
$$UR_x^{CH} = e^{0.2960 \cdot urban_x}\ \forall x \in X \tag{7.22}$$
$$FH_x = \frac{OH_x}{1 + KF \cdot MS_x^{FH} \cdot TT_x \cdot TS_x \cdot UR_x^{FH}}\ \forall x \in X \tag{7.23}$$

$$CH_x = \frac{OH_x}{1 + KC \cdot MS_x^{CH} \cdot TK_x \cdot UR_x^{CH}} \ \forall x \in X \tag{7.24}$$

$$IH_x = CH_x - FH_x \ \forall x \in X \tag{7.25}$$

$$PH_x = OH_x - FH_x - IH_x \ \forall x \in X \tag{7.26}$$

where:

$ms_x$ = maximum timetable train speed at highway-rail grade crossing $x$ (miles per hour); $ms_x = S_x \ \forall x \in X$. Assume $ms_x = 1, x \in X$ when there are no data available.
$thru_x$ = number of through trains per day at highway-rail grade crossing $x$ (trains per day); Assume $thru_x = 1, x \in X$ when there are no data available.
$switch_x$ = switch trains per day at highway-rail grade crossing $x$ (trains per day); Assume $switch_x = 1, x \in X$ when there are no data available.
$urban_x$ = if a highway-rail grade crossing is urban at highway-rail grade crossing $x$, $urban_x = 1$, else $urban_x = 0$; Assume $urban_x = 0, x \in X$ when there are no data available.
$tracks_x$ = number of railroad tracks at highway-rail grade crossing $x$ (tracks); Assume $tracks_x = 1, x \in X$ when there are no data available.
$OH_x$ = overall hazard at highway-rail grade crossing $x$ (no units);
$FH_x$ = fatality hazard at highway-rail grade crossing $x$ (no units);
$CH_x$ = casualty hazard at highway-rail grade crossing $x$ (no units);
$IH_x$ = injury hazard at highway-rail grade crossing $x$ (no units);
$PH_x$ = property damage hazard at highway-rail grade crossing $x$ (no units).

Note that the canonical severity prediction methodology, provided by the GradeDec.NET Reference Manual, was developed for assessing the accident severity at highway-rail grade crossings. The GradeDec severity prediction methodology was adopted to assess the hazard severity under this project due to lack of prediction methodologies for quantifying the hazard severity (the available highway-rail grade crossing safety literature does not report any methods for assessing the hazard severity and primarily focuses on assessing the accident severity only).

The **RAP-2** mathematical model also requires assigning the weight values that are associated with different severity categories. In order to determine the weight values for the considered hazard severity categories, this project will rely on the data, reported by Iowa DOT (2006). Specifically, Iowa DOT (2006) discussed the societal costs, associated with fatal accidents ($FA$), injury accidents ($IA$), and property damage only accidents ($PDO$). The average costs of each fatality, injury, and property damage accident were assumed to be \$1,000,000, \$320,000, and \$26,000, respectively (Iowa DOT, 2006). Based on the latter cost data, a weight of each severity category ($W_s, s \in S$), required by the **RAP-2** mathematical model, can be estimated as follows:

$$W_{FA} = \frac{\$1{,}000{,}000}{(\$1{,}000{,}000 + \$320{,}000 + \$26{,}000)} = 0.74 \tag{7.27}$$

$$W_{IA} = \frac{\$320{,}000}{(\$1{,}000{,}000 + \$320{,}000 + \$26{,}000)} = 0.24 \tag{7.28}$$

$$W_{PDO} = \frac{\$26{,}000}{(\$1{,}000{,}000 + \$320{,}000 + \$26{,}000)} = 0.02 \tag{7.29}$$

The base values for the weights of fatality hazard ($W_{FH}$), injury hazard ($W_{IH}$), and property damage hazard ($W_{PH}$) would be set to $W_{FH} = 0.60$, $W_{IH} = 0.30$, and $W_{PH} = 0.10$. The latter values are within the same ranges, which have been adopted by Iowa DOT (2006). However, the values of weights are the parameters of the **RAP-2** mathematical model and can be adjusted by the user for each hazard severity category as needed (in case if societal costs of the accidents may change in future).

## 7.5. Complexity Analysis

This section of the report investigates complexity of the developed mathematical models (i.e., **RAP-1** and **RAP-2**). The complexity class will be determined for the **RAP-1** and **RAP-2** mathematical models. Based on the results from the complexity analysis, the appropriate solution algorithms will be further proposed in order to obtain high-quality solutions for the developed mathematical models in a reasonable computational time.

### *7.5.1. Complexity Classes*

In order to assess the difficulty or complexity of a problem, the "resources" that are required to solve a given problem should be determined. The term "resources" corresponds to the computational time and memory. It should be noted that the adopted solution approach doesn't have any effect on complexity of a problem (Cook, 2006). In terms of the computational time complexity, optimization problems can be classified as follows (Van Leeuwen, 1990):

1) polynomial (P) – the computational time increases with the problem size as a polynomial function (the problem can be solved fairly quickly);
2) nondeterministic polynomial time (NP) – although the problem cannot be solved quickly but the answer can be verified in a polynomial time;
3) nondeterministic polynomial time complete (NP-complete) – the answer cannot be found in a polynomial time, but it can be verified in a polynomial time. NP-complete are considered as the hardest problems of the NP class;
4) nondeterministic polynomial-time hard (NP-hard) – the problem cannot be solved in a polynomial time, and only certain problems (belonging to the NP-complete category) can be verified in a polynomial time.

Figure 48 illustrates complexity of different problem classes (a.k.a., Euler diagram for the complexity classes). The right-hand side of Figure 48 assumes that P = NP. The latter assumption makes that all of the P, NP, NP-complete, and even a portion of the NP-hard problems have the same computational complexity. On the other hand, in the left-hand side of Figure 48 assumes that P ≠ NP, and it is more difficult to recognize what category the problem belongs to, as different problem categories share some common areas of the Euler diagram. However, in both cases (i.e., when P = NP and when P ≠ NP), NP-hard problems have the highest complexity as compared to the other problem classes, and there are no algorithms in the state-of-the-art literature that can obtain the global optimal solution for these problems in a reasonable computational time.

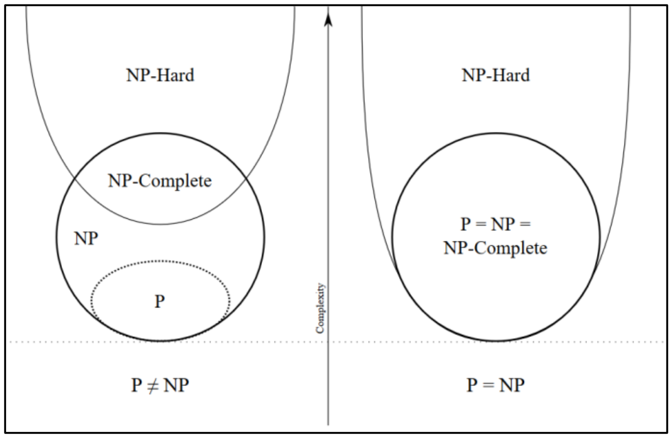


**Figure 48** Relationships between different problem classes and their corresponding complexity.
*Source: Wikipedia (2018a). NP-hardness*

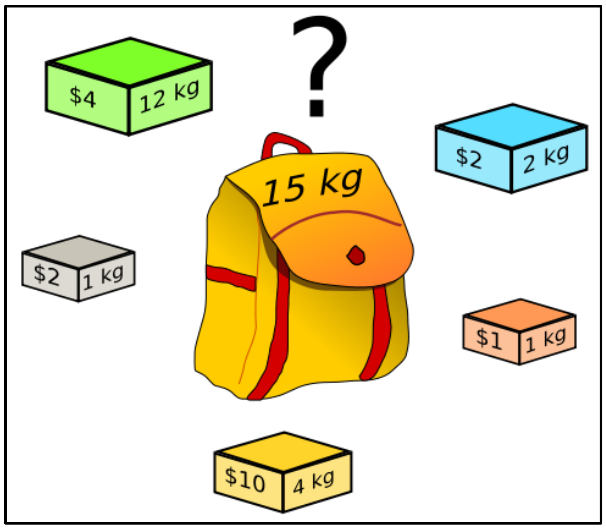


**Figure 49** A simple example of the knapsack problem.
*Source: Wikipedia (2018b). Knapsack Problem*

***7.5.2. Complexity of the Developed Mathematical Models***

The features of the mathematical models, proposed for resource allocation among the highway-rail grade crossings in the State of Florida under this project (see sections 7.2 and 7.3 of this report for more details), have been thoroughly investigated. Each one of the developed mathematical models was found to have a lot of similarities with the knapsack problem. The knapsack problem is a well-known combinatorial decision problem, which aims to accommodate a series of items with different values and weights into a knapsack (the knapsack is another name for a backpack). The common objective function of the knapsack problem is to maximize the total value of the items placed into the knapsack, considering the limited capacity of the knapsack. Figure 49 illustrates a simple example of the knapsack problem. There is a knapsack with a maximum capacity of 15 kg, and there are five items with different values (i.e., dollar amounts) and weights, where the ratio of value per weight is different for each item. Now, it should be decided which items should be placed into the knapsack, aiming to maximize the total value of the items and considering the maximum knapsack capacity as a constraint (i.e., the total weight of the items cannot exceed the knapsack capacity) (Mathews, 1896).

Similar to the knapsack problem, both **RAP-1** and **RAP-2** mathematical models aim to select Florida's highway-rail grade crossings for upgrading and determine the appropriate type of upgrading (considering the fact that the cost and/or the effectiveness of each countermeasure may vary), aiming to minimize the overall hazard at the highway-rail grade crossings (in case of the **RAP-1** mathematical model) or minimize the overall hazard severity at the highway-rail grade crossings (in case of the **RAP-2** mathematical model), taking into account the total available budget constraint.

### *7.5.3. Types of the Knapsack Problem*
There are different types of the knapsack problem, which vary depending on the major assumptions adopted and the problem features (e.g., number and type of items to be placed in the knapsack, single-objective problem vs. multi-objective problem, and number of knapsacks considered). The multi-objective knapsack problem, multi-dimensional knapsack problem, multiple knapsack problem, quadratic knapsack problem, and subset-sum problem are some of the well-known types of the knapsack problem (Khuri et al., 1994; Chang et al., 1995; Güntzer and Jungnickel, 2000; Fréville, 2004; Pisinger, 2007; Bazgan et al., 2009) and will be described in the following sections of the report.

#### *Multi-Objective Knapsack Problem*
In this type of *the knapsack problem*, several objectives are defined in the optimization model. For example, consider a liner shipping company, which aims to maximize the profit of its business and ensure that vessels will arrive at the assigned ports in a timely manner. However, the environmental issues should be considered at the same time (e.g., if vessels sail at a higher speed, they will burn more fuel and produce more emissions). Therefore, the total cost of emissions produced by oceangoing vessels throughout the transport of containers along the liner shipping route should be minimized. In this case, the solution that only provides the maximum profit or the solution that only minimizes the total emissions will not be appropriate. For *multi-objective optimization problems* (including *the multi-objective knapsack problem* as well), there should be a solution or a set of solutions that provides the best tradeoff between the conflicting objective functions (Chang et al., 1995; Chang et al., 2000).

#### *Multi-Dimensional Knapsack Problem*
In this type of *the knapsack problem*, the knapsack is divided into several sections and each section has a specific capacity. The objective is to maximize the total value of the items in the knapsack, while the summation of the item weights in each section should be limited to its corresponding capacity (Fréville, 2004). *The multi-dimensional knapsack problems* are computationally more complex than *the multi-objective knapsack problems*, even for a two-dimensional case. Specifically, a typical *multi-dimensional knapsack problem* doesn't have a polynomial-time approximation scheme (i.e., a type of the approximation algorithm for optimization models) unless P = NP (please see section 7.5.1 of this report for details regarding the notations of the problem complexity classes) (Kulik and Shachnai, 2010). Akbar et al. (2006) discussed *the multi-dimensional multiple-choice knapsack problem*, where there is a group of items and each item requires a certain number of resources. The objective of *the multi-*

*dimensional multiple-choice knapsack problem* is to pick exactly one item from each group, aiming to maximize the total value of the items and considering the resource constraints of the knapsack.

***Multiple Knapsack Problem***
*The multiple knapsack problem* is defined as *a simple knapsack problem* with more than one knapsack. Although it may seem a simple difference as compared to *the typical knapsack problem*, Chekuri and Khanna (2005) showed that *the multiple knapsack problem* has a polynomial-time approximation scheme. Also, *the multiple knapsack problem* is often compared with *the bin packing problem* in computer science. However, there is a significant difference between *the multiple knapsack problem* and *the bin packing problem*. Specifically, in case of *the bin packing problem*, all the items have to be packed in a certain bin. However, in case of *the multiple knapsack problem*, only a subset of the items has to be packed in a certain knapsack.

***Quadratic Knapsack Problem***
*The quadratic knapsack problem* is an extension of a typical *knapsack problem*, which was introduced by Witzgall (1975). Instead of a linear objective function, *the quadratic knapsack problem* aims to maximize the quadratic objective function, which expresses the total value of the items placed into the knapsack. *The quadratic knapsack problem* generally has binary and/or linear capacity constraints. Originally, Witzgall (1975) formulated *the quadratic knapsack problem* in order to select the optimal locations of satellite stations, aiming to maximize the total volume carried within the electronic message systems (the messages were assumed to be submitted electronically via satellite). Nowadays, mathematical formulations for *the quadratic knapsack problem* have been widely used in different fields, including telecommunication, transportation network, computer science, and economics.

***Subset-Sum Problem***
*The subset-sum problem* is a special type of *the knapsack problem*, where the weight and the value of items are equal. In other words, the ratio of value per weight for all the items, placed to a given knapsack, is equal to one (Karp, 1972). A basic example of *a subset-sum problem* can be formulated as follows. Assume that a set of integers $A = \{5,4,2,1,-8,3\}$ has been given. Are there any subsets of integers within set $A$, where a summation of integers in a given subset would be equal to zero? It can be noticed that subsets $s_1 = \{5,2,1,-8\}$, $s_2 = \{5,-8,3\}$, and $s_3 = \{4,1,-8,3\}$ meet the objective (i.e., a summation of integers within each one the aforementioned subsets is equal to zero).

***7.5.4. Review of the Solution Algorithms for the Knapsack Problem***
Generally, many resource allocation problems, where the available funds have to be distributed among certain areas and the total budget is limited, can be reduced to a typical knapsack problem. In terms of complexity, the decision problems, which can be reduced to the knapsack problem, are NP-complete. Therefore, there is no algorithm that will be able to solve such problems in a polynomial time (Mathews, 1896). However, some algorithms have been introduced in the computer science literature, which would be able to present a reasonable tradeoff between the quality of solutions and the required computational time for the knapsack problem (Andonov et al., 2000). These solution approaches can be generally classified as: (1) exact optimization methods; (2) commercial software; and (3) approximation methods.

The exact optimization methods for the knapsack problem received a great interest from the research community during 60s, 70s, and 80s. Gilmore and Gomory (1966) proposed a set of dynamic programming algorithms for the knapsack problem. Theoretical aspects of different knapsack functions were investigated and were further used as a foundation for the proposed dynamic programming algorithms. The study concluded that certain decision problems, which could be reduced to the knapsack problem, might have special features and should be investigated more in detail. Then, Green (1967) proposed some extensions of the method, presented by Gilmore and Gomory (1966), whereas Weingartner and Ness (1967) developed a number of new algorithms within the dynamic programming framework. Marsten and Morin (1976) combined dynamic programming with a Branch-and-Bound approach in order to solve the multi-dimensional knapsack problem. A set of low-time consuming heuristics and linear programming (LP) bounds were introduced to improve the computational performance of the developed solution method. Isaka (1983) and Ibaraki (1987) improved performance of a dynamic programming approach for the knapsack problem by removing irrelevant states. These studies led to a modified basic dynamic programming approach and brought out new ideas for developing alternative solution algorithms.

Although a lot of studies, proposing the exact optimization methods for solving the knapsack problem, have been published to date, there was a need for development of new solution methodologies. Specifically, alternative solution methodologies were needed in order to obtain solutions for the large-size instances of the knapsack problem in a reasonable computational time. Cabot (1970) proposed an enumeration technique, which was based on the Fourier-Motzkin elimination method. The numerical experiments demonstrated that the proposed approach was superior for the one-dimensional knapsack problem as compared to the multi-dimensional knapsack problem. Thesen (1975) developed a Recursive Branch-and-Bound Algorithm for the multi-dimensional knapsack problem. It was found that the presented algorithm was able to obtain the optimal solutions quite quickly even for the large-size problem instances. However, a substantial amount of computational time was required to verify the solutions. The first linear programming-based Branch-and-Bound method for the multi-dimensional knapsack problem was developed by Shih (1979). The computational experiments showcased that the developed algorithm outperformed the improved Balas algorithm and the original Balas algorithm in terms of the computational time for the considered problem instances.

Lorie and Savage (1955) presented a Lagrangean-based heuristic for 0-1 integer programming, where all the constraint sets were relaxed and transferred into the objective function. The study served as a foundation to the new solution methods for the knapsack problem, which were based on the Lagrangean multipliers. Nemhauser and Ullman (1969) demonstrated that the problem of finding the optimal set of the Lagrangean multipliers could be reduced to the dual problem of the LP relaxation. Barcia and Holm (1988) designed a Bound Improving Sequence Algorithm for the knapsack problem, which relied on the Lagrangean relaxation. A decreasing sequence of upper bounds on the optimal value of the objective function was achieved by adding cuts. However, the presented approach had a major drawback, which consisted in the fact that several hard subset-sum problems had to be solved exactly in order to ensure convergence.

Although the presented exact methodologies for solving the knapsack problem could return the global optimal solution, some commercial software packages were developed as well. The commercial software packages have more user-friendly interfaces for researchers and practitioners, who are not professional programmers. For example, CPLEX, originally developed by Robert E. Bixby and then sold to the CPLEX Optimization Inc. in 1988, is considered as one of the well-known commercial software for solving large-scale mixed-integer programming models. In 2009, CPLEX was acquired by IBM, which now maintains the IBM ILOG CPLEX Optimization Studio (IBM, 2019). Xpress is another commercial software package, which can solve different problems, including linear programming (LP), mixed-integer linear programming (MILP), convex quadratic programming (QP), convex quadratically constrained quadratic programming (QCQP), second-order cone programming (SOCP), as well as mixed-integer counterparts of the QP, QCQP, and SOCP problems. Originally, Xpress was developed by Dash Optimization but then was acquired by FICO (FICO, 2019). Nemhauser et al. (1994) introduced a new software package, called MINTO (stands for Mixed-Integer Optimizer), which solves mixed-integer linear programs using the Branch-and-Bound Algorithm along with application of linear programming relaxations. The software package has a number of features, including primal heuristics, constraint classification, preprocessing, and constraint generation. Furthermore, the software user is able to specify a variety of application routines in order to customize MINTO for achieving the maximum efficiency for a given problem of interest.

If the problem size (e.g., the number of variables, the number of constraint sets) increases, the exact optimization methods and commercial software may not be able to solve the knapsack problem in a reasonable computational time. Thus, the approximation methods were developed, which can be classified as heuristic algorithms and metaheuristic algorithms. Unlike the exact optimization methods, heuristic algorithms and metaheuristic algorithms do not guarantee the global optimality of the produced solutions; however, they are able to produce good-quality solutions in a reasonable computational time. Heuristic algorithms are problem-dependent (i.e., can be typically applied to a specific class of optimization problems). Many heuristic algorithms are greedy throughout the search process (i.e., select only superior solutions), which increases the probability of converging in a local optimum as compared to metaheuristic algorithms. On the other hand, metaheuristic algorithms are not problem-dependent (i.e., can be applied to different classes of optimization problems) and they are generally able to explore the search space in a more effective way as compared to heuristic algorithms (Eiben and Smith, 2015).

A large number of heuristic algorithms were proposed for solving the knapsack problems, and some of the well-known heuristic algorithms are further described in this section of the report. Senju and Toyoda (1968) proposed a dual heuristic for the optimization problems with 0-1 variables. The proposed heuristic started the search process with the all-ones solution and setting the variables to zero one at a time based on the increasing ratios until the feasibility requirements were met. The developed solution approach was found to be efficient for the cases with a large number of candidate solutions and restricting conditions. A primal Greedy Algorithm was proposed by Toyoda (1975). A Greedy Algorithm is a recursive process that takes a locally optimal solution at each stage, aiming to find the global optimum at termination. The results showed that the proposed Greedy Algorithm outperformed CPLEX, which relied on a depth-first search branch-and-bound mode. Hanafi et al. (1996) developed a two-stage multi-start algorithm, which embedded different heuristic principles in a flexible fashion. A set of randomly generated feasible solutions were initiated, and a group of local search strategies improved the solutions step by step. Threshold accepting and noising methods were introduced in the proposed algorithms in order to enhance its performance. Chekuri and Khanna (2005) proposed a polynomial time approximation scheme (PTAS) for the multiple knapsack problem. The study highlighted that the multiple knapsack problem can be considered as a special case of the generalized assignment problem, where the item size and the profit may vary depending on the assigned bin. It was also shown that slight generalizations of the multiple knapsack problem were APX-hard (APX is an abbreviation for "approximable").

A number of metaheuristic algorithms have been also developed to solve different types of the knapsack problem. Drexl (1988) applied a Simulated Annealing (SA) metaheuristic for the multi-dimensional knapsack problem. The SA metaheuristic is inspired from the annealing phenomenon, which is widely used in metallurgy. In order to maintain feasibility of the solutions, generated throughout the search process, a special 2-exchange random move was introduced within the developed solutions algorithm. Dueck and Wirsching (1989) and Dueck and Scheuer (1990) proposed a deterministic version of the SA metaheuristic algorithm, which was called Threshold Accepting. The Threshold Accepting algorithm was found to be more promising as compared to the SA algorithm, which was developed by Drexl (1988). Dammeyer and Voss (1991) conducted a pioneering research on Tabu Search (TS) for the multi-dimensional knapsack problem. The study compared the static and dynamic strategies, which were used to manage the Tabu List. The numerical experiments demonstrated superiority of the dynamic strategy. Moreover, a dynamic version of the TS algorithm was found to be more promising as compared to the SA algorithm.

Glover and Kochenberger (1996) relied on the tunneling effect (which was based on the property that all the near-optimal solutions belong to the boundary of the feasible space) and the strategic oscillation scheme (which alternated between constructive and destructive phases and facilitated the search by varying the search depth on each side of the feasible boundary) in order to solve the multi-dimensional knapsack problem. The developed methodology was found to be promising, as high-quality computational results were obtained for the large-size problem instances with up to 25 constraint sets and 500 variables. Evolutionary Algorithms (EAs) have been also used to solve the knapsack problems. For example, Khuri et al. (1994) developed an EA with the standard algorithmic operators. However, the fitness function of the proposed EA algorithm penalized the infeasible individuals (i.e., the infeasible solutions to the problem). Battiti and Tecchiolli (1992) and Ohlsson et al. (1993) were the first studies that applied Neural Networks (NNs) to solve the knapsack problems. The computational experiments indicated that NNs were not efficient for the knapsack problems, as they tended to produce the final solutions that violated some of the constraint sets. For a more detailed review of different solution algorithms, which have been used to solve the knapsack problems, this report refers to Fréville (2004).

# 8. SOLUTION METHODOLOGY

This section of the report presents a set of algorithms, which were proposed to solve the **RAP-1** and **RAP-2** mathematical models. The proposed solution algorithms can be classified into two groups, including the following: (1) exact optimization algorithms; and (2) heuristic algorithms. The advantage of using exact optimization algorithms consists in the fact that they will return the global optimal solution for each one of the formulated mathematical models. Specifically, exact optimization algorithms will suggest a set of highway-rail grade crossings, which have to be upgraded, and the type of upgrading for each one of the selected crossings that will yield the best possible objective function value (i.e., the least possible overall hazard at the highway-rail grade crossings in case of the **RAP-1** mathematical model and the least possible hazard severity at the highway-rail grade crossings in case of the **RAP-2** mathematical model). However, exact optimization algorithms may require a significant computational time in order to obtain the global optimal solution for a given mathematical model. Since both **RAP-1** and **RAP-2** mathematical models can be reduced to the knapsack problem (which has a high computational complexity, as discussed in section 7.5 of this report), several heuristic algorithms were developed in order to obtain good-quality solutions within a reasonable computational time. The exact optimization algorithms, which will be used as a part of this project, are presented in section 8.1, while the heuristic algorithms are described in section 8.2.

## 8.1. Exact Optimization Algorithm

Two exact optimization algorithms will be used to solve the **RAP-1** and **RAP-2** mathematical models to the global optimality, including MATLAB's function "intlinprog" and CPLEX that are both discussed in detail next.

### *8.1.1. MATLAB's Function "intlinprog"*

The MATLAB's optimization toolbox has function "intlinprog", which is widely used for mixed-integer linear programming (MathWorks, 2019a). The "intlinprog" function is based on a well-known Branch-and-Bound (B&B) algorithm. The B&B algorithm was proposed by Land and Doig (1960) and involves a systematic enumeration of candidate solutions throughout the state space search. A set of candidate solutions form a rooted tree, and the B&B algorithm explores and evaluates branches of this tree. The algorithm checks a given branch against the estimated lower and upper bounds on the optimal solution before enumerating candidate solutions within that branch. After checking the bounds, the B&B algorithm discards a given branch if it cannot produce superior solutions as compared to the one, which has been identified so far throughout the search process. The algorithm terminates once a certain stopping criterion is achieved (e.g., computational time, optimality gap).

The "intlinprog" function of the MATLAB's optimization toolbox includes the following arguments (MathWorks, 2019a):

$$x = intlinprog(f, intcon, A_{ineq}, b_{ineq}, A_{eq}, b_{eq}, lb, ub, options) \quad (8.1)$$

where:

$x$ = solution vector;

$f$ = coefficient vector;

$intcon$ = vector of integer constraints, which indicates the components of decision variable $x$ that can take only integer values;
$A_{ineq}$ = matrix of linear inequality constraints;
$b_{ineq}$ = vector of linear inequality constraints;
$A_{eq}$ = matrix of linear equality constraints;
$b_{eq}$ = vector of linear equality constraints;
$lb$ = vector of lower bounds;
$ub$ = vector of upper bounds;
$options$ = options for the "intlinprog" function (options allow changing the branching rule, constraint tolerance, heuristics for searching feasible points, maximum computational time, and other features – for more details please refer to MathWorks [2019a]).

In order to apply the "intlinprog" function, the considered mathematical model should be presented in the following standard form (**SF**):

**SF:**

$min_x f^T x$ (8.2)

**Subject to:**

$x(intcon)$ are integers (8.3)

$A_{ineq} \cdot x \leq b_{ineq}$ (8.4)

$A_{eq} \cdot x = b_{eq}$ (8.5)

$lb \leq x \leq ub$ (8.6)

The objective function (8.2) aims to minimize a certain performance measure (calculated using the coefficient vector and the solution vector). Constraint set (8.3) imposes restrictions on values of certain decision variable components (i.e., some of the components have to be integers). Constraint set (8.4) represents the inequality constraints of the considered mathematical model. Constraint set (8.5) represents the equality constraints of the considered mathematical model. Constraint set (8.6) imposes lower and upper bounds on values of the decision variable.

In order to demonstrate application of the "intlinprog" function, consider a small-size problem instance with 10 highway-rail grade crossings and 3 countermeasures for the **RAP-1** mathematical model (similar steps would be applicable for the **RAP-2** mathematical model). The values of parameters for the **RAP-1** mathematical model will be generated randomly. The overall hazard of a given highway-rail grade crossing is determined by parameter $OH(x)$. Parameter $OH(x)$ should be assigned using a 10-by-1 vector as follows:

*OH(x) = [6.98*
*3.89*
*4.21*
*6.56*
*6.60*
*4.36*
*3.89*
*2.18*

*0.41*
*4.07];*

The eligibility of implementing a countermeasure at a given highway-rail grade crossing is determined by parameter $p(x,c)$, which is equal to 1 if countermeasure $c$ is eligible to be implemented at highway-rail grade crossing $x$; otherwise, it is equal to zero. Parameter $p(x,c)$ should be assigned using a 10-by-3 matrix as follows:

*p(x,c) = [0, 0, 0*
*1, 1, 0*
*0, 1, 1*
*0, 0, 1*
*0, 1, 0*
*1, 0, 0*
*0, 0, 0*
*0, 1, 1*
*1, 1, 0*
*0, 0, 0];*

The effectiveness of a countermeasure at a given highway-rail grade crossing is determined by parameter $EF(x,c)$. Parameter $EF(x,c)$ should be assigned using a 10-by-3 matrix as follows:

*EF(x,c) = [0.68, 0.99, 0.51*
*0.51, 0.82, 0.68*
*0.95, 0.52, 0.65*
*0.98, 0.58, 0.75*
*0.62, 0.97, 0.90*
*0.50, 0.73, 0.58*
*0.96, 0.91, 0.96*
*0.81, 0.59, 0.60*
*0.93, 0.78, 0.94*
*0.61, 0.67, 0.76];*

The cost of implementing a countermeasure at a given highway-rail grade crossing is determined by parameter $CA(x,c)$. Parameter $CA(x,c)$ should be assigned using a 10-by-3 matrix as follows:

*CA(x,c) = [$462,400, $980,100, $260,100*
*$260,100, $672,400, $462,400*
*$902,500, $270,400, $422,500*
*$960,400, $336,400, $562,500*
*$384,400, $940,900, $810,000*
*$250,000, $532,900, $336,400*
*$921,600, $828,100, $921,600*
*$656,100, $348,100, $360,000*
*$864,900, $608,400, $883,600*

*$372,100, $448,900, $577,600];*

The total available budget is determined by parameter $TAB$. Parameter $TAB$ should be assigned using a scalar as follows: $TAB = \$234{,}417{,}631.73$.

In order to prepare the coefficient vector ($f$), the objective function (7.1) of the **RAP-1** mathematical model should be reformulated as follows:

$$\begin{aligned} min\sum_{x\in X}[1-\sum_{c\in C}(EF_{xc}\cdot \boldsymbol{z}_{xc})]\cdot OH_x &= min[\sum_{x\in X}OH_x-\sum_{x\in X}\sum_{c\in C}(EF_{xc}\cdot \boldsymbol{z}_{xc})\cdot OH_x] \\ &= min[-\sum_{x\in X}\sum_{c\in C}(EF_{xc}\cdot \boldsymbol{z}_{xc})\cdot OH_x] \end{aligned} \quad (8.7)$$

Note that component $\sum_{x\in X} OH_x$ of the objective function was omitted, since it represents a constant for the **RAP-1** mathematical model (i.e., the overall hazard at all the considered highway-rail grade crossings). Based on equation (8.7), the coefficient vector $f$ will have the following values:

*f = [-4.746, -6.910, -3.560, -1.984, -3.190, -2.645, -4.000, -2.189, -2.737, -6.429, …*
*-3.805, -4.920, -4.092, -6.402, -5.940, -2.180, -3.183, -2.529, -3.734, -3.540, …*
*-3.734, -1.766, -1.286, -1.308, -0.381, -0.320, -0.385, -2.483, -2.727, -3.093];*

Since all the components of decision variable $x$ have to be integers, vector of integer constraints $intcon$ will have the following values:

*intcon = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15,*
*16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30];*

The **RAP-1** mathematical model has three linear inequality constraints – constraint set (7.2), constraint set (7.3), and constraint set (7.4). Based on constraint sets (7.2) and (7.4), matrix of linear inequality constraints $A_{ineq}$ can be represented using a 11-by-30 matrix as follows:

*Aineq = [1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0*
*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1*
*462400, 980100, 260100, 260100, 672400, 462400, 902500, 270400, 422500, 960400, …*
*336400, 562500, 384400, 940900, 810000, 250000, 532900, 336400, 921600, 828100, …*
*921600, 656100, 348100, 360000, 864900, 608400, 883600, 372100, 448900, 577600];*

Vector of linear inequality constraints $b_{ineq}$ can be represented using a 11-by-1 vector as follows:

*Bineq = [1*
*1*
*1*
*1*
*1*
*1*
*1*
*1*
*1*
*1*
*234417631.73];*

The next arguments in the "intlinprog" function are matrix of linear equality constraints ($A_{eq}$) and vector of linear equality constraints ($b_{eq}$). Since the **RAP-1** mathematical model does not have any equality constraint sets, matrix of linear equality constraints $A_{eq}$ and vector of linear equality constraints $b_{eq}$ will be set as follows:

*Aeq = []; beq =[];*

As for the lower bounds on the components of decision variable $x$, all the components of decision variable $x$ can be set by the **RAP-1** mathematical model equal to zero (e.g., the available budget is not sufficient to implement any countermeasures at the considered highway-rail grade crossings; the considered highway-rail grade crossings are not eligible for any of the available countermeasures). Based on the latter feature of the **RAP-1** mathematical model, the vector of lower bounds $lb$ will have the following values:

*lb = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0];*

On the other hand, the upper bounds on the components of decision variable $x$ are defined by the eligibility of implementing a countermeasure at a given highway-rail grade crossing (i.e., values of parameter $p(x,c)$). If highway-rail grade crossing $x$ is not eligible for countermeasure $c$, the upper bound will be set as $ub(x,c) = p(x,c) = 0$. However, if highway-rail grade crossing $x$ is eligible for countermeasure $c$, the upper bound will be set as $ub(x,c) = p(x,c) = 1$. For the considered small-size problem instance, the vector of upper bounds $ub$ will have the following values:

*ub = [0, 0, 0, 1, 1, 0, 0, 1, 1, 0, 0, 1, 0, 1, 0, 1, 0, 0, 0, 0, 0, 0, 1,1, 1, 1, 0, 0, 0, 0];*

The last argument in the "intlinprog" function is $options$. Assume all the settings to be default, except the relative optimality gap. The relative optimality gap will be set to 1.00%. By default, the relative optimality gap is set to 0.01%, which may incur an additional computational time (i.e., the algorithm will perform more iterations in order to achieve the target optimality gap).

The relative optimality gap for the “intlinprog” function can be specified within the MATLAB’s environment as follows:

*options = optimoptions('intlinprog','RelativeGapTolerance',0.01);*

After setting the values for all the arguments of the “intlinprog” function, it can be executed in order to solve the **RAP-1** mathematical model to the global optimality. The following command should be entered in the MATLAB’s command window to call the “intlinprog” function:

*intlinprog(f,intcon,Aineq,Bineq,[],[],lb,ub,options)*

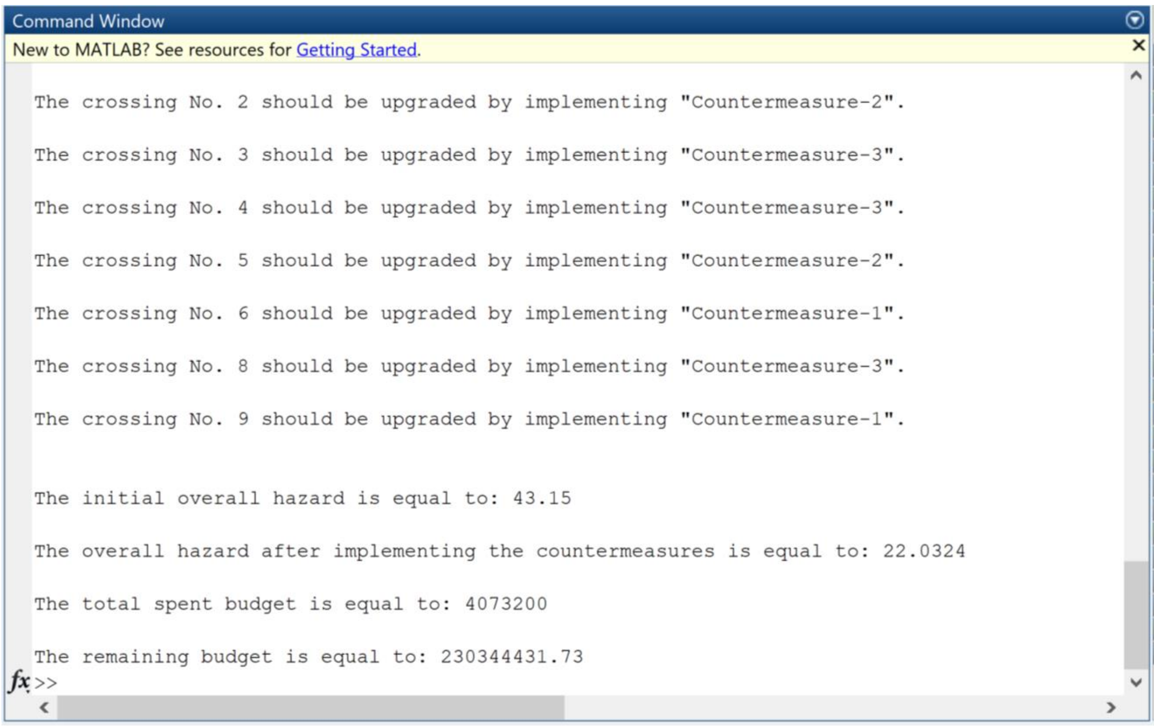

**Figure 50** The results obtained by the “intlinprog” function.

The results, obtained by the “intlinprog” function for the considered small-size problem instance of the **RAP-1** mathematical model, are presented in Figure 50. It can be observed that a total of seven highway-rail grade crossings were selected for upgrading. Highway-rail grade crossings “1”, “7”, and “10” have not been upgraded, since they are not eligible for any of the available countermeasures (i.e., $p_{xc} = 0 \; \forall x = 1,7,10; c \in C$). Implementation of countermeasures allowed reducing the overall hazard from 43.1500 to 22.0324 at the considered highway-rail grade crossings and incurred a total of $4,073,200.00. The remaining budget comprises $234,417,631.73 - $4,073,200.00 = $230,344,431.73. Therefore, the “intlinprog” function was found to be efficient with identification of the optimal upgrading type at eligible highway-rail grade crossings for the considered small-size problem instance.

### *8.1.2. CPLEX*

As it was mentioned in section 7.5.4 of this report, CPLEX, which was originally developed by Robert E. Bixby and further acquired by the CPLEX Optimization Inc. in 1988, is considered as one of the well-known commercial solvers for large-scale mixed-integer programming models. In 2009, IBM acquired CPLEX and currently maintains the IBM ILOG CPLEX Optimization Studio (IBM, 2019). CPLEX is able to solve the following categories of optimization models: (1) linear programming models; (2) integer programming models; (3) mixed-integer programming models; (4) quadratic programming models; (5) mixed-integer quadratic programming models; (6) quadratic constrained programming models; and (7) mixed-integer quadratic constrained programming models (Lima, 2010). CPLEX relies on the Brach-and-Cut (B&C) algorithm, which is essentially an extension of the B&B algorithm. A canonical B&B algorithm may not perform well for the large-size problem instances, since the number of algorithmic iterations grows exponentially due to increasing number of variables in the mathematical model.

In order to improve efficiency of the search process and reduce the number of algorithmic iterations, the B&C algorithm applies a pre-processing step and generates additional cutting planes (Lima, 2010). The following techniques are deployed at the pre-processing stage: (1) identification of the redundancy; (2) identification of the infeasibility; (3) improvement of the bounds; and (4) rounding (primarily for the integer and mixed-integer programming models). Moreover, CPLEX also applies certain probing techniques throughout pre-processing that assist with fixing binary variable to either 0 or 1. After pre-processing step, CPLEX applies a number of cutting planes, including Knapsack covers, cliques, flow covers, implied bounds, mixed-integer rounding cuts, Gomory mixed-integer cuts, disjunctive cuts, and others (Lima, 2010). The purpose of using different types of cutting planes is to obtain a tight linear relaxation for a given mixed-integer programming problem. Note that the number and type of cutting planes may vary from one version of CPLEX to another.

CPLEX also deploys a set of heuristics to facilitate exploration of various domains of the search space. The heuristics can be classified into two groups, including the following: (a) node heuristics; and (b) neighborhood exploration heuristics. The key objectives of introducing the node heuristics are to strengthen bounds, fix a set of integer infeasible variables, and solve the linear relaxation. The key objective of introducing the neighborhood exploration heuristics is to explore a given neighborhood of the search space for superior solutions. The neighborhood exploration heuristics, which are used within CPLEX, include Relaxation Induced Neighborhood Search, Local Branching, Guided Dives, and Evolutionary Algorithms. Under this project, CPLEX will be executed using the General Algebraic Modeling System (GAMS, 2019). GAMS will be called from the MATLAB environment throughout the numerical experiments.

### 8.2. Heuristic Algorithms

Two sets of heuristic algorithms were developed under this project. The first set of heuristic algorithms was designed to solve the **RAP-1** mathematical model, while the second set of heuristic algorithms was developed to solve the **RAP-2** mathematical model. Both sets of heuristics apply certain sorting procedures in order to select the highway-rail grade crossings for upgrading and determine the appropriate type of upgrading. A detailed description of the heuristic algorithms, which were used for the **RAP-1** mathematical model, is provided in section 8.2.1 of the report, while section 8.2.2 discusses the heuristic algorithms, which were used for the **RAP-2** mathematical model.

### *8.2.1. Heuristic Algorithms for the RAP-1 Mathematical Model*

The first set of algorithms includes a total of four heuristics, which were developed to solve the **RAP-1** mathematical model, including the following: (1) the Most Profitable Hazard Reduction (MPHR) heuristic; (2) the Most Effective Hazard Reduction (MEHR) heuristic; (3) the Profitable Hazard Reduction (PHR) heuristic; and (4) the Effective Hazard Reduction (EHR) heuristic. All the developed heuristic algorithms aim to determine a set of highway-rail grade crossings, which have to be upgraded, and the type of upgrading for each one of the selected crossings that will yield the least possible overall hazard at the highway-rail grade crossings.

#### *The Most Profitable Hazard Reduction (MPHR) Heuristic*

The first heuristic for the **RAP-1** mathematical model, named as the Most Profitable Hazard Reduction (MPHR) heuristic, creates a highway-rail grade crossing priority list, where higher priority will be given to the highway-rail grade crossings that have higher hazard reduction-to-cost ratios. A countermeasure with the highest hazard reduction-to-cost ratio will be selected for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest hazard reduction-to-cost ratio at the next highway-rail grade crossing in the priority list, MPHR will assign eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). The main steps of the MPHR heuristic are provided in **Algorithm 1**. Note that **Algorithm 1** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation “$CM$” was introduced to denote the term “countermeasure”, while notation “$HRCR$” was used to denote “the hazard reduction-to-cost ratio”.

In step 0, the MPHR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the hazard reduction-to-cost ratios – $HRCR$; and the remaining budget – $RB$). In step 1, the $HRCR$ values are estimated for all the highway-rail grade crossing and countermeasure pairs. In step 2, MPHR determines the highest $HRCR$ ($\overline{HRCR}$) and feasible countermeasure with the highest $HRCR$ ($\overline{CM}$) for each one of the considered highway-rail grade crossings. In step 3, all the considered highway-rail grade crossings and associated countermeasures are sorted based on the $\overline{HRCR}$ values in the descending order, and the highway-rail grade crossing priority list is created. Also, the MPHR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 3. After that, MPHR enters the first loop (steps 4-10), where the next highway-rail grade crossing in the priority list is selected in step 5. In step 6, the countermeasure with $\overline{HRCR}$ is selected for a given highway-rail grade crossing. In step 7, the countermeasure with $\overline{HRCR}$ is assigned for a given highway-rail grade crossing. The remaining budget ($RB$) and the highway-rail grade crossing priority list ($List$) are updated in steps 8 and 9, respectively. The MPHR heuristic exits the loop, once the remaining budget is not sufficient for implementation of the countermeasure with $\overline{HRCR}$ at the next highway-rail grade crossing in the priority list.

**Algorithm 1:** The Most Profitable Hazard Reduction (MPHR) Heuristic

$\boldsymbol{MPHR}(X, C, OH, p, EF, CA, TAB)$

**in:** $X = \{1, \ldots, n\}$ - set of crossings; $C = \{1, \ldots, m\}$ - set of countermeasures; $OH$ - overall hazard at each crossing; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |HRCR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◃ Initialization

1: $HRCR \leftarrow (OH \cdot EF)/CA$ ◃ Estimate the hazard reduction-to-cost ratio

2: $[\overline{HRCR}, \overline{CM}] \leftarrow \boldsymbol{argmax}(p, HRCR)$ ◃ Determine the highest $HRCR$ and feasible $CM$ with the highest $HRCR$

3: $[List, \overline{CM}] \leftarrow \boldsymbol{sort}(p, \overline{CM}, \overline{HRCR})$ ◃ Sort the eligible crossings and associated $\overline{CM}$ based on $\overline{HRCR}$

4: **while** $List \neq \emptyset$ **and** $RB \geq CA_{(List_1)(\overline{CM}_1)}$ **do**

5: $\quad x \leftarrow List_1$ ◃ Select the next crossing in the list

6: $\quad c \leftarrow \overline{CM}_1$ ◃ Select the $CM$ with $\overline{HRCR}$ for that crossing

7: $\quad \boldsymbol{z}_{xc} \leftarrow 1$ ◃ Assign the $CM$ with $\overline{HRCR}$ for the selected crossing

8: $\quad RB \leftarrow RB - CA_{xc}$ ◃ Update the remaining budget

9: $\quad List \leftarrow List - \{x\}$ ◃ Remove the selected crossing from the list

10: **end while**

11: **while** $List \neq \emptyset$ **do**

12: $\quad x \leftarrow List_1$ ◃ Select the next crossing in the list

13: $\quad$ **for all** $c \in C$ **do**

14: $\qquad$ **if** $CA_{xc} \leq RB$ **and** $p_{xc} = 1$ **do** ◃ Check the remaining budget and upgrade eligibility

15: $\qquad\quad \boldsymbol{z}_{xc} \leftarrow 1$ ◃ Assign the $CM$ for the selected crossing

16: $\qquad\quad RB \leftarrow RB - CA_{xc}$ ◃ Update the remaining budget

17: $\qquad\quad$ **break** ◃ Break "for" loop (starting at line 13)

18: $\qquad$ **end if**

19: $\quad$ **end for**

20: $\quad List \leftarrow List - \{x\}$ ◃ Remove the selected crossing from the list

21: **end while**

22: **return** $\boldsymbol{z}$

Then, MPHR enters the second loop (steps 11-21), where the remaining budget is used to implement eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). Specifically, the next highway-rail grade crossing in the priority list is selected in step 12. After that, the MPHR heuristic searchers for the first countermeasure, which can be implemented at a given highway-rail grade crossing (steps 13-19). The highway-rail grade crossing can be removed from the list without countermeasure implementation, if the remaining budget is not sufficient to implement any countermeasures at that highway-rail grade crossing and/or that highway-rail grade crossing is not eligible for any countermeasures. In step 20, the highway-rail grade crossing priority list is updated. MPHR is terminated when the highway-rail grade crossing priority list is empty (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

***The Most Effective Hazard Reduction (MEHR) Heuristic***

The second heuristic for the **RAP-1** mathematical model, named as the Most Effective Hazard Reduction (MEHR) heuristic, creates a highway-rail grade crossing priority list, where higher priority will be given to the highway-rail grade crossings that have higher hazard reduction-to-cost ratios. However, unlike the MPHR heuristic, MEHR assigns a countermeasure with the highest hazard reduction value for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest hazard reduction value at the next highway-rail grade crossing in the priority list, MEHR will assign eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). The main steps of the MEHR heuristic are provided in **Algorithm 2**. Note that **Algorithm 2** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation "$CM$" was introduced to denote the term "countermeasure", while notation "$HRCR$" was used to denote "the hazard reduction-to-cost ratio".

In step 0, the MEHR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the hazard reduction-to-cost ratios – $HRCR$; and the remaining budget – $RB$). In step 1, the effectiveness factor for the most effective and feasible countermeasure (i.e., the one that a given highway-rail grade crossing is eligible for) is determined for each highway-rail grade crossing. In step 2, the $HRCR$ values are estimated for all the pairs of the highway-rail grade crossings and the most effective countermeasures. In step 3, MEHR determines the highest $HRCR$ ($\overline{HRCR}$) and feasible countermeasure with the highest $HRCR$ ($\overline{CM}$) for each one of the considered highway-rail grade crossings. In step 4, all the considered highway-rail grade crossings and associated countermeasures are sorted based on the $\overline{HRCR}$ values in the descending order, and the highway-rail grade crossing priority list is created. Also, the MEHR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 4.

After that, MEHR enters the first loop (steps 5-11), where the next highway-rail grade crossing in the priority list is selected in step 6. In step 7, the countermeasure with $\overline{HRCR}$ is selected for a given highway-rail grade crossing. In step 8, the countermeasure with $\overline{HRCR}$ is assigned for a given highway-rail grade crossing. The remaining budget ($RB$) and the highway-rail grade crossing priority list ($List$) are updated in steps 9 and 10, respectively. The MEHR heuristic exits the loop, once the remaining budget is not sufficient for implementation of the countermeasure with $\overline{HRCR}$ at the next highway-rail grade crossing in the priority list.

Then, MEHR enters the second loop (steps 12-22), where the remaining budget is used to implement eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). Specifically, the next highway-rail grade crossing in the priority list is selected in step 13. After that, the MEHR heuristic searchers for the first countermeasure, which can be implemented at a given highway-rail grade crossing (steps 14-20). The highway-rail grade crossing can be removed from the list without countermeasure implementation, if the remaining budget is not sufficient to implement any countermeasures at that highway-rail grade crossing and/or that highway-rail grade crossing is not eligible for any countermeasures. In step 21, the highway-rail grade crossing priority list is updated. MEHR is terminated when the highway-rail grade crossing priority list is empty (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

---

**Algorithm 2:** The Most Effective Hazard Reduction (MEHR) Heuristic

$\boldsymbol{MEHR}(X, C, OH, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $OH$ - overall hazard at each crossing; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \varnothing; |HRCR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◁ Initialization

1: $\overline{EF} \leftarrow \boldsymbol{argmax}(p, EF)$ ◁ Determine the effectiveness factor for the most effective and feasible $CM$

2: $HRCR \leftarrow (OH \cdot \overline{EF})/CA$ ◁ Estimate the hazard reduction-to-cost ratio

3: $[\overline{HRCR}, \overline{CM}] \leftarrow \boldsymbol{argmax}(p, HRCR)$ ◁ Determine the highest $HRCR$ and feasible $CM$ with the highest $HRCR$

4: $[List, \overline{CM}] \leftarrow \boldsymbol{sort}(p, \overline{CM}, \overline{HRCR})$ ◁ Sort the eligible crossings and associated $\overline{CM}$ based on $\overline{HRCR}$

5: **while** $List \neq \varnothing$ **and** $RB \geq CA_{(List_1)(\overline{CM}_1)}$ **do**

6: $x \leftarrow List_1$ ◁ Select the next crossing in the list

7: $c \leftarrow \overline{CM}_1$ ◁ Select the $CM$ with $\overline{HRCR}$ for that crossing

8: $\boldsymbol{z}_{xc} \leftarrow 1$ ◁ Assign the $CM$ with $\overline{HRCR}$ for the selected crossing

9: $RB \leftarrow RB - CA_{xc}$ ◁ Update the remaining budget

10: $List \leftarrow List - \{x\}$ ◁ Remove the selected crossing from the list

11: **end while**

12: **while** $List \neq \varnothing$ **do**

13: $x \leftarrow List_1$ ◁ Select the next crossing in the list

14: **for all** $c \in C$ **do**

15: **if** $CA_{xc} \leq RB$ **and** $p_{xc} = 1$ **do** ◁ Check the remaining budget and upgrade eligibility

16: $\boldsymbol{z}_{xc} \leftarrow 1$ ◁ Assign the $CM$ for the selected crossing

17: $RB \leftarrow RB - CA_{xc}$ ◁ Update the remaining budget

18: **break** ◁ Break "for" loop (starting at line 14)

19: **end if**

20: **end for**

21: $List \leftarrow List - \{x\}$ ◁ Remove the selected crossing from the list

22: **end while**

23: **return** $\boldsymbol{z}$

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### *The Profitable Hazard Reduction (PHR) Heuristic*

Similar, to the MPHR heuristic, the third heuristic for the **RAP-1** mathematical model, named as the Profitable Hazard Reduction (PHR) heuristic, gives higher priority to the highway-rail grade crossings that have higher hazard reduction-to-cost ratios. However, PHR includes highway-rail grade crossing-countermeasure pairs in the priority list (unlike the MPHR heuristic that includes the considered highway-rail grade crossings only). The priority list is sorted based on the hazard reduction-to-cost ratios. Similar to MPHR, PHR will assign a countermeasure with the highest hazard reduction-to-cost ratio for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest hazard reduction-to-cost ratio at the next highway-rail grade crossing in the priority list, PHR will start considering other highway-rail grade crossing-countermeasure pairs in the priority list, based on the hazard reduction-to-cost ratios (unlike the MPHR heuristic that arbitrarily allocates the remaining budget among some of the highway-rail grade crossings in the priority list that have not been selected for upgrading without using any particular principle/rule). The main steps of the PHR heuristic are provided in **Algorithm 3**. Note that **Algorithm 3** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation "$CM$" was introduced to denote the term "countermeasure", while notation "$HRCR$" was used to denote "the hazard reduction-to-cost ratio".

**Algorithm 3:** The Profitable Hazard Reduction (PHR) Heuristic

$\boldsymbol{PHR}(X, C, OH, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $OH$ - overall hazard at each crossing; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |HRCR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◃ Initialization
1: **for all** $x \in X$ **do**
2: **for all** $c \in C$ **do**
3: $HRCR_{xc} \leftarrow (OH_x \cdot EF_{xc})/CA_{xc}$ ◃ Estimate the hazard reduction-to-cost ratio
4: $List \leftarrow List \cup \{x, c\}$ ◃ Add a crossing-countermeasure pair to the list
5: **end for**
6: **end for**
7: $List \leftarrow \boldsymbol{sort}(List, p, HRCR)$ ◃ Sort the list based on $HRCR$
8: **while** $List \neq \emptyset$ **and** $RB \geq min(CA)$ **do**
9: $x \leftarrow List_1^x$ ◃ Select the next crossing in the list
10: $c \leftarrow List_1^c$ ◃ Select the next $CM$ in the list
11: **if** $RB \geq CA_{xc}$ **do**
12: $\boldsymbol{z}_{xc} \leftarrow 1$ ◃ Assign the $CM$ for the selected crossing
13: $RB \leftarrow RB - CA_{xc}$ ◃ Update the remaining budget
14: $List \leftarrow List - \{x, :\}$ ◃ Remove all the crossing-countermeasure pairs from the list
15: **else**
16: $List \leftarrow List - \{x, c\}$ ◃ Remove the selected crossing-countermeasure pair from the list
17: **end if**
18: **end while**
19: **return** $\boldsymbol{z}$

In step 0, the PHR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the hazard reduction-to-cost ratios – $HRCR$; and the remaining budget – $RB$). After that, the PHR heuristic enters the first loop (steps 1-6) in order to estimate the $HRCR$ values for all the highway-rail grade crossing-countermeasure pairs and construct the priority list. As it was highlighted earlier, unlike the MPHR heuristic that constructs the priority list using the considered highway-rail grade crossings only, PHR constructs the priority list using the highway-rail grade crossing-countermeasure pairs. In step 7, all the highway-rail grade crossing-countermeasure pairs are sorted based on the $HRCR$ values in the descending order in the priority list. Also, the PHR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 7.

Then, PHR enters the second loop (steps 8-18), where the next highway-rail grade crossing in the priority list and the associated countermeasure are selected in steps 9 and 10, respectively. After that, the PHR heuristic checks whether the remaining budget is sufficient to implement a given countermeasure at the considered highway-rail grade crossing (steps 11-17). If the remaining budget is sufficient, PHR assigns that countermeasure to the considered highway-rail grade crossing (step 12), updates the remaining budget (step 13), and removes all the crossing-countermeasure pairs associated with the highway-rail grade crossing that was assigned for upgrading from the priority list (step 14). Otherwise (i.e., the remaining budget is not sufficient to implement a given countermeasure at the considered highway-rail grade crossing), the PHR heuristic removes the selected crossing-countermeasure pair from the priority list in step 16 (while other crossing-countermeasure pairs associated with that highway-rail grade crossing may be still present in the priority list; so, PHR will be able to analyze the countermeasures with lower hazard reduction-to-cost ratios and lower installation costs). PHR is terminated when the highway-rail grade crossing priority list is empty or the remaining budget is not sufficient to implement the countermeasure with the least installation cost (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

***The Effective Hazard Reduction (EHR) Heuristic***

Similar, to the PHR heuristic, the fourth heuristic for the **RAP-1** mathematical model, named as the Effective Hazard Reduction (EHR) heuristic, creates the priority list using highway-rail grade crossing-countermeasure pairs. However, unlike the PHR heuristic, EHR sorts the highway-rail grade crossing-countermeasure pairs in the priority list, based on the hazard reduction values. The EHR will assign a countermeasure with the highest hazard reduction value for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest hazard reduction value at the next highway-rail grade crossing in the priority list, EHR will start considering other highway-rail grade crossing-countermeasure pairs in the priority list, based on the hazard reduction values. The main steps of the EHR heuristic are provided in **Algorithm 4**. Note that **Algorithm 4** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation “$CM$” was introduced to denote the term “countermeasure”, while notation “$HR$” was used to denote “the hazard reduction”.

In step 0, the EHR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the hazard reduction values – $HR$; and the remaining budget – $RB$). After that, the EHR heuristic enters the first loop (steps 1-6) in order to estimate the $HR$ values for all the highway-rail grade crossing-countermeasure pairs and construct the priority list. In step 7, all the highway-rail grade crossing-countermeasure pairs are sorted based on the $HR$ values in the descending order in the priority list. Also, the EHR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 7. Then, EHR enters the second loop (steps 8-18), where the next highway-rail grade crossing in the priority list and the associated countermeasure are selected in steps 9 and 10, respectively. After that, the EHR heuristic checks whether the remaining budget is sufficient to implement a given countermeasure at the considered highway-rail grade crossing (steps 11-17). If the remaining budget is sufficient, EHR assigns that countermeasure to the considered highway-rail grade crossing (step 12), updates the remaining budget (step 13), and removes all the crossing-countermeasure pairs associated with the highway-rail grade crossing that was assigned for upgrading from the priority list (step 14).

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**Algorithm 4:** The Effective Hazard Reduction (EHR) Heuristic

$\boldsymbol{EHR}(X, C, OH, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $OH$ - overall hazard at each crossing; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |HR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◃ Initialization
1: **for all** $x \in X$ **do**
2:     **for all** $c \in C$ **do**
3:         $HR_{xc} \leftarrow (OH_x \cdot EF_{xc})$ ◃ Estimate the hazard reduction
4:         $List \leftarrow List \cup \{x, c\}$ ◃ Add a crossing-countermeasure pair to the list
5:     **end for**
6: **end for**
7: $List \leftarrow \boldsymbol{sort}(List, p, HR)$ ◃ Sort the list based on $HR$
8: **while** $List \neq \emptyset$ **and** $RB \geq min(CA)$ **do**
9:     $x \leftarrow List_1^x$ ◃ Select the next crossing in the list
10:     $c \leftarrow List_1^c$ ◃ Select the next $CM$ in the list
11:     **if** $RB \geq CA_{xc}$ **do**
12:         $\boldsymbol{z}_{xc} \leftarrow 1$ ◃ Assign the $CM$ for the selected crossing
13:         $RB \leftarrow RB - CA_{xc}$ ◃ Update the remaining budget
14:         $List \leftarrow List - \{x, :\}$ ◃ Remove all the crossing-countermeasure pairs from the list
15:     **else**
16:         $List \leftarrow List - \{x, c\}$ ◃ Remove the selected crossing-countermeasure pair from the list
17:     **end if**
18: **end while**
19: **return** $\boldsymbol{z}$

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Otherwise (i.e., the remaining budget is not sufficient to implement a given countermeasure at the considered highway-rail grade crossing), the EHR heuristic removes the selected crossing-countermeasure pair from the priority list in step 16 (while other crossing-countermeasure pairs associated with that highway-rail grade crossing may be still present in the priority list; so, EHR will be able to analyze the countermeasures with lower hazard reduction values and lower installation costs). EHR is terminated when the highway-rail grade crossing priority list is empty or the remaining budget is not sufficient to implement the countermeasure with the least installation cost (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

### *8.2.2. Heuristic Algorithms for the RAP-2 Optimization Problem*

The second set of algorithms includes a total of four heuristics, which were developed to solve the **RAP-2** mathematical model, including the following: (1) the Most Profitable Severity Reduction (MPSR) heuristic; (2) the Most Effective Severity Reduction (MESR) heuristic; (3) the Profitable Severity Reduction (PSR) heuristic; and (4) the Effective Severity Reduction (ESR) heuristic. All the developed heuristic algorithms aim to determine a set of highway-rail grade crossings, which have to be upgraded, and the type of upgrading for each one of the selected crossings that will yield the least possible overall hazard severity at the highway-rail grade crossings.

#### *The Most Profitable Severity Reduction (MPSR) Heuristic*

The first heuristic for the **RAP-2** mathematical model, named as the Most Profitable Severity Reduction (MPSR) heuristic, creates a highway-rail grade crossing priority list, where higher priority will be given to the highway-rail grade crossings that have higher severity reduction-to-cost ratios. A countermeasure with the highest severity reduction-to-cost ratio will be selected for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest severity reduction-to-cost ratio at the next highway-rail grade crossing in the priority list, MPSR will assign eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). The main steps of the MPSR heuristic are provided in **Algorithm 5**. Note that **Algorithm 5** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation “$CM$” was introduced to denote the term “countermeasure”, while notation “$SRCR$” was used to denote “the severity reduction-to-cost ratio”.

In step 0, the MPSR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the severity reduction-to-cost ratios – $SRCR$; and the remaining budget – $RB$). In step 1, the $SRCR$ values are estimated for all the highway-rail grade crossing and countermeasure pairs. In step 2, MPSR determines the highest $SRCR$ ($\overline{SRCR}$) and feasible countermeasure with the highest $SRCR$ ($\overline{CM}$) for each one of the considered highway-rail grade crossings. In step 3, all the considered highway-rail grade crossings and associated countermeasures are sorted based on the $\overline{SRCR}$ values in the descending order, and the highway-rail grade crossing priority list is created. Also, the MPSR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 3. After that, MPSR enters the first loop (steps 4-10), where the next highway-rail grade crossing in the priority list is selected in step 5. In step 6, the countermeasure with $\overline{SRCR}$ is selected for a given highway-rail grade crossing. In step 7, the countermeasure with $\overline{SRCR}$ is assigned for a given highway-rail grade crossing. The remaining budget ($RB$) and the highway-rail grade crossing priority list ($List$) are updated in steps 8 and 9, respectively. The MPSR heuristic exits the loop, once the remaining budget is not sufficient for implementation of the countermeasure with $\overline{SRCR}$ at the next highway-rail grade crossing in the priority list.

**Algorithm 5:** The Most Profitable Severity Reduction (MPSR) Heuristic

$\boldsymbol{MPSR}(X, C, S, HS, W, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $S = \{1, \dots, k\}$ - set of severity categories; $HS$ - hazard severity at each crossing; $W$ - severity weights; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |SRCR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◁ Initialization

1: $SRCR \leftarrow (HS \cdot W \cdot EF)/CA$ ◁ Estimate the severity reduction-to-cost ratio

2: $[\overline{SRCR}, \overline{CM}] \leftarrow \boldsymbol{argmax}(p, SRCR)$ ◁ Determine the highest $SRCR$ and feasible $CM$ with the highest $SRCR$

3: $[List, \overline{CM}] \leftarrow \boldsymbol{sort}(p, \overline{CM}, \overline{SRCR})$ ◁ Sort the eligible crossings and associated $\overline{CM}$ based on $\overline{SRCR}$

4: **while** $List \neq \emptyset$ **and** $RB \geq CA_{(List_1)(\overline{CM}_1)}$ **do**

5: $x \leftarrow List_1$ ◁ Select the next crossing in the list

6: $c \leftarrow \overline{CM}_1$ ◁ Select the $CM$ with $\overline{SRCR}$ for that crossing

7: $\boldsymbol{z}_{xc} \leftarrow 1$ ◁ Assign the $CM$ with $\overline{SRCR}$ for the selected crossing

8: $RB \leftarrow RB - CA_{xc}$ ◁ Update the remaining budget

9: $List \leftarrow List - \{x\}$ ◁ Remove the selected crossing from the list

10: **end while**

11: **while** $List \neq \emptyset$ **do**

12: $x \leftarrow List_1$ ◁ Select the next crossing in the list

13: **for all** $c \in C$ **do**

14: **if** $CA_{xc} \leq RB$ **and** $p_{xc} = 1$ **do** ◁ Check the remaining budget and upgrade eligibility

15: $\boldsymbol{z}_{xc} \leftarrow 1$ ◁ Assign the $CM$ for the selected crossing

16: $RB \leftarrow RB - CA_{xc}$ ◁ Update the remaining budget

17: **break** ◁ Break "for" loop (starting at line 13)

18: **end if**

19: **end for**

20: $List \leftarrow List - \{x\}$ ◁ Remove the selected crossing from the list

21: **end while**

22: **return** $\boldsymbol{z}$

Then, MPSR enters the second loop (steps 11-21), where the remaining budget is used to implement eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). Specifically, the next highway-rail grade crossing in the priority list is selected in step 12. After that, the MPSR heuristic searchers for the first countermeasure, which can be implemented at a given highway-rail grade crossing (steps 13-19). The highway-rail grade crossing can be removed from the list without countermeasure implementation, if the remaining budget is not sufficient to implement any countermeasures at that highway-rail grade crossing and/or that highway-rail grade crossing is not eligible for any countermeasures. In step 20, the highway-rail grade crossing priority list is updated. MPSR is terminated when the highway-rail grade crossing priority list is empty (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

***The Most Effective Severity Reduction (MESR) Heuristic***

The second heuristic for the **RAP-2** mathematical model, named as the Most Effective Severity Reduction (MESR) heuristic, creates a highway-rail grade crossing priority list, where higher priority will be given to the highway-rail grade crossings that have higher severity reduction-to-cost ratios. However, unlike the MPSR heuristic, MESR assigns a countermeasure with the highest severity reduction value for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest severity reduction value at the next highway-rail grade crossing in the priority list, MESR will assign eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). The main steps of the MESR heuristic are provided in **Algorithm 6**. Note that **Algorithm 6** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation "$CM$" was introduced to denote the term "countermeasure", while notation "$SRCR$" was used to denote "the severity reduction-to-cost ratio".

In step 0, the MESR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the severity reduction-to-cost ratios – $SRCR$; and the remaining budget – $RB$). In step 1, the effectiveness factor for the most effective and feasible countermeasure (i.e., the one that a given highway-rail grade crossing is eligible for) is determined for each highway-rail grade crossing. In step 2, the $SRCR$ values are estimated for all the pairs of the highway-rail grade crossings and the most effective countermeasures. In step 3, MESR determines the highest $SRCR$ ($\overline{SRCR}$) and feasible countermeasure with the highest $SRCR$ ($\overline{CM}$) for each one of the considered highway-rail grade crossings. In step 4, all the considered highway-rail grade crossings and associated countermeasures are sorted based on the $\overline{SRCR}$ values in the descending order, and the highway-rail grade crossing priority list is created. Also, the MESR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 4.

After that, MESR enters the first loop (steps 5-11), where the next highway-rail grade crossing in the priority list is selected in step 6. In step 7, the countermeasure with $\overline{SRCR}$ is selected for a given highway-rail grade crossing. In step 8, the countermeasure with $\overline{SRCR}$ is assigned for a given highway-rail grade crossing. The remaining budget ($RB$) and the highway-rail grade crossing priority list ($List$) are updated in steps 9 and 10, respectively. The MESR heuristic exits the loop, once the remaining budget is not sufficient for implementation of the countermeasure with $\overline{SRCR}$ at the next highway-rail grade crossing in the priority list.

Then, MESR enters the second loop (steps 12-22), where the remaining budget is used to implement eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading). Specifically, the next highway-rail grade crossing in the priority list is selected in step 13. After that, the MESR heuristic searchers for the first countermeasure, which can be implemented at a given highway-rail grade crossing (steps 14-20). The highway-rail grade crossing can be removed from the list without countermeasure implementation, if the remaining budget is not sufficient to implement any countermeasures at that highway-rail grade crossing and/or that highway-rail grade crossing is not eligible for any countermeasures. In step 21, the highway-rail grade crossing priority list is updated. MESR is terminated when the highway-rail grade crossing priority list is empty (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

**Algorithm 6:** The Most Effective Severity Reduction (MESR) Heuristic

$\boldsymbol{MESR}(X, C, S, HS, W, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $S = \{1, \dots, k\}$ - set of severity categories; $HS$ - hazard severity at each crossing; $W$ - severity weights; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |SRCR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◁ Initialization
1: $\overline{EF} \leftarrow \boldsymbol{argmax}(p, EF)$ ◁ Determine the effectiveness factor for the most effective and feasible $CM$
2: $SRCR \leftarrow (HS \cdot W \cdot \overline{EF})/CA$ ◁ Estimate the severity reduction-to-cost ratio
3: $[\overline{SRCR}, \overline{CM}] \leftarrow \boldsymbol{argmax}(p, SRCR)$ ◁ Determine the highest $SRCR$ and feasible $CM$ with the highest $SRCR$
4: $[List, \overline{CM}] \leftarrow \boldsymbol{sort}(p, \overline{CM}, \overline{SRCR})$ ◁ Sort the eligible crossings and associated $\overline{CM}$ based on $\overline{SRCR}$
5: **while** $List \neq \emptyset$ **and** $RB \geq CA_{(List_1)(\overline{CM}_1)}$ **do**
6: $x \leftarrow List_1$ ◁ Select the next crossing in the list
7: $c \leftarrow \overline{CM}_1$ ◁ Select the $CM$ with $\overline{SRCR}$ for that crossing
8: $\boldsymbol{z}_{xc} \leftarrow 1$ ◁ Assign the $CM$ with $\overline{SRCR}$ for the selected crossing
9: $RB \leftarrow RB - CA_{xc}$ ◁ Update the remaining budget
10: $List \leftarrow List - \{x\}$ ◁ Remove the selected crossing from the list
11: **end while**
12: **while** $List \neq \emptyset$ **do**
13: $x \leftarrow List_1$ ◁ Select the next crossing in the list
14: **for all** $c \in C$ **do**
15: **if** $CA_{xc} \leq RB$ **and** $p_{xc} = 1$ **do** ◁ Check the remaining budget and upgrade eligibility
16: $\boldsymbol{z}_{xc} \leftarrow 1$ ◁ Assign the $CM$ for the selected crossing
17: $RB \leftarrow RB - CA_{xc}$ ◁ Update the remaining budget
18: **break** ◁ Break "for" loop (starting at line 14)
19: **end if**
20: **end for**
21: $List \leftarrow List - \{x\}$ ◁ Remove the selected crossing from the list
22: **end while**
23: **return** $\boldsymbol{z}$

### *The Profitable Severity Reduction (PSR) Heuristic*

Similar, to the MPSR heuristic, the third heuristic for the **RAP-2** mathematical model, named as the Profitable Severity Reduction (PSR) heuristic, gives higher priority to the highway-rail grade crossings that have higher severity reduction-to-cost ratios. However, PSR includes highway-rail grade crossing-countermeasure pairs in the priority list (unlike the MPSR heuristic that includes the considered highway-rail grade crossings only). The priority list is sorted based on the severity reduction-to-cost ratios. Similar to MPSR, PSR will assign a countermeasure with the highest severity reduction-to-cost ratio for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest severity reduction-to-cost ratio at the next highway-rail grade crossing in the priority list, PSR will start considering other highway-rail grade crossing-countermeasure pairs in the priority list, based on the severity reduction-to-cost ratios (unlike the MPSR heuristic that arbitrarily allocates the remaining budget among some of the highway-rail grade crossings in the priority list that have not been selected for upgrading without using any particular principle/rule). The main steps of the PSR heuristic are provided in **Algorithm 7**. Note that **Algorithm 7** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation "$CM$" was introduced to denote the term "countermeasure", while notation "$SRCR$" was used to denote "the severity reduction-to-cost ratio".

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**Algorithm 7:** The Profitable Severity Reduction (PSR) Heuristic

$\boldsymbol{PSR}(X, C, S, HS, W, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $S = \{1, \dots, k\}$ - set of severity categories; $HS$ - hazard severity at each crossing; $W$ - severity weights; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |SRCR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◃ Initialization
1: **for all** $x \in X$ **do**
2: **for all** $c \in C$ **do**
3: $SRCR_{xc} \leftarrow ([\sum_{s \in S} HS_{xs} \cdot W_s] \cdot EF_{xc})/CA_{xc}$ ◃ Estimate the severity reduction-to-cost ratio
4: $List \leftarrow List \cup \{x, c\}$ ◃ Add a crossing-countermeasure pair to the list
5: **end for**
6: **end for**
7: $List \leftarrow \boldsymbol{sort}(List, p, SRCR)$ ◃ Sort the list based on $SRCR$
8: **while** $List \neq \emptyset$ **and** $RB \geq min(CA)$ **do**
9: $x \leftarrow List_1^x$ ◃ Select the next crossing in the list
10: $c \leftarrow List_1^c$ ◃ Select the next $CM$ in the list
11: **if** $RB \geq CA_{xc}$ **do**
12: $\boldsymbol{z}_{xc} \leftarrow 1$ ◃ Assign the $CM$ for the selected crossing
13: $RB \leftarrow RB - CA_{xc}$ ◃ Update the remaining budget
14: $List \leftarrow List - \{x, :\}$ ◃ Remove all the crossing-countermeasure pairs from the list
15: **else**
16: $List \leftarrow List - \{x, c\}$ ◃ Remove the selected crossing-countermeasure pair from the list
17: **end if**
18: **end while**
19: **return** $\boldsymbol{z}$

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In step 0, the PSR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the severity reduction-to-cost ratios – $SRCR$; and the remaining budget – $RB$). After that, the PSR heuristic enters the first loop (steps 1-6) in order to estimate the $SRCR$ values for all the highway-rail grade crossing-countermeasure pairs and construct the priority list. As it was highlighted earlier, unlike the MPSR heuristic that constructs the priority list using the considered highway-rail grade crossings only, PSR constructs the priority list using the highway-rail grade crossing-countermeasure pairs. In step 7, all the highway-rail grade crossing-countermeasure pairs are sorted based on the $SRCR$ values in the descending order in the priority list. Also, the PSR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 7.

Then, PSR enters the second loop (steps 8-18), where the next highway-rail grade crossing in the priority list and the associated countermeasure are selected in steps 9 and 10, respectively. After that, the PSR heuristic checks whether the remaining budget is sufficient to implement a given countermeasure at the considered highway-rail grade crossing (steps 11-17). If the remaining budget is sufficient, PSR assigns that countermeasure to the considered highway-rail grade crossing (step 12), updates the remaining budget (step 13), and removes all the crossing-countermeasure pairs associated with the highway-rail grade crossing that was assigned for upgrading from the priority list (step 14). Otherwise (i.e., the remaining budget is not sufficient to implement a given countermeasure at the considered highway-rail grade crossing), the PSR heuristic removes the selected crossing-countermeasure pair from the priority list in step 16 (while other crossing-countermeasure pairs associated with that highway-rail grade crossing may be still present in the priority list; so, PSR will be able to analyze the countermeasures with lower severity reduction-to-cost ratios and lower installation costs). PSR is terminated when the highway-rail grade crossing priority list is empty or the remaining budget is not sufficient to implement the countermeasure with the least installation cost (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

***The Effective Severity Reduction (ESR) Heuristic***

Similar, to the PSR heuristic, the fourth heuristic for the **RAP-2** mathematical model, named as the Effective Severity Reduction (ESR) heuristic, creates the priority list using highway-rail grade crossing-countermeasure pairs. However, unlike the PSR heuristic, ESR sorts the highway-rail grade crossing-countermeasure pairs in the priority list, based on the severity reduction values. The ESR will assign a countermeasure with the highest severity reduction value for each highway-rail grade crossing (considering eligibility of highway-rail grade crossings for the available countermeasures), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest severity reduction value at the next highway-rail grade crossing in the priority list, ESR will start considering other highway-rail grade crossing-countermeasure pairs in the priority list, based on the severity reduction values. The main steps of the ESR heuristic are provided in **Algorithm 8**. Note that **Algorithm 8** adopts the nomenclature described in section 7.1 of this report. An additional abbreviation "$CM$" was introduced to denote the term "countermeasure", while notation "$SR$" was used to denote "the severity reduction".

In step 0, the ESR heuristic initializes the data structures for storing the key algorithmic variables (i.e., the countermeasure to crossing decision variable – $\boldsymbol{z}$; the highway-rail grade crossing priority list – $List$; the severity reduction values – $SR$; and the remaining budget – $RB$). After that, the ESR heuristic enters the first loop (steps 1-6) in order to estimate the $SR$ values for all the highway-rail grade crossing-countermeasure pairs and construct the priority list. In step 7, all the highway-rail grade crossing-countermeasure pairs are sorted based on the $SR$ values in the descending order in the priority list. Also, the ESR heuristic eliminates all the highway-rail grade crossings which are not eligible for any of the available countermeasures from the analysis in step 7. Then, ESR enters the second loop (steps 8-18), where the next highway-rail grade crossing in the priority list and the associated countermeasure are selected in steps 9 and 10, respectively. After that, the ESR heuristic checks whether the remaining budget is sufficient to implement a given countermeasure at the considered highway-rail grade crossing (steps 11-17). If the remaining budget is sufficient, ESR assigns that countermeasure to the considered highway-rail grade crossing (step 12), updates the remaining budget (step 13), and removes all the crossing-countermeasure pairs associated with the highway-rail grade crossing that was assigned for upgrading from the priority list (step 14).

**Algorithm 8:** The Effective Severity Reduction (ESR) Heuristic

$\boldsymbol{ESR}(X, C, S, HS, W, p, EF, CA, TAB)$

**in:** $X = \{1, \dots, n\}$ - set of crossings; $C = \{1, \dots, m\}$ - set of countermeasures; $S = \{1, \dots, k\}$ - set of severity categories; $HS$ - hazard severity at each crossing; $W$ - severity weights; $p$ - crossing eligibility for upgrading; $EF$ - effectiveness factors for countermeasures; $CA$ - cost of applying each countermeasure; $TAB$ - total available budget

**out:** $\boldsymbol{z}$ - selection of countermeasures at the considered crossings

0: $|\boldsymbol{z}| \leftarrow n \cdot m; List \leftarrow \emptyset; |SR| \leftarrow n \cdot m; RB \leftarrow TAB$ ◃ Initialization
1: **for all** $x \in X$ **do**
2: **for all** $c \in C$ **do**
3: $SR_{xc} \leftarrow ([\sum_{s \in S} HS_{xs} \cdot W_s] \cdot EF_{xc})$ ◃ Estimate the severity reduction
4: $List \leftarrow List \cup \{x, c\}$ ◃ Add a crossing-countermeasure pair to the list
5: **end for**
6: **end for**
7: $List \leftarrow \boldsymbol{sort}(List, p, SR)$ ◃ Sort the list based on $SR$
8: **while** $List \neq \emptyset$ **and** $RB \geq min(CA)$ **do**
9: $x \leftarrow List_1^x$ ◃ Select the next crossing in the list
10: $c \leftarrow List_1^c$ ◃ Select the next $CM$ in the list
11: **if** $RB \geq CA_{xc}$ **do**
12: $\boldsymbol{z}_{xc} \leftarrow 1$ ◃ Assign the $CM$ for the selected crossing
13: $RB \leftarrow RB - CA_{xc}$ ◃ Update the remaining budget
14: $List \leftarrow List - \{x, :\}$ ◃ Remove all the crossing-countermeasure pairs from the list
15: **else**
16: $List \leftarrow List - \{x, c\}$ ◃ Remove the selected crossing-countermeasure pair from the list
17: **end if**
18: **end while**
19: **return** $\boldsymbol{z}$

Otherwise (i.e., the remaining budget is not sufficient to implement a given countermeasure at the considered highway-rail grade crossing), the ESR heuristic removes the selected crossing-countermeasure pair from the priority list in step 16 (while other crossing-countermeasure pairs associated with that highway-rail grade crossing may be still present in the priority list; so, ESR will be able to analyze the countermeasures with lower severity reduction values and lower installation costs). ESR is terminated when the highway-rail grade crossing priority list is empty or the remaining budget is not sufficient to implement the countermeasure with the least installation cost (i.e., the recourse allocation procedure has been completed, and necessary countermeasures have been assigned to the highway-rail grade crossings that were selected for upgrading).

# 9. SOLUTION METHODOLOGY EVALUATION

All the solution algorithms, developed for the **RAP-1** and **RAP-2** mathematical models, were evaluated for public highway-rail grade crossings in the State of Florida. As of November of 2018, the FRA crossing inventory database contained the records for a total of 6,089 public highway-rail grade crossings, located in the State of Florida. The overall hazard at the considered highway-rail grade crossings was estimated using the Florida Priority Index Formula (see section 7.4.1 of this report for more details). The hazard severity (i.e., fatality hazard, injury hazard, and property damage hazard) at the considered highway-rail grade crossings was assessed using the GradeDec severity prediction methodology (see section 7.4.3 of this report for more details). The base values for the weights of fatality hazard, injury hazard, and property damage hazard were set to 0.60, 0.30, and 0.10, respectively. A total of 11 countermeasures, discussed in the GradeDec.NET Reference Manual (U.S. DOT, 2014), were used throughout evaluation of the developed solution algorithms (see section 7.4.2 of this report for more details). The effectiveness factors and the installation costs for the considered countermeasures were also adopted from the GradeDec.NET Reference Manual (see section 7.4.2 of this report for more details). The feasibility of countermeasure implementation was assigned based on the protection class at the considered highway-rail grade crossings (see section 7.4.2 of this report for more details).

A total of 12 problem instances were developed for evaluation of the solution algorithms for the **RAP-1** and **RAP-2** mathematical models by changing the total available budget as follows: (1) problem instance 1 – $TAB =$ \$7.5M; (2) problem instance 2 – $TAB =$ \$8.0M; (3) problem instance 3 – $TAB =$ \$8.5M; (4) problem instance 4 – $TAB =$ \$9.0M; (5) problem instance 5 – $TAB =$ \$9.5M; (6) problem instance 6 – $TAB =$ \$10.0M; (7) problem instance 7 – $TAB =$ \$10.5M; (8) problem instance 8 – $TAB =$ \$11.0M; (9) problem instance 9 – $TAB =$ \$11.5M; (10) problem instance 10 – $TAB =$ \$12.0M; (11) problem instance 11 – $TAB =$ \$12.5M; and (12) problem instance 12 – $TAB =$ \$13.0M. Note that the adopted values for the total available budget are in line with the ones, reported by Florida's Highway-Rail Grade Crossing Safety Action Plan (FDOT, 2011) [page 10 of the report]. Also, a total of 121 different scenarios were developed for each problem instance by changing the number of public highway-rail grade crossings (i.e., cardinality of set $X$ – $|X|$) and the number of available countermeasures (i.e., cardinality of set $C$ – $|C|$). Specifically, the following scenarios were modeled for the number of public highway-rail grade crossings: (1) $|X| = 600$; (2) $|X| = 1200$; (3) $|X| = 1800$; (4) $|X| = 2400$; (5) $|X| = 3000$; (6) $|X| = 3600$; (7) $|X| = 4200$; (8) $|X| = 4800$; (9) $|X| = 5400$; (10) $|X| = 6000$; and (11) $|X| = 6089$. On the other hand, the number of available countermeasures was changed from 1 to 11 with an increment of 1 countermeasure.

The purpose of developing various problem instances and scenarios is to determine how performance of the proposed solution algorithms will be affected from changing the total available budget, the number of public highway-rail grade crossings, and the number of available countermeasures for the **RAP-1** and **RAP-2** mathematical models. Performance of the developed solution algorithms will be assessed in terms of the two major performance indicators – objective function values and computational time. Both performance indicators are commonly considered in operations research throughout evaluation of different algorithms (Dulebenets, 2017, 2018a-c, 2019; Dulebenets et al., 2017, 2018, 2019). Moreover, the objective function values and computational time are critical for efficient resource allocation among the highway-rail grade crossings in the State of Florida. The objective function values determine the quality of suggested solutions, returned by the proposed solution algorithms (i.e.., how close the suggested resource allocation decision to the optimal resource allocation decision). In the meantime, the computational time (i.e., the CPU time) is important as well, considering the fact that the resource allocation decisions should be made in a timely manner. Furthermore, in certain cases the FDOT personnel may be required to conduct various sensitivity analyses (e.g., consideration of additional countermeasures, changes in the total available budget, consideration of private highway-rail grade crossings along with public highway-rail grade crossings), which will be challenging when the adopted solution algorithm requires a significant computational time.

The MPHR, MEHR, PHR, EHR, MPSR, MESR, PSR, and ESR heuristic algorithms were encoded within the MATLAB environment (MathWorks, 2019a). The developed heuristic algorithms were evaluated against CPLEX, which was executed via the GAMS environment. All the numerical experiments have been performed on a CPU with Dell Intel(R) Core™ i7 Processor, 32 GB of RAM, and Operating System Windows 10. The evaluation results for the algorithms, developed to solve the **RAP-1** mathematical model (i.e., the MPHR, MEHR, PHR, and EHR heuristic algorithms), are presented in section 9.1, while section 9.2 discusses the evaluation results for the algorithms, developed to solve the **RAP-2** mathematical model (i.e., the MPSR, MESR, PSR, and ESR heuristic algorithms).

Note that the "intlinprog" function (available within the MATLAB environment) has been withdrawn from the analysis for both **RAP-1** and **RAP-2** mathematical models based on the preliminary numerical experiments due to the following reasons:

1) The "intlinprog" function required a substantial CPU time in order to solve the scenarios with a relatively small number of public highway-rail grade crossings and available countermeasures. For example, the CPU time, required by the "intlinprog" function to solve the **RAP-1** mathematical model with 600 highway-rail grade crossings, 8 available countermeasures, and the total available budget of $7.5M, on average over five replications comprised 6,154.84 sec (102.58 min). Also, the CPU time, required by the "intlinprog" function to solve the **RAP-2** mathematical model with 600 highway-rail grade crossings, 8 available countermeasures, and the total available budget of $7.5M, on average over five replications comprised 5,157.50 sec (85.96 min).
2) It was found that for certain scenarios the "intlinprog" function violated constraint sets of the **RAP-1** and **RAP-2** mathematical models. Specifically, the "intlinprog" function suggested implementation of the countermeasures with the total installation cost, exceeding the total available budget, which can be considered as infeasible throughout resource allocation among the highway-rail grade crossings.

## 9.1. Evaluation of the Algorithms for the RAP-1 Mathematical Model

### *9.1.1. Solution Quality for RAP-1*

CPLEX and the MPHR, MEHR, PHR, and EHR heuristic algorithms were executed to solve the **RAP-1** mathematical model for all the generated scenarios of each problem instance. A total of five replications were performed for each one of the considered solution algorithms in order to estimate the average computational time values. Note that the objective function values, returned by the developed solution algorithms, did not change from one replication to another, as all the algorithms are deterministic in their nature. The average overall hazard values, obtained by CPLEX, MPHR, MEHR, PHR, and EHR, over the generated problem instances are presented in Table 60, Table 61, Table 62, Table 63, Table 64, and Figure 51 for each one of the developed scenarios for the **RAP-1** mathematical model. Furthermore, Table 65 shows the average overall hazard values, obtained by CPLEX, MPHR, MEHR, PHR, and EHR, over the generated scenarios for each one of the developed problem instances for the **RAP-1** mathematical model.

The average overall hazard values, obtained by CPLEX, MPHR, MEHR, PHR, and EHR comprised 1,755,123.6, 1,769,527.6, 2,061,902.0, 1,769,495.1, and 2,034,204.7, respectively, over the generated scenarios for the developed problem instances. Therefore, the MPHR and PHR heuristic algorithms obtained the solutions for the **RAP-1** mathematical model, which were close to the optimal solutions (obtained by CPLEX) for all the developed problem instances. The difference in the objective function values for the solutions, suggested by the MPHR and PHR heuristics, and the optimal ones on average did not exceed 0.82% over the developed problem instances (see Table 65). It was observed that the PHR heuristic provided the solutions with lower overall hazard values as compared to the MPHR heuristic for some of the developed scenarios, as it allocates the remaining budget more effectively once the countermeasures with the highest hazard reduction-to-cost ratios have been implemented at the hazardous highway-rail grade crossings (see section 8.2.1 of this report for more details).

On the other hand, the MEHR and EHR heuristic algorithms demonstrated quite a substantial difference in the objective function values as compared to the optimal ones. Specifically, CPLEX outperformed the MEHR and EHR heuristics in terms of the objective function values on average by 17.48% and 15.90% over the developed problem instances (see Table 65). Therefore, prioritization of the highway-rail grade crossings for safety improvement projects based on the hazard reduction-to-cost ratios (adopted within MPHR and PHR) was found to be more promising as compared to prioritization of the highway-rail grade crossings for safety improvement projects based on combination of the hazard reduction-to-cost ratios and the hazard reduction (adopted within MEHR) or solely based on the hazard reduction (adopted within EHR).

**Table 60** The average overall hazard values, obtained by CPLEX, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 2356841 | 2356841 | 2137398 | 1286807 | 1201624 | 1084387 | 627220 | 533588 | 483335 | 483335 | 483081 |
| **1200** | 2611044 | 2611044 | 2356289 | 1543326 | 1458453 | 1341448 | 823067 | 722965 | 559746 | 559746 | 559731 |
| **1800** | 2704583 | 2704583 | 2435065 | 1638663 | 1553790 | 1436785 | 918487 | 818375 | 629431 | 629431 | 629516 |
| **2400** | 2749022 | 2749022 | 2481217 | 1685709 | 1600837 | 1483832 | 965679 | 865392 | 674973 | 674973 | 674936 |
| **3000** | 2765920 | 2765920 | 2499111 | 1703603 | 1618730 | 1501726 | 983438 | 883233 | 692802 | 692802 | 692777 |
| **3600** | 2790086 | 2790086 | 2524357 | 1729835 | 1644962 | 1527958 | 1009745 | 909583 | 717594 | 717594 | 717600 |
| **4200** | 3332385 | 3332385 | 3087948 | 2281336 | 2198406 | 2083058 | 1556801 | 1457622 | 1255414 | 1255414 | 1255437 |
| **4800** | 3357274 | 3357274 | 3112838 | 2306256 | 2223328 | 2107985 | 1581807 | 1482617 | 1280466 | 1280466 | 1280489 |
| **5400** | 3362617 | 3362617 | 3118180 | 2311605 | 2228677 | 2113335 | 1587174 | 1487982 | 1285843 | 1285843 | 1285866 |
| **6000** | 3395543 | 3395543 | 3153672 | 2349589 | 2266777 | 2151503 | 1625402 | 1526133 | 1323454 | 1323454 | 1323439 |
| **6089** | 3398952 | 3398952 | 3157161 | 2353181 | 2270369 | 2155096 | 1629004 | 1529734 | 1327063 | 1327063 | 1327048 |

**Table 61** The average overall hazard values, obtained by MPHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 2356841 | 2356841 | 2137398 | 1286807 | 1201624 | 1084387 | 643415 | 543705 | 499623 | 499623 | 499623 |
| **1200** | 2611044 | 2611044 | 2356289 | 1543326 | 1458453 | 1341448 | 831131 | 726742 | 567808 | 567808 | 567808 |
| **1800** | 2704583 | 2704583 | 2435065 | 1638663 | 1553790 | 1436785 | 926453 | 822060 | 635632 | 635632 | 635632 |
| **2400** | 2749022 | 2749022 | 2481217 | 1685709 | 1600837 | 1483832 | 973500 | 869107 | 680642 | 680642 | 680642 |
| **3000** | 2765920 | 2765920 | 2499111 | 1703603 | 1618730 | 1501726 | 991394 | 887000 | 698517 | 698517 | 698517 |
| **3600** | 2790086 | 2790086 | 2524357 | 1729835 | 1644962 | 1527958 | 1017625 | 913231 | 723153 | 723153 | 723153 |
| **4200** | 3332385 | 3332385 | 3087948 | 2313721 | 2230457 | 2115342 | 1600154 | 1496204 | 1297348 | 1297348 | 1297348 |
| **4800** | 3357274 | 3357274 | 3112838 | 2338610 | 2255346 | 2140232 | 1625043 | 1521093 | 1322237 | 1322237 | 1322237 |
| **5400** | 3362617 | 3362617 | 3118180 | 2343953 | 2260689 | 2145574 | 1630386 | 1526436 | 1327580 | 1327580 | 1327580 |
| **6000** | 3395543 | 3395543 | 3153672 | 2381921 | 2298729 | 2183688 | 1668315 | 1564402 | 1364926 | 1364926 | 1364926 |
| **6089** | 3398952 | 3398952 | 3157161 | 2385509 | 2302316 | 2187276 | 1671902 | 1567989 | 1368514 | 1368514 | 1368514 |

**Table 62** The average overall hazard values, obtained by MEHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 2356841 | 2356841 | 2137398 | 1286193 | 1201298 | 1084371 | 1041189 | 1041189 | 1035325 | 1035325 | 1448476 |
| **1200** | 2611044 | 2611044 | 2356289 | 1543855 | 1459341 | 1342218 | 1299297 | 1299297 | 1293433 | 1293433 | 1717576 |
| **1800** | 2704583 | 2704583 | 2435127 | 1639192 | 1554678 | 1437555 | 1394635 | 1394635 | 1388771 | 1388771 | 1812914 |
| **2400** | 2749022 | 2749022 | 2481254 | 1686239 | 1601725 | 1484602 | 1441681 | 1441681 | 1435817 | 1435817 | 1859960 |
| **3000** | 2765920 | 2765920 | 2499147 | 1704132 | 1619618 | 1502495 | 1459575 | 1459575 | 1453711 | 1453711 | 1877854 |
| **3600** | 2790086 | 2790086 | 2524425 | 1730364 | 1645850 | 1528727 | 1485807 | 1485807 | 1479943 | 1479943 | 1904086 |
| **4200** | 3332385 | 3332385 | 3087972 | 2315304 | 2233015 | 2119283 | 1870221 | 1870221 | 1862126 | 1862126 | 2292330 |
| **4800** | 3357274 | 3357274 | 3112861 | 2340194 | 2257905 | 2144172 | 1895110 | 1895110 | 1887015 | 1887015 | 2317220 |
| **5400** | 3362617 | 3362617 | 3118204 | 2345536 | 2263247 | 2149515 | 1900452 | 1900452 | 1892358 | 1892358 | 2322562 |
| **6000** | 3395543 | 3395543 | 3153697 | 2383613 | 2301361 | 2187629 | 1938566 | 1938566 | 1930472 | 1930472 | 2360676 |
| **6089** | 3398952 | 3398952 | 3157285 | 2387201 | 2304949 | 2191216 | 1942154 | 1942154 | 1934059 | 1934059 | 2364264 |

**Table 63** The average overall hazard values, obtained by PHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 2356841 | 2356841 | 2137398 | 1286807 | 1201624 | 1084387 | 643415 | 543694 | 499623 | 499623 | 499623 |
| **1200** | 2611044 | 2611044 | 2356289 | 1543326 | 1458453 | 1341448 | 831131 | 726740 | 567746 | 567746 | 567746 |
| **1800** | 2704583 | 2704583 | 2435065 | 1638663 | 1553790 | 1436785 | 926453 | 822060 | 635289 | 635289 | 635289 |
| **2400** | 2749022 | 2749022 | 2481217 | 1685709 | 1600837 | 1483832 | 973500 | 869107 | 680487 | 680487 | 680487 |
| **3000** | 2765920 | 2765920 | 2499111 | 1703603 | 1618730 | 1501726 | 991394 | 887000 | 698378 | 698378 | 698378 |
| **3600** | 2790086 | 2790086 | 2524357 | 1729835 | 1644962 | 1527958 | 1017625 | 913231 | 723093 | 723093 | 723093 |
| **4200** | 3332385 | 3332385 | 3087948 | 2313721 | 2230457 | 2115342 | 1600154 | 1496200 | 1297266 | 1297266 | 1297266 |
| **4800** | 3357274 | 3357274 | 3112838 | 2338610 | 2255346 | 2140232 | 1625043 | 1521089 | 1322155 | 1322155 | 1322155 |
| **5400** | 3362617 | 3362617 | 3118180 | 2343953 | 2260689 | 2145574 | 1630386 | 1526432 | 1327498 | 1327498 | 1327498 |
| **6000** | 3395543 | 3395543 | 3153672 | 2381921 | 2298729 | 2183688 | 1668315 | 1564395 | 1364779 | 1364779 | 1364779 |
| **6089** | 3398952 | 3398952 | 3157161 | 2385509 | 2302316 | 2187276 | 1671902 | 1567983 | 1368366 | 1368366 | 1368366 |

**Table 64** The average overall hazard values, obtained by EHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 2356841 | 2356841 | 2137398 | 1289261 | 1207038 | 1087793 | 1073509 | 1067026 | 1011398 | 1011398 | 1147267 |
| **1200** | 2611044 | 2611044 | 2356289 | 1547107 | 1464963 | 1345901 | 1331618 | 1325134 | 1269507 | 1269507 | 1405375 |
| **1800** | 2704583 | 2704583 | 2435065 | 1642445 | 1560300 | 1441239 | 1426955 | 1420471 | 1364844 | 1364844 | 1500712 |
| **2400** | 2749022 | 2749022 | 2481217 | 1689491 | 1607347 | 1488285 | 1474001 | 1467518 | 1411890 | 1411890 | 1547759 |
| **3000** | 2765920 | 2765920 | 2499111 | 1707385 | 1625240 | 1506179 | 1491895 | 1485411 | 1429784 | 1429784 | 1565652 |
| **3600** | 2790086 | 2790086 | 2524357 | 1733617 | 1651472 | 1532411 | 1518127 | 1511643 | 1456016 | 1456016 | 1591884 |
| **4200** | 3332385 | 3332385 | 3087948 | 2315304 | 2233015 | 2119283 | 1848178 | 1838740 | 1732780 | 1732780 | 2279431 |
| **4800** | 3357274 | 3357274 | 3112838 | 2340194 | 2257905 | 2144172 | 1873067 | 1863629 | 1757670 | 1757670 | 2304320 |
| **5400** | 3362617 | 3362617 | 3118180 | 2345536 | 2263247 | 2149515 | 1878409 | 1868972 | 1763012 | 1763012 | 2309662 |
| **6000** | 3395543 | 3395543 | 3153672 | 2383613 | 2301361 | 2187629 | 1916523 | 1907086 | 1801126 | 1801126 | 2347776 |
| **6089** | 3398952 | 3398952 | 3157161 | 2387201 | 2304949 | 2191216 | 1920111 | 1910673 | 1804714 | 1804714 | 2351364 |

**Table 65** The average overall hazard values, obtained by the considered solution algorithms, for the developed problem instances [**RAP-1**].

| Instance | CPLEX | MPHR | MEHR | PHR | EHR |
|---|---|---|---|---|---|
| 1 | 1802758.3 | 1815438.4 | 2121317.9 | 1815406.3 | 2101462.2 |
| 2 | 1791588.0 | 1804746.6 | 2112177.9 | 1804708.2 | 2072767.2 |
| 3 | 1781509.6 | 1795053.4 | 2120578.3 | 1794991.0 | 2064098.6 |
| 4 | 1772367.5 | 1786104.7 | 2071113.3 | 1786081.1 | 2056414.6 |
| 5 | 1763982.3 | 1778066.2 | 2064504.8 | 1778038.9 | 2047866.9 |
| 6 | 1756185.5 | 1770446.2 | 2060952.6 | 1770434.4 | 2040753.4 |
| 7 | 1748741.0 | 1763316.8 | 2050754.1 | 1763305.9 | 2033795.5 |
| 8 | 1741493.6 | 1756434.4 | 2040743.6 | 1756369.4 | 2025694.2 |
| 9 | 1734805.1 | 1749871.5 | 2036525.8 | 1749860.9 | 2003522.8 |
| 10 | 1728510.2 | 1743901.9 | 2033874.6 | 1743871.3 | 1992358.2 |
| 11 | 1722629.4 | 1738196.8 | 2016882.2 | 1738184.9 | 1988633.1 |
| 12 | 1716912.7 | 1732753.7 | 2013398.7 | 1732688.4 | 1983089.9 |
| **Average:** | **1755123.6** | **1769527.6** | **2061902.0** | **1769495.1** | **2034204.7** |

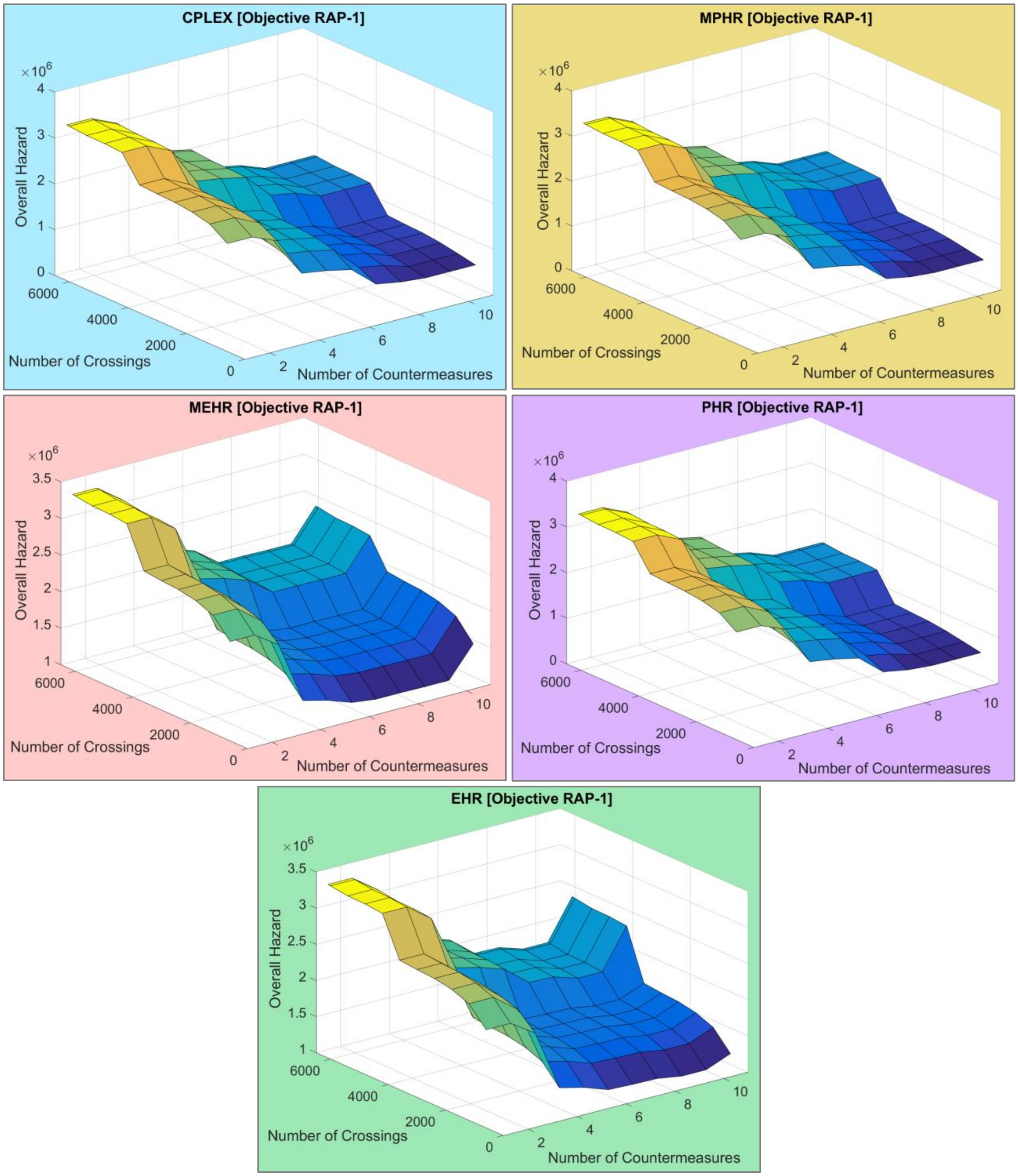



**Figure 51** The average overall hazard values, obtained by the considered solution algorithms, for the developed scenarios [**RAP-1**].

Furthermore, a detailed analysis of the scenarios, generated for the developed problem instances, indicated that the MEHR and EHR heuristics returned lower overall hazard values as compared to the MPHR and PHR heuristics for several scenarios with lower number of highway-rail grade crossings (e.g., MEHR outperformed MPHR and PHR for the scenario with $|X| = 600$ and

$|C| = 6$ – see Table 61, Table 62, and Table 63). Such pattern can be explained by the fact that selection of the most effective upgrades at the most hazardous highway-rail grade crossings would result in the highest hazard reduction, when the number of highway-rail grade crossings is not significant and the total available budget allows installation of the most effective countermeasures. However, MEHR did not outperform MPHR and PHR in terms of the overall hazard values by more than 0.18% over the generated scenarios of each problem instance. Also, EHR did not outperform MPHR and PHR in terms of the overall hazard values by more than 0.03% over the generated scenarios of each problem instance.

Performance of the MEHR and EHR heuristics is negatively affected with introduction of the countermeasures with high effectiveness factors and high installation costs (e.g., countermeasure "11" or grade separation, which has the effectiveness factor of 100% and the installation cost of $1,500,000 – see Figure 51), as both heuristics will select these high-cost countermeasures at the most hazardous highway-rail grade crossings, while the remaining budget will not be sufficient for upgrading any other crossings that have lower overall hazard values. On the other hand, both MPHR and PHR showcase a competitive performance and return the solutions, which are close to the optimal ones, for the problem instances with a large number of highway-rail grade crossings and availability of the countermeasures with high effectiveness factors and high installation costs, since they consider the hazard reduction-to-cost relationship for a given set of highway-rail grade crossings.

### ***9.1.2. CPU Time for RAP-1***

The average CPU time, required by CPLEX, MPHR, MEHR, PHR, and EHR, over the generated problem instances is presented in Table 66, Table 67, Table 68, Table 69, Table 70, and Figure 52 for each one of the developed scenarios for the **RAP-1** mathematical model. Furthermore, Table 71 shows the average CPU time, required by CPLEX, MPHR, MEHR, PHR, and EHR, over the generated scenarios for each one of the developed problem instances for the **RAP-1** mathematical model. It can be observed that the CPU time generally increased with increasing number of highway-rail grade crossings and available countermeasures for CPLEX and the developed heuristic algorithms. However, some CPU time fluctuations were noticed in certain cases (e.g., the CPU times for the MPHR heuristic – see Figure 52), which can be explained by the fact that the available CPU has been processing additional tasks along with execution of the solution algorithms (e.g., software updates, antivirus scan, etc.). The average CPU time, required by CPLEX, MPHR, MEHR, PHR, and HER, comprised 81.19 sec, 29.89 sec, 10.25 sec, 16.78, and 11.68 sec, respectively, over the generated scenarios for the developed problem instances. Such CPU time values can be considered as acceptable from the practical standpoint, and the FDOT personnel will be able to make the resource allocation decisions in a timely manner. However, large CPU time values were generally recorded for CPLEX, since it was executed from GAMS (i.e., an additional time incurred due to exchange of the data between MATLAB and GAMS).

**Table 66** The average CPU time, required by CPLEX, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 80.7745 | 80.7754 | 80.7777 | 80.7920 | 80.8063 | 80.8236 | 80.8460 | 80.8617 | 80.8709 | 80.8815 | 80.8905 |
| **1200** | 80.7789 | 80.7989 | 80.8194 | 80.8568 | 80.8840 | 80.9073 | 80.9319 | 80.9477 | 80.9652 | 80.9824 | 81.0014 |
| **1800** | 80.7985 | 80.8223 | 80.8586 | 80.9120 | 80.9413 | 80.9787 | 81.0152 | 81.0345 | 81.0530 | 81.0887 | 81.1319 |
| **2400** | 80.8178 | 80.8633 | 80.9173 | 80.9610 | 80.9896 | 81.0432 | 81.0884 | 81.1354 | 81.1644 | 81.2239 | 81.2714 |
| **3000** | 80.8383 | 80.9264 | 80.9604 | 80.9982 | 81.0429 | 81.1195 | 81.1833 | 81.2382 | 81.2741 | 81.3229 | 81.3932 |
| **3600** | 80.8618 | 80.9453 | 80.9903 | 81.0483 | 81.1091 | 81.2034 | 81.2745 | 81.3234 | 81.3868 | 81.4652 | 81.5185 |
| **4200** | 80.8908 | 80.9729 | 81.0246 | 81.0946 | 81.1785 | 81.2622 | 81.3716 | 81.4054 | 81.4737 | 81.5399 | 81.6232 |
| **4800** | 80.9090 | 81.0015 | 81.0628 | 81.1526 | 81.2571 | 81.3289 | 81.4139 | 81.4993 | 81.5705 | 81.6687 | 81.7621 |
| **5400** | 80.9336 | 81.0243 | 81.1095 | 81.2043 | 81.2917 | 81.3975 | 81.5027 | 81.5884 | 81.6916 | 81.7937 | 81.9257 |
| **6000** | 80.9620 | 81.0581 | 81.1587 | 81.2569 | 81.3546 | 81.4733 | 81.6366 | 81.6863 | 81.7994 | 81.9366 | 82.0741 |
| **6089** | 80.9663 | 81.0600 | 81.1673 | 81.2616 | 81.3599 | 81.5162 | 81.6143 | 81.7071 | 81.8245 | 81.9621 | 82.1037 |

**Table 67** The average CPU time, required by MPHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 29.2470 | 29.3004 | 29.2737 | 29.2691 | 29.3285 | 29.2809 | 29.3234 | 29.3253 | 29.4703 | 29.3381 | 29.3126 |
| **1200** | 29.4169 | 29.1793 | 29.1131 | 29.1029 | 29.1540 | 29.1628 | 29.1824 | 29.1764 | 29.1583 | 29.1677 | 29.2033 |
| **1800** | 29.2847 | 29.2918 | 29.4085 | 29.4158 | 29.4842 | 29.5561 | 29.4493 | 29.4261 | 29.5125 | 29.5298 | 29.7036 |
| **2400** | 29.5435 | 29.5668 | 29.7898 | 29.7110 | 29.5463 | 29.6020 | 29.5841 | 29.7176 | 29.7074 | 29.9064 | 29.8693 |
| **3000** | 29.8319 | 29.7516 | 29.9085 | 29.5543 | 29.5055 | 29.6105 | 29.5459 | 29.7420 | 29.5859 | 29.8370 | 29.7889 |
| **3600** | 29.4730 | 29.5851 | 29.6507 | 29.7779 | 29.6388 | 29.5300 | 29.5203 | 29.5918 | 29.6760 | 29.5706 | 29.6387 |
| **4200** | 29.5332 | 29.7144 | 29.7143 | 29.5571 | 29.6014 | 29.8462 | 30.2635 | 30.1892 | 30.0189 | 30.0241 | 29.9769 |
| **4800** | 29.8265 | 29.9506 | 30.1020 | 30.0814 | 30.0656 | 30.0729 | 30.0929 | 30.1483 | 30.3927 | 30.5604 | 30.5562 |
| **5400** | 30.2432 | 30.3121 | 30.5690 | 30.5529 | 30.4013 | 30.3660 | 30.2639 | 30.3922 | 30.4545 | 30.4291 | 30.5641 |
| **6000** | 30.3408 | 30.3367 | 30.2804 | 30.7697 | 30.7791 | 30.6845 | 30.5367 | 30.5812 | 30.6301 | 30.6761 | 30.8687 |
| **6089** | 30.6452 | 30.5914 | 30.7554 | 30.8705 | 30.7326 | 30.8943 | 30.8574 | 30.8604 | 30.9263 | 31.0708 | 31.0251 |

**Table 68** The average CPU time, required by MEHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 9.5761 | 9.3989 | 9.3748 | 9.3868 | 9.4068 | 9.4210 | 9.4048 | 9.4275 | 9.4446 | 9.4712 | 9.4701 |
| **1200** | 9.5078 | 9.5639 | 9.5373 | 9.5369 | 9.5549 | 9.5277 | 9.5560 | 9.5641 | 9.5965 | 9.5882 | 9.6005 |
| **1800** | 9.6481 | 9.6461 | 9.6767 | 9.6559 | 9.6459 | 9.6605 | 9.6877 | 9.7068 | 9.7112 | 9.7326 | 9.7846 |
| **2400** | 9.7477 | 9.8857 | 9.8516 | 9.8981 | 9.9052 | 9.9141 | 9.9483 | 9.9631 | 9.9732 | 9.9890 | 10.0718 |
| **3000** | 10.0156 | 9.9674 | 9.9786 | 10.0258 | 10.0620 | 10.0787 | 10.1122 | 10.1265 | 10.1559 | 10.1345 | 10.1560 |
| **3600** | 10.1270 | 10.1846 | 10.2168 | 10.1839 | 10.1882 | 10.2062 | 10.2539 | 10.2888 | 10.2952 | 10.3085 | 10.3292 |
| **4200** | 10.2202 | 10.2339 | 10.2540 | 10.3040 | 10.3371 | 10.3522 | 10.3666 | 10.4045 | 10.4198 | 10.4520 | 10.5625 |
| **4800** | 10.4047 | 10.3960 | 10.3749 | 10.5453 | 10.5745 | 10.5331 | 10.5494 | 10.5818 | 10.5939 | 10.6415 | 10.7836 |
| **5400** | 10.7982 | 10.7205 | 10.7143 | 10.8107 | 10.8445 | 10.8713 | 10.9151 | 10.9163 | 10.9437 | 10.9966 | 10.9820 |
| **6000** | 10.8036 | 10.8254 | 10.8689 | 10.9908 | 11.0159 | 11.0006 | 11.0248 | 11.0786 | 11.0826 | 11.0906 | 11.0934 |
| **6089** | 10.9061 | 10.9196 | 10.9717 | 11.1053 | 11.0923 | 11.0815 | 11.1428 | 11.1640 | 11.1805 | 11.2402 | 11.2814 |

**Table 69** The average CPU time, required by PHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 14.8088 | 14.7735 | 14.8296 | 14.7973 | 14.8467 | 14.9291 | 14.8803 | 14.9662 | 14.9125 | 14.9368 | 14.9688 |
| **1200** | 14.8924 | 14.9126 | 14.9285 | 14.9560 | 15.0683 | 15.1541 | 15.0748 | 15.1324 | 15.1961 | 15.3216 | 15.3745 |
| **1800** | 15.0548 | 15.0806 | 15.0940 | 15.1087 | 15.1535 | 15.2030 | 15.3044 | 15.3433 | 15.4989 | 15.5586 | 15.6333 |
| **2400** | 15.0713 | 15.1213 | 15.1365 | 15.2531 | 15.2407 | 15.4189 | 15.4948 | 15.5730 | 15.7874 | 15.8865 | 16.0417 |
| **3000** | 15.1235 | 15.2013 | 15.3029 | 15.2883 | 15.3728 | 15.4731 | 15.6745 | 15.7978 | 16.1630 | 16.4260 | 16.6320 |
| **3600** | 15.2995 | 15.4272 | 15.3833 | 15.4982 | 15.6129 | 15.7502 | 16.0442 | 16.1925 | 16.6076 | 16.8529 | 17.0912 |
| **4200** | 15.3900 | 15.4343 | 15.5640 | 15.7352 | 15.8787 | 16.0287 | 16.3299 | 16.5169 | 17.0241 | 17.3266 | 18.8858 |
| **4800** | 15.5321 | 15.5748 | 15.6944 | 15.8820 | 16.0153 | 16.2307 | 16.6154 | 16.9253 | 17.4770 | 19.8802 | 22.7300 |
| **5400** | 15.8520 | 15.9140 | 16.0670 | 16.2172 | 16.4289 | 16.6664 | 17.1680 | 17.5432 | 20.5227 | 23.6579 | 27.1832 |
| **6000** | 15.9258 | 16.0375 | 16.1930 | 16.4104 | 16.6774 | 16.9778 | 17.5030 | 20.0011 | 23.8097 | 27.6733 | 32.0034 |
| **6089** | 16.0867 | 16.1806 | 16.3669 | 16.6079 | 16.8886 | 17.1432 | 17.6530 | 20.5938 | 24.5019 | 28.5752 | 32.8449 |

**Table 70** The average CPU time, required by EHR, for the developed scenarios [**RAP-1**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 9.8884 | 9.7122 | 9.7573 | 9.7521 | 9.7549 | 9.7572 | 9.8060 | 9.7957 | 9.8461 | 9.8268 | 9.8661 |
| **1200** | 9.8189 | 9.8517 | 9.8342 | 9.8844 | 9.9262 | 9.9248 | 9.9839 | 9.9988 | 10.0418 | 10.0732 | 10.1052 |
| **1800** | 9.9764 | 10.0098 | 10.0522 | 10.0966 | 10.0871 | 10.1233 | 10.1614 | 10.2345 | 10.2945 | 10.3469 | 10.3836 |
| **2400** | 10.0710 | 10.1899 | 10.1608 | 10.2003 | 10.2788 | 10.2735 | 10.3131 | 10.4200 | 10.4764 | 10.6367 | 10.7152 |
| **3000** | 10.1669 | 10.1464 | 10.2292 | 10.2661 | 10.3691 | 10.4537 | 10.5529 | 10.6688 | 10.7836 | 10.9355 | 11.1397 |
| **3600** | 10.3081 | 10.3351 | 10.3631 | 10.5111 | 10.5876 | 10.6895 | 10.8356 | 10.9946 | 11.1514 | 11.3445 | 11.5504 |
| **4200** | 10.3182 | 10.3932 | 10.4760 | 10.5483 | 10.6999 | 10.8782 | 11.0200 | 11.2588 | 11.5016 | 11.7537 | 13.2588 |
| **4800** | 10.4922 | 10.5278 | 10.6269 | 10.7645 | 10.9351 | 11.1007 | 11.3490 | 11.7163 | 12.0288 | 14.4867 | 17.2892 |
| **5400** | 10.8954 | 10.9965 | 11.1051 | 11.2703 | 11.4902 | 11.7583 | 12.0496 | 12.3549 | 15.2010 | 18.5071 | 21.9593 |
| **6000** | 11.0115 | 11.1597 | 11.2921 | 11.5501 | 11.7909 | 12.0931 | 12.4173 | 15.1988 | 18.7893 | 22.8704 | 27.2813 |
| **6089** | 11.3145 | 11.3816 | 11.4938 | 11.7130 | 11.9681 | 12.3213 | 12.6361 | 15.5444 | 19.3112 | 23.4300 | 27.9599 |

**Table 71** The average CPU time, required by the considered solution algorithms, for the developed problem instances [**RAP-1**].

| Instance | CPLEX | MPHR | MEHR | PHR | EHR |
|---|---|---|---|---|---|
| 1 | 81.2341 | 22.9996 | 2.8711 | 9.6014 | 4.3790 |
| 2 | 81.1790 | 23.4100 | 4.3074 | 10.7004 | 5.7838 |
| 3 | 81.1772 | 24.7488 | 5.7418 | 12.9317 | 7.2130 |
| 4 | 81.1997 | 26.0894 | 7.1103 | 14.2918 | 8.6722 |
| 5 | 81.1887 | 27.4256 | 8.0442 | 14.8401 | 10.0820 |
| 6 | 81.1955 | 28.8453 | 9.4199 | 15.8962 | 10.9678 |
| 7 | 81.1694 | 30.1043 | 10.7273 | 17.2545 | 11.7212 |
| 8 | 81.1568 | 33.0137 | 12.0542 | 18.5729 | 13.1138 |
| 9 | 81.1526 | 34.5303 | 13.3985 | 19.8464 | 15.3944 |
| 10 | 81.1760 | 34.0772 | 14.7706 | 21.1538 | 16.7427 |
| 11 | 81.2046 | 35.6770 | 16.1121 | 22.4718 | 17.3051 |
| 12 | 81.1855 | 37.7855 | 18.4550 | 23.8091 | 18.7206 |
| **Average:** | **81.1849** | **29.8922** | **10.2510** | **16.7808** | **11.6746** |

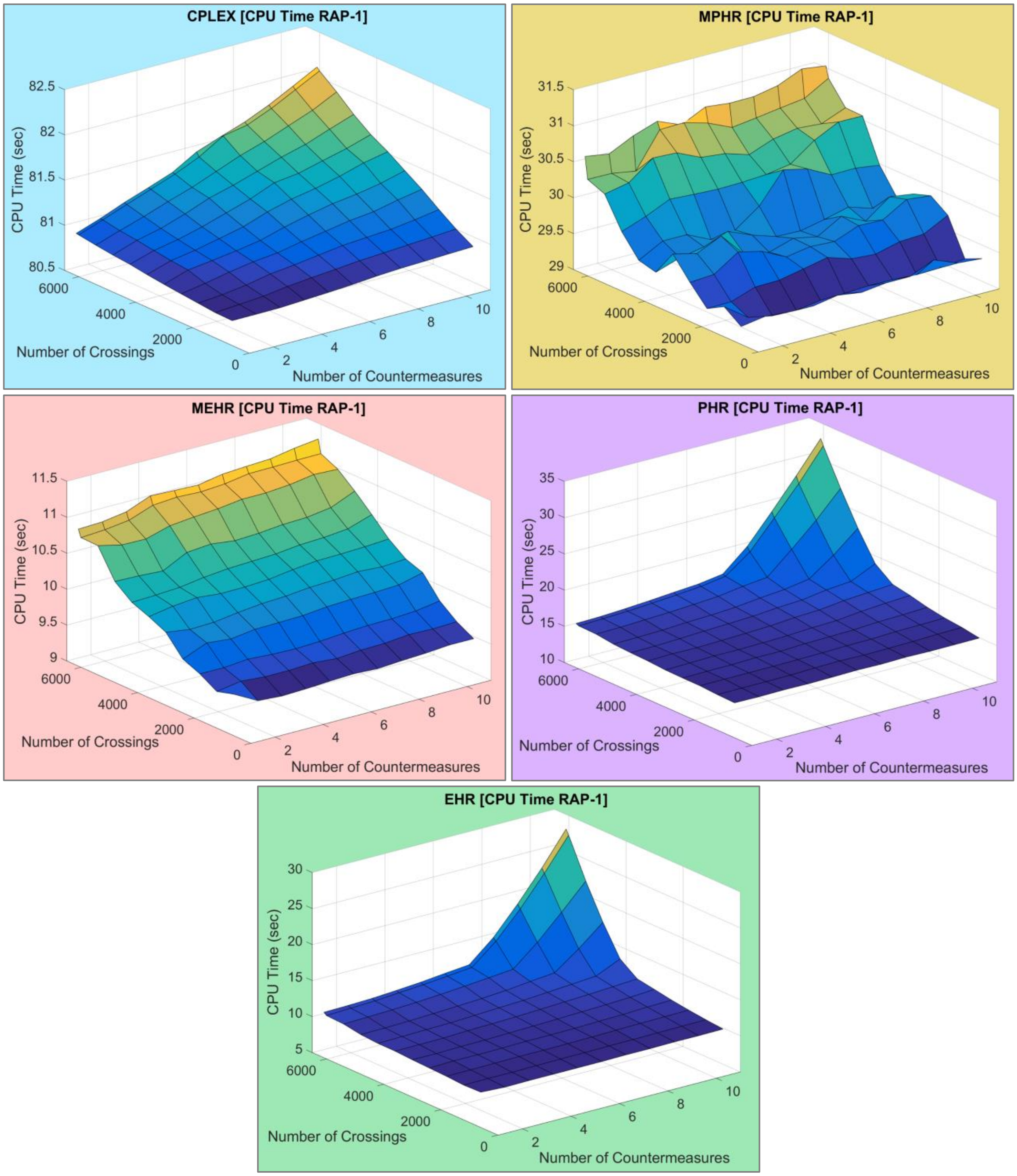



**Figure 52** The average CPU time, required by the considered solution algorithms, for the developed scenarios [**RAP-1**].

### *9.1.3. Solution Algorithm Recommendation for RAP-1*

Based on a detailed evaluation of CPLEX and the MPHR, MEHR, PHR, and EHR heuristic algorithms for the **RAP-1** mathematical model, it was found that all the considered solution algorithms are promising in terms of the CPU time. However, the MEHR and EHR heuristic algorithms were substantially outperformed by CPLEX, MPHR, and PHR in terms of the objective function values. Although CPLEX was able to obtain the global optimal solutions for all the generated scenarios of each problem instance within a reasonable computational time, there may be some challenges with implementation of CPLEX for the **RAP-1** mathematical model. The latter can be explained by the fact that the FDOT personnel will be required to have a license to use CPLEX. On the other hand, the proposed heuristic algorithms can be embedded within standalone applications, which do not require any licenses.

As for the MPHR and PHR heuristics, the PHR heuristic provided the solutions with lower overall hazard values as compared to the MPHR heuristic for some of the developed scenarios, as it allocates the remaining budget more effectively once the countermeasures with the highest hazard reduction-to-cost ratios have been implemented at the hazardous highway-rail grade crossings. Specifically, the PHR heuristic consistently assigns countermeasures to the hazardous highway-rail grade crossings based the hazard reduction-to-cost ratios throughout the resource allocation procedure (see section 8.2.1 of this report for more details). On the other hand, the MPHR heuristic assigns the countermeasures with the highest hazard reduction-to-cost ratios to the hazardous highway-rail grade crossings, while the remaining budget is used to implement eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading) without considering the hazard reduction-to-cost ratios for these crossings. Hence, the PHR heuristic is superior to the MPHR heuristic from the methodological standpoint and is recommended as a solution algorithm for the **RAP-1** mathematical model.

## 9.2. Evaluation of the Algorithms for the RAP-2 Mathematical Model

### *9.2.1. Solution Quality for RAP-2*

CPLEX and the MPSR, MESR, PSR, and ESR heuristic algorithms were executed to solve the **RAP-2** mathematical model for all the generated scenarios of each problem instance. A total of five replications were performed for each one of the considered solution algorithms in order to estimate the average computational time values. Note that the objective function values, returned by the developed solution algorithms, did not change from one replication to another, as all the algorithms are deterministic in their nature. The average overall hazard severity values, obtained by CPLEX, MPSR, MESR, PSR, and ESR, over the generated problem instances are presented in Table 72, Table 73, Table 74, Table 75, Table 76, and Figure 53 for each one of the developed scenarios for the **RAP-2** mathematical model. Furthermore, Table 77 shows the average overall hazard severity values, obtained by CPLEX, MPSR, MESR, PSR, and ESR, over the generated scenarios for each one of the developed problem instances for the **RAP-2** mathematical model.

**Table 72** The average overall hazard severity values, obtained by CPLEX, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 471374 | 471374 | 433505 | 257037 | 238130 | 213721 | 123495 | 104717 | 94607 | 94607 | 94361 |
| **1200** | 521975 | 521975 | 477647 | 307915 | 289346 | 264864 | 160565 | 140190 | 108678 | 108678 | 108678 |
| **1800** | 539787 | 539787 | 492614 | 326032 | 307463 | 282980 | 178675 | 158288 | 121211 | 121211 | 121227 |
| **2400** | 548362 | 548362 | 501383 | 335061 | 316492 | 292009 | 187695 | 167329 | 129747 | 129747 | 129741 |
| **3000** | 551653 | 551653 | 504844 | 338522 | 319952 | 295470 | 191161 | 170789 | 133200 | 133200 | 133200 |
| **3600** | 555824 | 555824 | 509190 | 343026 | 324456 | 299974 | 195687 | 175286 | 137484 | 137484 | 137471 |
| **4200** | 645335 | 645335 | 602586 | 433779 | 415677 | 391557 | 285963 | 265721 | 225989 | 225989 | 226078 |
| **4800** | 650083 | 650083 | 607340 | 438537 | 420436 | 396317 | 290745 | 270500 | 230781 | 230781 | 230778 |
| **5400** | 651121 | 651121 | 608378 | 439576 | 421474 | 397355 | 291672 | 271435 | 231732 | 231732 | 231730 |
| **6000** | 656718 | 656718 | 614388 | 446085 | 427989 | 403871 | 297950 | 277728 | 237931 | 237931 | 237929 |
| **6089** | 657282 | 657282 | 614984 | 446687 | 428591 | 404473 | 298554 | 278332 | 238536 | 238536 | 238534 |

**Table 73** The average overall hazard severity values, obtained by MPSR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 471374 | 471374 | 433505 | 257037 | 238130 | 213721 | 127234 | 106794 | 97877 | 97877 | 97877 |
| **1200** | 521975 | 521975 | 477647 | 307915 | 289346 | 264864 | 162709 | 141231 | 110918 | 110918 | 110918 |
| **1800** | 539787 | 539787 | 492614 | 326032 | 307463 | 282980 | 180798 | 159316 | 122905 | 122905 | 122905 |
| **2400** | 548362 | 548362 | 501383 | 335061 | 316492 | 292009 | 189827 | 168346 | 131325 | 131325 | 131325 |
| **3000** | 551653 | 551653 | 504844 | 338522 | 319952 | 295470 | 193288 | 171806 | 134772 | 134772 | 134772 |
| **3600** | 555824 | 555824 | 509190 | 343026 | 324456 | 299974 | 197792 | 176310 | 139045 | 139045 | 139045 |
| **4200** | 645335 | 645335 | 602586 | 440137 | 421915 | 397835 | 294692 | 273298 | 234451 | 234451 | 234451 |
| **4800** | 650083 | 650083 | 607340 | 444891 | 426668 | 402588 | 299446 | 278052 | 239205 | 239205 | 239205 |
| **5400** | 651121 | 651121 | 608378 | 445928 | 427706 | 403626 | 300483 | 279089 | 240242 | 240242 | 240242 |
| **6000** | 656718 | 656718 | 614388 | 452439 | 434214 | 410134 | 306959 | 285569 | 246579 | 246579 | 246579 |
| **6089** | 657282 | 657282 | 614984 | 453040 | 434815 | 410735 | 307560 | 286170 | 247180 | 247180 | 247180 |

**Table 74** The average overall hazard severity values, obtained by MESR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 471374 | 470415 | 432547 | 256814 | 238352 | 213937 | 202423 | 202423 | 201126 | 201126 | 296496 |
| **1200** | 521975 | 520748 | 476474 | 307977 | 289463 | 265067 | 256753 | 256753 | 255385 | 255385 | 347056 |
| **1800** | 539787 | 538448 | 491807 | 326093 | 307580 | 283184 | 274870 | 274870 | 273502 | 273502 | 365172 |
| **2400** | 548362 | 546860 | 500674 | 335123 | 316609 | 292213 | 283899 | 283899 | 282531 | 282531 | 374202 |
| **3000** | 551653 | 550172 | 504134 | 338583 | 320070 | 295673 | 287360 | 287360 | 285991 | 285991 | 377662 |
| **3600** | 555824 | 554403 | 508491 | 343087 | 324574 | 300177 | 291864 | 291864 | 290495 | 290495 | 382166 |
| **4200** | 645335 | 645335 | 602586 | 440137 | 421915 | 397835 | 354219 | 354219 | 352981 | 352981 | 447195 |
| **4800** | 650083 | 650083 | 607340 | 444891 | 426668 | 402588 | 358972 | 358972 | 357735 | 357735 | 451949 |
| **5400** | 651121 | 651121 | 608378 | 445928 | 427706 | 403626 | 360010 | 360010 | 358772 | 358772 | 452986 |
| **6000** | 656718 | 656718 | 614388 | 452439 | 434214 | 410134 | 366517 | 366517 | 365280 | 365280 | 459494 |
| **6089** | 657282 | 657282 | 614984 | 453040 | 434815 | 410735 | 367119 | 367119 | 365881 | 365881 | 460095 |

**Table 75** The average overall hazard severity values, obtained by PSR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 471374 | 471374 | 433505 | 257037 | 238130 | 213721 | 127234 | 106794 | 97877 | 97877 | 97877 |
| **1200** | 521975 | 521975 | 477647 | 307915 | 289346 | 264864 | 162709 | 141228 | 110895 | 110895 | 110895 |
| **1800** | 539787 | 539787 | 492614 | 326032 | 307463 | 282980 | 180798 | 159314 | 122864 | 122864 | 122864 |
| **2400** | 548362 | 548362 | 501383 | 335061 | 316492 | 292009 | 189827 | 168343 | 131307 | 131307 | 131307 |
| **3000** | 551653 | 551653 | 504844 | 338522 | 319952 | 295470 | 193288 | 171804 | 134761 | 134761 | 134761 |
| **3600** | 555824 | 555824 | 509190 | 343026 | 324456 | 299974 | 197792 | 176308 | 139008 | 139008 | 139008 |
| **4200** | 645335 | 645335 | 602586 | 440137 | 421915 | 397835 | 294692 | 273296 | 234402 | 234402 | 234402 |
| **4800** | 650083 | 650083 | 607340 | 444891 | 426668 | 402588 | 299446 | 278049 | 239155 | 239155 | 239155 |
| **5400** | 651121 | 651121 | 608378 | 445928 | 427706 | 403626 | 300483 | 279087 | 240193 | 240193 | 240193 |
| **6000** | 656718 | 656718 | 614388 | 452439 | 434214 | 410134 | 306959 | 285569 | 246538 | 246538 | 246538 |
| **6089** | 657282 | 657282 | 614984 | 453040 | 434815 | 410735 | 307560 | 286170 | 247139 | 247139 | 247139 |

**Table 76** The average overall hazard severity values, obtained by ESR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 471374 | 470415 | 432547 | 257433 | 239121 | 214417 | 211471 | 210176 | 201233 | 201233 | 226296 |
| **1200** | 521975 | 520748 | 476477 | 308735 | 290434 | 265747 | 262801 | 261506 | 252563 | 252563 | 277626 |
| **1800** | 539787 | 538448 | 491870 | 326851 | 308550 | 283864 | 280918 | 279622 | 270680 | 270680 | 295743 |
| **2400** | 548362 | 546860 | 500806 | 335881 | 317580 | 292893 | 289947 | 288652 | 279709 | 279709 | 304772 |
| **3000** | 551653 | 550172 | 504266 | 339341 | 321040 | 296353 | 293408 | 292112 | 283169 | 283169 | 308232 |
| **3600** | 555824 | 554403 | 508627 | 343845 | 325544 | 300857 | 297912 | 296616 | 287673 | 287673 | 312736 |
| **4200** | 645335 | 645335 | 602586 | 440137 | 421915 | 397835 | 355238 | 351729 | 347846 | 347846 | 441300 |
| **4800** | 650083 | 650083 | 607340 | 444891 | 426668 | 402588 | 359992 | 356483 | 352600 | 352600 | 446054 |
| **5400** | 651121 | 651121 | 608378 | 445928 | 427706 | 403626 | 361030 | 357520 | 353637 | 353637 | 447092 |
| **6000** | 656718 | 656718 | 614388 | 452439 | 434214 | 410134 | 367537 | 364028 | 360145 | 360145 | 453599 |
| **6089** | 657282 | 657282 | 614984 | 453040 | 434815 | 410735 | 368139 | 364630 | 360746 | 360746 | 454201 |

**Table 77** The average overall hazard severity values, obtained by the considered solution algorithms, for the developed problem instances [**RAP-2**].

| Instance | CPLEX | MPSR | MESR | PSR | ESR |
|---|---|---|---|---|---|
| 1 | 348227.2 | 350835.6 | 414025.1 | 350820.8 | 409626.2 |
| 2 | 345960.7 | 348706.3 | 413755.8 | 348694.1 | 407723.8 |
| 3 | 343946.4 | 346773.6 | 412041.1 | 346768.7 | 403869.5 |
| 4 | 342080.2 | 345002.4 | 404133.4 | 344992.4 | 402275.5 |
| 5 | 340414.2 | 343390.1 | 405017.3 | 343376.2 | 400441.6 |
| 6 | 338779.6 | 341825.1 | 402815.9 | 341815.0 | 398961.1 |
| 7 | 337344.6 | 340412.2 | 400018.3 | 340402.6 | 397559.1 |
| 8 | 335944.2 | 339064.2 | 397008.1 | 339053.5 | 396298.2 |
| 9 | 334608.9 | 337801.3 | 397052.9 | 337796.5 | 394716.8 |
| 10 | 333545.3 | 336630.6 | 393861.8 | 336623.7 | 389561.8 |
| 11 | 332224.7 | 335490.5 | 390915.7 | 335486.0 | 388406.8 |
| 12 | 331327.9 | 334426.2 | 390775.0 | 334419.4 | 387516.3 |
| **Average:** | **338700.3** | **341696.5** | **401785.0** | **341687.4** | **398079.7** |

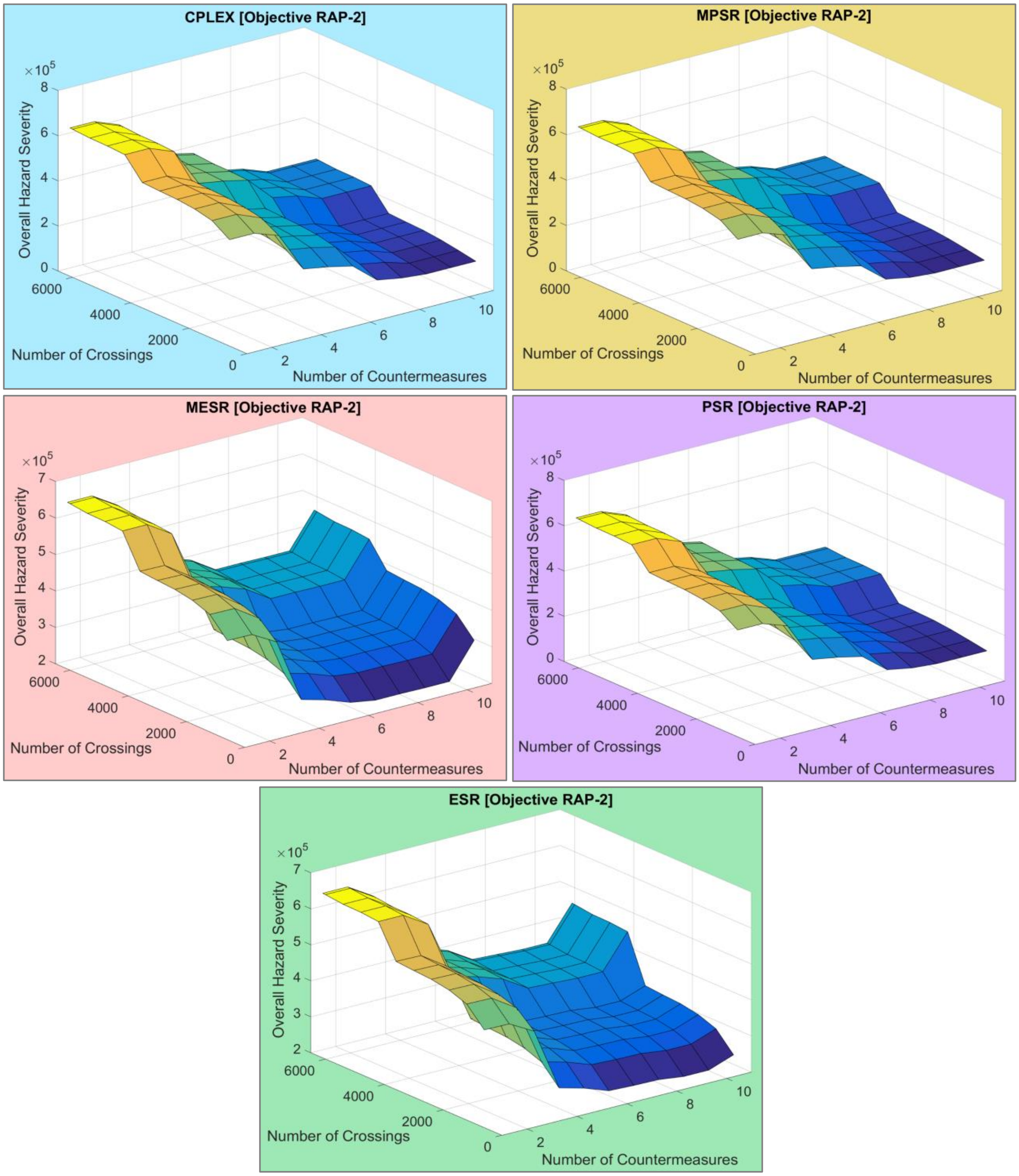



**Figure 53** The average overall hazard severity values, obtained by the considered solution algorithms, for the developed scenarios [**RAP-2**].

The average overall hazard severity values, obtained by CPLEX, MPSR, MESR, PSR, and ESR, comprised 338,700.3, 341,696.5, 401,785.0, 341,687.4, and 398,079.7, respectively, over the generated scenarios for the developed problem instances. Therefore, the MPSR and PSR heuristic algorithms obtained the solutions for the **RAP-2** mathematical model, which were close to the optimal solutions (obtained by CPLEX) for all the developed problem instances. The difference in the objective function values for the solutions, suggested by the MPSR and PSR heuristics, and the optimal ones on average did not exceed 0.88% over the developed problem instances (see Table 77). It was observed that the PSR heuristic provided the solutions with lower overall hazard severity values as compared to the MPSR heuristic for some of the developed scenarios, as it allocates the remaining budget more effectively once the countermeasures with the highest severity reduction-to-cost ratios have been implemented at the hazardous highway-rail grade crossings (see section 8.2.2 of this report for more details).

On the other hand, the MESR and ESR heuristic algorithms demonstrated quite a substantial difference in the objective function values as compared to the optimal ones. Specifically, CPLEX outperformed the MESR and ESR heuristics in terms of the objective function values on average by 18.63% and 17.53% over the developed problem instances (see Table 77). Therefore, prioritization of the highway-rail grade crossings for safety improvement projects based on the severity reduction-to-cost ratios (adopted within MPSR and PSR) was found to be more promising as compared to prioritization of the highway-rail grade crossings for safety improvement projects based on combination of the severity reduction-to-cost ratios and the severity reduction (adopted within MESR) or solely based on the severity reduction (adopted within ESR).

Furthermore, a detailed analysis of the scenarios, generated for the developed problem instances, indicated that the MESR and ESR heuristics returned lower overall hazard severity values as compared to the MPSR and PSR heuristics for several scenarios with lower number of highway-rail grade crossings (e.g., MESR outperformed MPSR and PSR for the scenario with $|X| = 600$ and $|C| = 3$ – see Table 73, Table 74, and Table 75). Such pattern can be explained by the fact that selection of the most effective upgrades at the most hazardous highway-rail grade crossings would result in the highest severity reduction, when the number of highway-rail grade crossings is not significant and the total available budget allows installation of the most effective countermeasures. However, MESR did not outperform MPSR and PSR in terms of the overall hazard severity values by more than 0.28% over the generated scenarios of each problem instance. Also, ESR did not outperform MPSR and PSR in terms of the overall hazard severity values by more than 0.28% over the generated scenarios of each problem instance.

Performance of the MESR and ESR heuristics is negatively affected with introduction of the countermeasures with high effectiveness factors and high installation costs (e.g., countermeasure “11” or grade separation, which has the effectiveness factor of 100% and the installation cost of $1,500,000 – see Figure 53), as both heuristics will select these high-cost countermeasures at the most hazardous highway-rail grade crossings, while the remaining budget will not be sufficient for upgrading any other crossings that have lower overall hazard severity values. On the other hand, both MPSR and PSR showcase a competitive performance and return the solutions, which are close to the optimal ones, for the problem instances with a large number of highway-rail grade crossings and availability of the countermeasures with high effectiveness factors and high installation costs, since they consider the severity reduction-to-cost relationship for a given set of highway-rail grade crossings.

### *9.2.2. CPU Time for RAP-2*

The average CPU time, required by CPLEX, MPSR, MESR, PSR, and ESR, over the generated problem instances is presented in Table 78, Table 79, Table 80, Table 81, Table 82, and Figure 54 for each one of the developed scenarios for the **RAP-2** mathematical model. Furthermore, Table 83 shows the average CPU time, required by CPLEX, MPSR, MESR, PSR, and ESR, over the generated scenarios for each one of the developed problem instances for the **RAP-2** mathematical model. It can be observed that the CPU time generally increased with increasing number of highway-rail grade crossings and available countermeasures for CPLEX and the developed heuristic algorithms. However, some CPU time fluctuations were noticed in certain cases (e.g., the CPU times for CPLEX – see Figure 54), which can be explained by the fact that the available CPU has been processing additional tasks along with execution of the solution algorithms (e.g., software updates, antivirus scan, etc.). The average CPU time, required by CPLEX, MPSR, MESR, PSR, and ESR, comprised 79.64 sec, 14.52 sec, 13.94 sec, 15.01 sec, and 15.24 sec, respectively, over the generated scenarios for the developed problem instances. Such CPU time values can be considered as acceptable from the practical standpoint, and the FDOT personnel will be able to make the resource allocation decisions in a timely manner. However, large CPU time values were generally recorded for CPLEX, since it was executed from GAMS (i.e., an additional time incurred due to exchange of the data between MATLAB and GAMS).

### *9.2.3. Solution Algorithm Recommendation for RAP-2*

Based on a detailed evaluation of CPLEX and the MPSR, MESR, PSR, and ESR heuristic algorithms for the **RAP-2** mathematical model, it was found that all the considered solution algorithms are promising in terms of the CPU time. However, the MESR and ESR heuristic algorithms were substantially outperformed by CPLEX, MPSR, and PSR in terms of the objective function values. Although CPLEX was able to obtain the global optimal solutions for all the generated scenarios of each problem instance within a reasonable computational time, there may be some challenges with implementation of CPLEX for the **RAP-2** mathematical model. The latter can be explained by the fact that the FDOT personnel will be required to have a license to use CPLEX. On the other hand, the proposed heuristic algorithms can be embedded within standalone applications, which do not require any licenses.

As for the MPSR and PSR heuristics, the PSR heuristic provided the solutions with lower overall hazard severity values as compared to the MPSR heuristic for some of the developed scenarios, as it allocates the remaining budget more effectively once the countermeasures with the highest severity reduction-to-cost ratios have been implemented at the hazardous highway-rail grade crossings. Specifically, the PSR heuristic consistently assigns countermeasures to the hazardous highway-rail grade crossings based the severity reduction-to-cost ratios throughout the resource allocation procedure (see section 8.2.2 of this report for more details). On the other hand, the MPSR heuristic assigns the countermeasures with the highest severity reduction-to-cost ratios to the hazardous highway-rail grade crossings, while the remaining budget is used to implement eligible countermeasures at some of the highway-rail grade crossings in the priority list (that have not been selected for upgrading) without considering the severity reduction-to-cost ratios for these crossings. Hence, the PSR heuristic is superior to the MPSR heuristic from the methodological standpoint and is recommended as a solution algorithm for the **RAP-2** mathematical model.

**Table 78** The average CPU time, required by CPLEX, for the developed scenarios [**RAP-2**].

| **\|X\|/\|C\|** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 78.1152 | 78.1345 | 78.0735 | 78.2496 | 78.4018 | 78.4654 | 79.2582 | 79.0363 | 78.9103 | 79.3645 | 78.9979 |
| **1200** | 78.8253 | 78.7452 | 78.5650 | 78.5456 | 78.9007 | 79.1243 | 79.3920 | 78.8767 | 78.9122 | 79.1154 | 79.6670 |
| **1800** | 79.5435 | 79.4421 | 79.6235 | 79.6972 | 79.7160 | 79.1980 | 79.5875 | 79.0246 | 78.6709 | 78.6359 | 78.8410 |
| **2400** | 78.1995 | 78.2152 | 78.3845 | 78.3674 | 78.5125 | 78.9265 | 78.9907 | 79.0060 | 78.9286 | 79.2428 | 78.9863 |
| **3000** | 78.7694 | 78.8593 | 79.8122 | 80.0227 | 79.8848 | 79.9828 | 80.1295 | 80.3419 | 80.2780 | 80.2533 | 80.4663 |
| **3600** | 79.9554 | 79.9982 | 80.4447 | 80.3286 | 80.1242 | 80.3462 | 80.2832 | 80.4872 | 80.4628 | 80.4709 | 80.7084 |
| **4200** | 80.1171 | 80.1286 | 80.1782 | 80.5216 | 80.4455 | 80.2854 | 79.8860 | 79.6930 | 79.8938 | 80.0513 | 80.0915 |
| **4800** | 79.5179 | 79.6656 | 79.6522 | 79.5901 | 79.4177 | 79.1783 | 79.1711 | 79.3042 | 78.7250 | 79.3657 | 79.8406 |
| **5400** | 78.8334 | 78.7014 | 79.3696 | 79.7351 | 79.7001 | 79.6122 | 79.5514 | 80.0116 | 80.5458 | 80.5982 | 80.6544 |
| **6000** | 79.4377 | 80.0701 | 79.6431 | 80.3101 | 80.7020 | 80.0002 | 80.2962 | 80.6164 | 80.8468 | 81.0791 | 80.8330 |
| **6089** | 79.6577 | 79.5125 | 80.0327 | 80.1204 | 80.4464 | 80.4450 | 81.2358 | 80.8149 | 81.3618 | 81.2863 | 81.4503 |

**Table 79** The average CPU time, required by MPSR, for the developed scenarios [**RAP-2**].

| **\|X\|/\|C\|** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 13.6129 | 13.4505 | 13.4887 | 13.4915 | 13.5207 | 13.5072 | 13.4687 | 13.5030 | 13.5268 | 13.5583 | 13.7174 |
| **1200** | 13.6077 | 13.5256 | 13.5804 | 13.6632 | 13.7950 | 13.8495 | 13.8243 | 13.8276 | 13.8438 | 13.8482 | 13.8304 |
| **1800** | 13.7555 | 13.8419 | 13.9402 | 13.8863 | 13.9226 | 14.0255 | 14.0105 | 14.0005 | 14.0231 | 14.0445 | 14.1912 |
| **2400** | 14.1757 | 14.2251 | 14.1368 | 14.1381 | 14.1574 | 14.2075 | 14.2126 | 14.3791 | 14.2640 | 14.2175 | 14.2516 |
| **3000** | 14.2017 | 14.2965 | 14.3015 | 14.3502 | 14.3776 | 14.3051 | 14.2972 | 14.3736 | 14.3439 | 14.3850 | 14.4361 |
| **3600** | 14.3491 | 14.4320 | 14.4180 | 14.4422 | 14.4663 | 14.5229 | 14.5045 | 14.4602 | 14.5135 | 14.5407 | 14.5565 |
| **4200** | 14.4230 | 14.4152 | 14.4874 | 14.6071 | 14.6438 | 14.5601 | 14.5801 | 14.6574 | 14.6737 | 14.6930 | 14.7919 |
| **4800** | 14.5974 | 14.5920 | 14.6493 | 14.6314 | 14.7802 | 14.8253 | 14.7704 | 14.8144 | 14.8484 | 14.8536 | 14.9670 |
| **5400** | 15.0174 | 15.0795 | 15.0629 | 15.1592 | 15.1215 | 15.1712 | 15.2390 | 15.2501 | 15.2658 | 15.2763 | 15.3381 |
| **6000** | 15.1160 | 15.1732 | 15.2398 | 15.3456 | 15.3313 | 15.4081 | 15.5209 | 15.4710 | 15.5004 | 15.5445 | 15.6166 |
| **6089** | 15.3122 | 15.3171 | 15.3795 | 15.4609 | 15.5603 | 15.6317 | 15.7009 | 15.6829 | 15.7126 | 15.8010 | 15.8352 |

**Table 80** The average CPU time, required by MESR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 12.9651 | 12.7661 | 12.8772 | 12.8397 | 12.8447 | 12.8532 | 12.8607 | 12.8812 | 12.8978 | 12.9064 | 12.9283 |
| **1200** | 12.9521 | 12.9943 | 13.0544 | 12.9634 | 12.9749 | 13.0693 | 13.1820 | 13.2188 | 13.2266 | 13.2226 | 13.2749 |
| **1800** | 13.2836 | 13.2963 | 13.3334 | 13.3672 | 13.3404 | 13.3814 | 13.4225 | 13.4113 | 13.4616 | 13.3822 | 13.4560 |
| **2400** | 13.4414 | 13.4003 | 13.4332 | 13.4374 | 13.4850 | 13.5126 | 13.5224 | 13.5569 | 13.6033 | 13.5915 | 13.6265 |
| **3000** | 13.5538 | 13.6425 | 13.6209 | 13.6183 | 13.6484 | 13.7046 | 13.7337 | 13.7823 | 13.7770 | 13.7519 | 13.7713 |
| **3600** | 13.7040 | 13.7325 | 13.7529 | 13.8655 | 13.8464 | 13.8571 | 13.9467 | 13.9217 | 13.9340 | 13.9528 | 13.9638 |
| **4200** | 13.9138 | 13.9087 | 13.9336 | 14.0190 | 14.0019 | 14.0430 | 14.0816 | 14.0925 | 14.0950 | 14.1654 | 14.1851 |
| **4800** | 14.0832 | 14.1107 | 14.1496 | 14.2033 | 14.2024 | 14.2251 | 14.2770 | 14.3038 | 14.3431 | 14.3608 | 14.3974 |
| **5400** | 14.4137 | 14.4954 | 14.5931 | 14.8775 | 14.7570 | 14.6404 | 14.6828 | 14.7034 | 14.7845 | 14.7661 | 14.7822 |
| **6000** | 14.6068 | 14.6651 | 14.7069 | 14.7961 | 14.8429 | 14.9019 | 15.0304 | 14.9664 | 15.0266 | 15.0264 | 15.0533 |
| **6089** | 14.8546 | 14.8811 | 14.9325 | 15.0313 | 15.0736 | 15.1089 | 15.1132 | 15.2573 | 15.2738 | 15.2028 | 15.2407 |

**Table 81** The average CPU time, required by PSR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 12.8720 | 12.6995 | 12.6972 | 12.7371 | 12.7535 | 12.7807 | 12.8677 | 12.8674 | 12.8316 | 13.0274 | 12.9670 |
| **1200** | 12.8998 | 12.8970 | 12.9415 | 12.9613 | 12.9877 | 13.0110 | 13.1305 | 13.2058 | 13.2340 | 13.3351 | 13.3920 |
| **1800** | 13.0470 | 13.0758 | 13.1399 | 13.1809 | 13.2104 | 13.2903 | 13.3530 | 13.4441 | 13.6187 | 13.7027 | 13.7968 |
| **2400** | 13.2449 | 13.3043 | 13.4091 | 13.3561 | 13.4429 | 13.4970 | 13.7086 | 13.7350 | 14.0496 | 14.1472 | 14.2193 |
| **3000** | 13.3705 | 13.4014 | 13.4558 | 13.5632 | 13.5948 | 13.6765 | 13.8721 | 13.9689 | 14.3289 | 14.4522 | 14.6508 |
| **3600** | 13.4116 | 13.4708 | 13.5658 | 13.7145 | 13.7712 | 13.8567 | 14.1428 | 14.3297 | 14.7933 | 15.0099 | 15.2544 |
| **4200** | 13.5678 | 13.6784 | 13.7592 | 13.9820 | 14.0052 | 14.1829 | 14.5554 | 14.7334 | 15.2318 | 15.5132 | 17.0457 |
| **4800** | 13.7695 | 13.8965 | 13.9831 | 14.1042 | 14.3332 | 14.5427 | 14.9101 | 15.1750 | 15.7363 | 18.2158 | 21.0497 |
| **5400** | 14.2298 | 14.4373 | 14.5199 | 14.6913 | 14.9553 | 15.1517 | 15.5760 | 15.9186 | 18.9566 | 22.1767 | 25.7316 |
| **6000** | 14.4461 | 14.5597 | 14.7513 | 14.9483 | 15.1797 | 15.4688 | 16.0366 | 18.5200 | 22.3103 | 26.3872 | 30.5333 |
| **6089** | 14.5829 | 14.7443 | 14.9002 | 15.1110 | 15.3729 | 15.6650 | 16.2377 | 19.1379 | 22.9813 | 26.9326 | 31.3887 |

**Table 82** The average CPU time, required by ESR, for the developed scenarios [**RAP-2**].

| \|X\|/\|C\| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **600** | 13.1382 | 12.9814 | 12.9927 | 12.9814 | 13.0074 | 13.0263 | 13.1382 | 13.0400 | 13.0754 | 13.0935 | 13.0743 |
| **1200** | 13.0736 | 13.1250 | 13.1014 | 13.1788 | 13.1869 | 13.2668 | 13.3253 | 13.2624 | 13.2998 | 13.3281 | 13.3668 |
| **1800** | 13.3049 | 13.3258 | 13.3308 | 13.3390 | 13.4225 | 13.4439 | 13.5200 | 13.5982 | 13.6496 | 13.8228 | 13.8573 |
| **2400** | 13.5152 | 13.5466 | 13.5404 | 13.6298 | 13.7174 | 13.7184 | 13.9214 | 14.0339 | 14.0670 | 14.1169 | 14.1947 |
| **3000** | 13.6429 | 13.7362 | 13.8492 | 13.8902 | 14.0031 | 14.0825 | 14.1244 | 14.2401 | 14.3713 | 14.6329 | 14.8428 |
| **3600** | 13.8598 | 13.9042 | 13.9974 | 14.0576 | 14.2709 | 14.4654 | 14.5994 | 14.7752 | 14.9736 | 15.1728 | 15.3889 |
| **4200** | 14.1929 | 14.2461 | 14.3682 | 14.4652 | 14.6158 | 14.7604 | 14.9933 | 15.1966 | 15.3702 | 15.6180 | 17.1961 |
| **4800** | 14.3241 | 14.3131 | 14.4238 | 14.5235 | 14.7186 | 14.9502 | 15.1745 | 15.4122 | 15.7082 | 18.0788 | 20.8454 |
| **5400** | 14.5356 | 14.6249 | 14.7753 | 14.9603 | 15.2465 | 15.6085 | 15.8404 | 16.0815 | 18.7773 | 22.0812 | 25.5845 |
| **6000** | 14.7957 | 15.0053 | 15.1206 | 15.3549 | 15.5104 | 15.8177 | 16.2093 | 18.6140 | 22.1001 | 26.0331 | 30.3101 |
| **6089** | 14.9322 | 15.0848 | 15.2977 | 15.5417 | 15.7237 | 16.0098 | 16.3139 | 19.1884 | 22.7999 | 26.6726 | 31.0681 |

**Table 83** The average CPU time, required by the considered solution algorithms, for the developed problem instances [**RAP-2**].

| Instance | CPLEX | MPSR | MESR | PSR | ESR |
|---|---|---|---|---|---|
| 1 | 69.9911 | 3.9560 | 3.3479 | 4.6314 | 4.4462 |
| 2 | 70.9460 | 6.0069 | 5.2160 | 6.4073 | 6.2969 |
| 3 | 73.0394 | 8.0679 | 7.1945 | 8.2830 | 8.5575 |
| 4 | 72.2399 | 10.1245 | 9.6549 | 10.7905 | 10.6734 |
| 5 | 75.9433 | 12.2229 | 11.0833 | 12.8405 | 12.5062 |
| 6 | 81.3307 | 13.7113 | 12.7959 | 14.1511 | 14.6446 |
| 7 | 79.6609 | 15.5128 | 14.6753 | 16.0397 | 16.3512 |
| 8 | 82.1378 | 17.2391 | 16.5429 | 17.9721 | 18.0089 |
| 9 | 82.4937 | 19.4961 | 18.4784 | 19.4171 | 19.4612 |
| 10 | 89.0162 | 20.8236 | 20.3190 | 21.3125 | 21.3299 |
| 11 | 87.8737 | 22.5603 | 22.2184 | 23.2041 | 24.2457 |
| 12 | 90.9694 | 24.5690 | 25.7563 | 25.0734 | 26.3221 |
| **Average:** | **79.6368** | **14.5242** | **13.9402** | **15.0102** | **15.2370** |

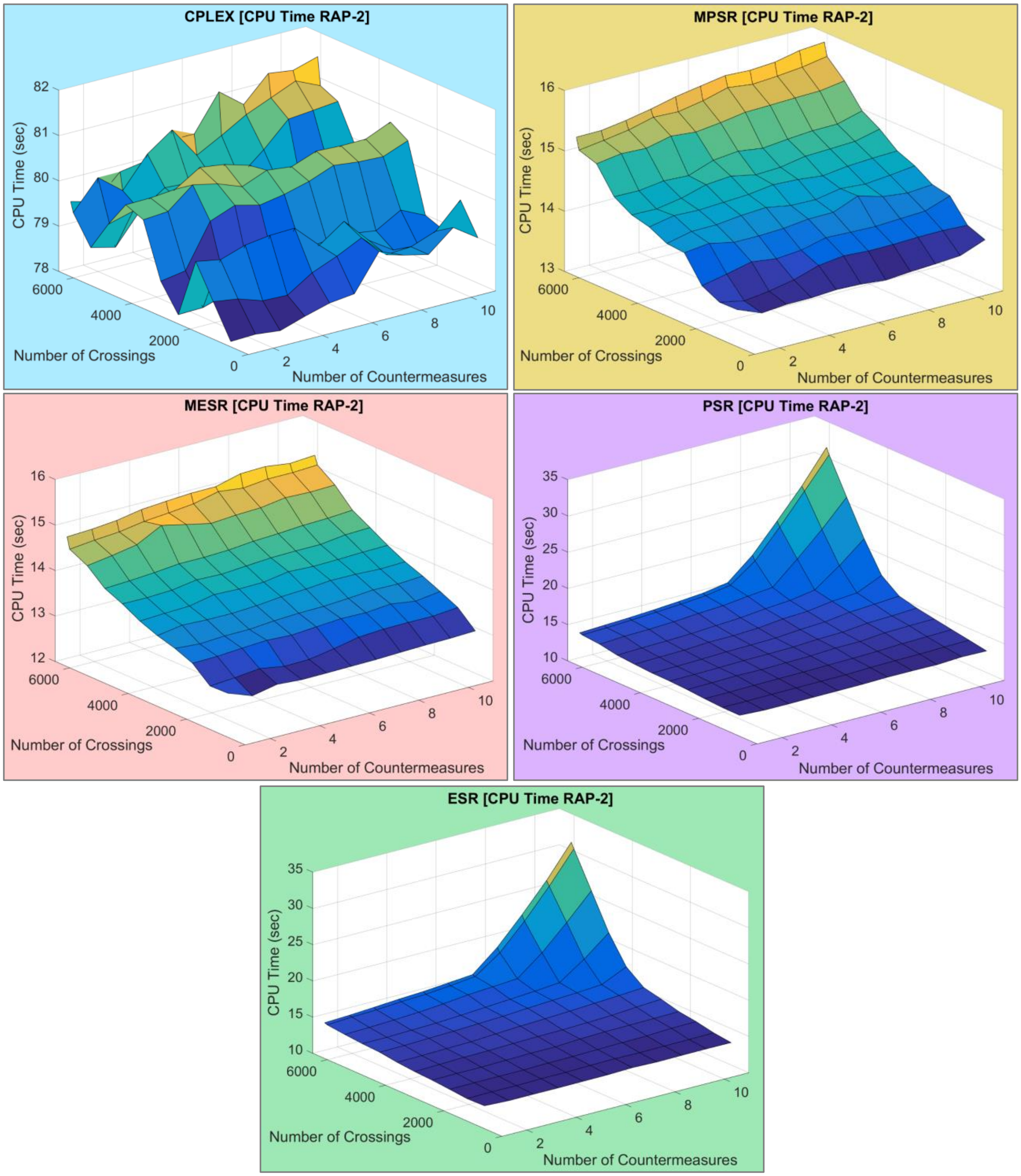



**Figure 54** The average CPU time, required by the considered solution algorithms, for the developed scenarios [**RAP-2**].

# 10. DEVELOPMENT OF THE STANDALONE APPLICATION "HRX SAFETY IMPROVEMENT"

Under this section of the report, the standalone application, named as "HRX Safety Improvement" ("HRX" stands for "highway-rail grade crossing"), is presented. First, the standalone application "HRX Safety Improvement" employs the Florida Priority Index Formula in order to prioritize the highway-rail grade crossings in the State of Florida for upgrading based on the Florida Priority Index (FPI) values. Later on, it distributes the available monetary resources among the chosen highway-rail grade crossings to upgrade them by implementing the available countermeasures, which were previously specified by the user. The purpose of the application, installation guidelines, and basic user guidelines are outlined in this section of the report. More details regarding the developed application along with illustrative examples on how to use the application are provided in the user manual, which accompanies this report.

## 10.1. Purpose of the Application

The State of Florida is one of the most populous states in the U.S. with an increasing number of passengers and freight traffic. Due to increasing passenger and freight traffic volumes, a significant number of accidents between highway vehicles and passing trains has been recorded in the State of Florida over the past years. Accidents at highway-rail grade crossings necessitate application of the appropriate countermeasures at the highway-rail grade crossings in order to improve safety for highway travelers. However, due to the significant number of highway-rail grade crossings in the State of Florida and budget limitations, upgrading all the highway-rail grade crossings is infeasible. Therefore, only a limited number of highway-rail grade crossings can be upgraded, considering the limited financial resources. Hence, the existing highway-rail grade crossings have to be ranked for upgrading based on the potential for accident occurrence (i.e., the overall highway-rail grade crossing hazard). This study has developed a standalone application, named as "HRX Safety Improvement", which can assist the FDOT personnel with ranking the highway-rail grade crossings in the State of Florida. The standalone application "HRX Safety Improvement" assesses the highway-rail grade crossing hazard based on the average daily traffic volume, average daily train volume, train speed, protection factor, and accident history parameter (the total number of accidents in the last five years or since the year of last improvement in case there was an upgrade). Furthermore, the developed standalone application "HRX Safety Improvement" can assist the FDOT personnel with assignment of the eligible countermeasures to the considered highway-rail grade crossings in order to conduct an efficient resource allocation. Specifically, the standalone application "HRX Safety Improvement" considers the available budget and assigns countermeasures to the highway-rail grade crossings in order to minimize the overall hazard or the overall hazard severity at the highway-rail grade crossings (based on the user's choice).

## 10.2. Installation Guidelines

In order to install the standalone application "HRX Safety Improvement" on a given PC, the following steps should be successfully completed:

1. It is assumed that the installation file will be placed to folder "**C:\HRX_Safety_Improvement**". Open folder "**C:\HRX_Safety_Improvement**" (see Figure 55).

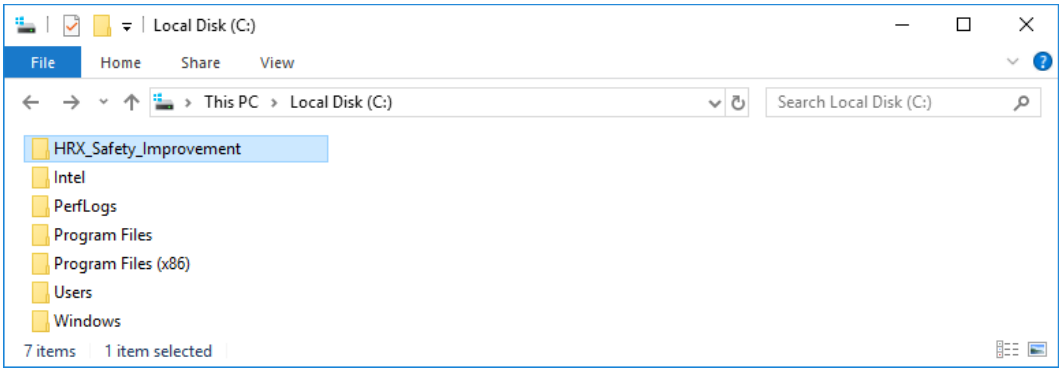



**Figure 55** The folder containing the installation file.

2. Execute file "**HRX_Safety_Improvement.exe**" (see Figure 56). The installer will start running (see Figure 57). Click "**Next**".

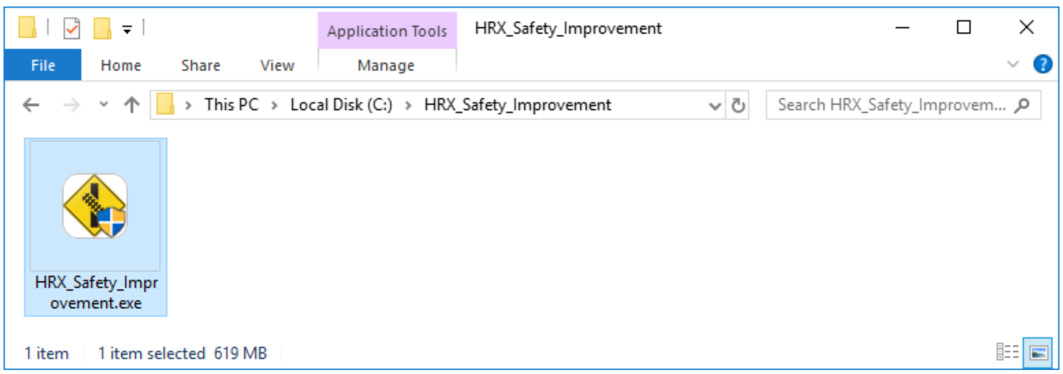



**Figure 56** The installer of the standalone application "HRX Safety Improvement".

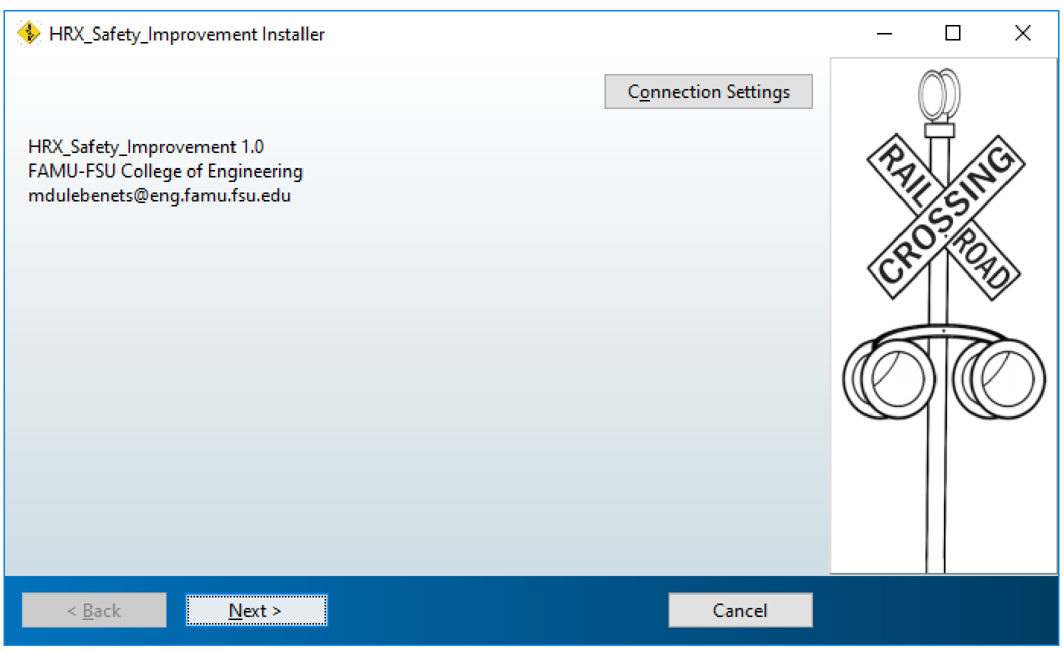



**Figure 57** The installation window of the standalone application "HRX Safety Improvement".

3. Select a directory, where the installation files of the standalone application "HRX Safety Improvement" will be placed (e.g., folder "**C:\Program Files\HRX_Safety_Improvement**" – see Figure 58). For convenience, "**Add a shortcut to the desktop**" option can be chosen.

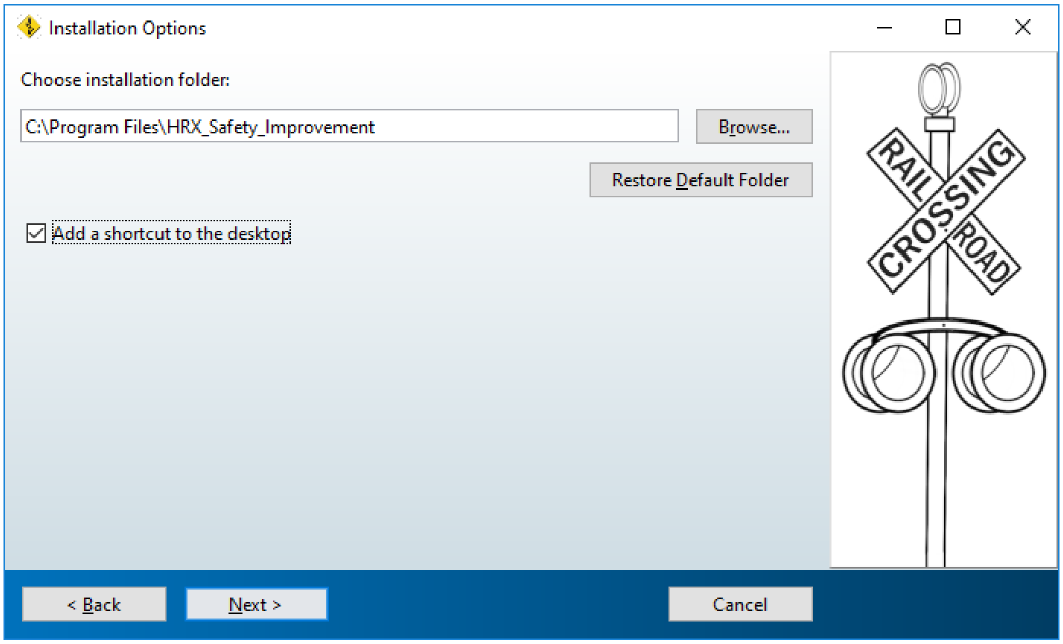



**Figure 58** The installation directory for the standalone application "HRX Safety Improvement".

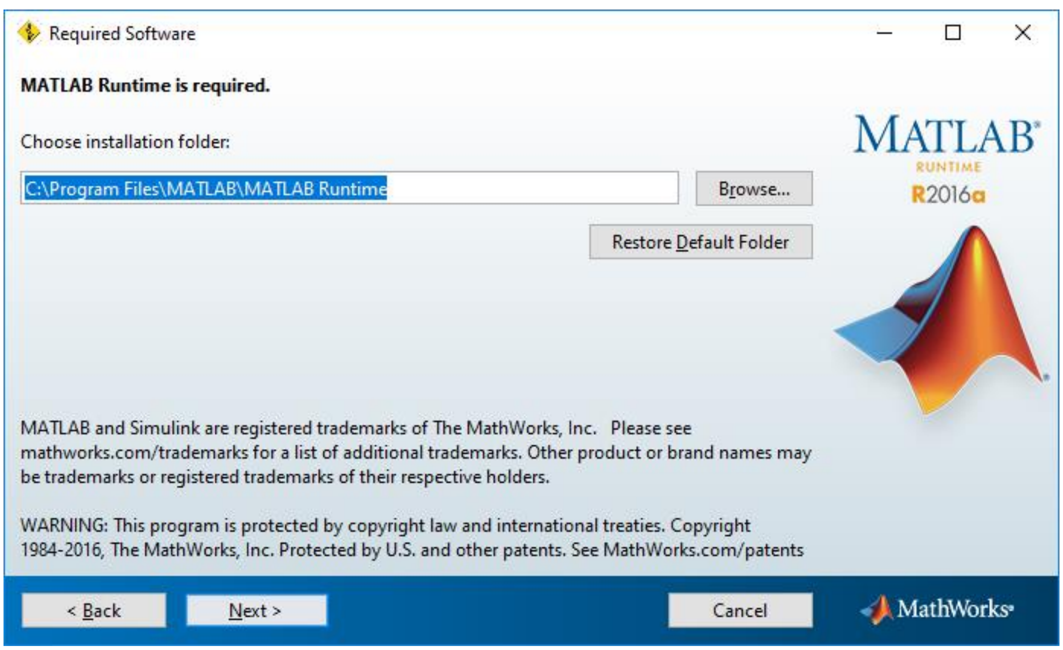



**Figure 59** The installation directory for MATLAB Runtime.

4. MATLAB Runtime (MathWorks, 2019b), a standalone set of shared libraries that is required to execute MATLAB components or applications without installing MATLAB, is essential to run the standalone application "HRX Safety Improvement". MATLAB Runtime is included in the application package. However, the user needs to select a directory, where the

installation files of MATLAB Runtime will be saved (e.g., folder "**C:\Program Files\MATLAB\MATLAB Runtime**" – see Figure 59).

5. Accept the terms of the license agreement and then click "**Next**" (see Figure 60).

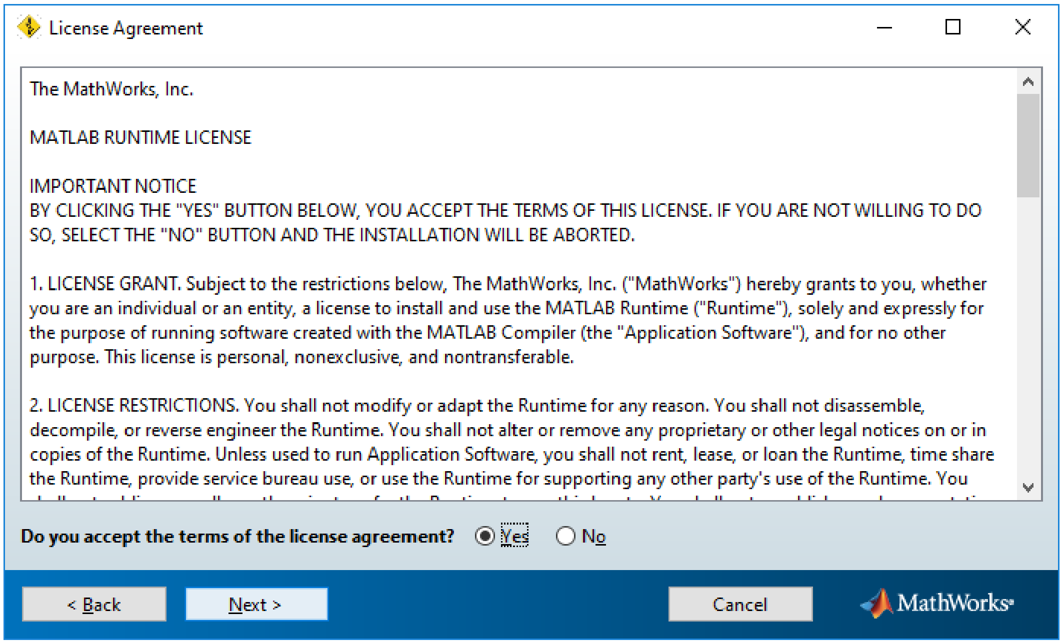


**Figure 60** Accepting the terms of the license agreement.

6. A confirmation window, showing the installation directories of the standalone application "HRX Safety Improvement" and MATLAB Runtime, will pop up. Click "**Install**" on that window (see Figure 61).

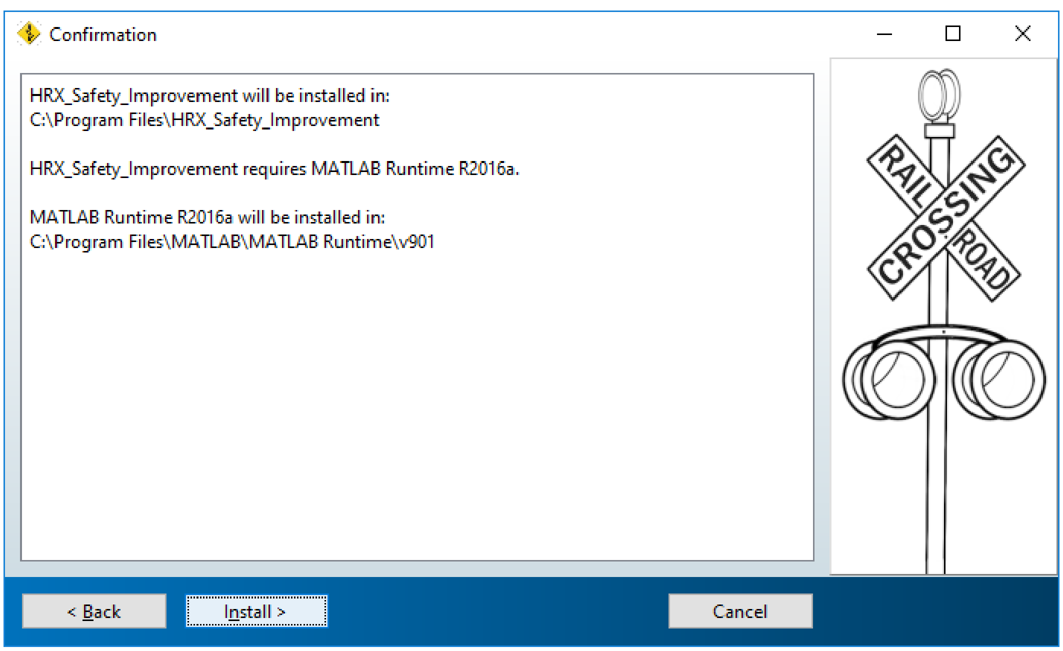


**Figure 61** The confirmation window showing the installation directories.

7. When the installation starts running, a progress bar will appear (see Figure 62).

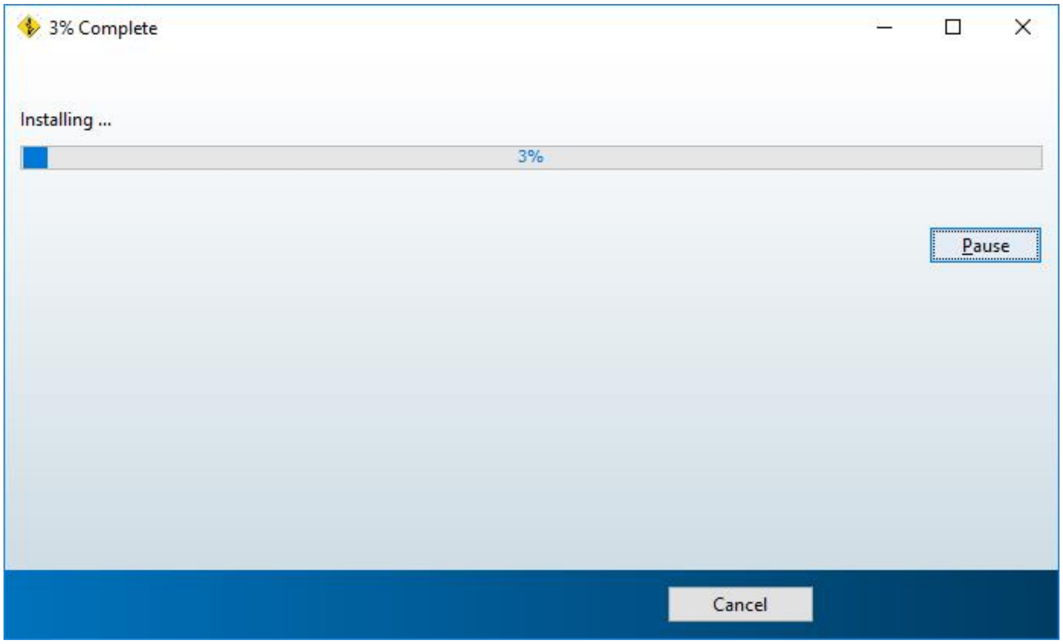



**Figure 62** The installation progress.

8. When the installation is complete, a window confirming a successful completion will pop up (see Figure 63). Click "**Finish**" on that window.

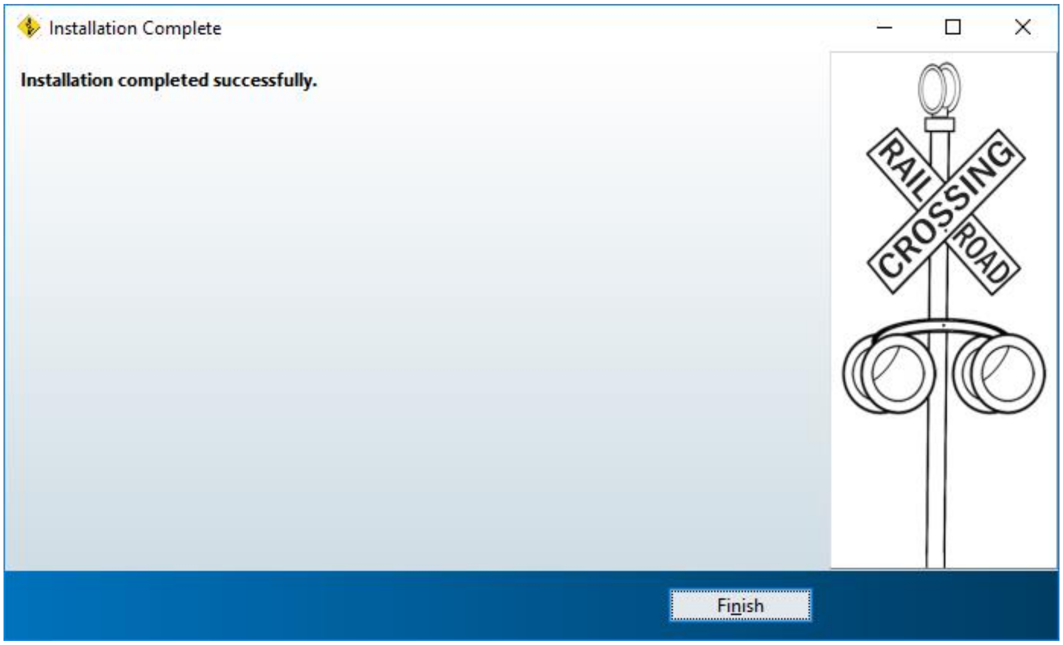



**Figure 63** The installation completion.

### 10.3. User Guidelines

This section provides some basic user guidelines for the standalone application "HRX Safety Improvement". Specifically, the following aspects are further discussed: (1) Major Assumptions;

(2) User Interface; (3) Common Inputs; (4) FPI Estimation; (5) HRX Resource Allocation; and (6) Error Messages.

### *10.3.1. Major Assumptions*

The standalone application "HRX Safety Improvement" requires certain data from the FRA crossing inventory database and the FRA highway-rail grade crossing accident database in order to estimate the FPI values for the considered highway-rail grade crossings. Specifically, the application requires the average daily traffic volume, average daily train volume, train speed, existing protection, and accident history for the last five years. The following assumptions have been used throughout estimation of the FPI values for the considered highway-rail grade crossings:

1) If no information regarding a given highway-rail grade crossing's ownership (i.e., public or private) is available, the highway-rail grade crossing will be excluded from the analysis. The rationale behind such exclusion is that this highway-rail grade crossing could be abandoned or not controlled by the State of Florida. In the latter case, a private company may be responsible for application of countermeasures at the corresponding highway-rail grade crossings.
2) The values of certain predictors of the Florida Priority Index Formula will be assumed to be "1" for the cases when "zero" values or no values are reported in the FRA crossing inventory database. These predictors include the following: (1) annual average daily traffic (AADT); (2) total number of thru trains per day; (3) total number of switch trains per day; (4) maximum train timetable speed; and (5) number of main and other tracks. The latter assumption is necessary to ensure that the standalone application will not return any abnormal FPI values (e.g., "-∞", "+∞") for the considered highway-rail grade crossings.
3) If no protection is reported for a given highway-rail grade crossing, the worst-case protection factor value will be used in the analysis. The worst-case protection factor value is "1.00", which is adopted for the highway-rail grade crossings with passive warning devices in the Florida Priority Index Formula. The latter approach will allow avoiding elimination of certain highway-rail grade crossings from the analysis due to the lack of protection information in the FRA crossing inventory database. Also, such assumption will produce more conservative FPI values for the considered highway-rail grade crossings.
4) If no data are available regarding the classification of the roadway intersecting a railroad, the roadway will be assumed to be in a rural setting. Such assumption will produce more conservative values of the hazard severity for the considered highway-rail grade crossings.
5) The prioritization or ranking of highway-rail grade crossings will be based on the FPI values (as the primary ranking criterion) and the exposure values (as the secondary ranking criterion). Note that the exposure is estimated as the product of AADT and the number of trains per day. If two highway-rail grade crossings have the same FPI value, a higher rank will be given to the highway-rail grade crossing with a higher exposure value.

As it was discussed in section 7 of the report, two optimization models were developed for resource allocation among the highway-rail grade crossings in the State of Florida, including: (1) the Resource Allocation Problem 1 (**RAP-1**), which minimizes the overall hazard, and (2) the Resource Allocation Problem 2 (**RAP-2**), which minimizes the overall hazard severity. Several heuristic algorithms were developed to solve the **RAP-1** and **RAP-2** optimization models. The previously conducted numerical experiments demonstrated that the Profitable Hazard Reduction (PHR) heuristic and the Profitable Severity Reduction (PSR) heuristic returned the best solutions for **RAP-1** and **RAP-2**, respectively (see section 8.2 the report for more details about the aforementioned heuristic algorithms). Hence, the developed standalone application “HRX Safety Improvement” allocates resources using the PHR and PSR heuristics, depending on the “**Objective to Minimize**” selected by the user. In particular, if the user selects to minimize the overall hazard from the corresponding pop-up menu (which will be described in section 10.3.2 of the report), the standalone application “HRX Safety Improvement” conducts resource allocation using PHR. On the other hand, if the user chooses to minimize the overall hazard severity, the PSR heuristic is utilized by the application to solve the optimization model and distribute resources among the selected highway-rail grade crossings. The following assumptions have been followed throughout resource allocation (i.e., assignment of countermeasures) among the considered highway-rail grade crossings:

1) The PHR heuristic creates a priority list of highway-rail grade crossing-countermeasure pairs and sorts them based on the hazard reduction-to-cost ratios. Then, PHR assigns the countermeasure with the highest hazard reduction-to-cost ratio for each highway-rail grade crossing (considering the eligibility of highway-rail grade crossings for the countermeasures specified by the user), as long as the available budget allows. Once the remaining budget is not sufficient for implementation of the countermeasure with the highest hazard reduction-to-cost ratio at the next highway-rail grade crossing in the priority list, PHR starts considering the other highway-rail grade crossing-countermeasure pairs in the priority list, based on the hazard reduction-to-cost ratios.
2) The PSR heuristic generates a priority list of highway-rail grade crossing-countermeasure pairs and sorts them by the severity reduction-to-cost ratios. Then, as long as there is enough budget available, the countermeasure with the highest severity reduction-to-cost ratio is assigned to each highway-rail grade crossing (considering the eligibility of highway-rail grade crossings for the countermeasures specified by the user). Once the remaining budget is not sufficient for implementation of the countermeasure with the highest severity reduction-to-cost ratio at the next highway-rail grade crossing in the priority list, the PSR heuristic starts considering the other highway-rail grade crossing-countermeasure pairs in the priority list, based on the severity reduction-to-cost ratios.
3) A total of 11 countermeasures, discussed in the GradeDec.Net Reference Manual (U.S. DOT, 2014), have been considered in this project. However, not all of the countermeasures can be implemented at every single highway-rail grade crossing. The feasibility of implementation of each countermeasure at a given highway-rail grade crossing was considered based on the existing protection of highway-rail grade crossings (see section 7.4.2 of the report for more details).
4) The values of the effectiveness factors of the countermeasures were adopted from the Rail-Highway Grade Crossing Handbook (U.S. DOT, 2007) and the GradeDec.Net Reference Manual (U.S. DOT, 2014, pages 25-26). If more than one value was available for a given countermeasure, the lowest value was adopted.
5) The installation costs of the considered countermeasures at highway-rail grade crossings were adopted from the GradeDec.Net Reference Manual (U.S. DOT, 2014, pages 59-60).
6) Under this project, the FPI values and the GradeDec severity prediction methodology were adopted to assess the hazard severity of a given highway-rail grade crossing due to lack of

the prediction methodologies for quantifying the hazard severity (see section 7.4.3 of the report for more details).

7) The weight values of the hazard severity categories for the **RAP-2** mathematical model were adopted using the report by Iowa DOT (2006) and were further set at $W_{FH} = 0.60$ for fatality hazard, $W_{IH} = 0.30$ for injury hazard, and $W_{PH} = 0.10$ for property damage hazard.
8) The overall hazard at a given highway-rail grade crossing, used by the **RAP-1** mathematical model, is equal to the summation of fatality, injury, and property damage hazards for that highway-rail grade crossing.

### *10.3.2. User Interface*

The user interface of the standalone application "HRX Safety Improvement" is presented in Figure 64. The user interface has three sections: (1) "**Common Inputs**", which is located at the top of the interface; (2) "**FPI Estimation**", which is located in the middle of the interface; and (3) "**HRX Resource Allocation**", which is located at the bottom of the interface. The following color coding was adopted for the application interface: (1) yellow color was used for the fields where the user has to specify the path or select one of the available options from a drop-down menu; and (2) magenta color was used for the fields where the user has to type the values manually.

In the "**Common Inputs**" section, there are two buttons, named as "**HRX Database**" and "**Exports Results**". The button "**HRX Database**" is used to provide the location (i.e., path) to the Excel database, which contains the information that will be further used throughout resource allocation among the highway-rail grade crossings. The button "**Export Results**" is utilized to provide the location (i.e., path) in the Windows Operating System and save the results in the Excel format. The message windows on the right side of the aforementioned buttons show the locations specified by the user. The "**FPI Estimation**" section has two buttons on the left, named as "**FL HRX Inventory**" and "**FL Accident Data**". These buttons can load the highway-rail grade crossings inventory file and five accident data files, respectively. There is a message window on the right side of the "**FL HRX Inventory**" button that shows the location of the crossing inventory file. Similarly, a message window on the right side of the "**FL Accident Data**" button shows the path of the accident data files. The "**FPI Estimation**" section includes a pop-up menu, named as "**Crossing Type**", which allows the user to select different types of highway-rail grade crossings for the analysis, including the following: (1) "**Public Only**", (2) "**Private Only**", and (3) "**Both**". There is also a textbox, named as "**Prediction Year**". The year, for which the FPI values are to be estimated, should be entered into the "**Prediction Year**" textbox. At the bottom-right corner of the "**FPI Estimation**" section, there is a button, named as "**Estimate FPI**". After pressing the "**Estimate FPI**" button, the standalone application starts estimating the FPI values of highway-rail grade crossings and exports the FPI values along with the associated data to an Excel file.

In the third section of the standalone application "HRX Safety Improvement", which is "**HRX Resource Allocation**", two textboxes, named as "**Index of Crossings**" and "**Index of Countermeasures**", have been provided to insert the index of the highway-rail grade crossings to be considered throughout resource allocation and the index of the countermeasures to be considered throughout resource allocation, respectively. The pop-up menu on the right side of the "**Index of Countermeasures**" textbox is used to select the "**Objective to Minimize**" that provides the user with two options, which are "**Overall Hazard**" and "**Overall Hazard Severity**". When all the aforementioned input data are successfully set, the user should press the "**HRX Resource Allocation**" button, so the standalone application "HRX Safety Improvement" can start assigning the available countermeasures to the specified highway-rail grade crossings, based on the budget available. After a successful execution, the budget information will be shown in three textboxes, named as: (1) "**Total Budget Available**"; (2) "**Total Budget Spent**"; and (3) "**Total Remaining Budget**" (see the bottom of the user interface in Figure 64).

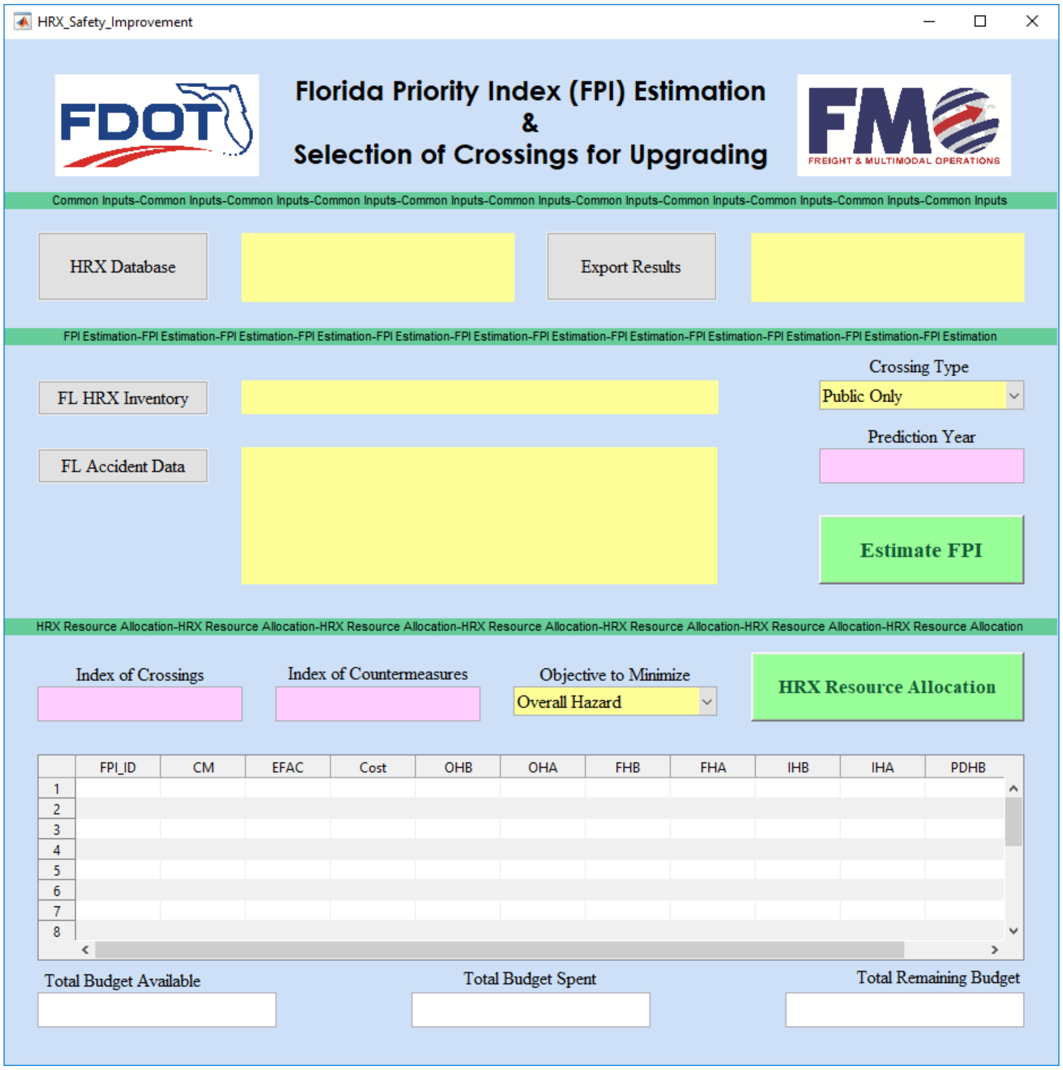



**Figure 64** The user interface for the standalone application "HRX Safety Improvement".

Moreover, some of the results will appear in the table at the bottom of the user interface, which include the following features:

- FPI_ID – rank/index of a highway-rail grade crossing (based on the estimated FPI values);
- CM – index of the countermeasure assigned to a highway-rail grade crossing;
- EFAC – effectiveness factor of the assigned countermeasure;

- Cost – cost to implement a given countermeasure at a highway-rail grade crossing;
- OHB – overall hazard of a highway-rail grade crossing before implementing a given countermeasure;
- OHA – overall hazard of a highway-rail grade crossing after implementing a given countermeasure;
- FHB – fatality hazard of a highway-rail grade crossing before implementing a given countermeasure;
- FHA – fatality hazard of a highway-rail grade crossing after implementing a given countermeasure;
- IHB – injury hazard of a highway-rail grade crossing before implementing a given countermeasure;
- IHA – injury hazard of a highway-rail grade crossing after implementing a given countermeasure;
- PDHB – property damage hazard of a highway-rail grade crossing before implementing a given countermeasure; and
- PDHA – property damage hazard of a highway-rail grade crossing after implementing a given countermeasure.

Note that FHB, FHA, IHB, IHA, PDHB, and PDHA are applicable if the "**Objective to Minimize**" is selected as "**Overall Hazard Severity**"; otherwise the term "N/A" (i.e., Not Applicable) will be shown in the corresponding columns.

### *10.3.3. Common Inputs*

In order to estimate the FPI values for the highway-rail grade crossings in the State of Florida and perform resource allocation among the highway-rail grade crossings, the user has to provide certain common input data. Specifically, the standalone application "HRX Safety Improvement" requires the user to load the database with the information regarding the considered highway-rail grade crossings and the available countermeasures by pressing the button "**HRX Database**" (see Figure 65). By default, the user can work with the database "**FDOT_HRX-project_2018.xlsx**", which was developed by the research team as a part of this project. The HRX database contains the information that will be further used throughout resource allocation among the highway-rail grade crossings. As it will be discussed in section 10.3.4 of this report, the standalone application "HRX Safety Improvement" will be automatically updating the HRX database based on the user input (e.g., if the user requests estimating the FPI values for both private and public highway-rail grade crossings, the standalone application "HRX Safety Improvement" will calculate the FPI values for both private and public highway-rail grade crossings and will paste the required data into the HRX database – i.e., the user will not be required to paste any values manually). However, the user will able to make the appropriate changes in the HRX database before conducting resource allocation (e.g., add another countermeasure, update the default installation costs of the available countermeasures, adjust the FPI values for certain highway-rail grade crossings, etc.). Once the HRX database is loaded, the message window on the right side of the "**HRX Database**" button will show the location (i.e., path) of the selected file (see Figure 65).

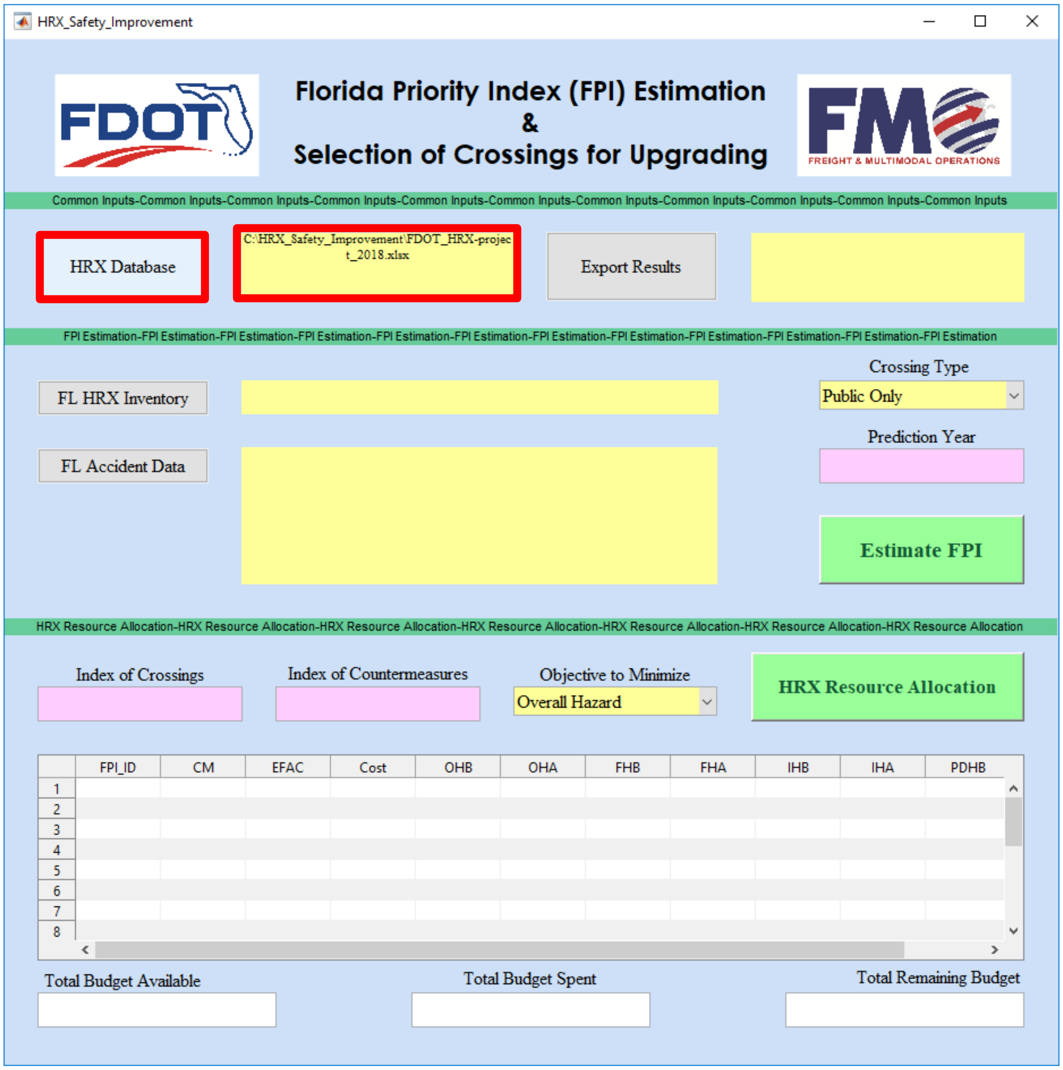



**Figure 65** Loading the database with highway-rail grade crossings and countermeasures.

Moreover, the standalone application "HRX Safety Improvement" requires the user to specify the path, where the output Excel files (generated after estimation of the FPI values and performing resource allocation) will be exported. The "**Export Results**" button on the user interface allows specifying the location for the output Excel files (see Figure 66). Once the user specifies the export location (i.e., path) for the output Excel files, the message window on the right side of the "**Export Results**" button will show that export location in the Windows Operating System.

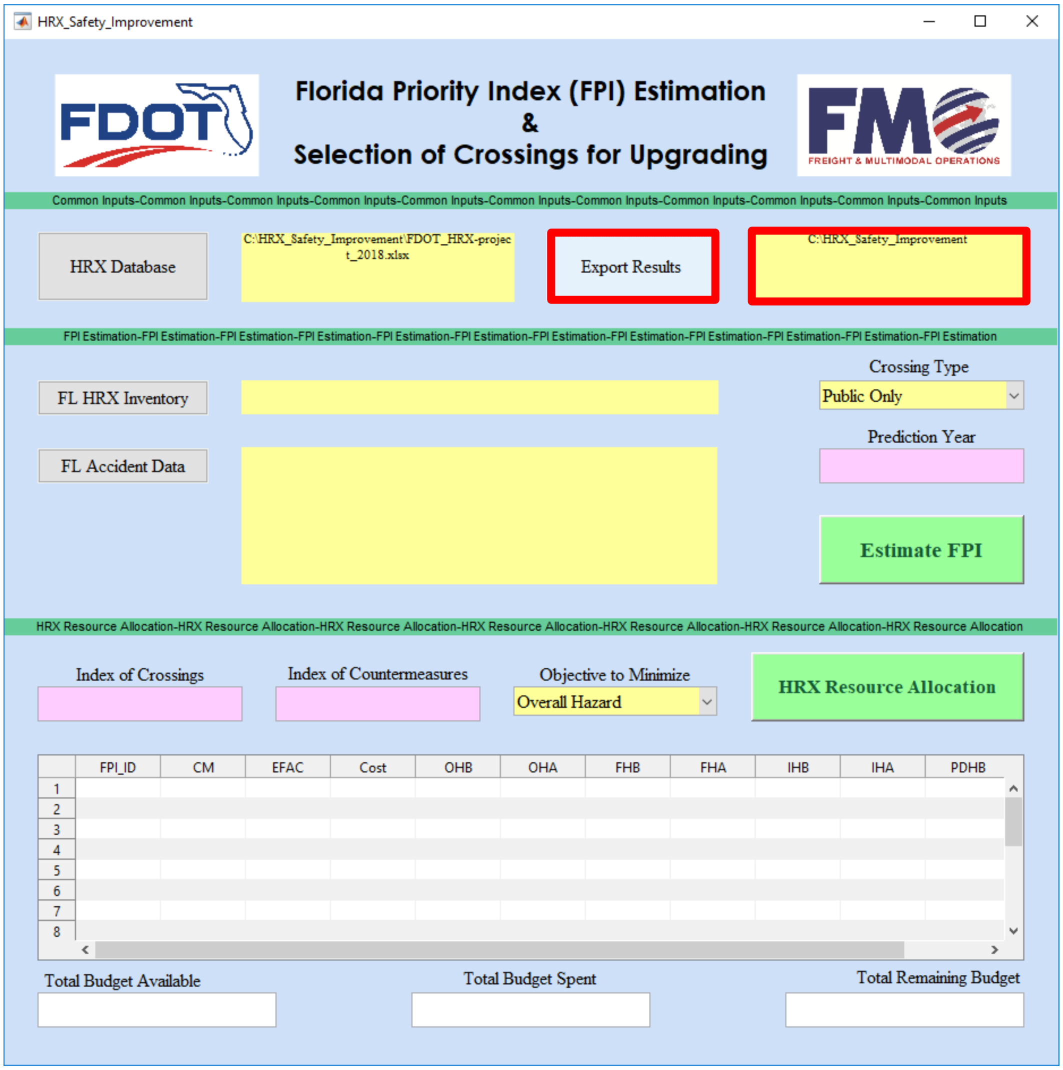



**Figure 66** Specifying the location to export the results.

### *10.3.4. FPI Estimation*

The section "**FPI Estimation**" of the standalone application "HRX Safety Improvement" ranks the highway-rail grade crossings based the on the FPI values estimated using the Florida Priority Index Formula, which is described in sections 6.4 and 7.4.1 of the report. If two highway-rail grade crossings have the same FPI value, the highway-rail grade crossing with a higher exposure value will be assigned a higher rank. Note that the exposure of a given highway-rail grade crossing is estimated as a product of AADT and the number of trains per day.

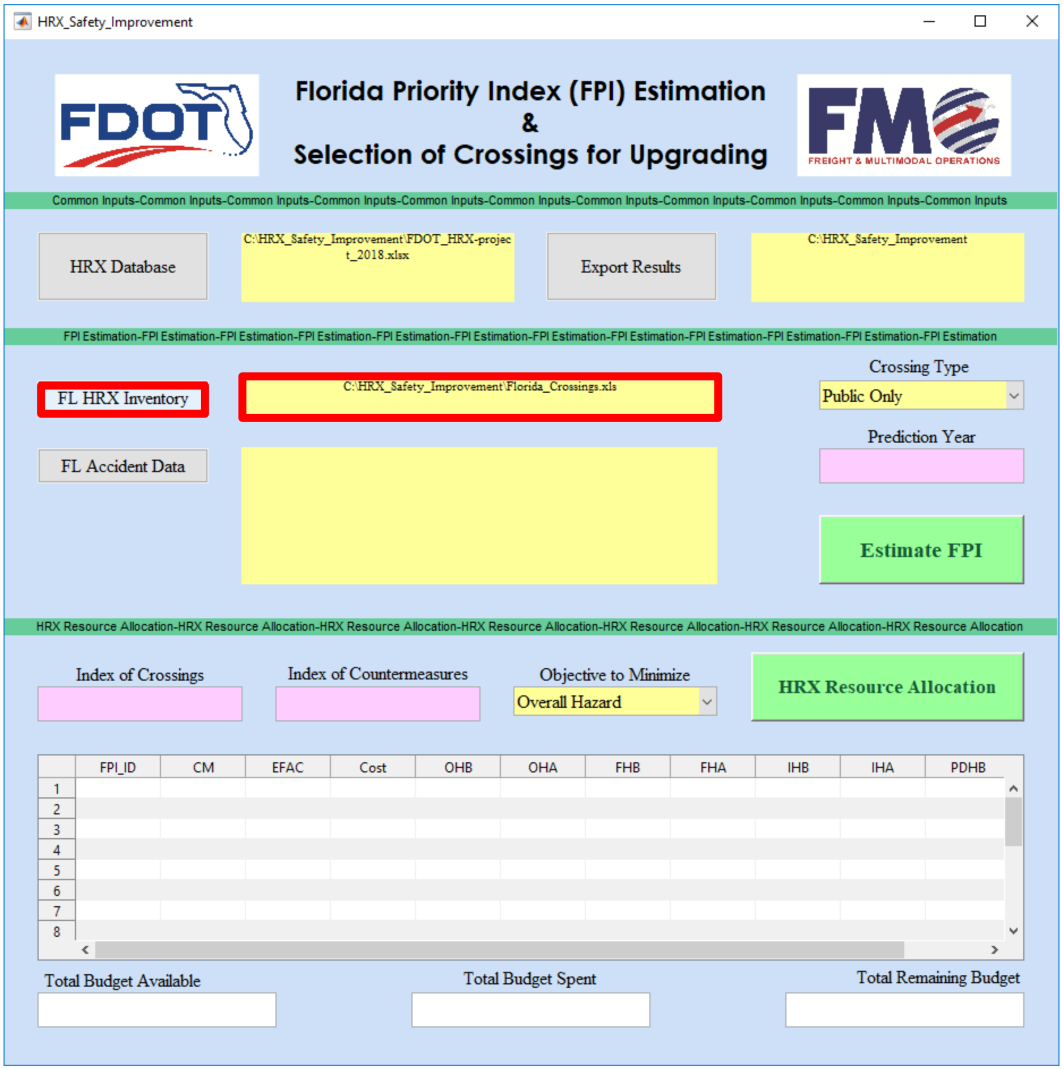



**Figure 67** Loading the crossing inventory data.

In order to estimate the FPI values for the highway-rail grade crossings, the user has to load the Florida crossing inventory data in the Excel format. The Florida crossing inventory data can be downloaded from the FRA crossing inventory database. After downloading, the crossing inventory file can be named as "**Florida_Crossings**" (or other appropriate name set by the user). The "**FL HRX Inventory**" button on the user interface allows loading the crossing inventory file. Once the file is loaded, the message window on the right side of the "**FL HRX Inventory**" button will show the location of the crossing inventory file (see Figure 67).

The year, for which the FPI values are to be estimated, should be inserted in the "**Prediction Year**" textbox (see Figure 68). Furthermore, the user should load the Florida accident data for five years before the prediction year in the Excel format (e.g., the 2017-2013 accident data are required to compute the FPI values for the year of 2018). The accident data can be downloaded from the FRA highway-rail grade crossing accident database. However, the accident data should be downloaded for each single year. Therefore, there will be five files for five years of the accident data. Note that a specific naming convention must be followed for the accident data files to keep a correct order of the files. For example, if the prediction year is 2018, the accident data file for the 1st year before 2018 (the year of 2017) should be named as "**Florida Accident Data - 1st Year**"; the accident data file for the 2nd year before 2018 (the year of 2016) should be named as "**Florida Accident Data - 2nd Year**"; the accident data file for the 3rd year before 2018 (the year of 2015) should be named as "**Florida Accident Data - 3rd Year**"; the accident data file for the 4th year before 2018 (the year of 2014) should be named as "**Florida Accident Data - 4th Year**"; and the accident data file for the 5th year before 2018 (the year of 2013) should be named as "**Florida Accident Data - 5th Year**".

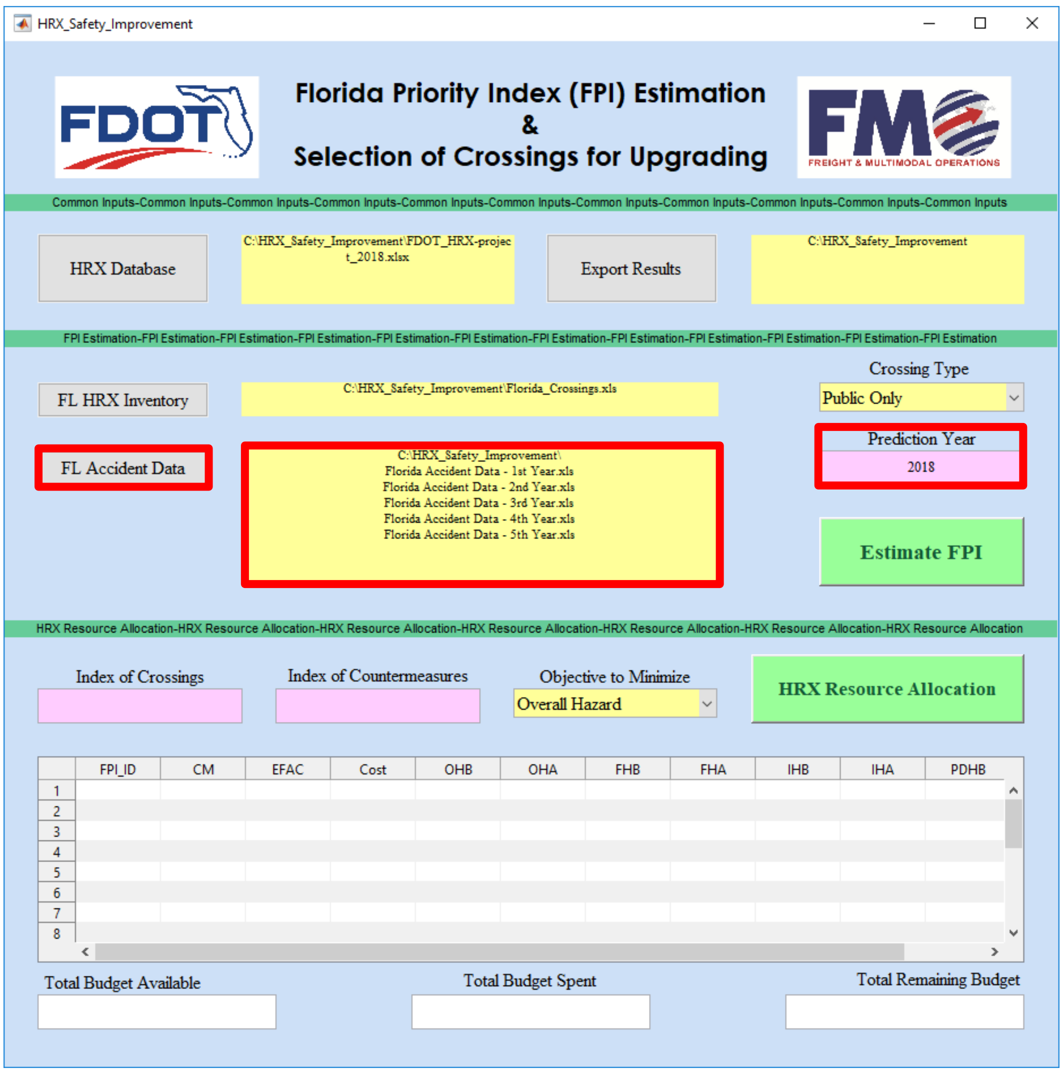


**Figure 68** Specifying the prediction year and loading the accident data.

Note that this report primarily relies on the term "accident", which is consistent with the highway-rail grade crossing safety literature. However, other stakeholders (e.g., railroad companies) primarily rely on the term "incident". Without loss of generality, the naming convention for the accident data files can be adjusted, as long as the order of files is kept based on the reporting year (e.g., "**Florida Accident Data - 1st Year**" can be renamed as "**Florida Incident Data - 1st Year**" – the standalone application "HRX Safety Improvement" will not return any errors). The "**FL Accident Data**" button on the user interface allows loading the five accident data files. Once the files are loaded, the message window on the right side of the "**FL Accident Data**" button will show the location (i.e., path) of the five accident data files (see Figure 68). Note that the five files must be loaded at once.

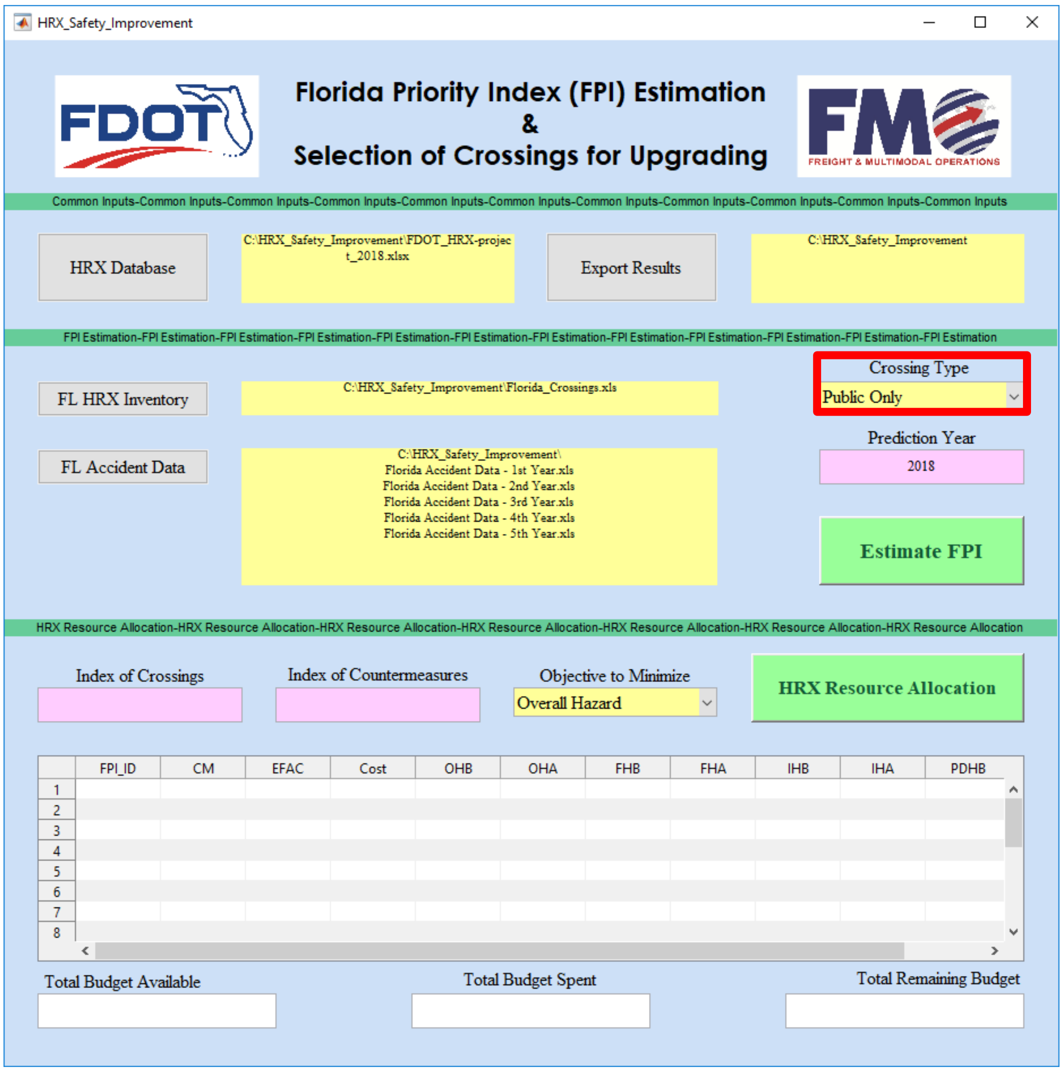



**Figure 69** Selection of the crossing type.

The standalone application "HRX Safety Improvement" can distinguish between public and private highway-rail grade crossings. Using the "**Crossing Type**" pop-up menu, the user can direct the standalone application to estimate the FPI values for the following types of highway-rail grade crossings: (1) "**Public Only**"; (2) "**Private Only**"; and (3) "**Both**" (see Figure 69).

However, if no crossing type is selected, the standalone application will choose public highway-rail grade crossings as default.

After successfully completing the previous steps, the user can execute the "**FPI Estimation**" section of the standalone application "HRX Safety Improvement" to rank the selected type(s) of highway-rail grade crossings by pressing the "**Estimate FPI**" button. When the "**Estimate FPI**" button is pressed, a progress bar, which states "**Estimating Florida Priority Index…**", will pop up (see Figure 70). Once the FPI values are successfully estimated, the progress bar will disappear.

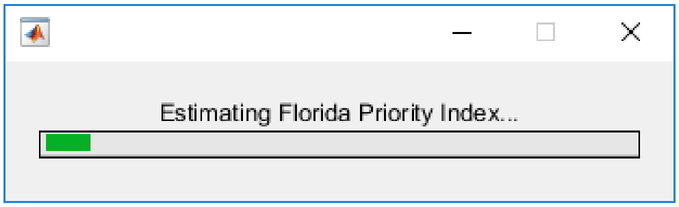
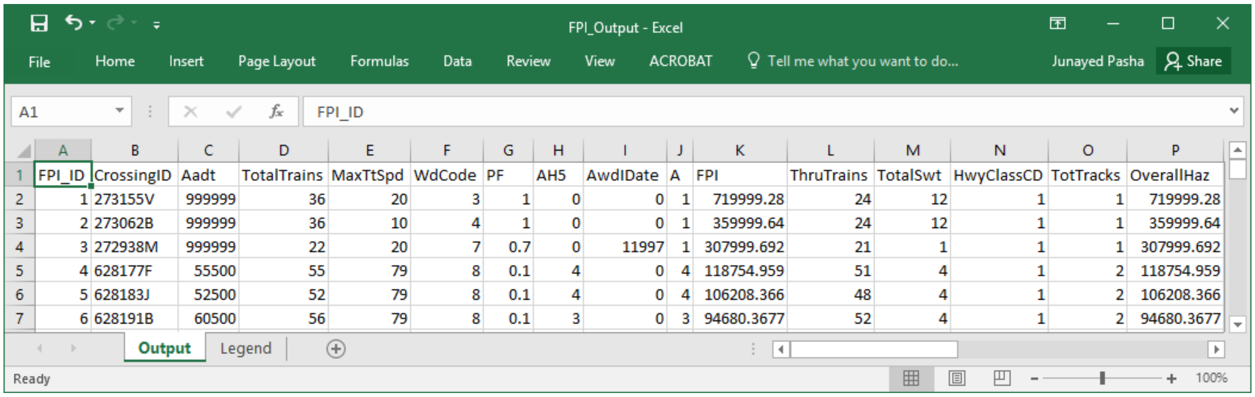



**Figure 70** The progress bar of "**FPI Estimation**".

**Note**: There is a certain condition, which can interrupt a successful execution of the standalone application "HRX Safety Improvement". Specifically, the standalone application "HRX Safety Improvement" cannot delete or modify an open Excel file. If the user has already executed the "**FPI Estimation**" section of the application successfully, opened some of the Excel files (e.g., "**FDOT_HRX-project_2018.xlsx**", "**FPI_Output.xlsx**", or other Excel files), and tries to run the application again, the application may not run successfully (i.e., "freeze"), even if the Excel files have been closed by the user (as the Windows Operating System may still have the Excel application invoked). In case if the standalone application "HRX Safety Improvement" gets frozen due to the Excel data exchange issues, the progress bar will not appear anymore after pressing the button "**Estimate FPI**" or the button "**HRX Resource Allocation**". However, if the user closes the application and restarts it, the application will resume working normally again. Therefore, the users are recommended to determine the analysis types they would like to conduct before executing the standalone application "HRX Safety Improvement". Also, the users are recommended to keep the Excel application closed, while performing certain procedures with the standalone application "HRX Safety Improvement", to insure that the standalone application "HRX Safety Improvement" works normally. In order to prevent the "freezing" issue, the latest version of the standalone application "HRX Safety Improvement" automatically closes open Excel files after pressing the button "**Estimate FPI**" or the button "**HRX Resource Allocation**".

***FPI Estimation Outputs***

The standalone application "HRX Safety Improvement" exports the FPI values of the considered highway-rail grade crossings and the associated data to the previously specified location in the Excel format (i.e., XLSX). The Excel file is named as "**FPI_Output.xlsx**". The results (of "**FPI Estimation**") are shown in the "**Output**" sheet of the file "**FPI_Output.xlsx**". Each row in the "**Output**" sheet represents a highway-rail grade crossing. A certain number of fields (i.e., columns) are shown in the "**Output**" sheet. Figure 71 presents an example, showing the "**Output**" sheet of the "**FPI_Output.xlsx**" file for the public highway-rail grade crossings in the State of Florida. This example showcases the data for 6,089 highway-rail grade crossings, as 6,089 public highway-rail grade crossings in the State of Florida are presented in the latest crossing inventory file, downloaded from the FRA crossing inventory database (as of November of 2018).



| FPI_ID | CrossingID | Aadt | TotalTrains | MaxTtSpd | WdCode | PF | AH5 | AwdIDate | A | FPI | ThruTrains | TotalSwt | HwyClassCD | TotTracks | OverallHaz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 273155V | 999999 | 36 | 20 | 3 | 1 | 0 | 0 | 1 | 719999.28 | 24 | 12 | 1 | 1 | 719999.28 |
| 2 | 273062B | 999999 | 36 | 10 | 4 | 1 | 0 | 0 | 1 | 359999.64 | 24 | 12 | 1 | 1 | 359999.64 |
| 3 | 272938M | 999999 | 22 | 20 | 7 | 0.7 | 0 | 11997 | 1 | 307999.692 | 21 | 1 | 1 | 1 | 307999.692 |
| 4 | 628177F | 55500 | 55 | 79 | 8 | 0.1 | 4 | 0 | 4 | 118754.959 | 51 | 4 | 1 | 2 | 118754.959 |
| 5 | 628183J | 52500 | 52 | 79 | 8 | 0.1 | 4 | 0 | 4 | 106208.366 | 48 | 4 | 1 | 2 | 106208.366 |
| 6 | 628191B | 60500 | 56 | 79 | 8 | 0.1 | 3 | 0 | 3 | 94680.3677 | 52 | 4 | 1 | 2 | 94680.3677 |

**Figure 71** The "**Output**" sheet of "**FPI_Output.xlsx**".

The meanings of all the headings in the "**Output**" sheet of "**FPI_Output.xlsx**", which represent various attributes of the considered highway-rail grade crossings, are further explained in the "**Legend**" sheet (see Figure 72). These attributes include the following:

- FPI_ID – rank/index of a highway-rail grade crossing;
- CrossingID – crossing inventory number;
- Aadt – annual average daily traffic (AADT) count;
- TotalTrains – total number of trains (daylight through + night time through + switching);
- MaxTtSpd – maximum timetable speed;
- WdCode – warning device code (1 = no signs or signals; 2 = other signs or signals; 3 = crossbucks; 4 = stop signs; 5 = special active warning devices; 6 = highway traffic signals, wigwags, bells, or other activated; 7 = flashing lights; 8 = all other gates; 9 = four quad (full barrier) gates);
- PF – protection factor (1.00 for passive; 0.70 for flashing lights; 0.10 for gates);
- AH5 – 5-year accident history;
- AwdIDate – installation date of current active warning devices;
- A – accident history parameter;
- FPI – the Florida Priority Index;
- ThruTrains – total number of through trains (daylight through + night time through);
- TotalSwt – total number of switching trains;
- HwyClassCD – functional classification of road at crossing (0 = rural; 1 = urban);
- TotTracks – number of main and other tracks;
- OverallHaz – overall hazard at a highway-rail grade crossing;
- FatHaz – fatality hazard at a highway-rail grade crossing;
- CasHaz – casualty hazard at a highway-rail grade crossing;
- InjHaz – injury hazard at a highway-rail grade crossing;
- PropHaz – property damage hazard at a highway-rail grade crossing;
- TypeXing – crossing type (2 = private; 3 = public)
- HwynrSig – does nearby highway intersection have traffic signals? (1 = yes; 2 = no);

- MonitorDev – highway monitoring devices (0 = none; 1 = yes-photo/video recording; 2 = yes-vehicle presence detection);
- PaveMrkIDs – pavement markings (0 = none; 1 = stop lines; 2 = railroad crossing symbols; 3 = dynamic envelope);
- PrempType – highway traffic signal preemption (1 = simultaneous; 2 = advance);
- DevelTypID – type of land use (11 = open space; 12 = residential; 13 = commercial; 14 = industrial; 15 = institutional; 16 = farm; 17 = recreational; 18 = railroad yard);
- TypeTrnSrvcIDs – type of train service (11 = freight; 12 = intercity passenger; 13 = commuter; 14 = transit; 15 = shared use transit; 16 = tourist/other);
- Whistban – quiet zone (0 = no; 1 = 24 hour; 2 = partial; 3 = Chicago excused);
- HwyNear – intersecting roadway within 500 feet? (1 = yes; 2 = no);
- HwyPved – is roadway/pathway paved? (1 = yes; 2 = no);
- Illumina – is crossing illuminated? (1 = yes; 2 = no);
- TraficLn – number of traffic lanes crossing railroad;
- XAngle – smallest crossing angle (1 = 0° – 29°; 2 = 30° – 59°; 3 = 60° – 90°);
- XSurfaceIDs – crossing surface (11 = timber; 12 = asphalt; 13 = asphalt and timber; 14 = concrete; 15 = concrete and rubber; 16 = rubber; 17 = metal; 18 = unconsolidated; 19 = composite; 20 = other [specify]);
- HwySpeed – highway speed limit;
- PctTruk – estimated percent trucks; and
- SchlBsCnt – average number of school bus count per day.

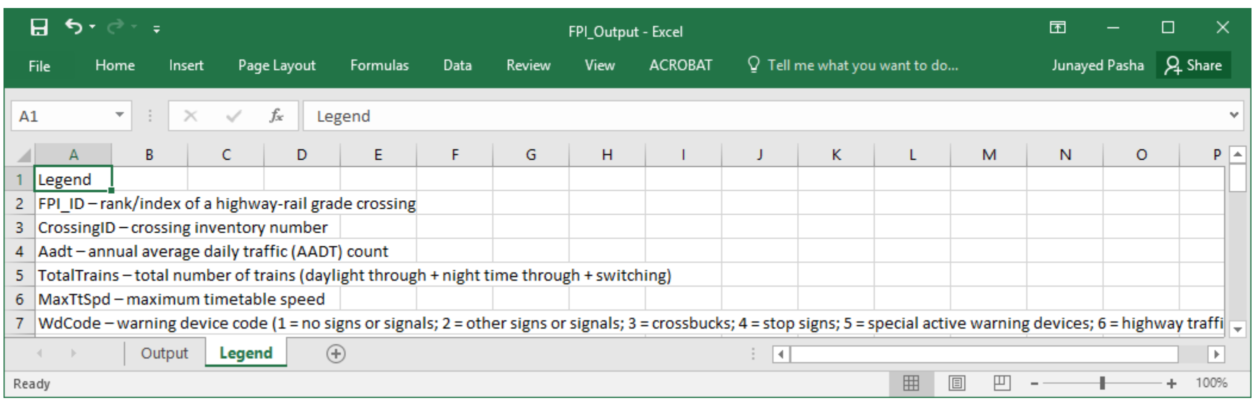
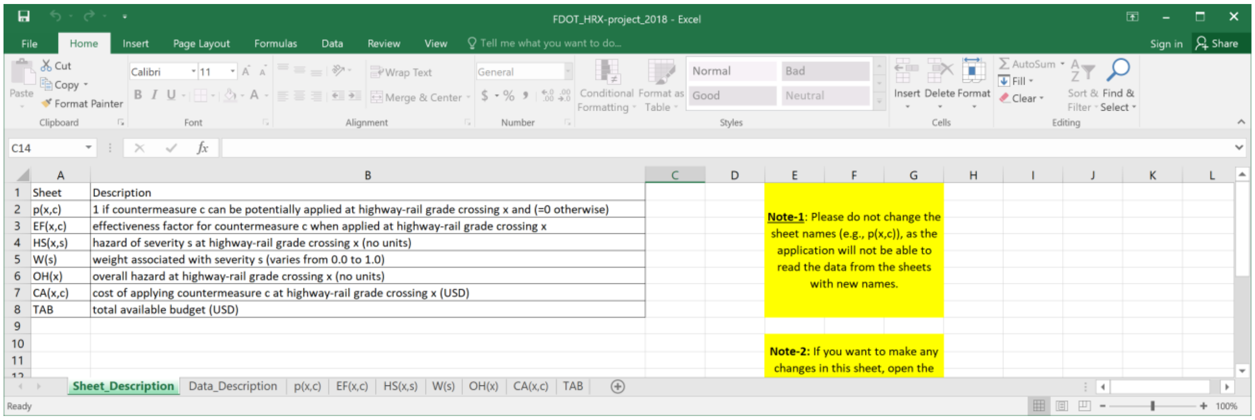



**Figure 72** The "**Legend**" sheet of "**FPI_Output.xlsx**".

### *HRX Database Updates*

The highway-rail grade crossing information, required for resource allocation (e.g., the FPI values, fatality hazard values, injury hazard values, property damage hazard values), will be transferred by the standalone application "HRX Safety Improvement" into the HRX database, which is named as "**FDOT_HRX-project_2018.xlsx**" (however, the users can rename the HRX database as appropriate). The HRX database contains nine sheets, namely: (1) "**Sheet_Description**"; (2) "**Data_Description**"; (3) "**p(x,c)**"; (4) "**EF(x,c)**"; (5) "**HS(x,s)**"; (6) "**W(s)**"; (7) "**OH(x)**"; (8) "**CA(x,c)**"; and (9) "**TAB**". A description of the information provided in these nine sheets is presented below.

1) **Sheet_Description**: This sheet explains the information, provided in different sheets of the HRX database, which is directly used by the standalone application "HRX Safety Improvement" (see Figure 73).

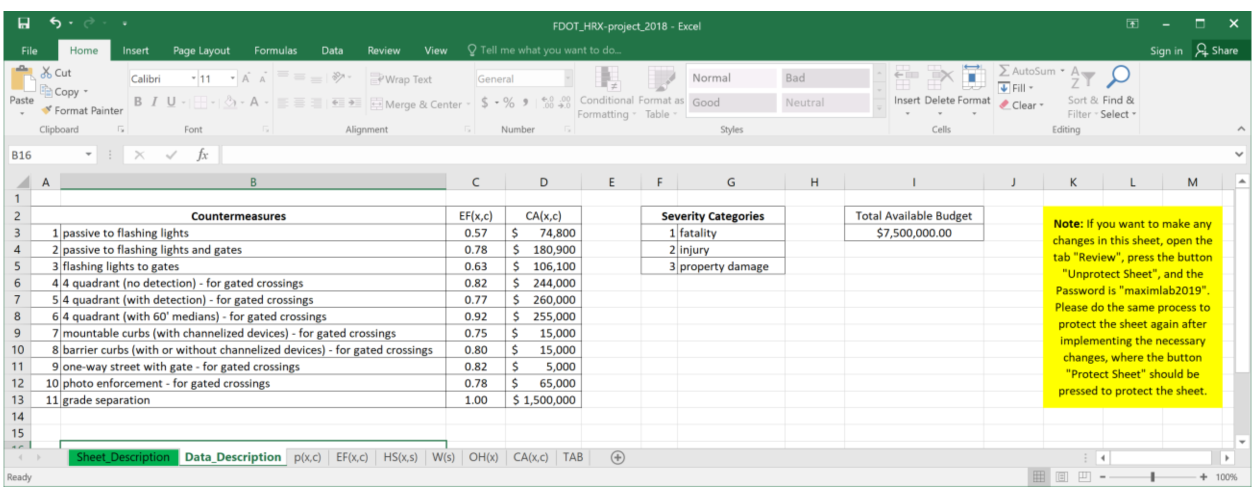


| Sheet | Description |
|---|---|
| p(x,c) | 1 if countermeasure c can be potentially applied at highway-rail grade crossing x and (=0 otherwise) |
| EF(x,c) | effectiveness factor for countermeasure c when applied at highway-rail grade crossing x |
| HS(x,s) | hazard of severity s at highway-rail grade crossing x (no units) |
| W(s) | weight associated with severity s (varies from 0.0 to 1.0) |
| OH(x) | overall hazard at highway-rail grade crossing x (no units) |
| CA(x,c) | cost of applying countermeasure c at highway-rail grade crossing x (USD) |
| TAB | total available budget (USD) |



**Figure 73** The "**Sheet_Description**" sheet of "**FDOT_HRX-project_2018.xlsx**".

2) **Data_Description**: This sheet presents the information regarding the default effectiveness factors for the considered countermeasures (as suggested by the GradeDec.Net Reference Manual – U.S. DOT, 2014), the default installation costs for the considered countermeasures (as suggested by the GradeDec.Net Reference Manual – U.S. DOT, 2014), the severity categories considered, and the total available budget (see Figure 74). Note that the values of the aforementioned parameters can be adjusted by the user. For example, if the user changes the installation cost for countermeasure "1" ("passive to flashing lights") from $74,800 to $50,000, the standalone application "HRX Safety Improvement" will be using the updated installation cost of $50,000 for countermeasure "1" and all the considered highway-rail grade crossings when preparing the necessary cost data (sheet "**CA(x,c)**").



| | Countermeasures | EF(x,c) | CA(x,c) |
|---|---|---|---|
| 1 | passive to flashing lights | 0.57 | $ 74,800 |
| 2 | passive to flashing lights and gates | 0.78 | $ 180,900 |
| 3 | flashing lights to gates | 0.63 | $ 106,100 |
| 4 | 4 quadrant (no detection) - for gated crossings | 0.82 | $ 244,000 |
| 5 | 4 quadrant (with detection) - for gated crossings | 0.77 | $ 260,000 |
| 6 | 4 quadrant (with 60' medians) - for gated crossings | 0.92 | $ 255,000 |
| 7 | mountable curbs (with channelized devices) - for gated crossings | 0.75 | $ 15,000 |
| 8 | barrier curbs (with or without channelized devices) - for gated crossings | 0.80 | $ 15,000 |
| 9 | one-way street with gate - for gated crossings | 0.82 | $ 5,000 |
| 10 | photo enforcement - for gated crossings | 0.78 | $ 65,000 |
| 11 | grade separation | 1.00 | $ 1,500,000 |

| | Severity Categories |
|---|---|
| 1 | fatality |
| 2 | injury |
| 3 | property damage |

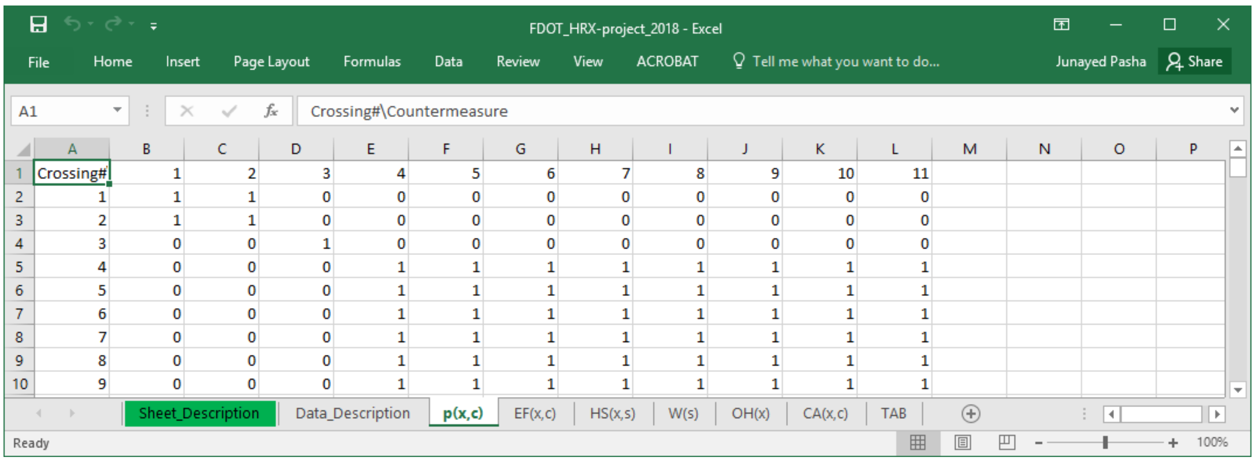
| Total Available Budget |
|---|
| $7,500,000.00 |



**Figure 74** The "**Data_Description**" sheet of "**FDOT_HRX-project_2018.xlsx**".

3) **p(x,c)**: This sheet specifies the eligibility of all the considered highway-rail grade crossings for the available countermeasures. Particularly, there is a matrix in this sheet, whose number of rows and columns are equal to the number of highway-rail grade crossings and

countermeasures, respectively (see Figure 75). A cell value of "1" in this matrix denotes that the corresponding highway-rail grade crossing is eligible for the corresponding countermeasure. In case of ineligibility, the cell value is "0". The default countermeasure eligibility values (as suggested by the GradeDec.Net Reference Manual – U.S. DOT, 2014) will be inserted for the considered highway-rail grade crossings by the standalone application "HRX Safety Improvement" into the sheet "**p(x,c)**". For example, passive highway-rail grade crossings are eligible for the two default countermeasures, suggested by the GradeDec.Net Reference Manual (U.S. DOT, 2014), including the following: (a) "passive to flashing lights"; and (b) "passive to flashing lights and gates".

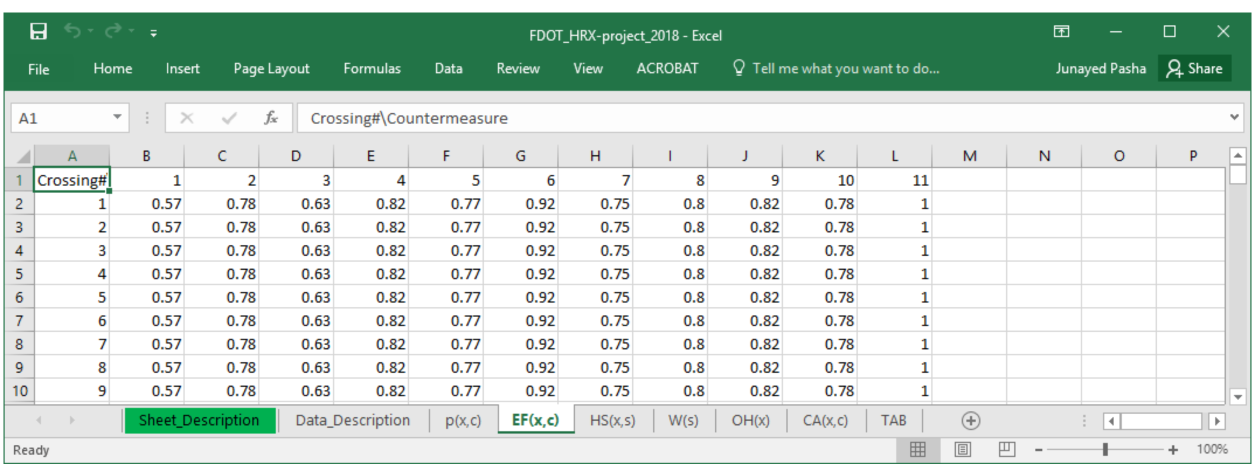


| Crossing#\Countermeasure | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |



**Figure 75** The "**p(x,c)**" sheet of "**FDOT_HRX-project_2018.xlsx**".

4) **EF(x,c)**: This sheet specifies the effectiveness values of the available countermeasures at each highway-rail grade crossing. This sheet includes a matrix, whose number of rows and columns are equal to the number of highway-rail grade crossings and countermeasures, respectively (see Figure 76). Each cell in the matrix specifies the effectiveness value of a given countermeasure (corresponding to the column of the matrix) at a given highway-rail grade crossing (corresponding to the row of the matrix). The default effectiveness values of the available countermeasures will be copied by the standalone application "HRX Safety Improvement" from the sheet "**Data_Description**" and pasted into the sheet "**EF(x,c)**".

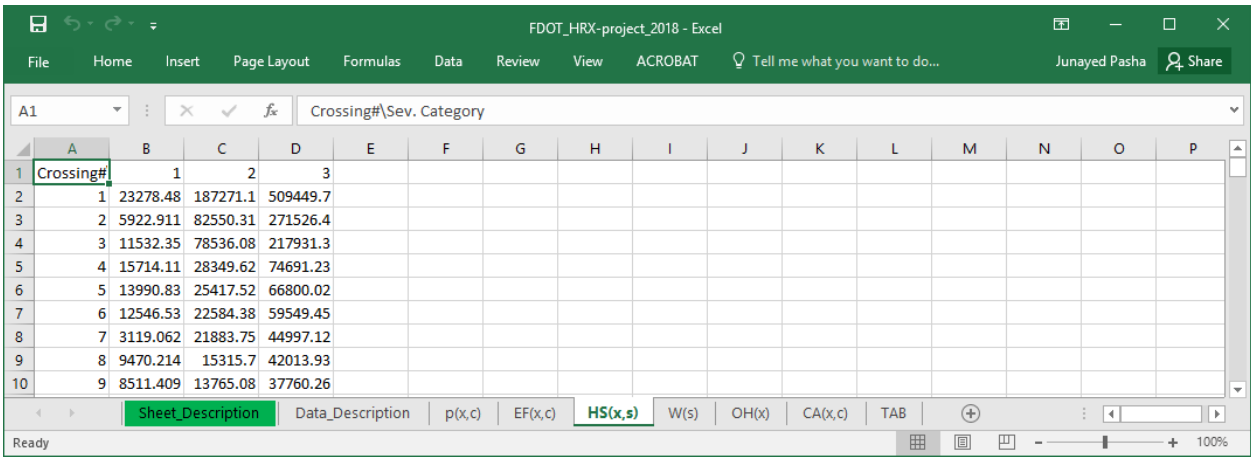


| Crossing#\Countermeasure | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 2 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 3 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 4 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 5 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 6 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 7 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 8 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |
| 9 | 0.57 | 0.78 | 0.63 | 0.82 | 0.77 | 0.92 | 0.75 | 0.8 | 0.82 | 0.78 | 1 |



**Figure 76** The "**EF(x,c)**" sheet of "**FDOT_HRX-project_2018.xlsx**".

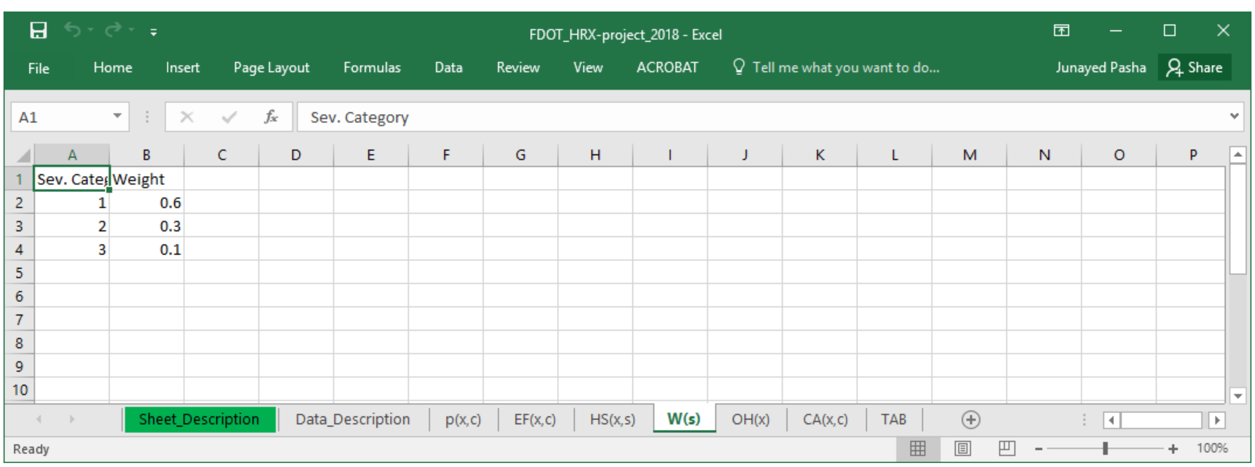
5) **HS(x,s)**: This sheet specifies the hazard value for each severity category at each highway-rail grade crossing. In particular, each highway-rail grade crossing is assigned a row with four cells (see Figure 77). From the left, the first cell denotes the highway-rail grade crossing number (i.e., rank/index of a highway-rail grade crossing based on its FPI value). The second, third, and fourth cells from the left specify fatality hazard severity, injury hazard severity, and property damage hazard severity at a given highway-rail grade crossing, respectively. The estimated hazard severity values for the considered highway-rail grade crossings will be copied by the standalone application "HRX Safety Improvement" from the sheet "**Output**" of the "**FPI_Output.xlsx**" file and pasted into the sheet "**HS(x,s)**".



| A | B | C | D |
|---|---|---|---|
| Crossing# | 1 | 2 | 3 |
| 1 | 23278.48 | 187271.1 | 509449.7 |
| 2 | 5922.911 | 82550.31 | 271526.4 |
| 3 | 11532.35 | 78536.08 | 217931.3 |
| 4 | 15714.11 | 28349.62 | 74691.23 |
| 5 | 13990.83 | 25417.52 | 66800.02 |
| 6 | 12546.53 | 22584.38 | 59549.45 |
| 7 | 3119.062 | 21883.75 | 44997.12 |
| 8 | 9470.214 | 15315.7 | 42013.93 |
| 9 | 8511.409 | 13765.08 | 37760.26 |

**Figure 77** The "**HS(x,s)**" sheet of "**FDOT_HRX-project_2018.xlsx**".

6) **W(s)**: This sheet shows the severity weight values considered for fatality hazard severity (the default value is set to 0.6), injury hazard severity (the default value is set to 0.3), and property damage hazard severity (the default value is set to 0.1) (see Figure 78).

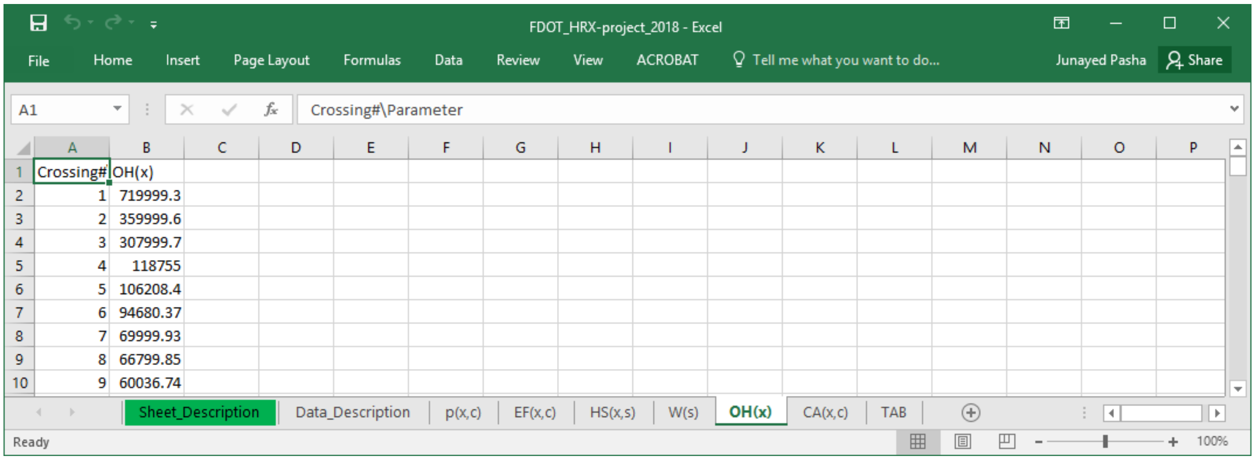


| A | B |
|---|---|
| Sev. Categ | Weight |
| 1 | 0.6 |
| 2 | 0.3 |
| 3 | 0.1 |

**Figure 78** The "**W(s)**" sheet of "**FDOT_HRX-project_2018.xlsx**".

7) **OH(x)**: This sheet presents the overall hazard values for all the highway-rail grade crossings considered for safety improvement projects (see Figure 79). As mentioned previously, the overall hazard values are calculated using the Florida Priority Index formula. The estimated overall hazard values for the considered highway-rail grade crossings will be copied by the

standalone application “HRX Safety Improvement” from the sheet “**Output**” of the “**FPI_Output.xlsx**” file and pasted into the sheet “**OH(x)**”.

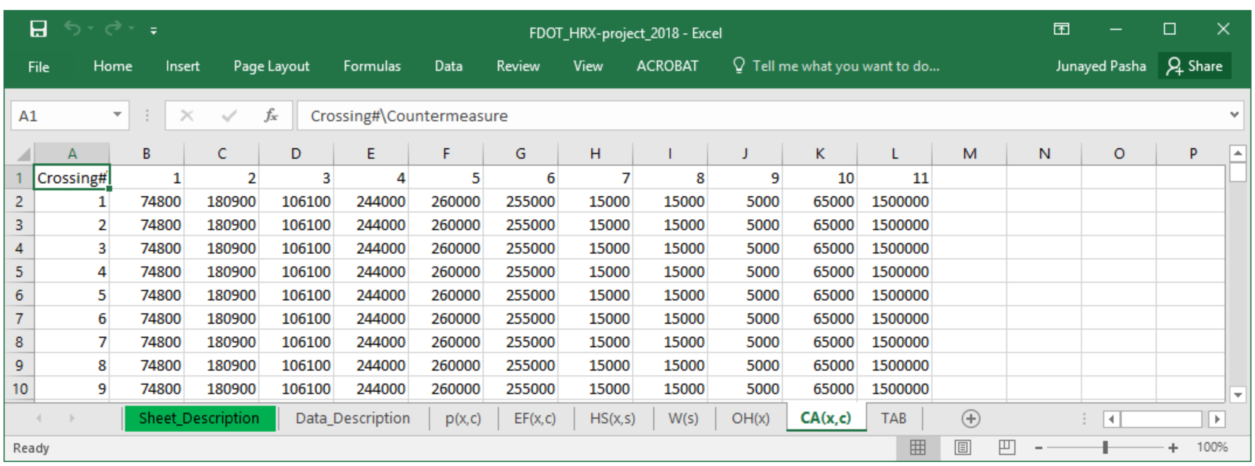


| Crossing# | OH(x) |
|---|---|
| 1 | 719999.3 |
| 2 | 359999.6 |
| 3 | 307999.7 |
| 4 | 118755 |
| 5 | 106208.4 |
| 6 | 94680.37 |
| 7 | 69999.93 |
| 8 | 66799.85 |
| 9 | 60036.74 |



**Figure 79** The “**OH(x)**” sheet of “**FDOT_HRX-project_2018.xlsx**”.

8) **CA(x,c)**: This sheet provides the installation costs of the available countermeasures at all the highway-rail grade crossings considered for safety improvement projects. Specifically, there is a matrix in this sheet, whose number of rows and columns are equal to the number of highway-rail grade crossings and countermeasures, respectively (see Figure 80). Each cell in the matrix specifies the cost to implement a given countermeasure (corresponding to the column of the matrix) at a given highway-rail grade crossing (corresponding to the row of the matrix). The default installation cost values of the available countermeasures will be copied by the standalone application “HRX Safety Improvement” from the sheet “**Data_Description**” and pasted into the sheet “**CA(x,c)**”.



| Crossing# | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 2 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 3 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 4 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 5 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 6 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 7 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 8 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |
| 9 | 74800 | 180900 | 106100 | 244000 | 260000 | 255000 | 15000 | 15000 | 5000 | 65000 | 1500000 |



**Figure 80** The “**CA(x,c)**” sheet of “**FDOT_HRX-project_2018.xlsx**”.

9) **TAB**: This sheet shows the value of the total available budget (TAB) that will be used for safety improvement projects at the considered highway-rail grade crossings (see Figure 81). The default total available budget will be copied by the standalone application “HRX Safety Improvement” from the sheet “**Data_Description**” and pasted into the sheet “**TAB**”.

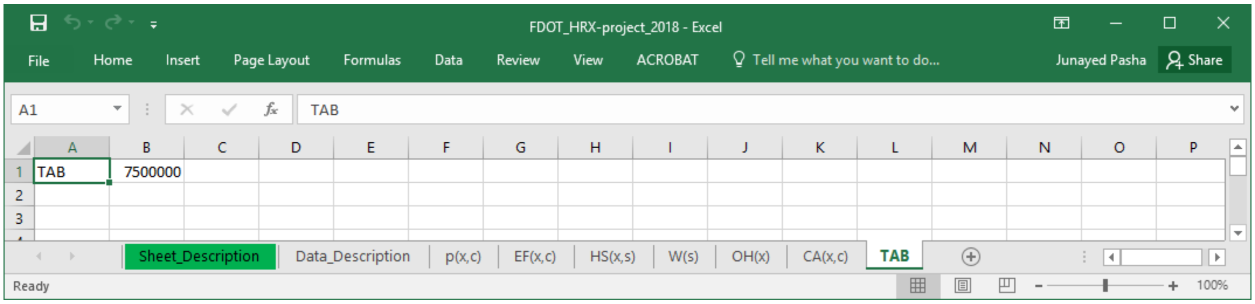



**Figure 81** The "**TAB**" sheet of "**FDOT_HRX-project_2018.xlsx**".

The first two sheets of the HRX database (i.e., "**Sheet_Description**" and "**Data_Description**") play very important roles in the standalone application "HRX Safety Improvement"; hence, they are protected by a password to avoid any unwanted and unintentional changes. Specifically, the standalone application "HRX Safety Improvement" reads the respective data from these two sheets based on the location of the cells in the sheets. For example, the "**FPI Estimation**" section of the standalone application "HRX Safety Improvement" reads the effectiveness values of countermeasures from the cells "C3" to "C13" in the second sheet (i.e., "**Data_Description**"), and if these data are relocated to any other cells, the application will not be able to retrieve the correct data from the sheet. Therefore, the user must avoid any relocation of the data related to the effectiveness values in the second sheet. The same applies to all the information included in the "**Data_Description**" sheet of the HRX database. In order to edit the data in the sheets "**Sheet_Description**" and "**Data_Description**", the user should open the "**Review**" tab in the respective sheet(s), press the "**Unprotect Sheet**" button, and type the password, which is "maximlab2019". The password can be changed by the users as needed. After implementing the necessary changes, the user should repeat the latter process to password-protect the edited sheet using the "**Protect Sheet**" button (instead of using the "**Unprotect Sheet**" button). The instructions on how to protect and unprotect the first two sheets are provided in first two sheets of the HRX database as well.

As mentioned earlier, the standalone application "HRX Safety Improvement" is composed of three sections, including "**Common Inputs**", "**FPI Estimation**", and "**HRX Resource Allocation**". Each section utilizes the HRX database for a particular purpose. The "**Common Inputs**" section receives the path to the HRX database and transfers it to the "**FPI Estimation**" section and the "**HRX Resource Allocation**" section without making any changes in the HRX database. The "**FPI Estimation**" section receives the path to the HRX database and makes necessary changes in the file (e.g., change the type of highway-rail grade crossings based on the user's choice and, therefore, modify the number of rows in certain sheets; change the FPI values; etc.), which can be further used in the "**HRX Resource Allocation**" section. In particular, the "**FPI Estimation**" section reads data from the second sheet (i.e., "**Data_Description**") and rewrites the last seven sheets (i.e., "**p(x,c)**", "**EF(x,c)**", "**HS(x,s)**", "**W(s)**", "**OH(x)**", "**CA(x,c)**", and "**TAB**"). If the user would like to manually edit some data in the "**Data_Description**" sheet of the HRX database, the editing must be completed before execution of the "**FPI Estimation**" section. On the other hand, if the user would like to manually make some changes in the last seven sheets (i.e., "**p(x,c)**", "**EF(x,c)**", "**HS(x,s)**", "**W(s)**", "**OH(x)**", "**CA(x,c)**", and "**TAB**") of the HRX database (e.g., change the installation cost or the effectiveness of a countermeasure at a highway-rail grade crossing, change the eligibility of a highway-rail grade crossing for a countermeasure, etc.) due to practical considerations, the changes must be made after execution of the "**FPI Estimation**" section (otherwise, the application will re-write the values, inserted by the user, and will paste the default values from the "**Data_Description**" sheet after pressing the button "**Estimate FPI**"). Moreover, if the user does not want to execute the "**FPI Estimation**" section, the changes in the HRX database can be made before or after uploading the Excel file in the "**Common Inputs**" section (as the "**Common Inputs**" section just provides the path of the HRX database to the "**FPI Estimation**" section and the "**HRX Resource Allocation**" section). However, all modifications to the HRX database must be done before performing resource allocation among highway-rail grade crossings using the "**HRX Resource Allocation**" section of the standalone application "HRX Safety Improvement".

**Note**: If the user would like to adopt the default values for all 11 countermeasures (i.e., default effectiveness factors and installation costs), as suggested by the GradeDec.Net Reference Manual (U.S. DOT, 2014), throughout resource allocation among highway-rail grade crossings, no manual changes will be required in the HRX database. The standalone application "HRX Safety Improvement" will prepare the required data for the HRX database based on the options, selected by the user on the application interface.

### *10.3.5. HRX Resource Allocation*

The "**HRX Resource Allocation**" section of the standalone application "HRX Safety Improvement" allocates the available countermeasures to the considered highway-rail grade crossings. In the "**HRX Resource Allocation**" section, the first input data that the user should provide are the "**Index of Crossings**" and the "**Index of Countermeasures**" (see Figure 82). In particular, the indices of the selected highway-rail grade crossings and the chosen countermeasures should be inserted in the "**Index of Crossings**" textbox and the "**Index of Countermeasures**" textbox, respectively. Note that the index of highway-rail grade crossings can be found in the outmost left column of the "**Output**" sheet in the Excel file "**FPI_Output.xlsx**" (the heading of the column is named as "**FPI_ID**").

Several alternatives have been provided for the user to insert the indices of highway-rail grade crossings and countermeasures. In particular, the user must use the characters defined below to specify the list of highway-rail grade crossings and countermeasures:

- Numbers: all the digits (i.e., 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9) are allowed;
- Delimiters: two characters (including comma "," and semicolon ";") are allowed to be used as delimiters; and
- Ranges: two characters (including hyphen "-" and colon ":") are allowed to define a range of highway-rail grade crossings and/or countermeasures.

Note that inserting any other character in the fields "**Index of Crossings**" and "**Index of Countermeasures**" will result in an error message, generated by the application.

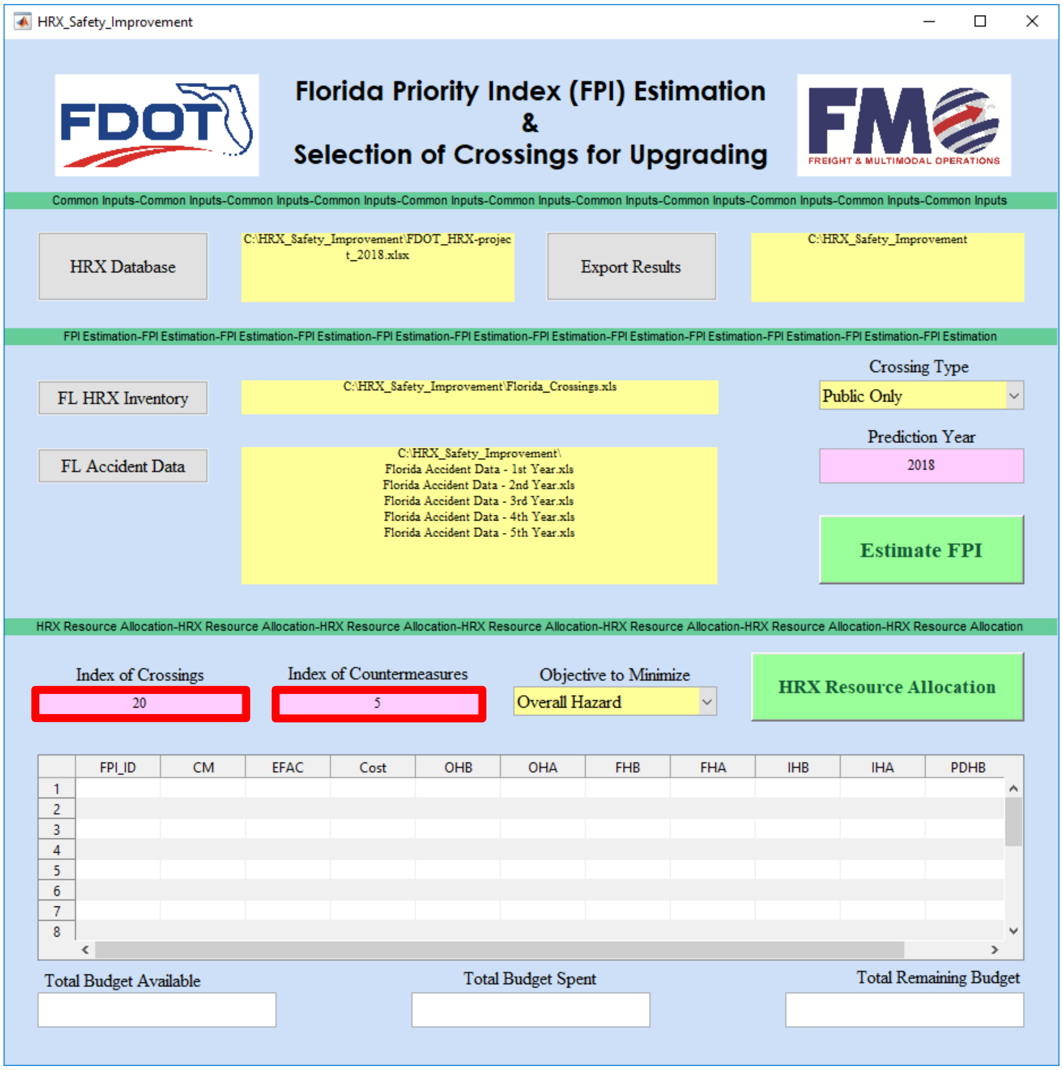



**Figure 82** Specifying the index of highway-rail grade crossings and the index of countermeasures.

Table 84 illustrates different alternatives that the user can select to insert the index of highway-rail grade crossings. In example 1, the first 8 consecutive highway-rail grade crossings are considered for upgrading, and the user can insert just the total number of highway-rail grade crossings to specify the index of crossings in the application (i.e., insertion alternative "1"). In example 2, the index of the first crossing, which is considered for upgrading, is not "1". Hence, the user is not allowed to insert just the total number of highway-rail grade crossings in the application. The second insertion alternative (i.e., "35-41") becomes the most convenient one for example 2. In example 3, there are two ranges of highway-rail grade crossing indices, where the first range comprises the highway-rail grade crossings ranked from 8$^{th}$ to 12$^{th}$, while the second range includes the highway-rail grade crossings ranked from 23$^{rd}$ to 27$^{th}$. As the two aforementioned ranges in example 3 are separate ranges, the user cannot insert the index of highway-rail grade crossings as "8-27". Hence, the second insertion alternative (i.e., "8-12,23-27") becomes the most convenient one for example 3. In example 4, there is a combination of ranges of highway-rail grade crossings and single highway-rail grade crossings, which are considered for upgrading. Therefore, the user cannot insert the index of highway-rail grade crossings as “8-27”. The second insertion alternative (i.e., “8-12,17,19,23-27”) can be considered as the most convenient one for example 4. The third insertion alternative is fairly straightforward, as the indices of highway-rail grade crossings are inserted one by one, and this alternative is applicable for all the examples. Note that the user is not required to insert the index of crossings in any specific order (e.g., ascending or descending). Furthermore, the user is not required to insert ranges or single highway-rail grade crossings in any order, as the application can handle all the possible insertion orders. Note that the user is not allowed to use any spacing between the characters, inserted in the field of “**Index of Crossings**”. Furthermore, all the aforementioned instructions, which are applicable for the field of “**Index of Crossings**”, will be valid for the field of “**Index of Countermeasures**”.

**Table 84** Examples for inserting the index of highway-rail grade crossings.

| Example | Index of Crossings | Insertion Alternative 1 | Insertion Alternative 2 | Insertion Alternative 3 |
|---|---|---|---|---|
| 1 | 1, 2, 3, 4, 5, 6, 7, 8 | 8 | 1-8 | 1,2,3,4,5,6,7,8 |
| 2 | 35, 36, 37, 38, 39, 40, 41 | N/A | 35-41 | 35,36,37,38,39,40, 41 |
| 3 | 8, 9, 10, 11, 12, 23, 24, 25, 26, 27 | N/A | 8-12,23-27 | 8,9,10,11,12,23,24, 25,26,27 |
| 4 | 8, 9, 10, 11, 12, 17, 19, 23, 24, 25, 26, 27 | N/A | 8-12,17,19,23-27 | 8,9,10,11,12,17,19, 23,24,25,26,27 |

As a part of this project, two optimization models (**RAP-1** and **RAP-2**) were developed to minimize “**Overall Hazard**” and “**Overall Hazard Severity**”, respectively. The user interface of the standalone application “HRX Safety Improvement” provides the user with the opportunity to select one of the aforementioned objectives using the “**Objective to Minimize**” pop-up menu, which is highlighted in Figure 83. If no objective is selected, the standalone application will aim to minimize the overall hazard by default.

After successfully completing the previous steps, the user can execute the standalone application “HRX Safety Improvement” to perform resource allocation among the considered highway-rail grade crossings by pressing the “**HRX Resource Allocation**” button. Once the “**HRX Resource Allocation**” button is pressed, a progress bar, which states “**Resource allocation is in process…**”, will pop up (see Figure 84). The progress bar will disappear after a successful completion of the resource allocation process. If the user previously selected “**Overall Hazard**” as the objective to minimize, the results of the “**HRX Resource Allocation**” section will be exported to an Excel file named as “**Resource Allocation-1.xlsx**”; otherwise (i.e., the user selected “**Overall Hazard Severity**” as the objective to minimize), the output Excel file will be named as “**Resource Allocation-2.xlsx**”.

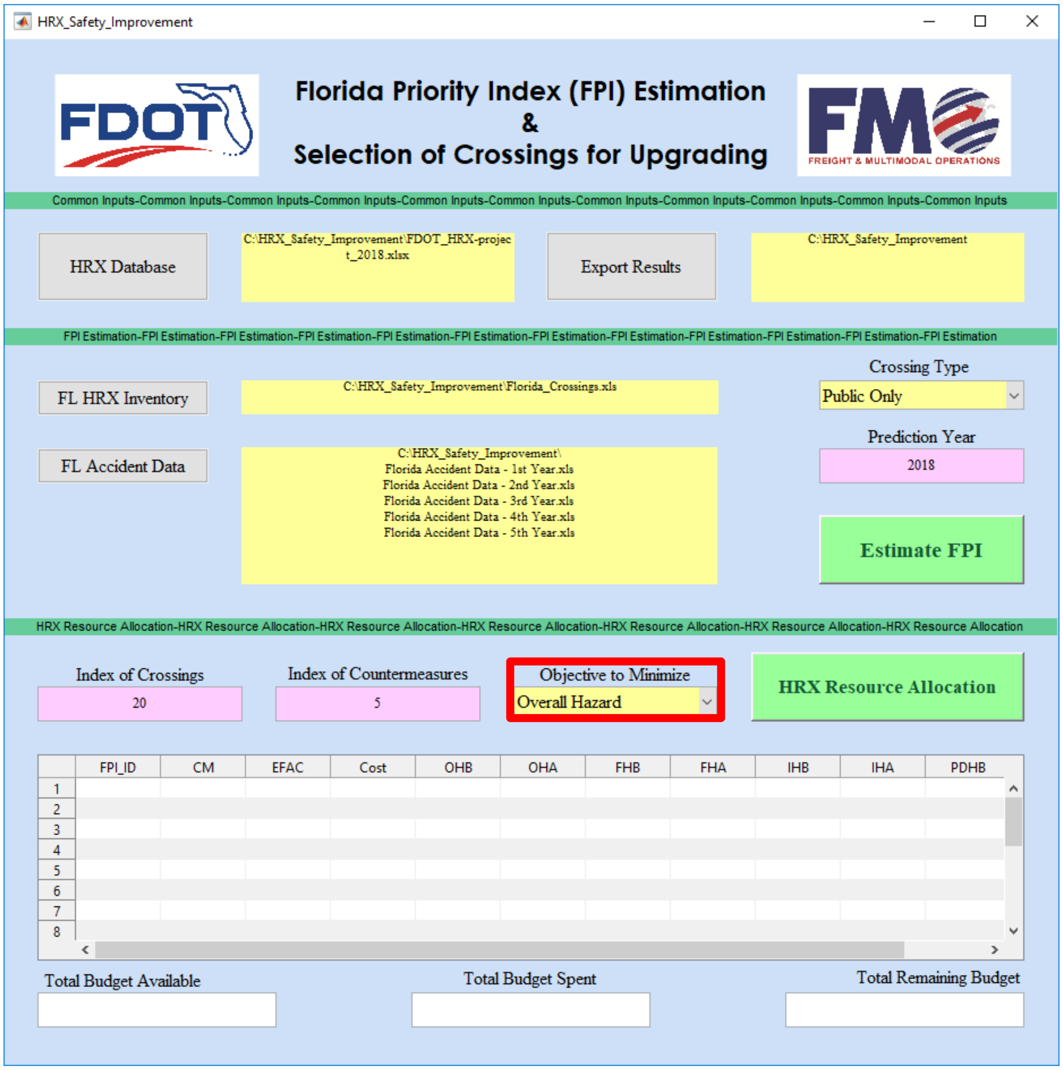



**Figure 83** Specifying the resource allocation objective.

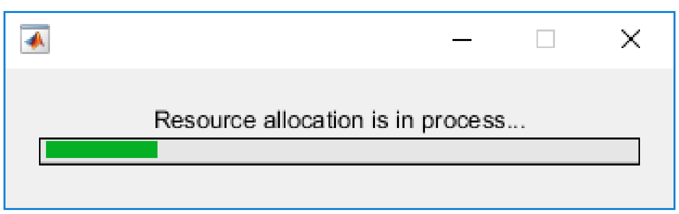



**Figure 84** The progress bar of "**HRX Resource Allocation**".

**Note**: There is a certain condition, which can interrupt a successful execution of the standalone application "HRX Safety Improvement". Specifically, the standalone application "HRX Safety Improvement" cannot delete or modify an open Excel file. If the user has already executed the "**HRX Resource Allocation**" section of the application successfully, opened some of the Excel files (e.g., "**Resource Allocation-1.xlsx**", "**Resource Allocation-2.xlsx**", or other Excel files), and tries to run the application again, the application may not run successfully (i.e., "freeze"), even if the Excel files have been closed by the user (as the Windows Operating System may still have the Excel application invoked). In case if the standalone application "HRX Safety

Improvement" gets frozen due to the Excel data exchange issues, the progress bar will not appear anymore after pressing the button "**Estimate FPI**" or the button "**HRX Resource Allocation**". However, if the user closes the application and restarts it, the application will resume working normally again. Therefore, the users are recommended to determine the analysis types they would like to conduct before executing the standalone application "HRX Safety Improvement". Also, the users are recommended to keep the Excel application closed, while performing certain procedures with the standalone application "HRX Safety Improvement", to insure that the standalone application "HRX Safety Improvement" works normally. In order to prevent the "freezing" issue, the latest version of the standalone application "HRX Safety Improvement" automatically closes open Excel files after pressing the button "**Estimate FPI**" or the button "**HRX Resource Allocation**".

***HRX Resource Allocation Outputs***

Upon completing the resource allocation, the table on the user interface will show different features of the highway-rail grade crossings selected for upgrading (see Figure 85). There are three fields at the bottom of the user interface, which show the financial information related to resource allocation, including the following data: (1) "**Total Budget Available"**; (2) "**Total Budget Spent**"; and (3) "**Total Remaining Budget**".

Moreover, the standalone application "HRX Safety Improvement" exports the resource allocation results to the previously specified location in the Excel format (i.e., XLSX). If the user previously selected "**Overall Hazard**" as the objective to minimize, the export Excel file will be named as "**Resource Allocation-1.xlsx**"; otherwise (i.e., the user selected "**Overall Hazard Severity**" as the objective to minimize) the export Excel file will be named as "**Resource Allocation-2.xlsx**". The results will be saved in two sheets of the Excel file (for both "**Resource Allocation-1.xlsx**" and "**Resource Allocation-2.xlsx**"). Figure 86, Figure 87, Figure 88, and Figure 89 illustrate the sheets of the Excel files "**Resource Allocation-1.xlsx**" and "**Resource Allocation-2.xlsx**", respectively. The "**Budget Info**" sheet of the output Excel file includes the same data as the ones shown in the three fields relevant to the financial information, which appears on the user interface. Furthermore, the "**Countermeasure Selection**" sheet of the output Excel file has several fields (i.e., columns), which include the same data as the ones shown in the table on the user interface. Specifically, the following information is provided:

- Crossing – rank/index of a highway-rail grade crossing;
- Countermeasure – index of the countermeasure assigned to a highway-rail grade crossing;
- Effectiveness Factor – effectiveness factor of the assigned countermeasure;
- Cost – cost to implement a given countermeasure at a highway-rail grade crossing;
- Overall Hazard Before – overall hazard of a highway-rail grade crossing before implementing a given countermeasure;
- Overall Hazard After – overall hazard of a highway-rail grade crossing after implementing a given countermeasure;
- Fatality Hazard Before – fatality hazard of a highway-rail grade crossing before implementing a given countermeasure (only when "**Overall Hazard Severity**" is minimized);

- Fatality Hazard After – fatality hazard of a highway-rail grade crossing after implementing a given countermeasure (only when "**Overall Hazard Severity**" is minimized);
- Injury Hazard Before – injury hazard of a highway-rail grade crossing before implementing a given countermeasure (only when "**Overall Hazard Severity**" is minimized);
- Injury Hazard After – injury hazard of a highway-rail grade crossing after implementing a given countermeasure (only when "**Overall Hazard Severity**" is minimized);
- Prop. Damage Hazard Before – property damage hazard of a highway-rail grade crossing before implementing a given countermeasure (only when "**Overall Hazard Severity**" is minimized); and
- Prop. Damage Hazard After – property damage hazard of a highway-rail grade crossing after implementing a given countermeasure (only when "**Overall Hazard Severity**" is minimized).

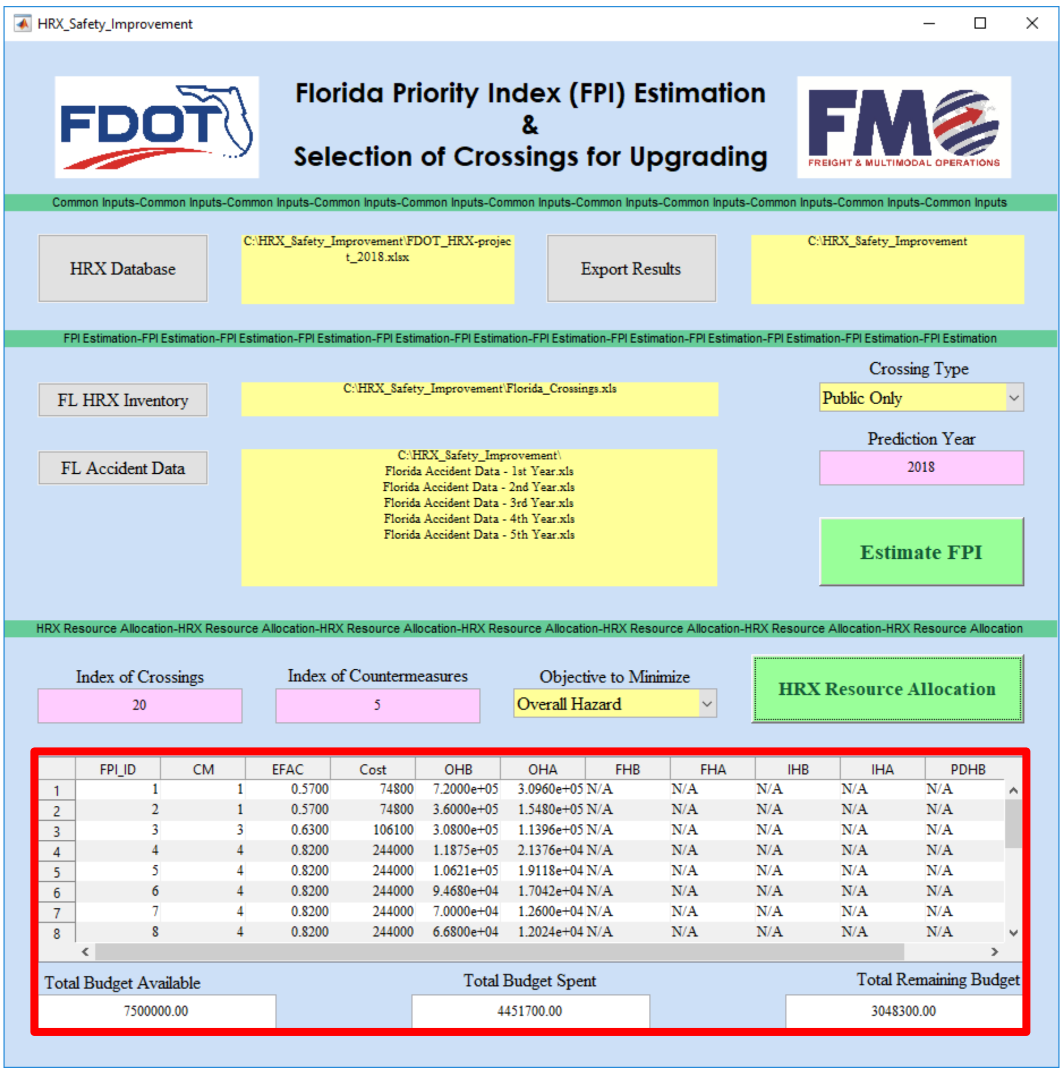
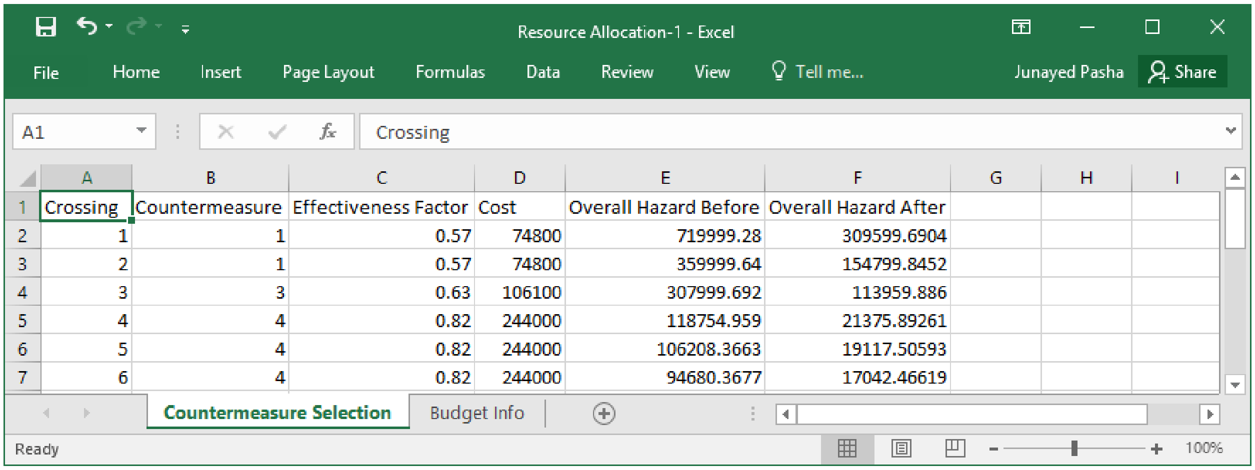
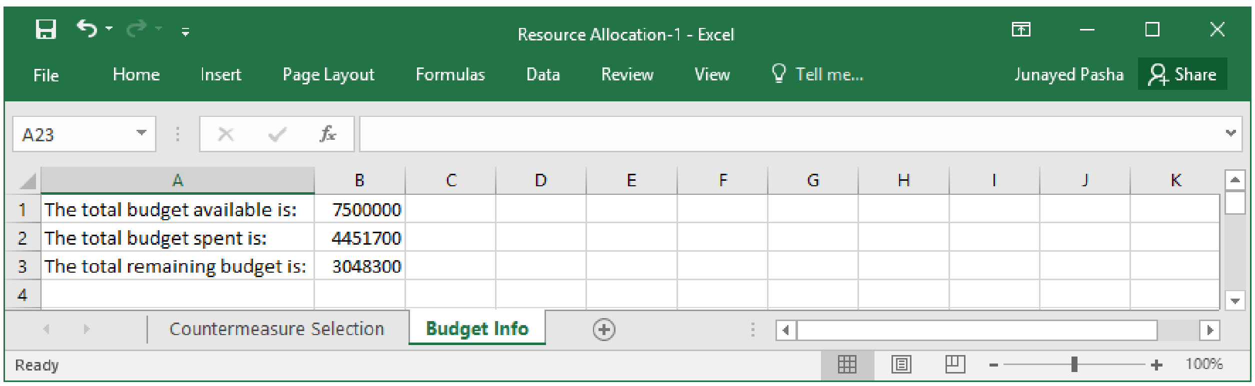



**Figure 85** The results displayed on the user interface.



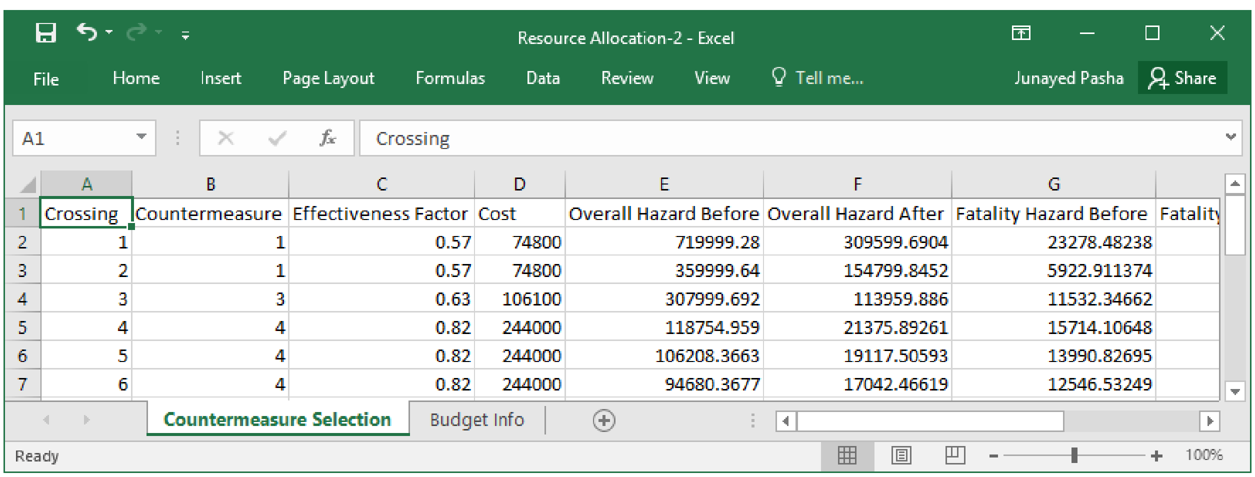
| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Crossing | Countermeasure | Effectiveness Factor | Cost | Overall Hazard Before | Overall Hazard After | | | |
| 2 | 1 | 1 | 0.57 | 74800 | 719999.28 | 309599.6904 | | | |
| 3 | 2 | 1 | 0.57 | 74800 | 359999.64 | 154799.8452 | | | |
| 4 | 3 | 3 | 0.63 | 106100 | 307999.692 | 113959.886 | | | |
| 5 | 4 | 4 | 0.82 | 244000 | 118754.959 | 21375.89261 | | | |
| 6 | 5 | 4 | 0.82 | 244000 | 106208.3663 | 19117.50593 | | | |
| 7 | 6 | 4 | 0.82 | 244000 | 94680.3677 | 17042.46619 | | | |

**Figure 86** The "**Countermeasure Selection**" sheet of "**Resource Allocation-1.xlsx**".



| | A | B |
|---|---|---|
| 1 | The total budget available is: | 7500000 |
| 2 | The total budget spent is: | 4451700 |
| 3 | The total remaining budget is: | 3048300 |

**Figure 87** The "**Budget Info**" sheet of "**Resource Allocation-1.xlsx**".



| | A | B | C | D | E | F | G | |
|---|---|---|---|---|---|---|---|---|
| 1 | Crossing | Countermeasure | Effectiveness Factor | Cost | Overall Hazard Before | Overall Hazard After | Fatality Hazard Before | Fatality |
| 2 | 1 | 1 | 0.57 | 74800 | 719999.28 | 309599.6904 | 23278.48238 | |
| 3 | 2 | 1 | 0.57 | 74800 | 359999.64 | 154799.8452 | 5922.911374 | |
| 4 | 3 | 3 | 0.63 | 106100 | 307999.692 | 113959.886 | 11532.34662 | |
| 5 | 4 | 4 | 0.82 | 244000 | 118754.959 | 21375.89261 | 15714.10648 | |
| 6 | 5 | 4 | 0.82 | 244000 | 106208.3663 | 19117.50593 | 13990.82695 | |
| 7 | 6 | 4 | 0.82 | 244000 | 94680.3677 | 17042.46619 | 12546.53249 | |

**Figure 88** The "**Countermeasure Selection**" sheet of "**Resource Allocation-2.xlsx**".

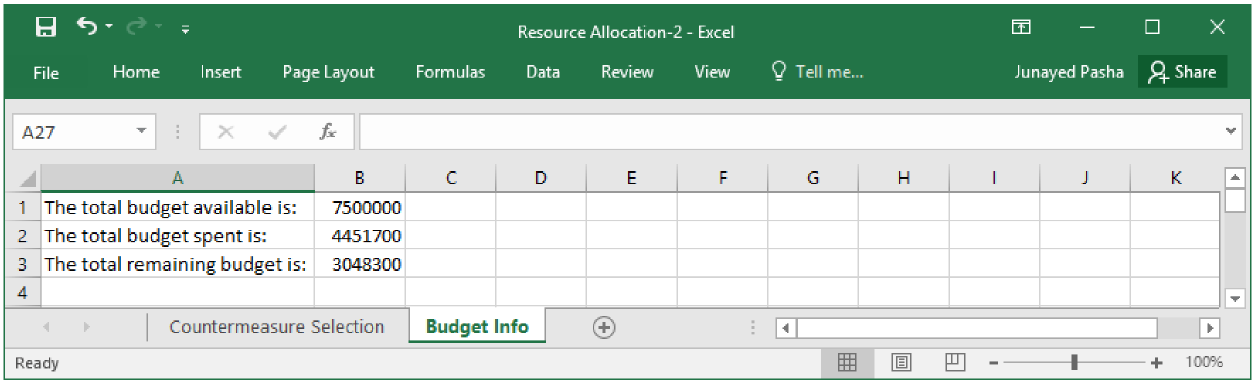
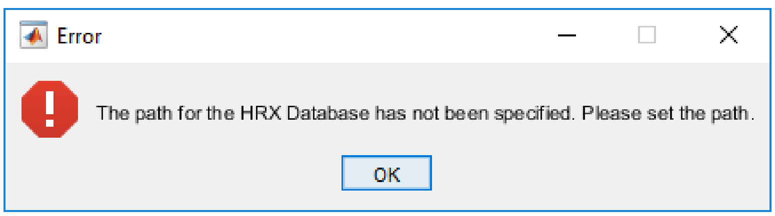



**Figure 89** The "**Budget Info**" sheet of "**Resource Allocation-2.xlsx**".

### *10.3.6. Error Messages*

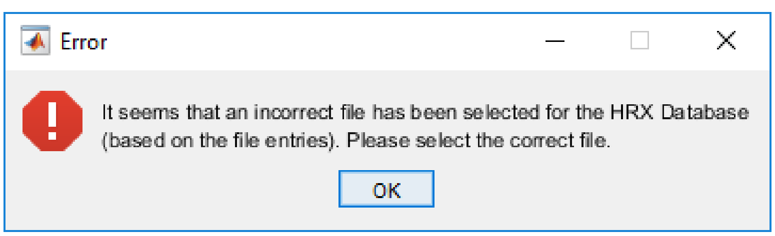
The following error messages may appear while executing the standalone application "HRX Safety Improvement":

(a) In case if the user has not specified the path for the HRX Database, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The path for the HRX Database has not been specified. Please set the path."



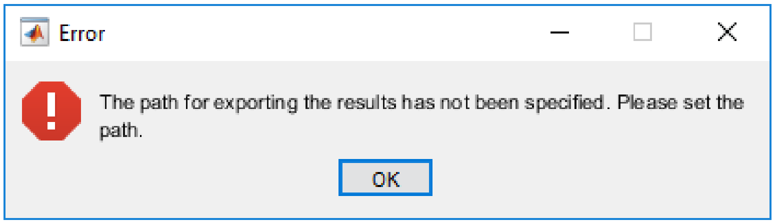

(a) The path for the HRX Database has not been specified.

(b) In case if the user has selected an incorrect file for the HRX Database (based on the file entries), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "It seems that an incorrect file has been selected for the HRX Database (based on the file entries). Please select the correct file."



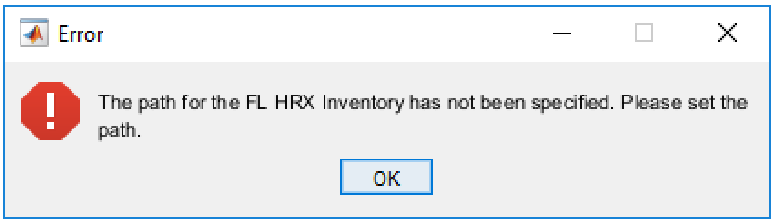

(b) An incorrect file has been selected for the HRX Database.

(c) In case if the user has not specified the path for exporting the results, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The path for exporting the results has not been specified. Please set the path."



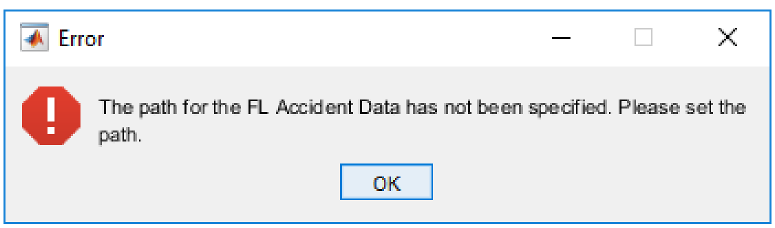

(c) The path for exporting the results has not been specified.

(d) In case if the user has not specified the path for the FL HRX Inventory, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The path for the FL HRX Inventory has not been specified. Please set the path."



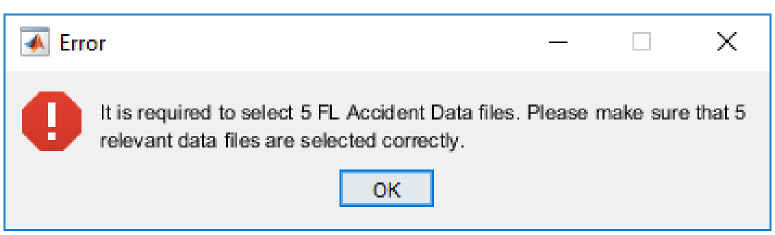

(d) The path for the crossing inventory data has not been specified.

(e) In case if the user has not specified the path for the FL Accident Data, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The path for the FL Accident Data has not been specified. Please set the path."



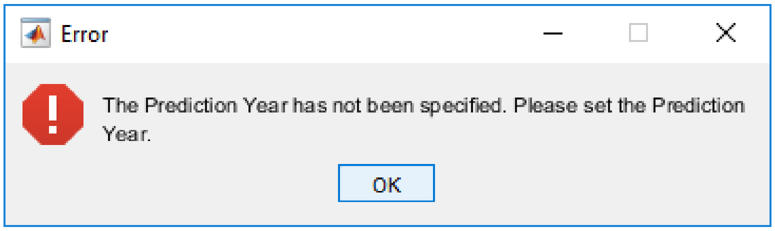

(e) The path for the accident data has not been specified.

(f) In case if the user has not selected the 5 FL Accident Data files (i.e., the accident data for 5 years before the prediction year), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "It is required to select 5 FL Accident Data files. Please make sure that 5 relevant data files are selected correctly."



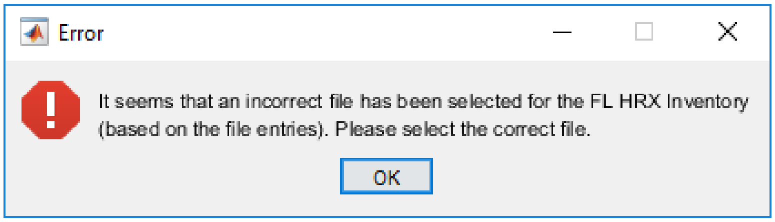

(f) The 5 accident data files have not been selected.

(g) In case if the user has not specified the prediction year, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The Prediction Year has not been specified. Please set the Prediction Year."



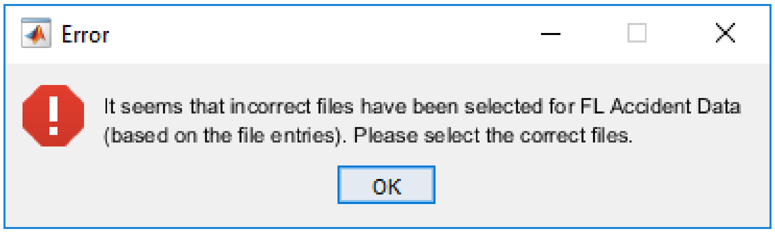

(g) The prediction year has not been specified.

(h) In case if the user has selected an incorrect file for the FL HRX Inventory (based on the file entries), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "It seems that an incorrect file has been selected for the FL HRX Inventory (based on the file entries). Please select the correct file."



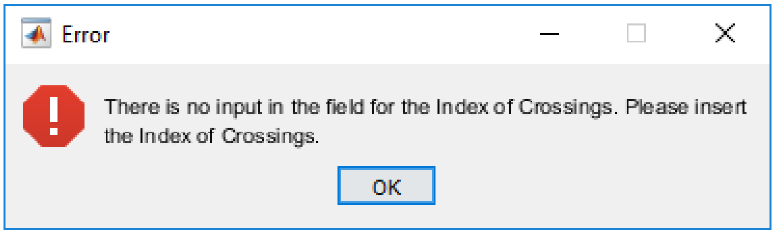

(h) Incorrect file has been selected for the crossing inventory data.

(i) In case if the user has selected incorrect files for the FL Accident Data (based on the file entries), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "It seems that incorrect files have been selected for the FL Accident Data (based on the file entries). Please select the correct files."



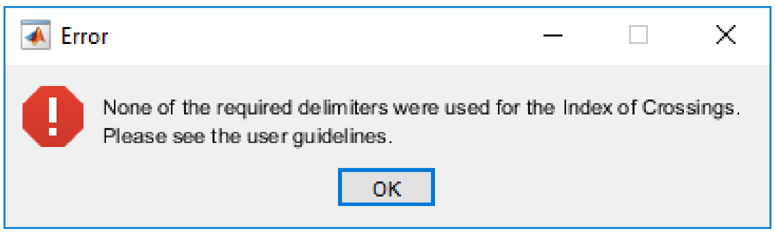

(i) Incorrect files have been selected for the accident data.

(j) In case if the user has not inserted the Index of Crossings, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "There is no input in the field for the Index of Crossings. Please insert the Index of Crossings."



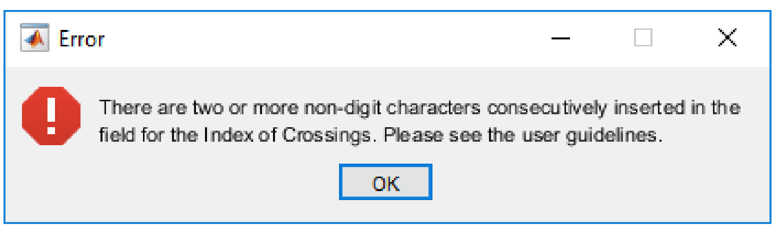

(j) The Index of Crossings has not been specified.

(k) In case if none of the required delimiters (see section 10.3.5) have been inserted by the user in the field for the Index of Crossings, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "None of the required delimiters were used for the Index of Crossings. Please see the user guidelines."



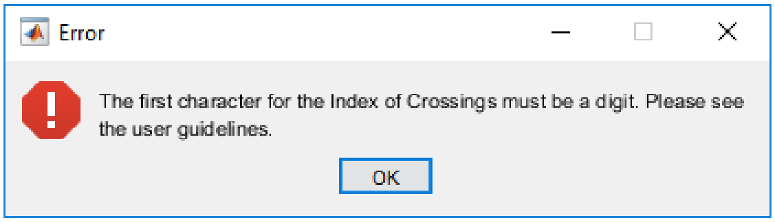

(k) None of the required delimiters have been inserted by the user for the Index of Crossings.

(l) In case if the user has inserted two or more allowed non-digit characters (i.e., comma, semicolon, hyphen, and colon) in the field for the Index of Crossings consecutively, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "There are two or more non-digit characters consecutively inserted in the field for the Index of Crossings. Please see the user guidelines."



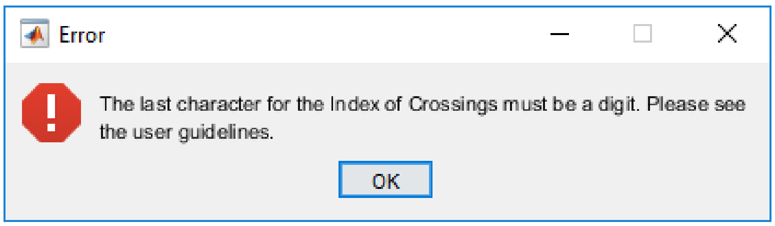

(l) Two or more allowed non-digit characters have been consecutively inserted in the field for the Index of Crossings.

(m) In case if the user has inserted a wrong character as the first character in the field for the Index of Crossings, which is not among the allowed characters (see section 10.3.5), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The first character for the Index of Crossings must be a digit. Please see the user guidelines."



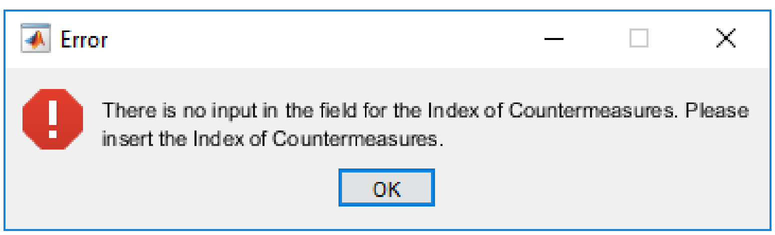

(m) A wrong character has been inserted by the user for the first character of Index of Crossings.

(n) In case if the user has inserted a wrong character as the last character in the field of Index of Crossings, which is not among the allowed characters (see section 10.3.5), the standalone application “HRX Safety Improvement” will return the following error message (see figure below): “The last character for the Index of Crossings must be a digit. Please see the user guidelines.”



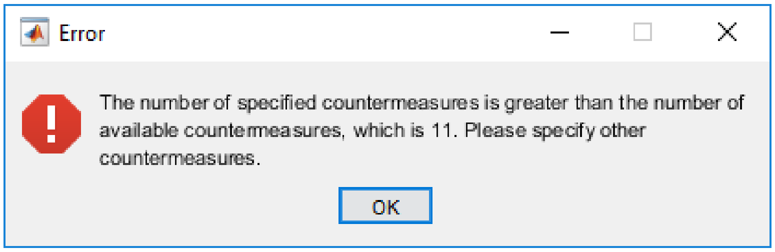

(n) A wrong character has been inserted by the user for the last character of Index of Crossings.

(o) In case if the user has not inserted the Index of Countermeasures, the standalone application “HRX Safety Improvement” will return the following error message (see figure below): “There is no input in the field for the Index of Countermeasures. Please insert the Index of Countermeasures.”



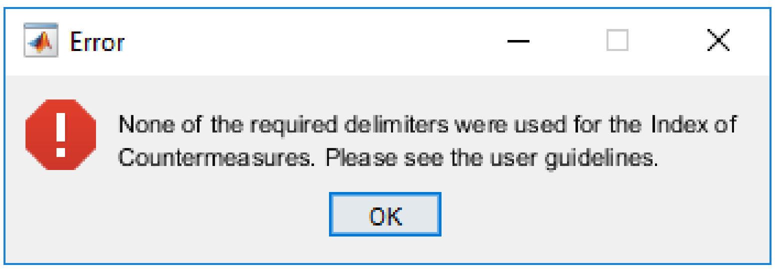

(o) The Index of Countermeasures has not been specified.

(p) In case if the user has specified the number of countermeasures, which is greater than the number of countermeasures available in the HRX Database, the standalone application “HRX Safety Improvement” will return the following error message (see figure below): “The number of specified countermeasures is greater than the number of available countermeasures, which is (11). Please specify other countermeasures.”



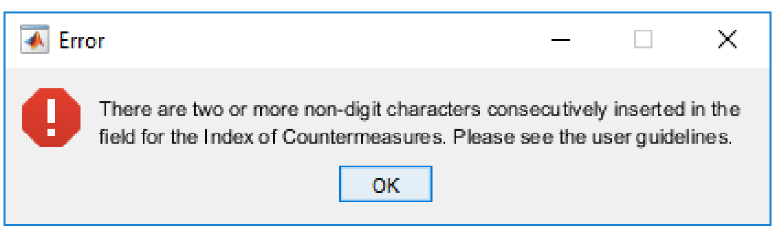

(p) The number of specified countermeasures is greater than the number of available countermeasures.

(q) In case if none of the required delimiters (see section 10.3.5) have been inserted by the user in the field for the Index of Countermeasures, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "None of the required delimiters were used for the Index of Countermeasures. Please see the user guidelines."



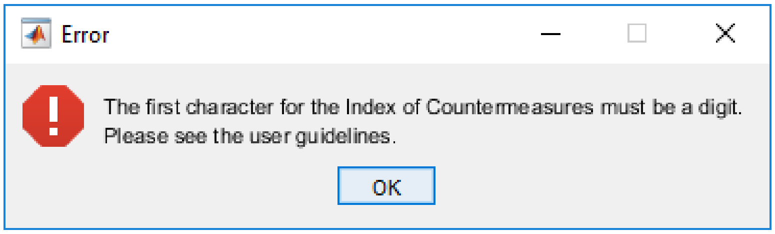

(q) None of the required delimiters have been inserted by the user for the Index of Countermeasures.

(r) In case if the user has inserted two or more allowed non-digit characters (i.e., comma, semicolon, hyphen, and colon) in the field for the Index of Countermeasures consecutively, the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "There are two or more non-digit characters consecutively inserted in the field for the Index of Countermeasures. Please see the user guidelines."



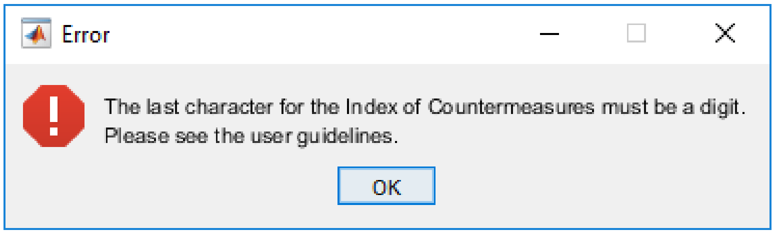

(r) Two or more allowed non-digit characters have been consecutively inserted in the field for the Index of Countermeasures.

(s) In case if the user has inserted a wrong character as the first character in the field for the Index of Countermeasures, which is not among the allowed characters (see section 10.3.5), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The first character for the Index of Countermeasures must be a digit. Please see the user guidelines."



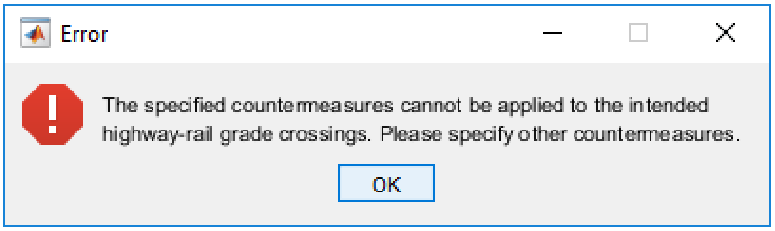

(s) A wrong character has been inserted by the user for the first character of Index of Countermeasures.

(t) In case if the user has inserted a wrong character as the last character in the field for the Index of Countermeasures, which is not among the allowed characters (see section 10.3.5), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The last character for the Index of Countermeasures must be a digit. Please see the user guidelines."




(t) A wrong character has been inserted by the user for the last character of Index of Countermeasures.

(u) In case if none of the specified countermeasures can be applied to the intended highway-rail grade crossings (due to certain physical and/or operational characteristics of the highway-rail grade crossings), the standalone application "HRX Safety Improvement" will return the following error message (see figure below): "The specified countermeasures cannot be applied to the intended highway-rail grade crossings. Please specify other countermeasures."




(u) None of the specified countermeasures can be applied to the intended highway-rail grade crossings.

# 11. METHODOLOGY APPLICATION

This section of the report presents a detailed description of the computational experiments, which were performed to showcase applicability of the proposed methodology for assessing potential overall hazard and hazard severity of the highway-rail grade crossings in the State of Florida and performing resource allocation among the existing highway-rail grade crossings in the State of Florida. In particular, the following types of analyses will be presented in this section: (1) sensitivity analysis for the total available budget; (2) sensitivity analysis for the number of available countermeasures; (3) sensitivity analysis for the hazard severity weight values of the **RAP-2** mathematical model; (4) resource allocation among various crossing types; and (5) consideration of additional criteria throughout the resource allocation.

## 11.1. Sensitivity Analysis for the Total Available Budget

Under this section of the report, the impact of the total available budget on resource allocation among the highway-rail grade crossings in the State of Florida is investigated. Specifically, a total of 12 scenarios were developed by changing the total available budget from $7.5M to $13.0M with an increment of $0.5M. All the 6,089 public highway-rail grade crossings in the State of Florida, extracted from the Federal Railroad Administration's (FRA) crossing inventory database (FRA, 2016), were investigated throughout the conducted analysis. Moreover, a total of 11 countermeasures (described in section 7.4.2 of this report) were considered for implementation at the highway-rail grade crossings. The developed optimization models (**RAP-1** and **RAP-2**) were solved using the PHR and PSR heuristics, respectively, in order to conduct the total available budget sensitivity analysis.

### *11.1.1. The Impact of the Total Available Budget on the Number of Highway-Rail Grade Crossings Upgraded by RAP-1 and RAP-2*

Figure 90 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-1**, for each one of the considered budget availability scenarios. A total of 1,198 and 1,723 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenarios 1 and 12 (with the lowest available budget and the highest available budget, respectively), when resource allocation was performed using **RAP-1**. As it is expected, the total number of highway-rail grade crossings upgraded by **RAP-1** increases with the total available budget. It can be observed that the function, representing the total number of highway-rail grade crossings upgraded using **RAP-1** based on the total available budget, is nonlinear. The latter finding highlights complexity of resource allocation based on **RAP-1**, as many different factors have to be considered throughout the highway-rail grade crossing upgrading decisions (e.g., eligibility of a highway-rail grade crossing for the considered countermeasures, different installation costs for the considered countermeasures, different effectiveness factors for the considered countermeasures, overall hazard of a highway-rail grade crossing, etc.).

Figure 91 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**, for each one of the considered budget availability scenarios. A total of 1,212 and 1,705 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenarios 1 and 12 (with the lowest available budget and the highest available budget, respectively), when resource allocation was performed using **RAP-**

**2**. As it is expected, the total number of highway-rail grade crossings upgraded by **RAP-2** increases with the total available budget. It can be observed that the function, representing the total number of highway-rail grade crossings upgraded using **RAP-2** based on the total available budget, is nonlinear. The latter finding highlights complexity of resource allocation based on **RAP-2**, as many different factors have to be considered throughout the highway-rail grade crossing upgrading decisions (e.g., eligibility of a highway-rail grade crossing for the considered countermeasures, different installation costs for the considered countermeasures, different effectiveness factors for the considered countermeasures, hazard severity of a highway-rail grade crossing, etc.).

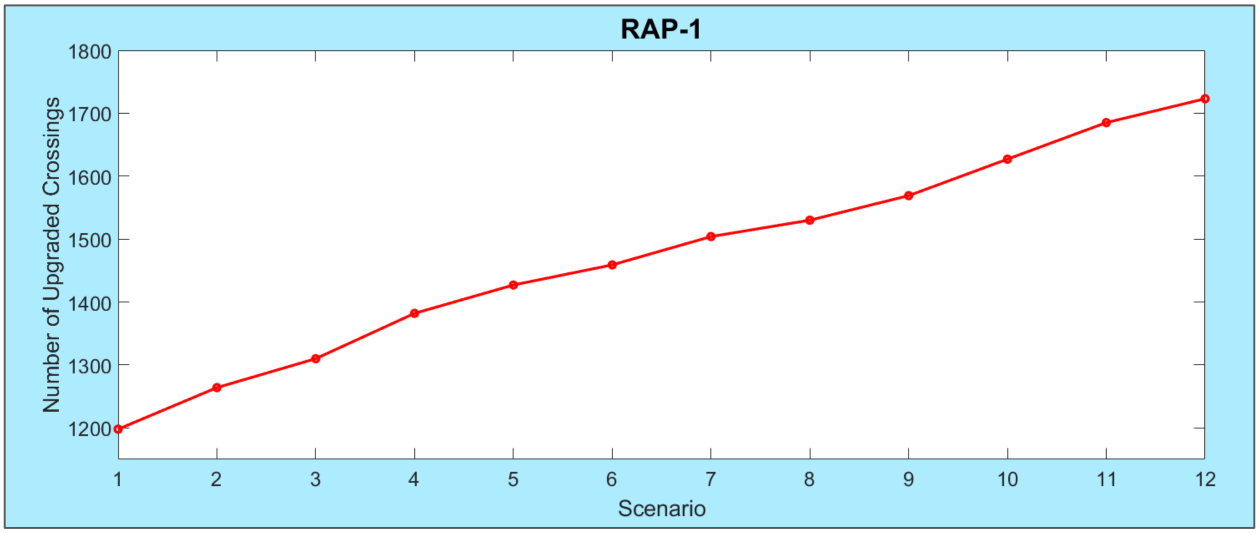



**Figure 90** The total number of highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #1).

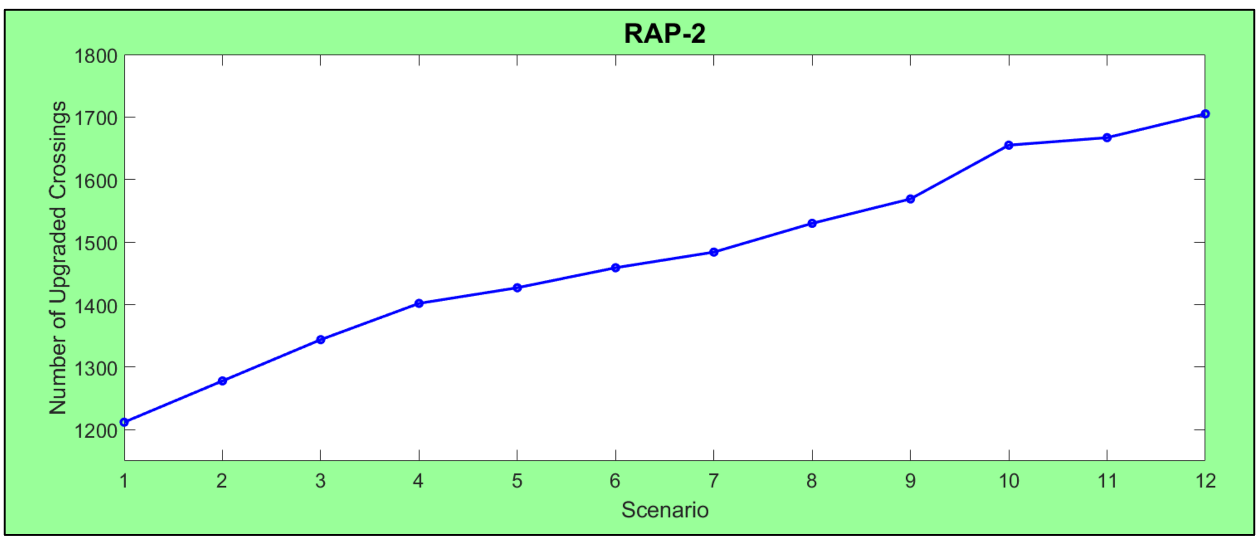



**Figure 91** The total number of highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #1).

### *11.1.2. The Impact of the Total Available Budget on the Overall Hazard Reduction for the Highway-Rail Grade Crossings Upgraded by RAP-1 and RAP-2*

Figure 92 depicts the overall hazard before implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-1**, for each one of the considered budget availability scenarios. It can be observed that the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, did not substantially change from increasing the total available budget. The latter pattern can be explained by the fact that the most hazardous highway-rail grade crossings were selected for upgrading even with the initial budget of $7.5M (i.e., scenario 1). The total number of highway-rail grade crossings, which were selected for upgrading by **RAP-1**, increased with the total available budget; however, the overall hazard of the highway-rail grade crossings, which were upgraded using the additional funds, was significantly lower as compared to the group of highway-rail grade crossings, which were upgraded using the initial budget. In particular, the average overall hazard before implementation of countermeasures at the 1,198 highway-rail grade crossings, which were selected for upgrading by **RAP-1** using the initial budget, comprised 3,084.21. On the other hand, the average overall hazard before implementation of countermeasures at the 525 highway-rail grade crossings, which were selected for upgrading by **RAP-1** using the additional funds, comprised only 180.68. Therefore, upgrading the highway-rail grade crossings with low hazard values did not substantially influence the overall hazard before implementation of countermeasures at the highway-rail grade crossings.

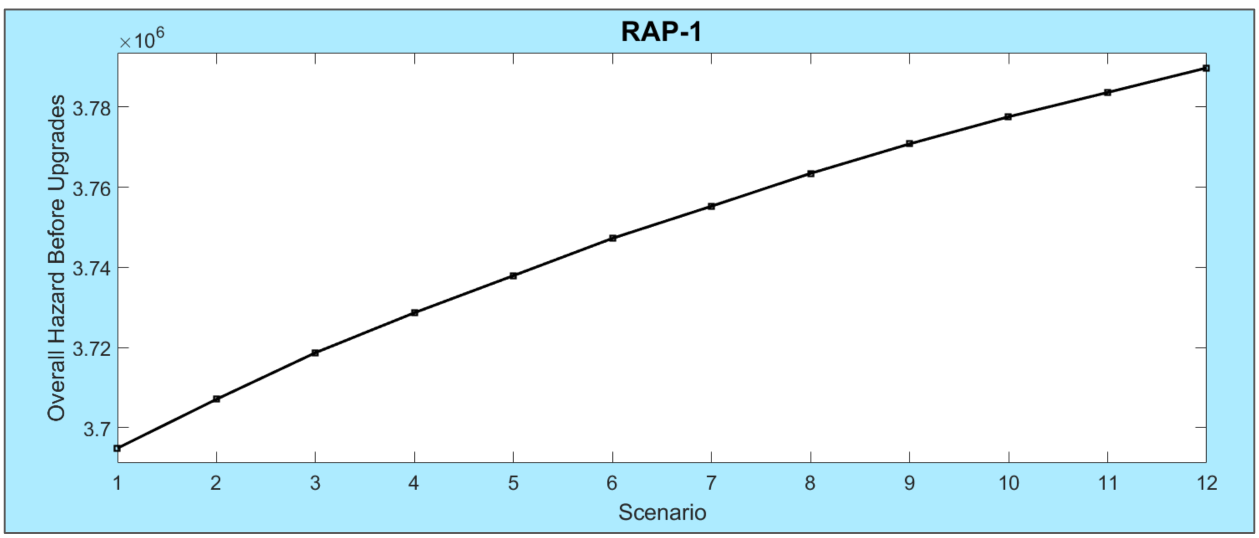



**Figure 92** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #1).

On the other hand, Figure 93 illustrates the overall hazard after implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-1**, for each one of the considered budget availability scenarios. It can be observed that application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(3.69 \cdot 10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 1. Moreover, the overall hazard decreased by $(3.79 \cdot 10^6 - 1.04 \cdot 10^6)/(3.79 \cdot 10^6) = 72.56\%$ for scenario 12. Therefore, the developed **RAP-1** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different budget availability scenarios.

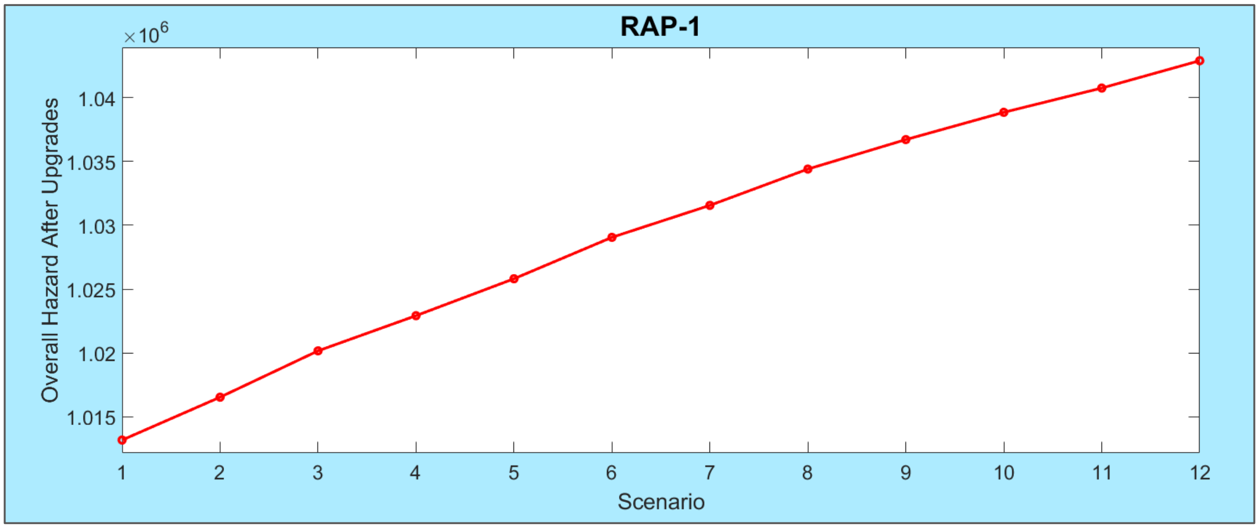



**Figure 93** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #1).

Figure 94 depicts the overall hazard before implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered budget availability scenarios. It can be observed that the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-2**, did not substantially change from increasing the total available budget. The latter pattern can be explained by the fact that the most hazardous highway-rail grade crossings were selected for upgrading even with the initial budget of $7.5M (i.e., scenario 1). The total number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**, increased with the total available budget; however, the overall hazard of the highway-rail grade crossings, which were upgraded using the additional funds, was significantly lower as compared to the group of highway-rail grade crossings, which were upgraded using the initial budget. In particular, the average overall hazard before implementation of countermeasures at the 1,212 highway-rail grade crossings, which were selected for upgrading by **RAP-2** using the initial budget, comprised 3,047.21. On the other hand, the average overall hazard before implementation of countermeasures at the 493 highway-rail grade crossings, which were selected for upgrading by **RAP-2** using the additional funds, comprised only 193.76. Therefore, upgrading the highway-rail grade crossings with low hazard values did not substantially influence the overall hazard before implementation of countermeasures at the highway-rail grade crossings.

On the other hand, Figure 95 illustrates the overall hazard after implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered budget availability scenarios. It can be observed that application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(3.69 \cdot$

$10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 1. Moreover, the overall hazard decreased by $(3.79 \cdot 10^6 - 1.04 \cdot 10^6)/(3.79 \cdot 10^6) = 72.56\%$ for scenario 12. Therefore, the developed **RAP-2** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different budget availability scenarios.

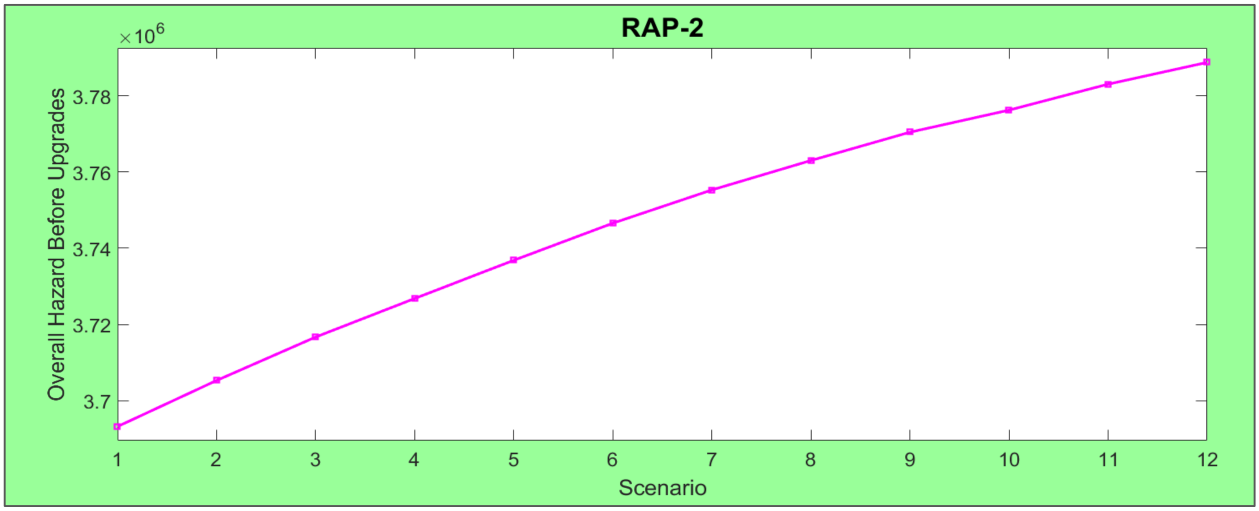



**Figure 94** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #1).

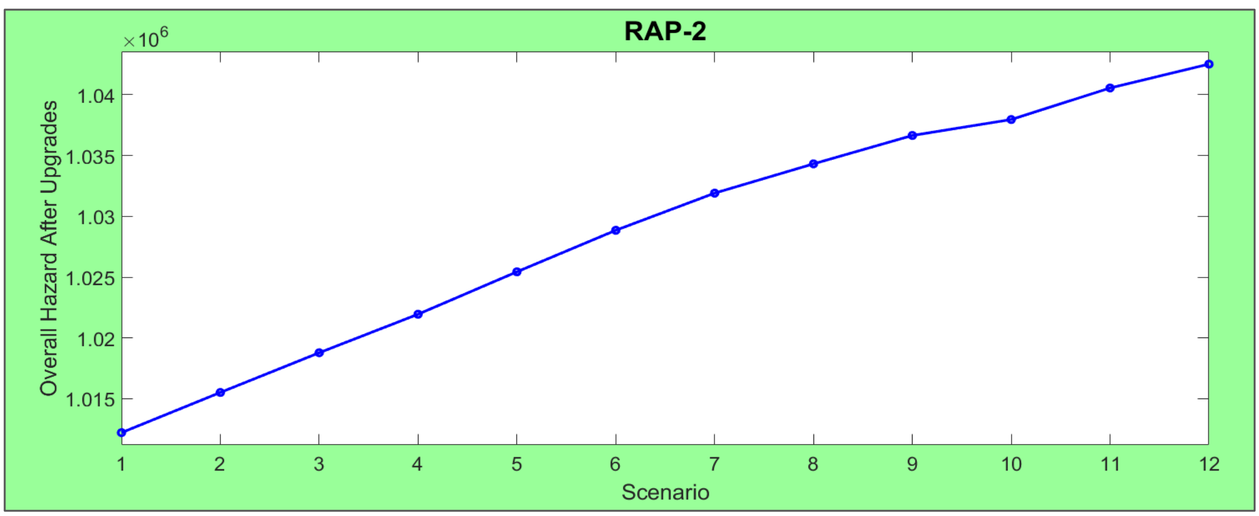



**Figure 95** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #1).

Note that the percentages in the overall hazard reduction at the highway-rail grade crossings, which were selected for upgrading, are similar for **RAP-1** and **RAP-2**. However, the number of the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, is different from the number of the highway-rail grade crossings, which were selected for upgrading by **RAP-2**. As indicated earlier, a total of 1,198 and 1,723 highway-rail grade crossings were selected by **RAP-1** for the budget availability scenarios 1 and 12. On the other hand, a total of 1,212 and 1,705 highway-rail grade crossings were selected by **RAP-2** for the budget availability scenarios

1 and 12. Such difference can be justified by the fact that **RAP-1** selects the highway-rail grade crossings for upgrading, aiming to minimize the overall hazard at the highway-rail grade crossings, while **RAP-2** selects the highway-rail grade crossings for upgrading, aiming to minimize the overall hazard severity at the highway-rail grade crossings (i.e., the expected fatality hazard, injury hazard, and property damage hazard values are considered throughout resource allocation by **RAP-2**).

### *11.1.3. The Impact of the Total Available Budget on the Average Installation Cost and the Average Effectiveness of Countermeasures Selected by RAP-1 and RAP-2*

The average installation cost and the average effectiveness of the countermeasures, which were selected by **RAP-1** at the public highway-rail grade crossings in the State of Florida, are presented in Figure 96 and Figure 97, respectively, for the considered budget availability scenarios. It can be observed that an increase in the total available budget allowed **RAP-1** selecting the countermeasures with higher installation cost at the considered highway-rail grade crossings. However, the maximum average installation cost of the countermeasures, which were selected by **RAP-1**, did not exceed $8,000 over all the developed budget availability scenarios. The latter pattern can be explained by the fact that the PHR heuristic, which was developed to solve the **RAP-1** mathematical model, selects the highway-rail grade crossings for upgrading and determines the appropriate upgrading type based on the hazard reduction-to-cost ratios. Therefore, the low-cost countermeasures (e.g., "mountable curbs [with channelized devices]" that have the installation cost of $15,000; "barrier curbs [with or without channelized devices]" that have the installation cost of $15,000; "one-way street with gate" that has the installation cost of $5,000) were preferential over the other countermeasures that have higher installation cost (e.g., "passive to flashing lights" that has the installation cost of $74,800; "flashing lights to gates" that has the installation cost of $106,100; "photo enforcement" that has the installation cost of $65,000). As underlined by Lin et al. (2017), low-cost countermeasures can be considered as efficient alternatives to improve safety at the highway-rail grade crossings in the State of Florida, taking into account the total available budget constraints.

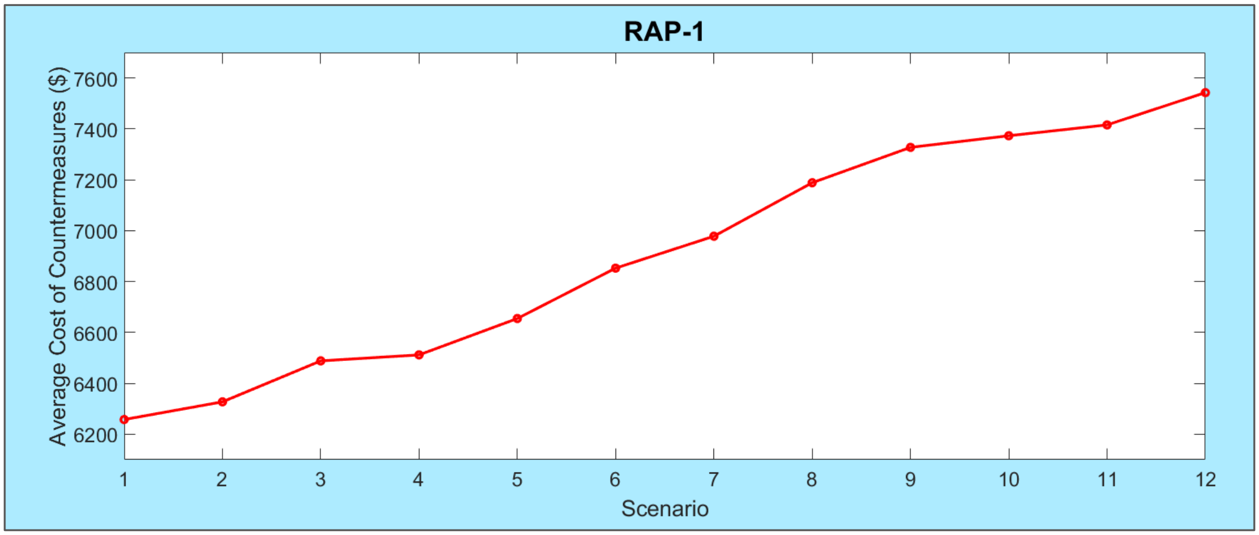



**Figure 96** The average installation cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #1).

Furthermore, the PHR heuristic was still selecting the countermeasures with fairly high effectiveness factors after increasing the total available budget from one scenario to another (see Figure 97). Specifically, the average effectiveness of the countermeasures, which were selected by **RAP-1**, varied between ≈0.813 and ≈0.817 for the considered budget availability scenarios. Such finding can be also explained by the nature of the proposed PHR heuristic, as it aims to select the countermeasures with the highest hazard reduction-to-cost ratios for the most hazardous public highway-rail grade crossings in the State of Florida.

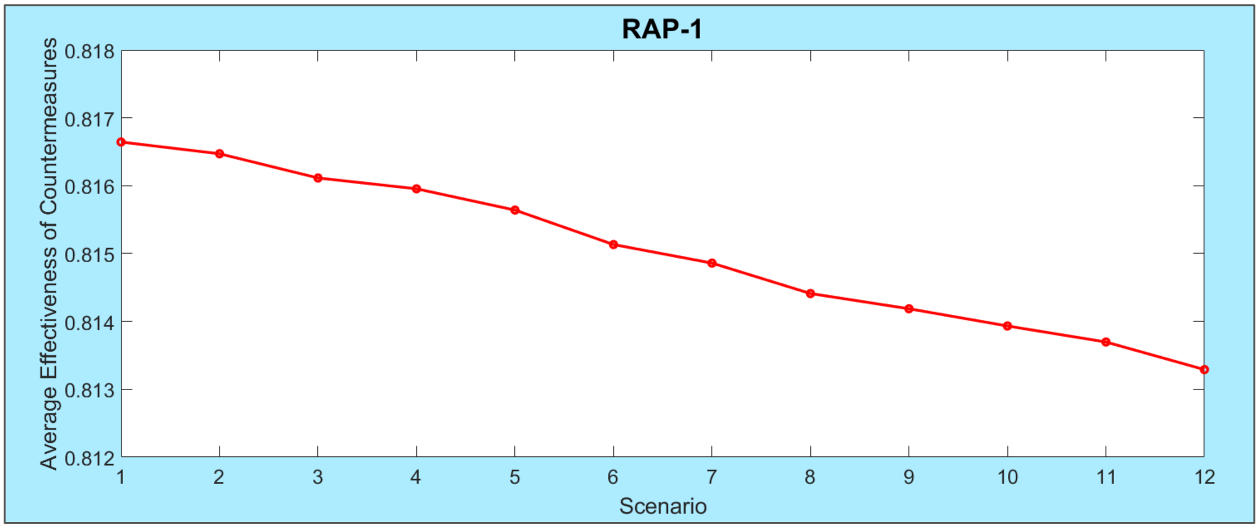



**Figure 97** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #1).

The average cost and the average effectiveness of countermeasures, which were selected by **RAP-2** at the public highway-rail grade crossings in the State of Florida for the considered budget availability scenarios, are presented in Figure 98 and Figure 99, respectively. It can be observed that an increase in the total available budget allowed **RAP-2** selecting the countermeasures with higher installation cost at the considered highway-rail grade crossings. However, the maximum average installation cost of the countermeasures, which were selected by **RAP-2**, did not exceed $8,000 over all the developed budget availability scenarios. The latter pattern can be explained by the fact that the PSR heuristic, which was developed to solve the **RAP-2** mathematical model, selects the highway-rail grade crossings for upgrading and determines the appropriate upgrading type based on the hazard severity reduction-to-cost ratios. Therefore, the low-cost countermeasures (e.g., "mountable curbs [with channelized devices]" that have the installation cost of $15,000; "barrier curbs [with or without channelized devices]" that have the installation cost of $15,000; "one-way street with gate" that has the installation cost of $5,000) were preferential over the other countermeasures that have higher installation cost (e.g., "passive to flashing lights" that has the installation cost of $74,800; "flashing lights to gates" that has the installation cost of $106,100; "photo enforcement" that has the installation cost of $65,000).

Furthermore, the PSR heuristic was still selecting the countermeasures with fairly high effectiveness factors after increasing the total available budget from one scenario to another (see Figure 99). Specifically, the average effectiveness of the countermeasures, which were selected by **RAP-2**, varied between ≈0.813 and ≈0.817 for the considered budget availability scenarios. Such finding can be also explained by the nature of the proposed PSR heuristic, as it aims to select the countermeasures with the highest hazard severity reduction-to-cost ratios for the most hazardous public highway-rail grade crossings in the State of Florida.

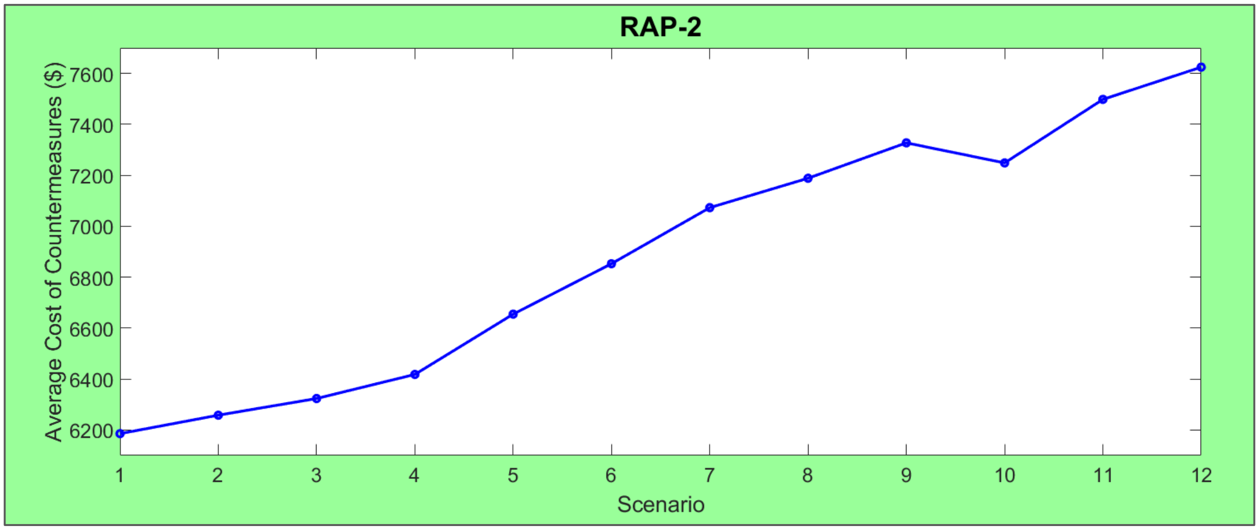



**Figure 98** The average installation cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #1).

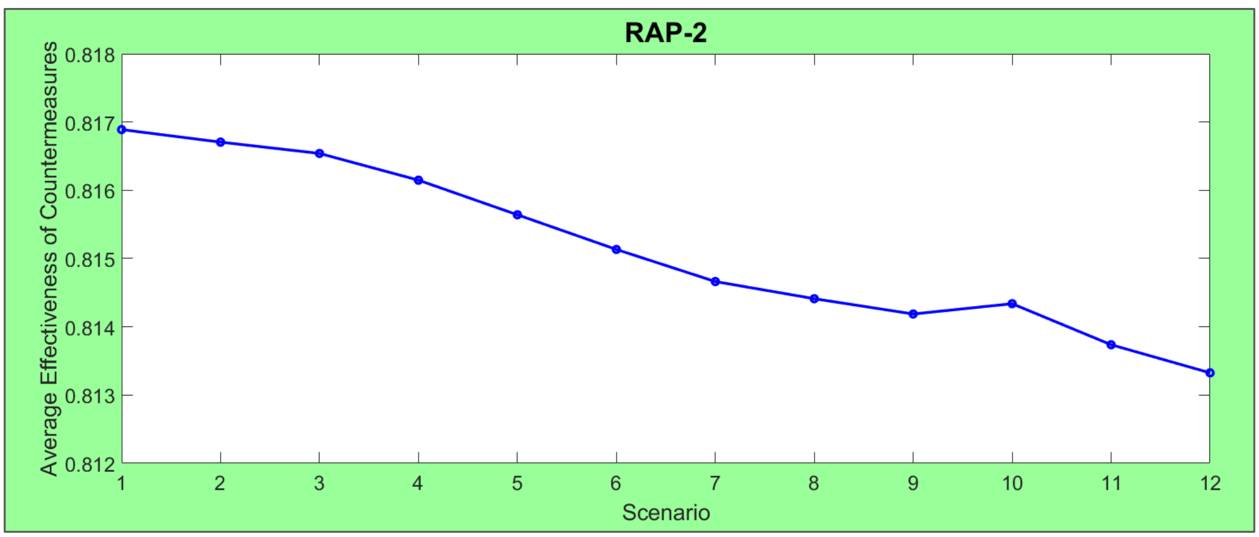



**Figure 99** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #1).

### 11.2. Sensitivity Analysis for the Number of Available Countermeasures

Under this section of the report, the impact of the number of available countermeasures on resource allocation among the highway-rail grade crossings in the State of Florida is investigated. Specifically, a total of 11 scenarios were developed by changing the number of available countermeasures from 1 to 11 with an increment of 1 countermeasure. All the 6,089 public highway-rail grade crossings in the State of Florida, extracted from the FRA crossing inventory database (FRA, 2016), were investigated throughout the analysis. Moreover, the total available budget was set equal to $7.5M. The developed optimization models (**RAP-1** and **RAP-2**) were solved using the PHR heuristic and the PSR heuristic, respectively, in order to conduct a sensitivity analysis for the number of available countermeasures.

#### *11.2.1. The Impact of the Countermeasure Availability on the Number of Highway-Rail Grade Crossings Upgraded by RAP-1 and RAP-2*

Figure 100 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-1**, for each one of the considered countermeasure availability scenarios. A total of 100 and 1,198 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenarios 1 and 11 (with the lowest and highest number of available countermeasures, respectively), when resource allocation was performed using **RAP-1**. In general, the total number of highway-rail grade crossings selected for upgrading by **RAP-1** increased with the total number of available countermeasures. The latter pattern can be justified by the fact that the installation cost of the available countermeasures and eligibility of the highway-rail grade crossings to implement the available countermeasures can substantially affect the number of upgraded highway-rail grade crossings. Specifically, there are a lot of gated highway-rail grade crossings in the State of Florida, which are not eligible for countermeasures "1", "2", "3" (more details regarding the considered countermeasures and eligibility of highway-rail grade crossings for these countermeasures can be found in section 7.4.2 of this report). Moreover, the installation cost for the first six countermeasures varies from $74,800 to $255,000, which justifies a quite low number of highway-rail grade crossings that were selected for upgrading by **RAP-1**. Consideration of low-cost countermeasures with the installation cost, varying from $5,000 to $15,000 (i.e., countermeasures "7", "8", and "9"), allowed significantly increasing the number of upgraded highway-rail grade crossings – see scenarios 7, 8, and 9 in Figure 100.

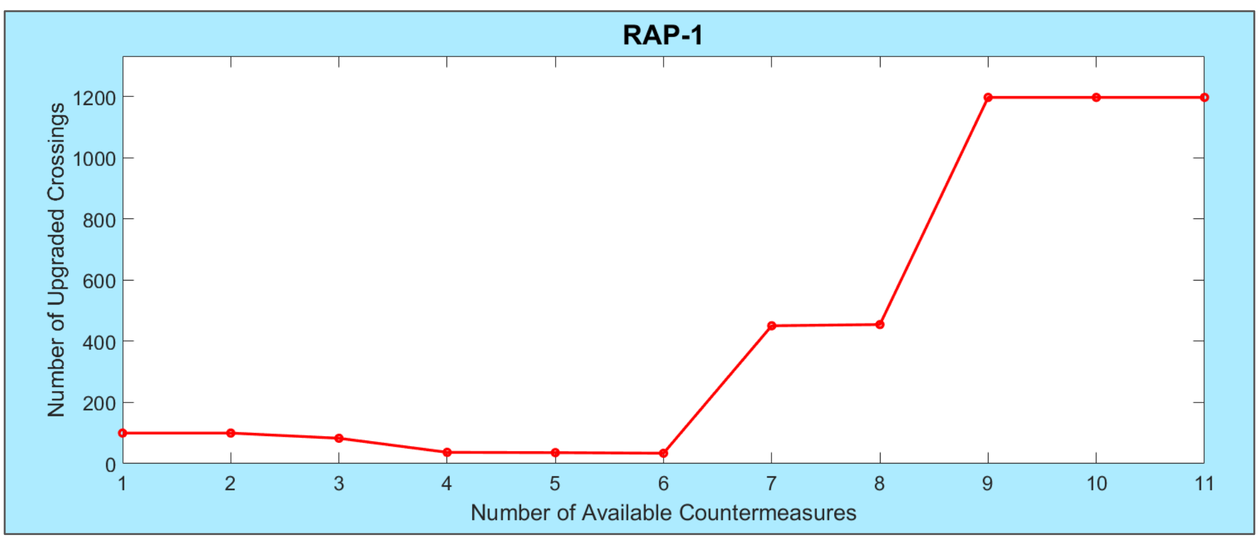



**Figure 100** The total number of highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #2).

Figure 101 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**, for each one of the considered countermeasure availability scenarios. A total of 100 and 1,212 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenarios 1 and 11 (with the lowest and highest number of available countermeasures, respectively), when resource allocation was performed using **RAP-2**. In general, the total number of highway-rail grade crossings selected for upgrading by **RAP-2** increases with the total number of available countermeasures. Similar to the analysis results when resource allocation was performed using **RAP-1**, the installation cost of the available countermeasures and eligibility of the highway-rail grade crossings to implement the available countermeasures were the primary factors, influencing the number of upgraded highway-rail grade crossings. Due to fairly high installation cost and eligibility requirements of the first six countermeasures, a quite low number of highway-rail grade crossings were selected for upgrading by **RAP-2**. However, introduction of the low-cost countermeasures (i.e., countermeasures "7", "8", and "9") allowed significantly increasing the number of upgraded highway-rail grade crossings – see scenarios 7, 8, and 9 in Figure 101.

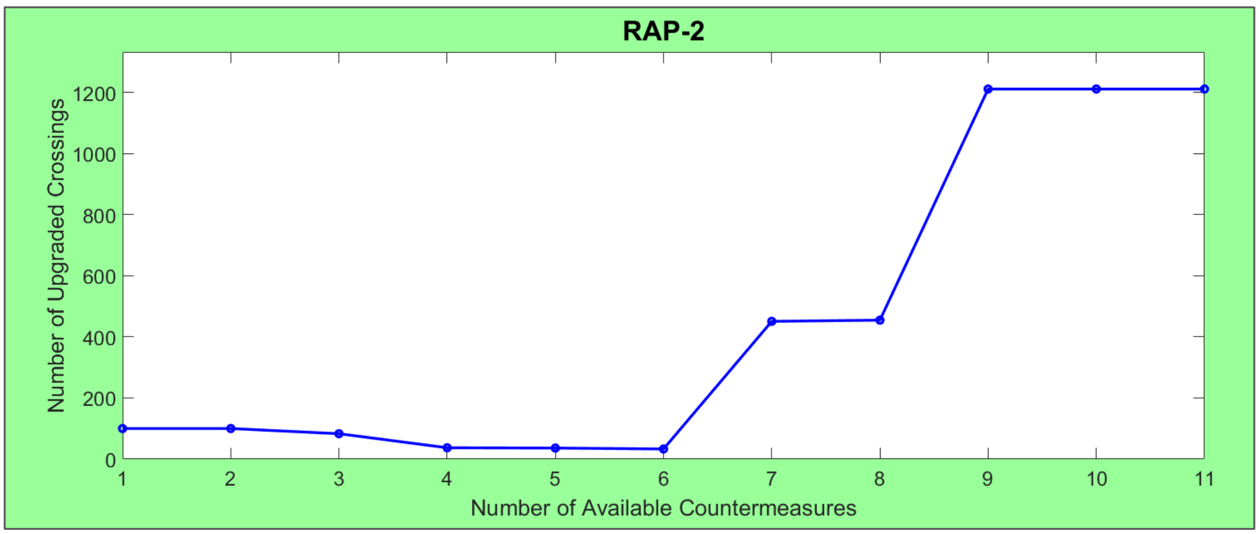



**Figure 101** The total number of highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #2).

### *11.2.2. The Impact of the Countermeasure Availability on the Overall Hazard Reduction for the Highway-Rail Grade Crossings Upgraded by RAP-1 and RAP-2*

Figure 102 depicts the overall hazard before implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-1**, for each one of the considered countermeasure availability scenarios. It can be observed that the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, substantially increased from increasing the number of available countermeasures. The latter pattern can be supported by the fact that an increasing number of the available countermeasures substantially increased the number of upgraded highway-rail grade crossings. Specifically, the number of highway-rail grade crossings, which were selected for upgrading by **RAP-1**, increased from 100 to 1,198 after increasing the number of number of available countermeasures from 1 to 11. Furthermore, the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, comprised $1.19 \cdot 10^6$ and $3.69 \cdot 10^6$ for scenarios 1 and 11, respectively.

Figure 103 illustrates the overall hazard after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-1**, for each one of the considered countermeasure availability scenarios. It can be observed that application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(1.19 \cdot 10^6 - 5.14 \cdot 10^5)/(1.19 \cdot 10^6) = 56.81\%$ for scenario 1. Moreover, the overall hazard decreased by $(3.69 \cdot 10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 11. Therefore, the developed **RAP-1** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different countermeasure availability scenarios.

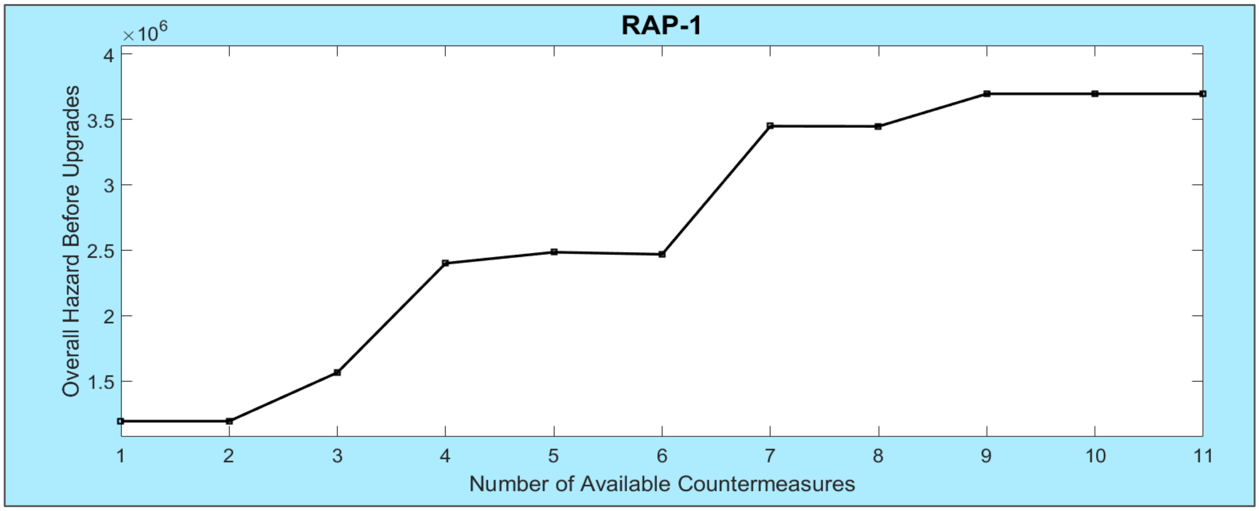



**Figure 102** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #2).

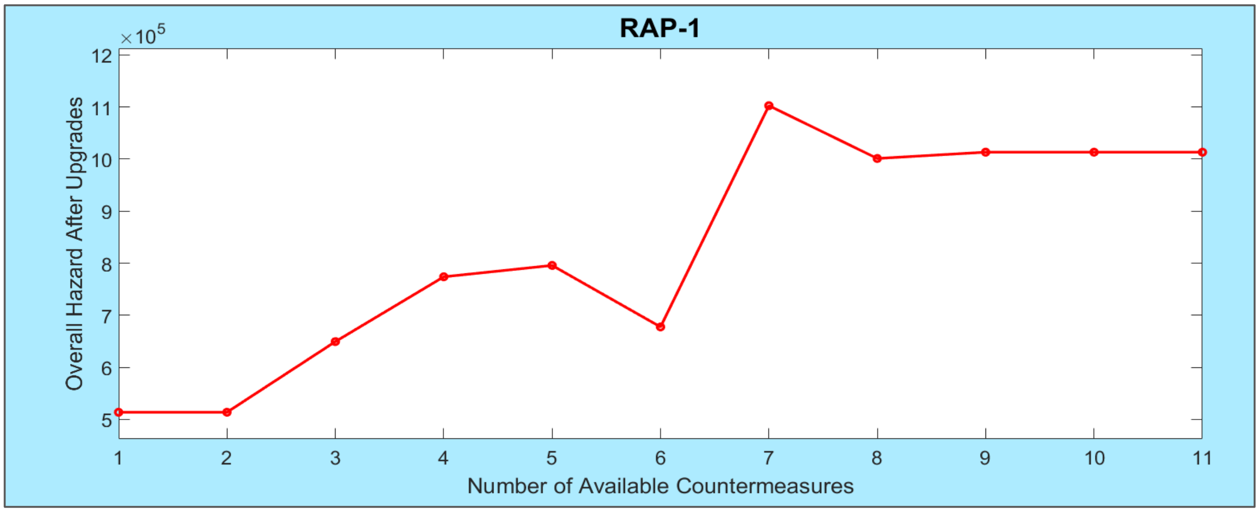



**Figure 103** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #2).

Figure 104 depicts the overall hazard before implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-**

**2**, for each one of the considered countermeasure availability scenarios. It can be observed that the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-2**, substantially increased from increasing the number of available countermeasures. The latter pattern can be supported by the fact that an increasing number of the available countermeasures substantially increased the number of upgraded highway-rail grade crossings. Specifically, the number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**, increased from 100 to 1,212 after increasing the number of number of available countermeasures from 1 to 11. Furthermore, the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-2**, comprised $1.19 \cdot 10^6$ and $3.69 \cdot 10^6$ for scenarios 1 and 11, respectively.

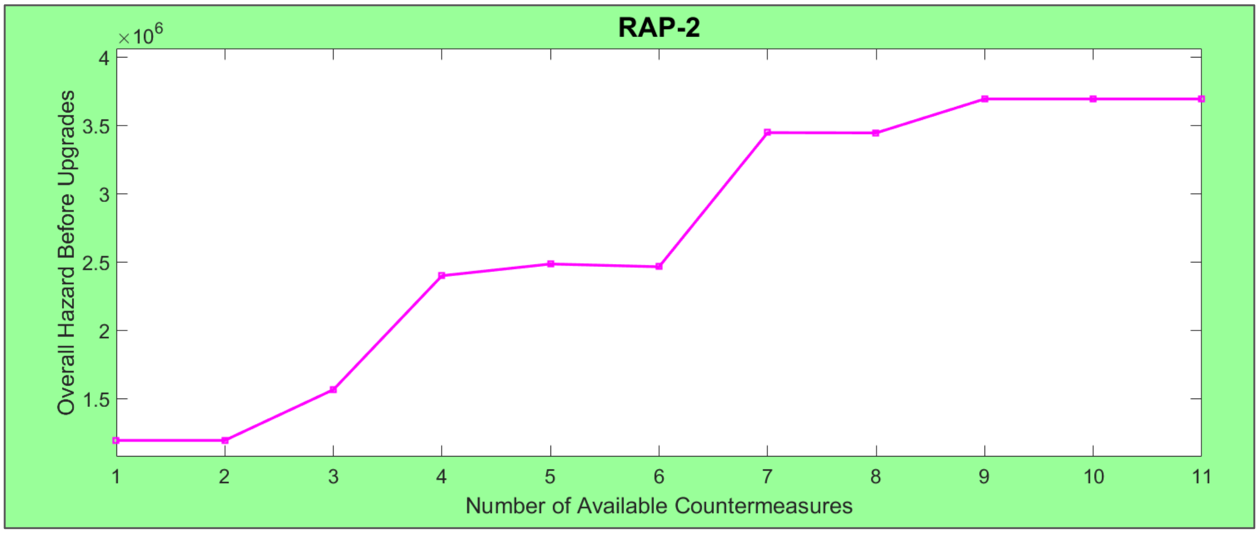



**Figure 104** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #2).

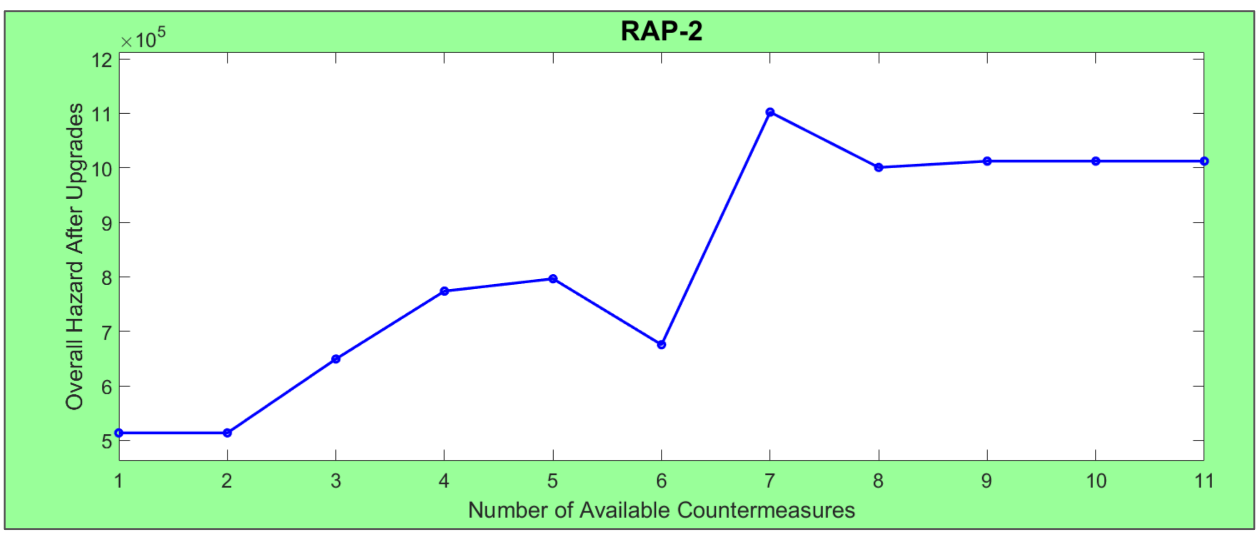



**Figure 105** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #2).

On the other hand, Figure 105 illustrates the overall hazard after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered countermeasure availability scenarios. It can be observed that application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(1.19 \cdot 10^6 - 5.14 \cdot 10^5)/(1.19 \cdot 10^6) = 56.81\%$ for scenario 1. Moreover, the overall hazard decreased by $(3.69 \cdot 10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 11. Therefore, the developed **RAP-2** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different countermeasure availability scenarios.

Note that the percentages in the overall hazard reduction at the highway-rail grade crossings, which were selected for upgrading, are similar for **RAP-1** and **RAP-2** for the considered countermeasure availability scenarios. However, the number of the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, is different from the number of the highway-rail grade crossings, which were selected for upgrading by **RAP-2**. As indicated earlier, a total of 100 and 1,198 highway-rail grade crossings were selected by **RAP-1** for the countermeasure availability scenarios 1 and 11. On the other hand, a total of 100 and 1,212 highway-rail grade crossings were selected by **RAP-2** for the countermeasure availability scenarios 1 and 11. Such difference can be justified by the fact that **RAP-1** selects the highway-rail grade crossings for upgrading, aiming to minimize the overall hazard at the highway-rail grade crossings, while **RAP-2** selects the highway-rail grade crossings for upgrading, aiming to minimize the overall hazard severity at the highway-rail grade crossings (i.e., the expected fatality hazard, injury hazard, and property damage hazard values are considered throughout resource allocation by **RAP-2**).

#### *11.2.3. The Impact of the Countermeasure Availability on the Average Installation Cost and the Average Effectiveness of Countermeasures Selected by RAP-1 and RAP-2*

The average installation cost and the average effectiveness of the countermeasures, which were selected by **RAP-1** at the public highway-rail grade crossings in the State of Florida, are presented in Figure 106 and Figure 107, respectively, for the considered countermeasure availability scenarios. It can be observed that an increase in the number of available countermeasures led to fluctuations in the average installation cost of the countermeasures, which were selected for the highway-rail grade crossings upgraded by **RAP-1**. For the first six countermeasure availability scenarios, when the installation cost of countermeasures varied from $74,800 to $255,000, the average installation cost for the countermeasures selected by **RAP-1** was fairly high. However, introduction of the low-cost countermeasures with the installation cost, varying from $5,000 to $15,000 (i.e., countermeasures “7”, “8”, and “9”), allowed significantly reducing the average installation cost for the countermeasures selected by **RAP-1**. The latter finding confirms the importance of low-cost countermeasures for effective resource allocation among the highway-rail grade crossings in the State of Florida.

Furthermore, based on the information, presented in Figure 107, it can be concluded that the average effectiveness of the countermeasures, which were selected for the highway-rail grade crossings upgraded by **RAP-1**, generally increased with an increasing number of the available countermeasures (with some fluctuations). Such finding can be supported by the fact that the low-cost countermeasures, which were selected for implementation at the highway-rail grade crossings by **RAP-1**, had fairly high effectiveness factors (e.g., “mountable curbs [with channelized devices]” that have the effectiveness factor of 0.75; “barrier curbs [with or without channelized devices]” that have the effectiveness factor of 0.80; “one-way street with gate” that has the effectiveness factor of 0.82). The effectiveness factors for other countermeasures were higher than 0.57 (the lowest effectiveness factor of 0.57 corresponds to “passive to flashing lights”). Moreover, selection of the countermeasures with low installation costs and high effectiveness factors can be justified by the nature of the PHR heuristic, developed to solve the **RAP-1** mathematical model. Specifically, the proposed PHR heuristic aims to select the countermeasures with the highest hazard reduction-to-cost ratios for the most hazardous public highway-rail grade crossings in the State of Florida.

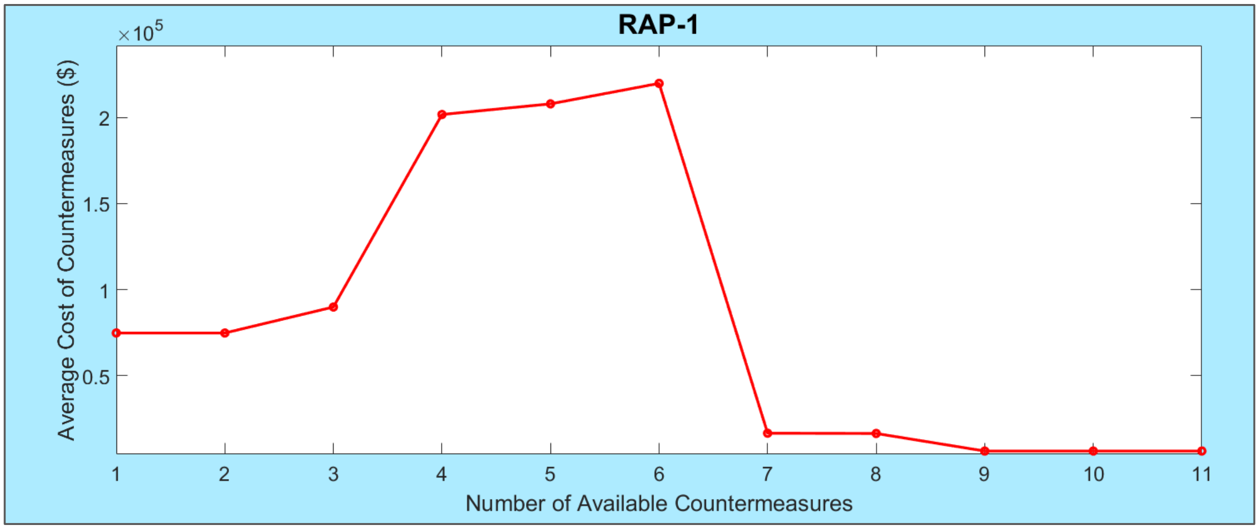



**Figure 106** The average installation cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #2).

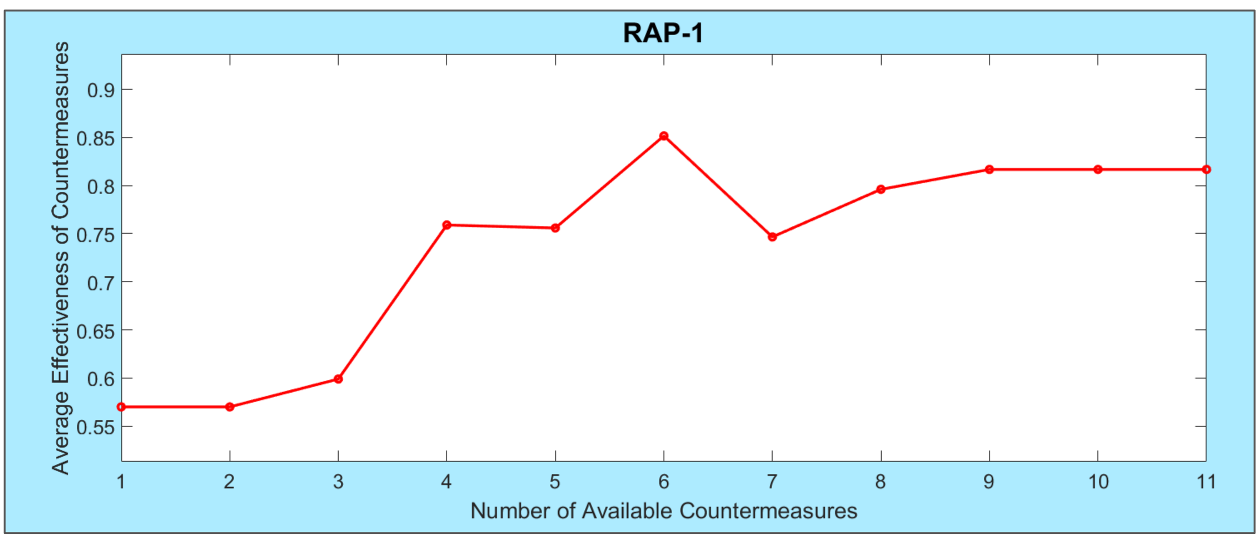



**Figure 107** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #2).

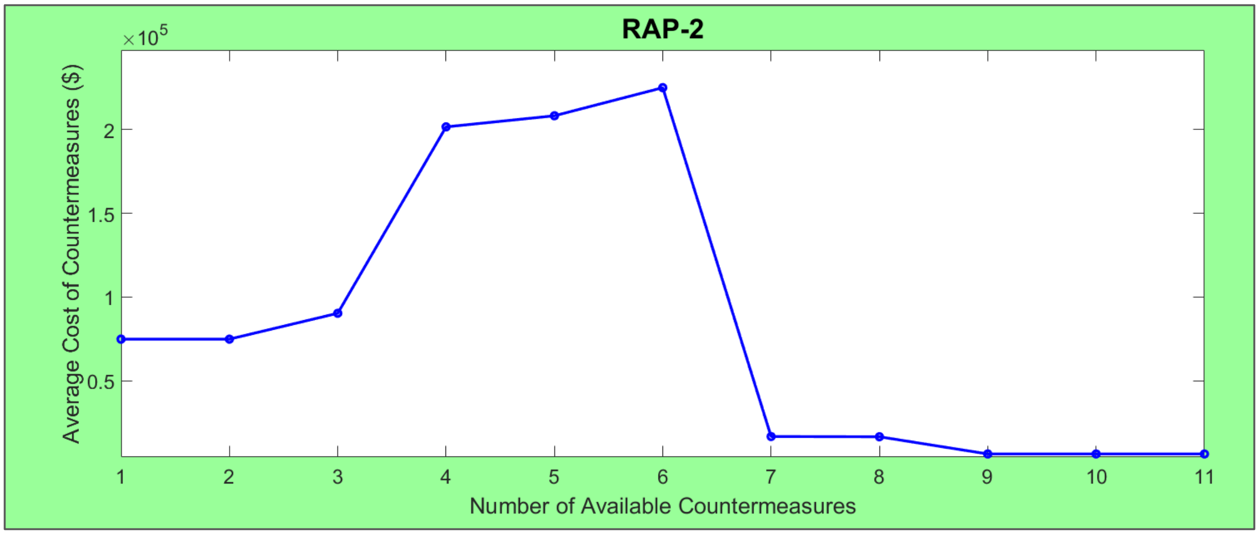



**Figure 108** The average installation cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #2).

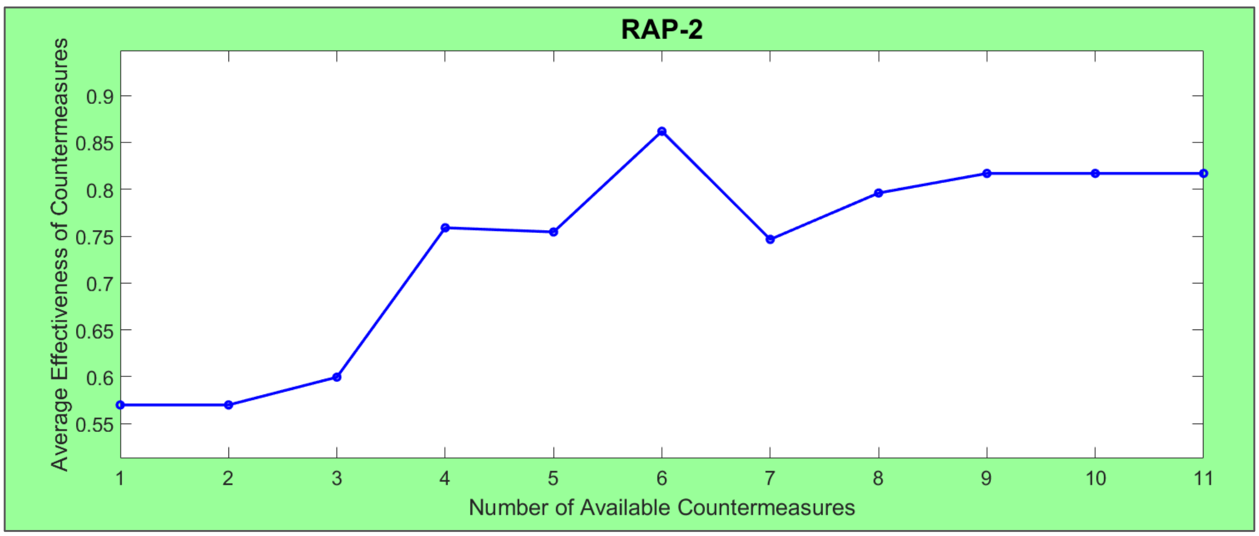



**Figure 109** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #2).

The average installation cost and the average effectiveness of countermeasures, which were selected by **RAP-2** at the public highway-rail grade crossings in the State of Florida, for the considered countermeasure availability scenarios are presented in Figure 108 and Figure 109, respectively. It can be observed that an increase in the number of available countermeasures led to fluctuations in the average installation cost of the countermeasures, which were selected for the highway-rail grade crossings upgraded by **RAP-2**. Similar to the analysis results when resource allocation was performed using **RAP-1**, the average installation cost for the countermeasures selected by **RAP-2** was fairly high for the first six countermeasure availability scenarios. However, introduction of the low-cost countermeasures (i.e., countermeasures "7", "8", and "9") allowed significantly reducing the average installation cost for the countermeasures selected by **RAP-2**. The latter finding again confirms the importance of low-cost countermeasures for effective resource allocation among the highway-rail grade crossings in the State of Florida.

Furthermore, based on the information, presented in Figure 109, it can be concluded that the average effectiveness of the countermeasures, which were selected for the highway-rail grade crossings upgraded by **RAP-2**, generally increased with an increasing number of the available countermeasures (with some fluctuations). Such finding can be supported by the fact that the low-cost countermeasures, which were selected for implementation at the highway-rail grade crossings by **RAP-2**, had fairly high effectiveness factors. Moreover, selection of the countermeasures with low installation costs and high effectiveness factors can be justified by the nature of the PSR heuristic, developed to solve the **RAP-2** mathematical model. Specifically, the proposed PSR heuristic aims to select the countermeasures with the highest hazard severity reduction-to-cost ratios for the most hazardous public highway-rail grade crossings in the State of Florida.

**Table 85** Developed scenarios for hazard severity weight values.

| Scenario | $W_{FH}$ | $W_{IH}$ | $W_{PH}$ |
|---|---|---|---|
| 1 | 0.600 | 0.300 | 0.100 |
| 2 | 0.620 | 0.285 | 0.095 |
| 3 | 0.640 | 0.270 | 0.090 |
| 4 | 0.660 | 0.255 | 0.085 |
| 5 | 0.680 | 0.240 | 0.080 |
| 6 | 0.700 | 0.225 | 0.075 |
| 7 | 0.720 | 0.210 | 0.070 |
| 8 | 0.740 | 0.195 | 0.065 |
| 9 | 0.760 | 0.180 | 0.060 |
| 10 | 0.780 | 0.165 | 0.055 |
| 11 | 0.800 | 0.150 | 0.050 |
| 12 | 0.820 | 0.135 | 0.045 |
| 13 | 0.840 | 0.120 | 0.040 |
| 14 | 0.860 | 0.105 | 0.035 |
| 15 | 0.880 | 0.090 | 0.030 |
| 16 | 0.900 | 0.075 | 0.025 |
| 17 | 0.920 | 0.060 | 0.020 |
| 18 | 0.940 | 0.045 | 0.015 |
| 19 | 0.960 | 0.030 | 0.010 |
| 20 | 0.980 | 0.015 | 0.005 |

### 11.3. Sensitivity Analysis for the Hazard Severity Weight Values (RAP-2)

Under this section of the report, the impact of the hazard severity weight values on resource allocation, performed by **RAP-2** among the highway-rail grade crossings in the State of Florida, is investigated. Specifically, a total of 20 scenarios were developed by changing the hazard severity weight values. The considered hazard severity weight values are presented in Table 85 for the developed scenarios. Note that terms $W_{FH}$, $W_{IH}$, and $W_{PH}$ in Table 85 stand for the fatality hazard, the injury hazard, and the property damage hazard, respectively. All the 6,089 public highway-rail grade crossings in the State of Florida, extracted from the FRA crossing inventory database (FRA, 2016), were investigated throughout the conducted analysis. Moreover, a total of 11 countermeasures (described in section 7.4.2 of this report) were considered for implementation at the considered highway-rail grade crossings, and the total available budget was set to $7.5M. The **RAP-2** optimization model was solved using the PSR heuristic in order to conduct a sensitivity analysis for the different sets of values for the hazard severity weights.

### *11.3.1. The Impact of the Hazard Severity Weight Values on the Number of Highway-Rail Grade Crossings Upgraded by RAP-2*

Figure 110 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**, for each one of the considered hazard severity weight scenarios. A total of 1,212 and 1,206 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenarios 1 and 20, respectively, when resource allocation was performed using **RAP-2**. It can be observed that an increase in the severity weight for the fatality hazard and a reduction in the severity weights for the injury hazard and the property damage hazard decreased the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**. The latter pattern can be justified by the fact that the PSR heuristic applied more expensive countermeasures with higher effectiveness factors in order to achieve higher hazard severity reduction at the most hazardous public highway-rail grade crossings in the State of Florida (i.e., the highway-rail grade crossings with the highest fatality hazard). However, implementation of more expensive countermeasures with higher effectiveness factors reduced the total number of highway-rail grade crossings, which can be upgraded by **RAP-2**, for the same total available budget.

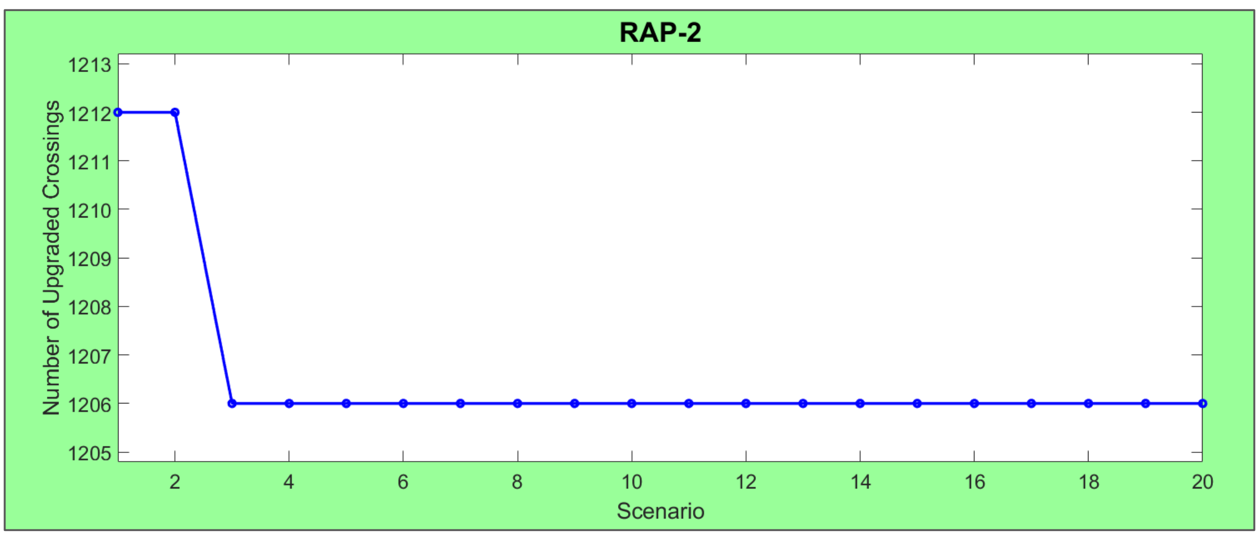



**Figure 110** The total number of highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

### *11.3.2. The Impact of the Hazard Severity Weight Values on the Overall Hazard Reduction for the Highway-Rail Grade Crossings Upgraded by RAP-2*

Figure 111 depicts the overall hazard before implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered hazard severity weight scenarios. On the other hand, Figure 112 showcases the overall hazard after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered hazard severity weight scenarios. It can be observed that the overall hazard severity before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-2**, decreased with increasing severity weight for the fatality hazard and decreasing severity weights for the injury hazard and the property damage hazard. The latter pattern can be supported by the fact that fewer highway-rail grade crossings were selected for upgrading by **RAP-2**, when the severity weight for the fatality hazard was increased, while the severity weights for the injury hazard and the property damage hazard were decreased from one scenario to another.

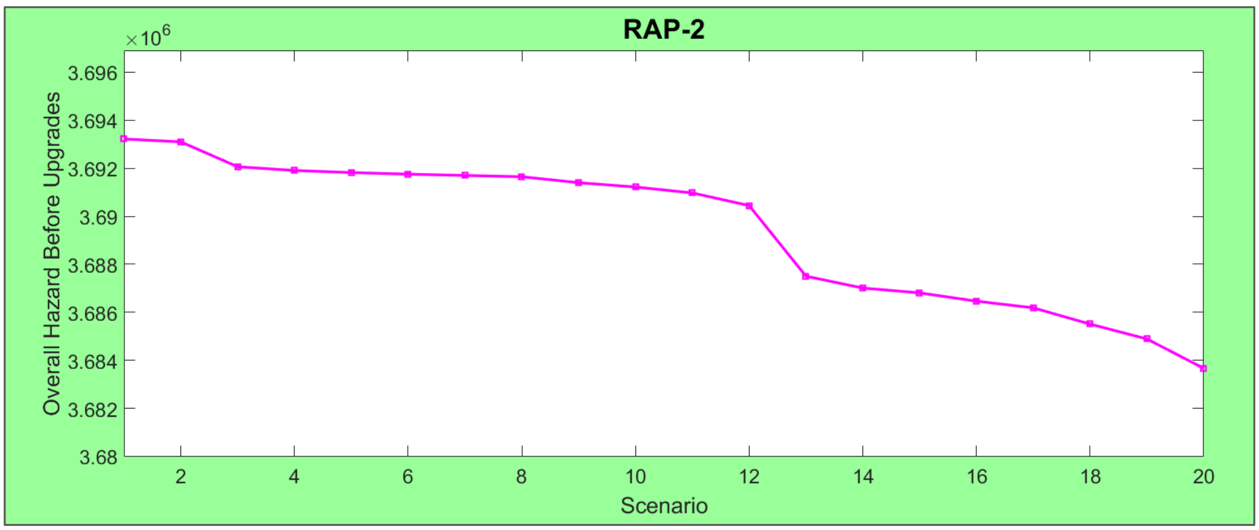



**Figure 111** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

Similarly, the overall hazard severity after implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-2**, decreased with increasing severity weight for the fatality hazard and decreasing severity weights for the injury hazard and the property damage hazard. However, application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(3.69 \cdot 10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 1. Moreover, the overall hazard decreased by $(3.68 \cdot 10^6 - 1.01 \cdot 10^6)/(3.68 \cdot 10^6) = 72.55\%$ for scenario 20. Therefore, the developed **RAP-2** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different hazard severity weight scenarios.

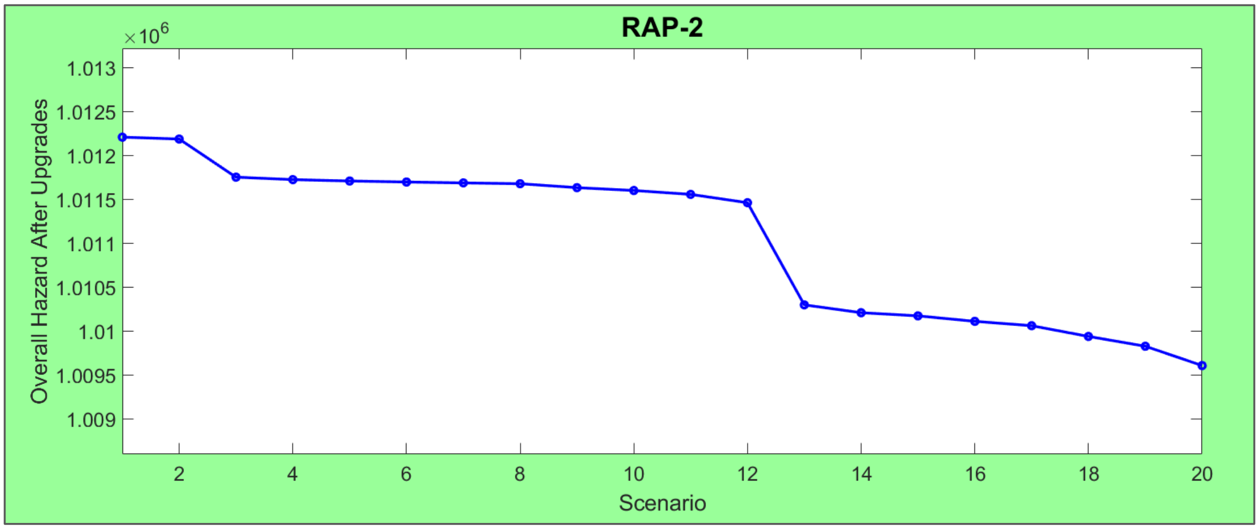



**Figure 112** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

The scope of the numerical experiments also included a detailed analysis of the overall hazard changes by severity category (i.e., the overall fatality hazard changes, the overall injury hazard changes, and the overall property damage hazard changes) before and after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered hazard severity weight scenarios. Figure 113 and Figure 114 show the overall fatality hazard before and after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, respectively. It can be observed that an increase in the severity weight for the fatality hazard and a reduction in the severity weights for the injury hazard and the property damage hazard increased the overall fatality hazard before implementation of countermeasures from one scenario to another. Therefore, the highway-rail grade crossings with higher fatality hazard were prioritized for upgrading by **RAP-2** after increasing in the severity weight for the fatality hazard from one scenario to another (although fewer highway-rail grade crossings were selected for upgrading by **RAP-2**). However, based on the information presented in Figure 114, it can be concluded that application of the selected countermeasures significantly decreased the overall fatality hazard at the highway-rail grade crossings. The latter finding highlights the efficiency of resource allocation based on the **RAP-2** mathematical model.

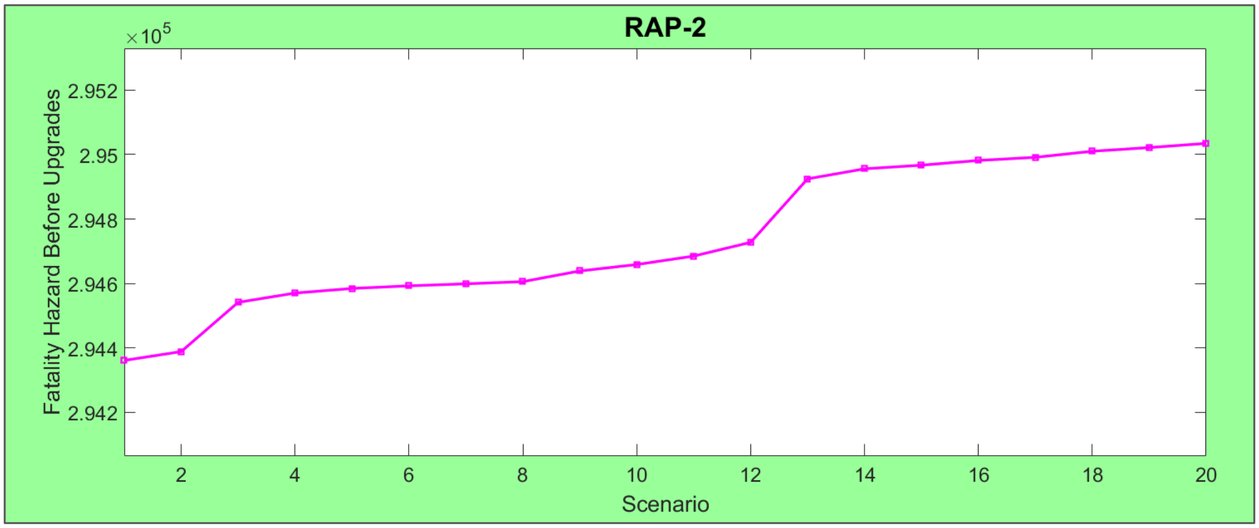



**Figure 113** The overall fatality hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

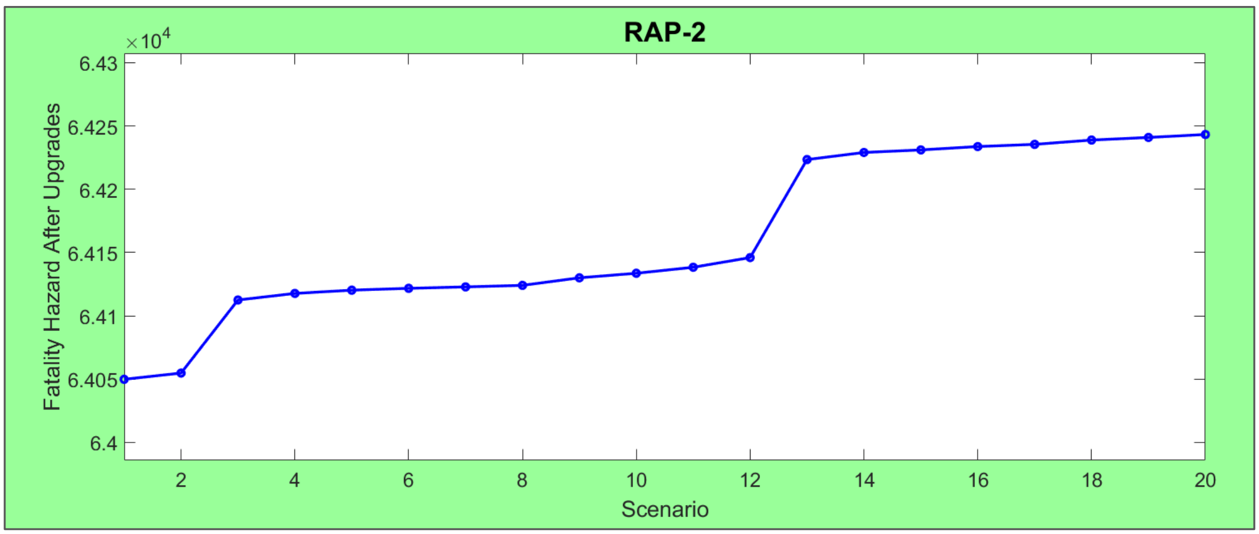



**Figure 114** The overall fatality hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

Figure 115 and Figure 116 show the overall injury hazard before and after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, respectively. It can be observed that an increase in the severity weight for the fatality hazard and a reduction in the severity weights for the injury hazard and the property damage hazard decreased the overall injury hazard before implementation of countermeasures from one scenario to another. The latter pattern can be supported by the fact that fewer highway-rail grade crossings were selected for upgrading by **RAP-2**, when the severity weight for the fatality hazard was increased, while the severity weights for the injury hazard and the property damage hazard were decreased from one scenario to another (the priority was given to the highway-rail grade crossings with higher fatality hazard). Furthermore, based on the information presented in Figure 116, it can be concluded that application of the selected countermeasures significantly decreased the overall injury hazard at the highway-rail grade crossings. The latter finding highlights the efficiency of resource allocation based on the **RAP-2** mathematical model.

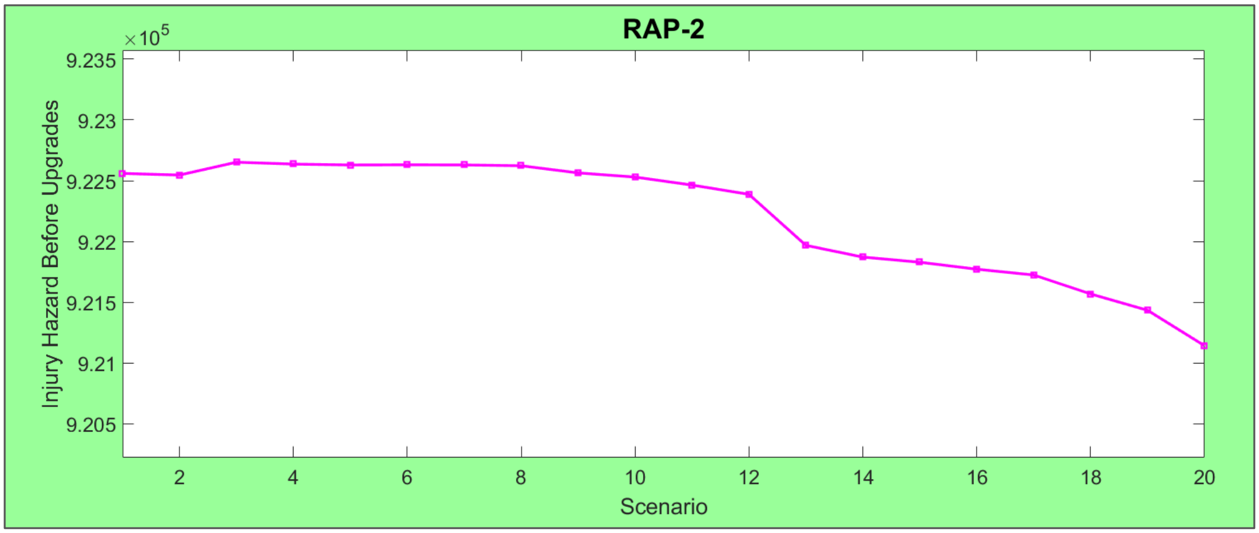



**Figure 115** The overall injury hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

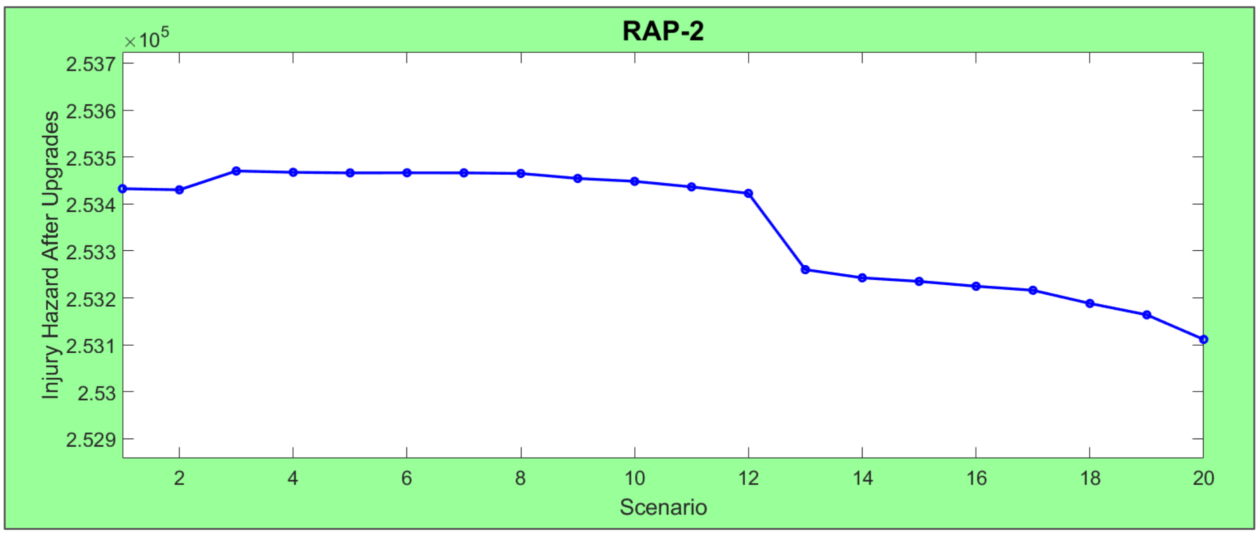



**Figure 116** The overall injury hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

Figure 117 and Figure 118 show the overall property damage hazard before and after implementation of countermeasures at the public highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, respectively. It can be observed that an increase in the severity weight for the fatality hazard and a reduction in the severity weights for the injury hazard and the property damage hazard decreased the overall property damage hazard before implementation of countermeasures from one scenario to another. The latter pattern can be supported by the fact that fewer highway-rail grade crossings were selected for upgrading by **RAP-2**, when the severity weight for the fatality hazard was increased, while the severity weights for the injury hazard and the property damage hazard were decreased from one scenario to another (the priority was given to the highway-rail grade crossings with higher fatality hazard). Furthermore, based on the information presented in Figure 118, it can be concluded that application of the selected countermeasures significantly decreased the overall property damage hazard at the highway-rail grade crossings. The latter finding highlights the efficiency of resource allocation based on the **RAP-2** mathematical model.

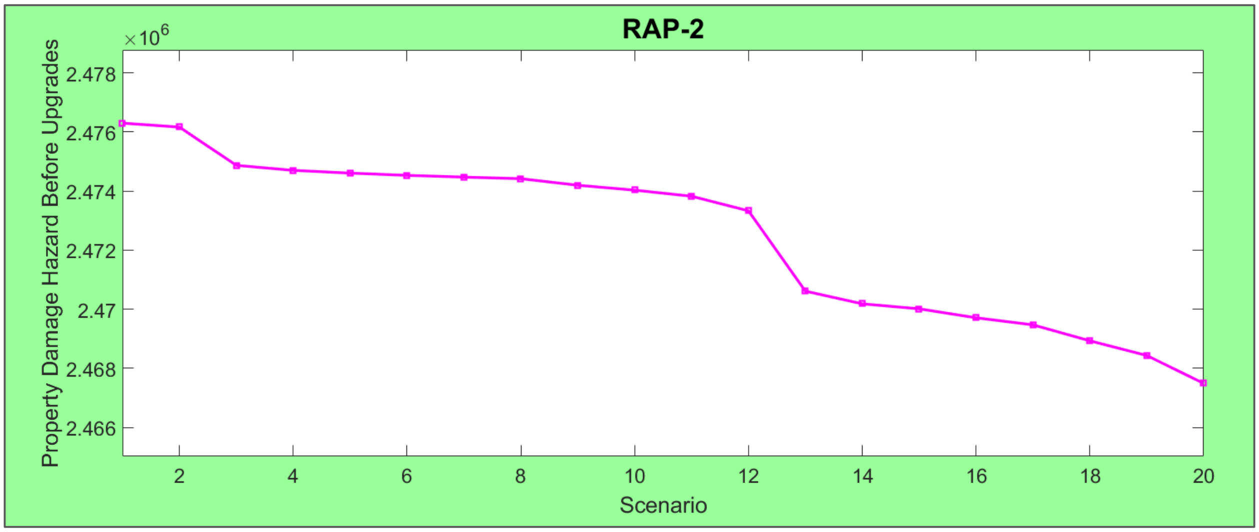



**Figure 117** The overall property damage hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

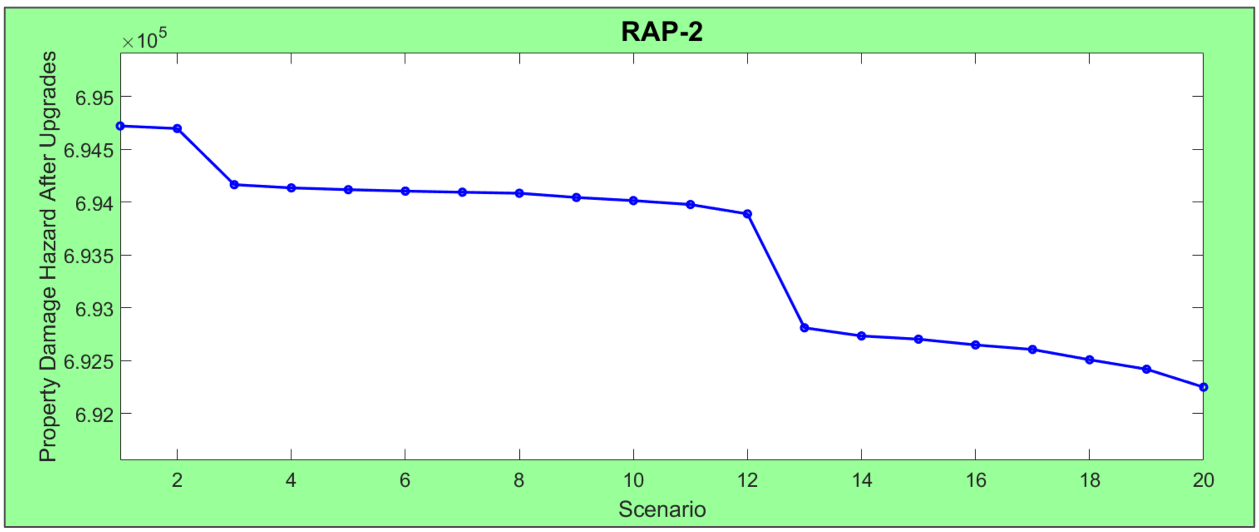



**Figure 118** The overall property damage hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

### *11.3.3. The Impact of the Hazard Severity Weight Values on the Average Installation Cost and the Average Effectiveness of Countermeasures Selected by RAP-2*

The average installation cost and the average effectiveness of the countermeasures, which were selected by **RAP-2** at the public highway-rail grade crossings in the State of Florida, are presented in Figure 119 and Figure 120, respectively, for each one of the considered hazard severity weight scenarios. It can be observed that an increase in the severity weight for the fatality hazard and a reduction in the severity weights for the injury hazard and the property damage hazard increased the average installation cost of the countermeasures, which were selected for the highway-rail grade crossings upgraded by **RAP-2**. Such finding can be explained by the fact that the PSR heuristic applied more expensive countermeasures with higher effectiveness factors in order to achieve higher hazard severity reduction at the most hazardous public highway-rail grade crossings in the State of Florida (i.e., the highway-rail grade crossings with the highest fatality hazard). However, the average installation cost of the selected countermeasures did not exceed $6,500, which indicates that the PSR heuristic primarily relied on the low-cost countermeasures in order to upgrade the most hazardous public highway-rail grade crossings in the State of Florida.

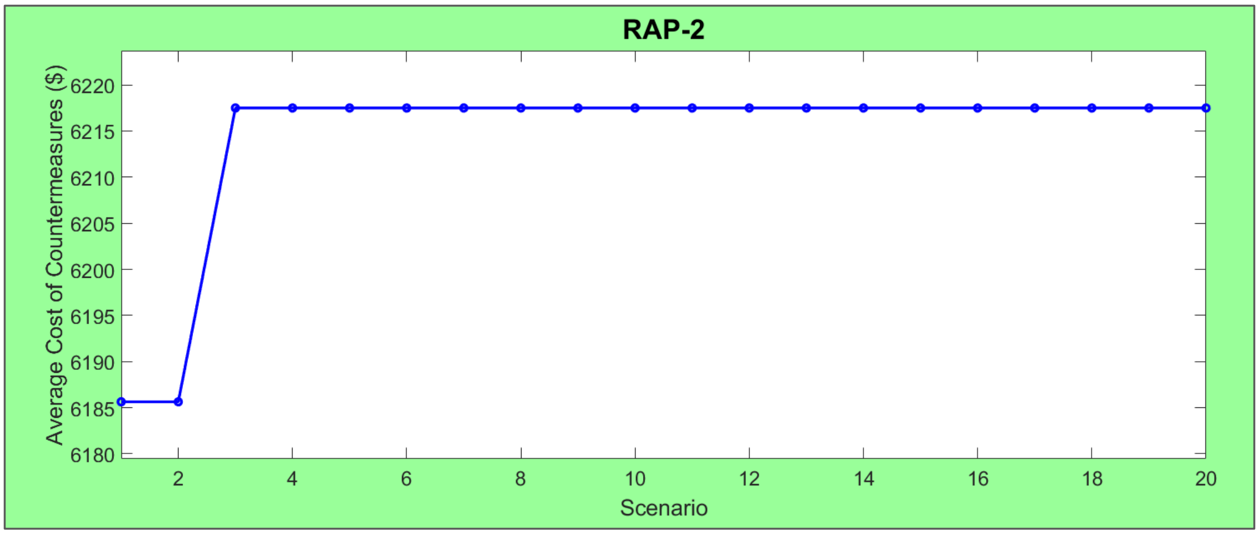



**Figure 119** The average cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

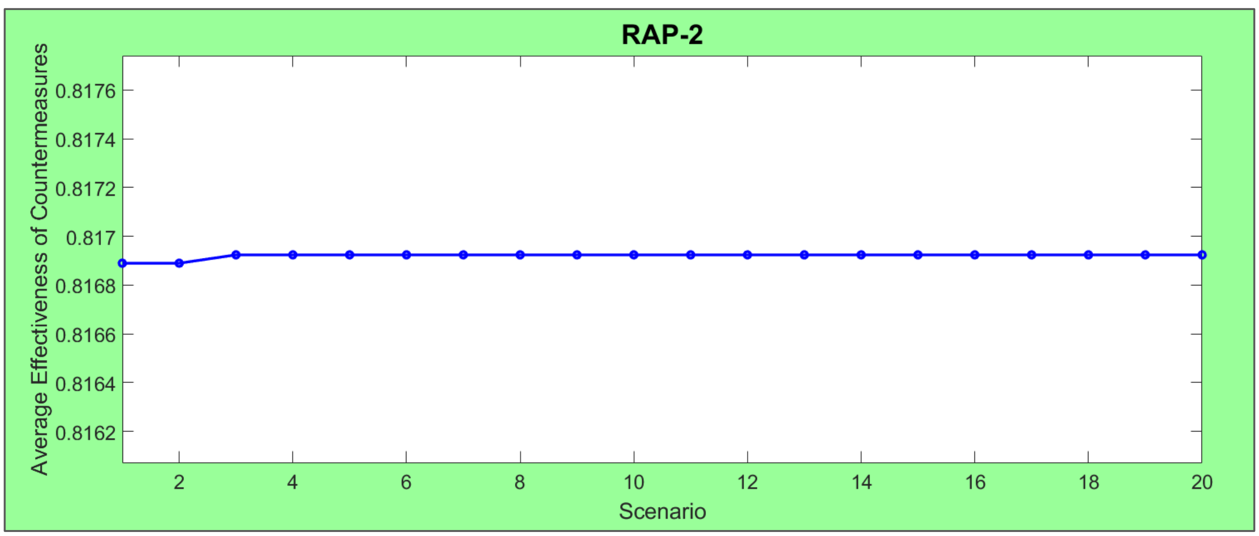



**Figure 120** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #3).

Furthermore, based on the information presented in Figure 120, it can be concluded that the PSR heuristic consistently selected the countermeasures with higher effectiveness factors for the considered hazard severity weight scenarios. The lowest average effectiveness factor was higher than 0.81 for the considered hazard severity weight scenarios. Moreover, the countermeasures with higher effectiveness factors were typically preferential over the countermeasures with lower effectiveness factors, when the severity weight for the fatality hazard was increased, while the severity weights for the injury hazard and the property damage hazard were decreased from one scenario to another. However, changes in the average effectiveness of countermeasures were not significant from one hazard severity weight scenario to another.

### 11.4. Resource Allocation among Various Crossing Types

Under this section of the report, resource allocation among various types of highway-rail grade crossings in the State of Florida is investigated. A total of 3 scenarios were developed by changing the type of highway-rail grade crossings considered. Specifically, all the 6,089 public highway-rail grade crossings in the State of Florida were investigated in scenario 1. In scenario 2, all the 2,888 private highway-rail grade crossings in the State of Florida were selected for the analysis. On the other hand, resource allocation in scenario 3 was conducted among all the 8,977 public and private highway rail-grade crossings in the State of Florida. The required information regarding physical and operational characteristics of public and private highway-rail grade crossings in the State of Florida was extracted from the FRA crossing inventory database (FRA, 2016). Note that the highway-rail grade crossings, which did not have any information regarding the crossing type in the FRA crossing inventory database (i.e., public or private), were discarded from the analysis. A total of 11 countermeasures (described in section 7.4.2 of this report) were considered for implementation at the considered highway-rail grade crossings. Moreover, the total available budget was set equal to $7.5M. The developed optimization models (**RAP-1**and **RAP-2**) were solved using the PHR and PSR heuristics, respectively, in order to conduct resource allocation among various crossing types.

#### *11.4.1. The Impact of the Crossing Type on the Number of Highway-Rail Grade Crossings Upgraded by RAP-1 and RAP-2*

Figure 121 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-1**, for each one of the considered crossing type scenarios. A total of 1,198 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenario 1, when resource allocation was performed using **RAP-1**. In scenario 2, only 111 highway-rail grade crossings out of 2,888 private highway-rail grade crossings were selected for upgrading. The reason behind the decrease in the number of selected highway-rail grade crossings from scenario 1 to scenario 2 consists in the fact that the average cost of implementing countermeasures at private highway-rail grade crossings was substantially higher than that of public highway-rail grade crossings. Hence, a lower number of private highway-rail grade crossings could be upgraded for the same total available budget.

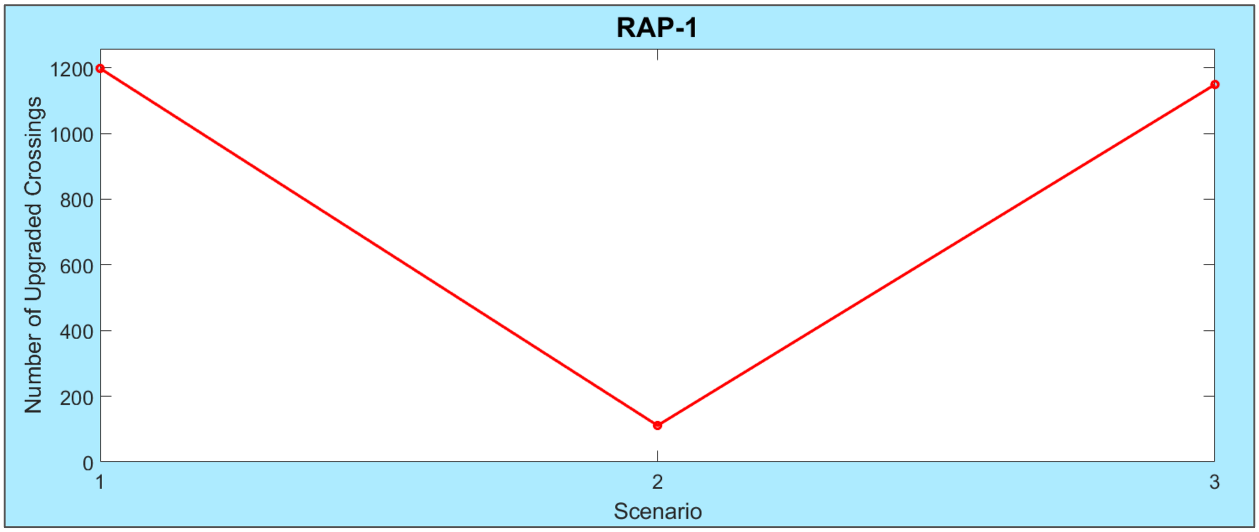


**Figure 121** The total number of highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #4).

Finally, a total of 1,149 highway-rail grade crossings out of 8,977 public and private highway-rail grade crossings in the State of Florida were selected for upgrading in scenario 3, which is slightly less than the number of crossings upgraded in scenario 1. The latter finding can be justified by the fact that the majority of highway-rail grade crossings upgraded in scenario 3 were public (1,143 out of 1,149 highway-rail grade crossings), and a very small portion of them were private (6 out of 1,149 highway-rail grade crossings). The PHR heuristic, which was developed to solve the **RAP-1** mathematical model, sorted the highway-rail grade crossings based on the hazard reduction-to-cost ratios in order to construct the priority list, and only a small number of private highway-rail grade crossings from that priority list were ranked high enough to be selected for upgrades considering the total available budget.

Figure 122 illustrates the total number of highway-rail grade crossings, which were selected for upgrading by **RAP-2**, for each one of the considered crossing type scenarios. A total of 1,212 highway-rail grade crossings out of 6,089 public highway-rail grade crossings in the State of Florida were upgraded for scenario 1, when resource allocation was performed using **RAP-2**. In scenario 2, only 111 highway-rail grade crossings out of 2,888 private highway-rail grade crossings were selected for upgrading. The reason behind the decrease in the number of selected highway-rail grade crossings from scenario 1 to scenario 2 consists in the fact that the average cost of implementing countermeasures at private highway-rail grade crossings was substantially higher than that of public highway-rail grade crossings. Hence, a lower number of private highway-rail grade crossings could be upgraded for the same total available budget.

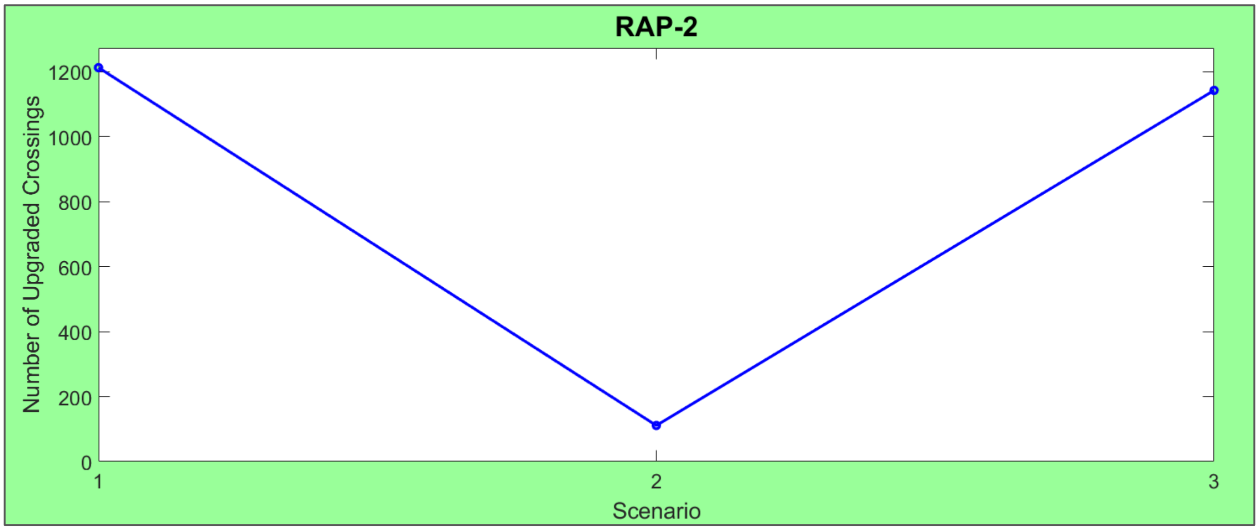



**Figure 122** The total number of highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #4).

Finally, a total of 1,142 highway-rail grade crossings out of 8,977 public and private highway-rail grade crossings in the State of Florida were selected for upgrading in scenario 3, which is slightly less than the number of crossings upgraded in scenario 1. The latter finding can be justified by the fact that the majority of highway-rail grade crossings upgraded in scenario 3 were public (1,136 out of 1,142 highway-rail grade crossings), and a very small portion of them were private (6 out of 1,142 highway-rail grade crossings). The PSR heuristic, which was developed to solve the **RAP-2** mathematical model, sorted the highway-rail grade crossings based on the hazard severity reduction-to-cost ratios in order to construct the priority list, and only a small number of private highway-rail grade crossings from that priority list were ranked high enough to be selected for upgrades considering the total available budget.

#### *11.4.2. The Impact of the Crossing Type on the Overall Hazard Reduction for the Highway-Rail Grade Crossings Upgraded by RAP-1 and RAP-2*

Figure 123 depicts the overall hazard before implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-1**, for each one of the considered crossing type scenarios. It can be observed that the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, changed substantially from scenario 1 to scenario 2 (by changing the type of crossings for resource allocation). Specifically, the overall hazard before implementation of countermeasures at the selected public and private highway-rail grade crossings comprised $3.69 \cdot 10^6$ and $5.81 \cdot 10^4$, respectively. Such reduction in the overall hazard before upgrades can be explained by the fact that the overall hazard at the most hazardous public highway-rail grade crossings was significantly higher than that of the most hazardous private highway-rail grade crossings. Furthermore, the number of public highway-rail grade crossings selected for upgrading in scenario 1 was more than 10 times the number of private highway-rail grade crossings selected for upgrading in scenario 2.

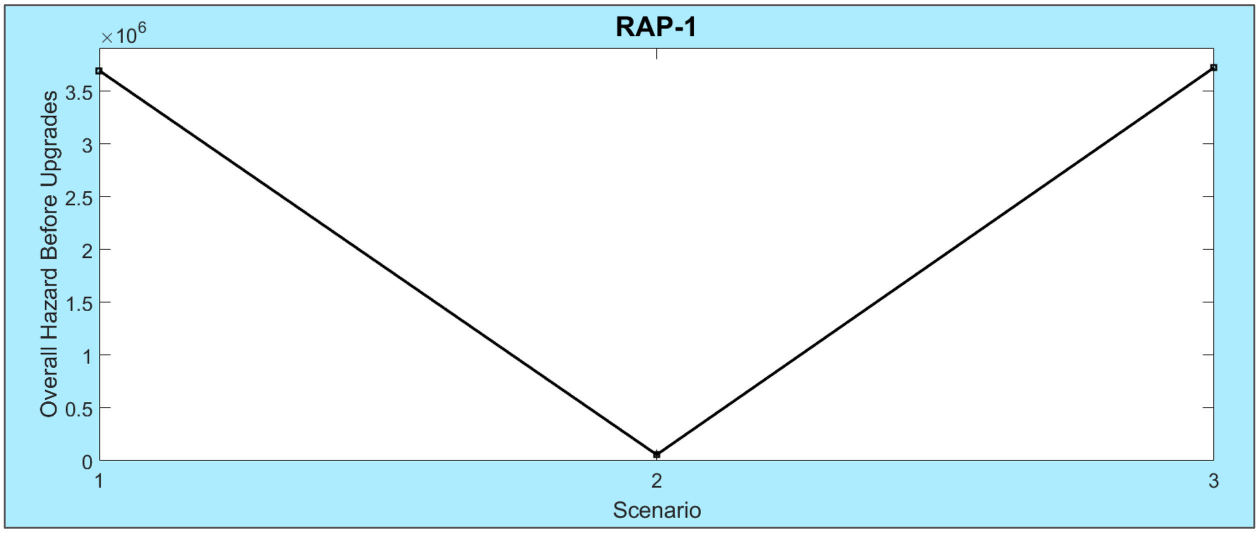



**Figure 123** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #4).

The overall hazard before implementation of countermeasures at the selected highway-rail grade crossings comprised $3.72 \cdot 10^6$ for scenario 3, which is very close to the value of the overall hazard before upgrades for scenario 1. The latter finding can be justified by the fact that almost all the highway-rail grade crossings selected for upgrading in scenario 3 were public (1,143 out of 1,149). Only six private highway-rail grade crossings with high overall hazard values were selected for upgrading in scenario 3. Hence, the overall hazard of the highway-rail grade crossings selected in scenario 3 was close to the overall hazard of the public highway-rail grade crossings selected in scenario 1.

On the other hand, Figure 124 illustrates the overall hazard after implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-1**, for each one of the considered crossing type scenarios. It can be observed that application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(3.69 \cdot 10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 1. Moreover, the overall hazard decreased by $(5.81 \cdot 10^4 - 2.49 \cdot 10^4)/(5.81 \cdot 10^4) = 57.14\%$ for scenario 2, and by $(3.72 \cdot 10^6 - 1.03 \cdot 10^6)/(3.72 \cdot 10^6) = 72.31\%$ for scenario 3. Therefore, the developed **RAP-1** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different crossing type scenarios.

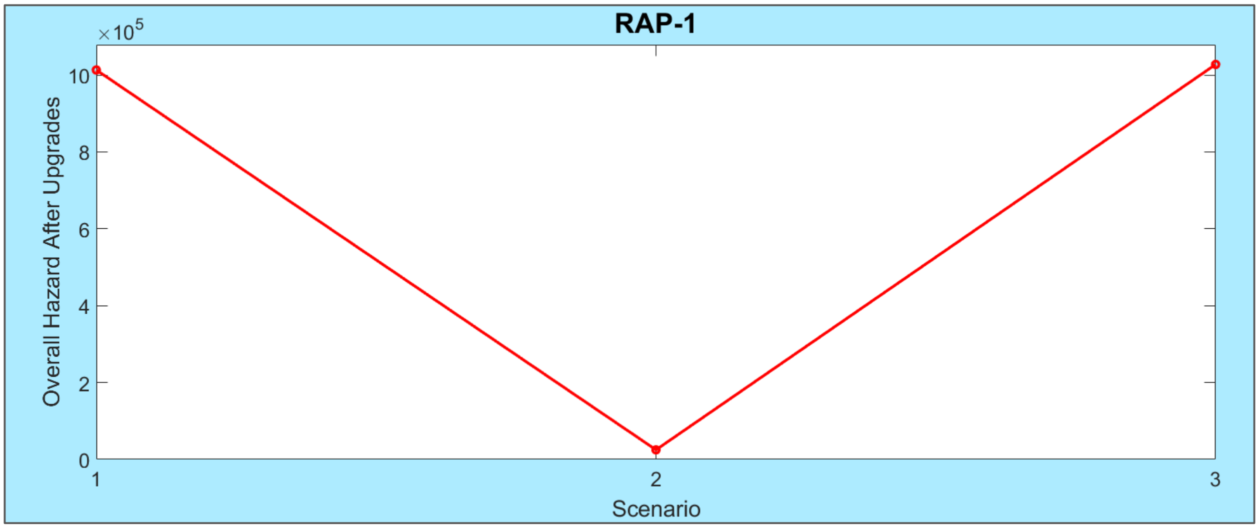



**Figure 124** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #4).

Figure 125 depicts the overall hazard before implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered crossing type scenarios. It can be observed that the overall hazard before implementation of countermeasures at the highway-rail grade crossings, which were selected for upgrading by **RAP-2**, changed substantially from scenario 1 to scenario 2 (by changing the type of crossings for resource allocation). Specifically, the overall hazard before implementation of countermeasures at the selected public and private highway-rail grade crossings comprised $3.69 \cdot 10^6$ and $5.81 \cdot 10^4$, respectively. Similar to the analysis results when resource allocation was performed using **RAP-1**, such reduction in the overall hazard before upgrades can be explained by the fact that the overall hazard at the most hazardous public highway-rail grade crossings was significantly higher than that of the most hazardous private highway-rail grade crossings. Furthermore, the number of public highway-rail grade crossings selected for upgrading in scenario 1 was more than 10 times the number of private highway-rail grade crossings selected for upgrading in scenario 2.

The overall hazard before implementation of countermeasures at the selected highway-rail grade crossings comprised $3.72 \cdot 10^6$ for scenario 3, which is very close to the value of the overall hazard before upgrades for scenario 1. The latter finding can be justified by the fact that almost all the highway-rail grade crossings selected for upgrading in scenario 3 were public (1,136 out of 1,142). Only six private highway-rail grade crossings with high overall hazard values were selected for upgrading in scenario 3. Hence, the overall hazard of the highway-rail grade crossings selected in scenario 3 was close to the overall hazard of the public highway-rail grade crossings selected in scenario 1.

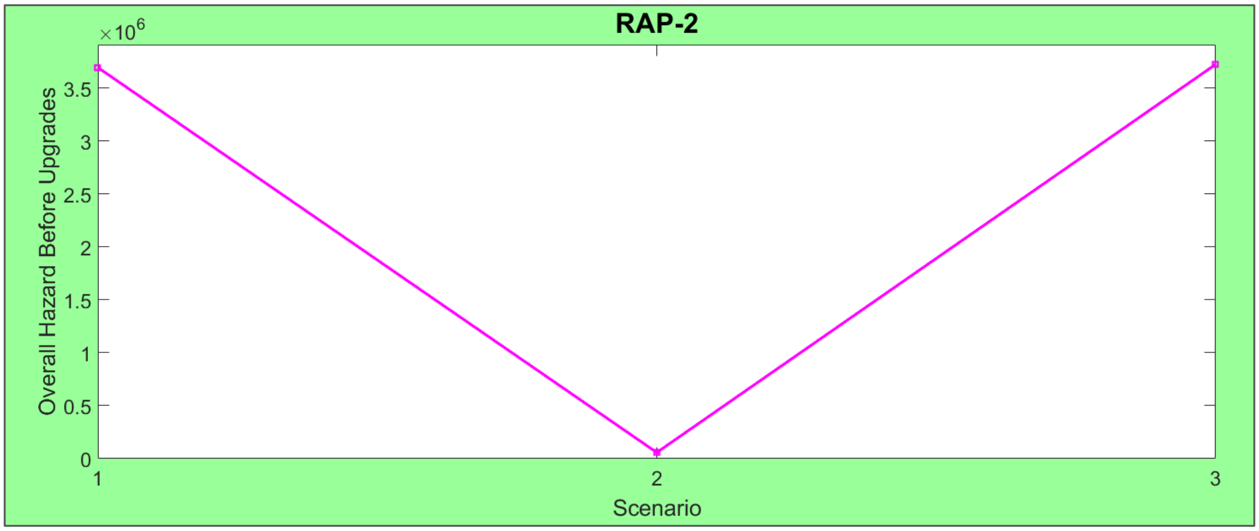



**Figure 125** The overall hazard before implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #4).

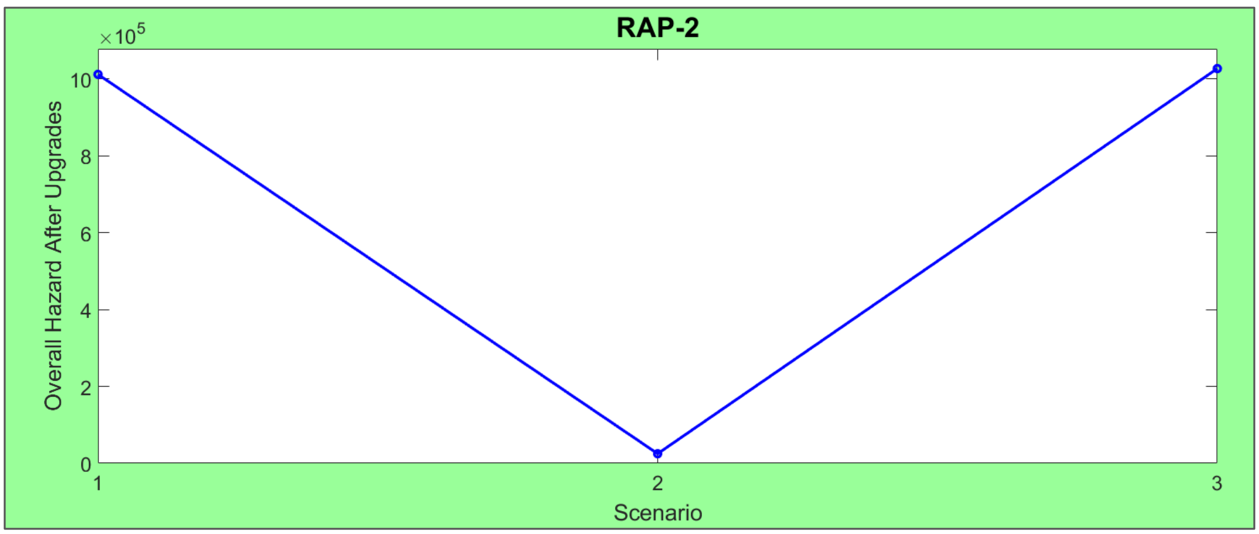



**Figure 126** The overall hazard after implementation of countermeasures at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #4).

On the other hand, Figure 126 illustrates the overall hazard after implementation of countermeasures at the highway-rail grade crossings in the State of Florida, which were selected for upgrading by **RAP-2**, for each one of the considered crossing type scenarios. It can be observed that application of the selected countermeasures significantly decreased the overall hazard at the highway-rail grade crossings. In particular, the overall hazard decreased by $(3.69 \cdot 10^6 - 1.01 \cdot 10^6)/(3.69 \cdot 10^6) = 72.63\%$ for scenario 1. Moreover, the overall hazard decreased by $(5.81 \cdot 10^4 - 2.49 \cdot 10^4)/(5.81 \cdot 10^4) = 57.14\%$ for scenario 2, and by $(3.72 \cdot 10^6 - 1.03 \cdot 10^6)/(3.72 \cdot 10^6) = 72.31\%$ for scenario 3. Therefore, the developed **RAP-2** mathematical model can serve as an effective decision support tool for the FDOT personnel and assist with reducing the overall hazard at the highway-rail grade crossings under different crossing type scenarios.

Note that the percentages in the overall hazard reduction at the highway-rail grade crossings, which were selected for upgrading, are similar for **RAP-1** and **RAP-2**. However, the number of the highway-rail grade crossings, which were selected for upgrading by **RAP-1**, is different from the number of the highway-rail grade crossings, which were selected for upgrading by **RAP-2**. As indicated earlier, a total of 1,198, 111, and 1,149 highway-rail grade crossings were selected for upgrading by **RAP-1** for scenarios 1, 2, and 3, respectively. On the other hand, a total of 1,212, 111, and 1,142 highway-rail grade crossings were selected for upgrading by **RAP-2** for scenarios 1, 2, and 3, respectively. Such difference can be justified by the fact that **RAP-1** selects the highway-rail grade crossings for upgrading, aiming to minimize the overall hazard at the highway-rail grade crossings, while **RAP-2** selects the highway-rail grade crossings for upgrading, aiming to minimize the overall hazard severity at the highway-rail grade crossings (the expected fatality hazard, injury hazard, and property damage hazard values are considered throughout resource allocation by **RAP-2**).

#### *11.4.3. The Impact of the Crossing Type on the Average Installation Cost and the Average Effectiveness of Countermeasures Selected by RAP-1 and RAP-2*

The average installation cost and the average effectiveness of the countermeasures, which were selected by **RAP-1** at the highway-rail grade crossings in the State of Florida, are presented in Figure 127 and Figure 128, respectively, for each one of the considered crossing type scenarios. The average installation cost of the countermeasures, which were selected by **RAP-1** for the public highway-rail grade crossings in scenario 1, did not exceed $6,500. The latter finding can by justified by the fact that the PHR heuristic, which was developed to solve the **RAP-1** mathematical model, selects the highway-rail grade crossings for upgrading and determines the appropriate upgrading type based on the hazard reduction-to-cost ratios. Therefore, the low-cost countermeasures (e.g., “mountable curbs [with channelized devices]” that have the installation cost of $15,000; “barrier curbs [with or without channelized devices]” that have the installation cost of $15,000; “one-way street with gate” that has the installation cost of $5,000) were preferential over the other countermeasures that have higher installation cost (e.g., “flashing lights to gates” that has the installation cost of $106,100; “photo enforcement” that has the installation cost of $65,000). Furthermore, a significant percentage (≈48.74%) of public highway-rail grade crossings were gated highway-rail grade crossings based on the FRA crossing inventory database (i.e., WdCode = 8 or 9). Only gated highway-rail grade crossings are eligible for the aforementioned low-cost countermeasures.

On the contrary, the average installation cost of the countermeasures, which were selected by **RAP-1** for the private highway-rail grade crossings in scenario 2, exceeded $67,500. Such a high installation cost can be explained by the fact that only a small percentage (<1.00%) of private highway-rail grade crossings were gated highway-rail grade crossings based on the FRA crossing inventory database. Therefore, the majority of private highway-rail grade crossings were not eligible for the low-cost countermeasures. Finally, the average installation cost of the countermeasures, which were selected by **RAP-1** for the highway-rail grade crossings in scenario 3, did not exceed $7,000. Thus, the average installation cost of countermeasures, obtained for scenario 1, was close to the average installation cost of countermeasures, obtained for scenario 3. Although the highway-rail grade crossings, which were selected for upgrading by **RAP-1** in scenario 3, consisted of both types of crossings, most of them were public and, hence, were eligible for implementation of the low-cost countermeasures.

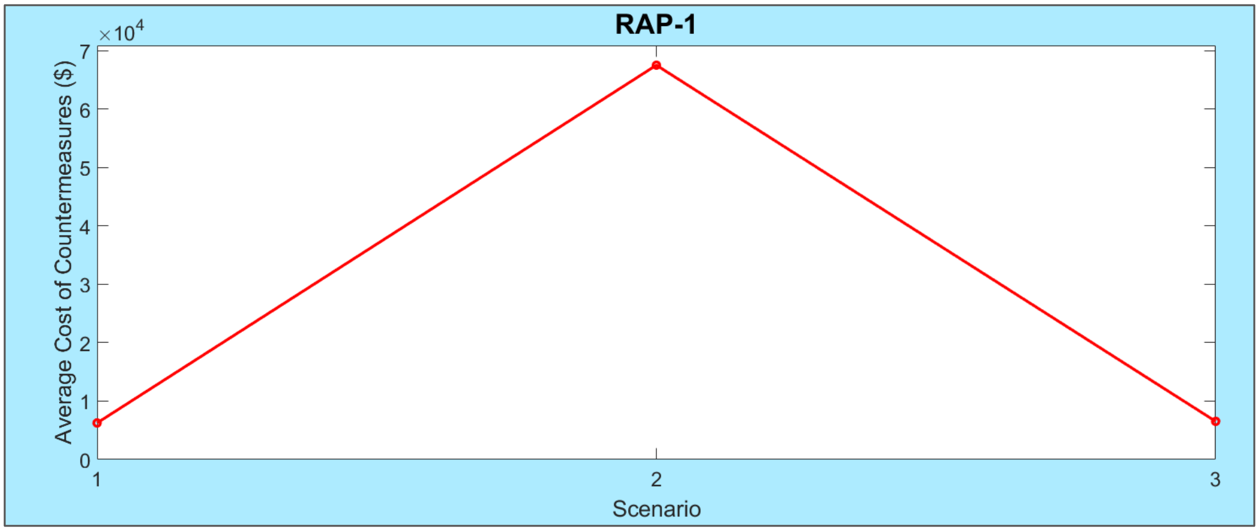



**Figure 127** The average installation cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #4).

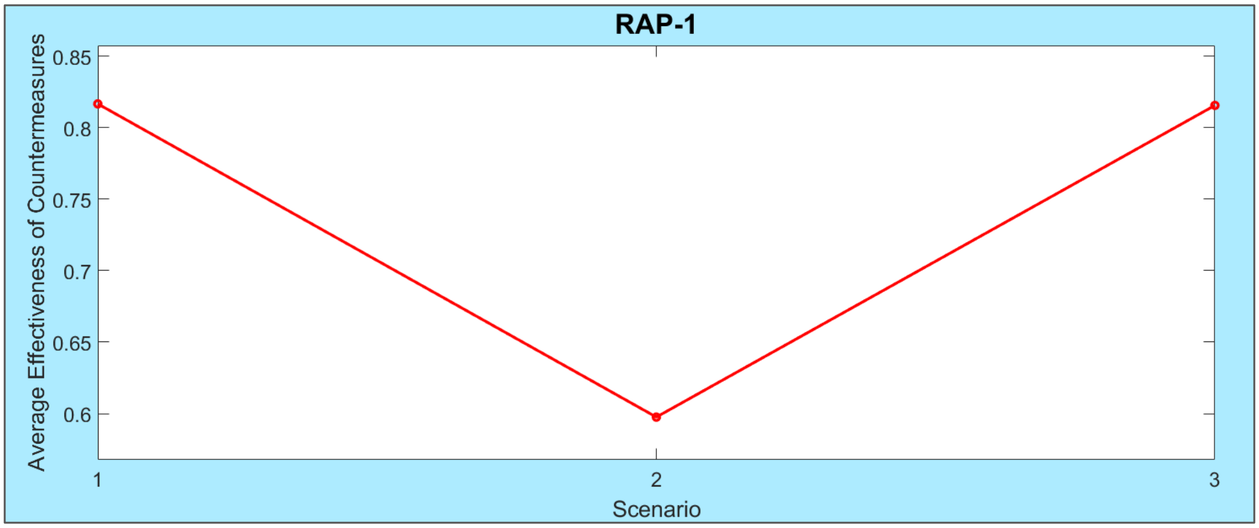



**Figure 128** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-1** (analysis #4).

Furthermore, based on the information presented in Figure 128, it can be concluded that the PHR heuristic consistently selected the countermeasures with higher effectiveness factors for the crossing type scenarios 1 and 3. The lowest average effectiveness factor was higher than 0.81 for the crossing type scenarios 1 and 3. The countermeasures with lower effectiveness factors were recorded for the crossing type scenario 2, as most of the private highway-rail grade crossings were not eligible for the low-cost countermeasures with fairly high effectiveness factors. Such a particular selection of countermeasures for the considered crossing type scenarios can be also explained by the nature of the proposed PHR heuristic, as it aims to select the countermeasures with the highest hazard reduction-to-cost ratios at the most hazardous public highway-rail grade crossings in the State of Florida.

The average installation cost and the average effectiveness of the countermeasures, which were selected by **RAP-2** at the highway-rail grade crossings in the State of Florida, are presented in Figure 129 and Figure 130, respectively, for each one of the considered crossing type scenarios. The average installation cost of the countermeasures, which were selected by **RAP-2** for the public highway-rail grade crossings in scenario 1, did not exceed $6,500. The latter finding can by justified by the fact that the PSR heuristic, which was developed to solve the **RAP-2** mathematical model, selects the highway-rail grade crossings for upgrading and determines the appropriate upgrading type based on the hazard severity reduction-to-cost ratios. Therefore, the low-cost countermeasures (e.g., "mountable curbs [with channelized devices]" that have the installation cost of $15,000; "barrier curbs [with or without channelized devices]" that have the installation cost of $15,000; "one-way street with gate" that has the installation cost of $5,000) were preferential over the other countermeasures that have higher installation cost (e.g., "flashing lights to gates" that has the installation cost of $106,100; "photo enforcement" that has the installation cost of $65,000). Furthermore, a significant percentage (≈48.74%) of public highway-rail grade crossings were gated highway-rail grade crossings based on the FRA crossing inventory database (i.e., WdCode = 8 or 9). Only gated highway-rail grade crossings are eligible for the aforementioned low-cost countermeasures.

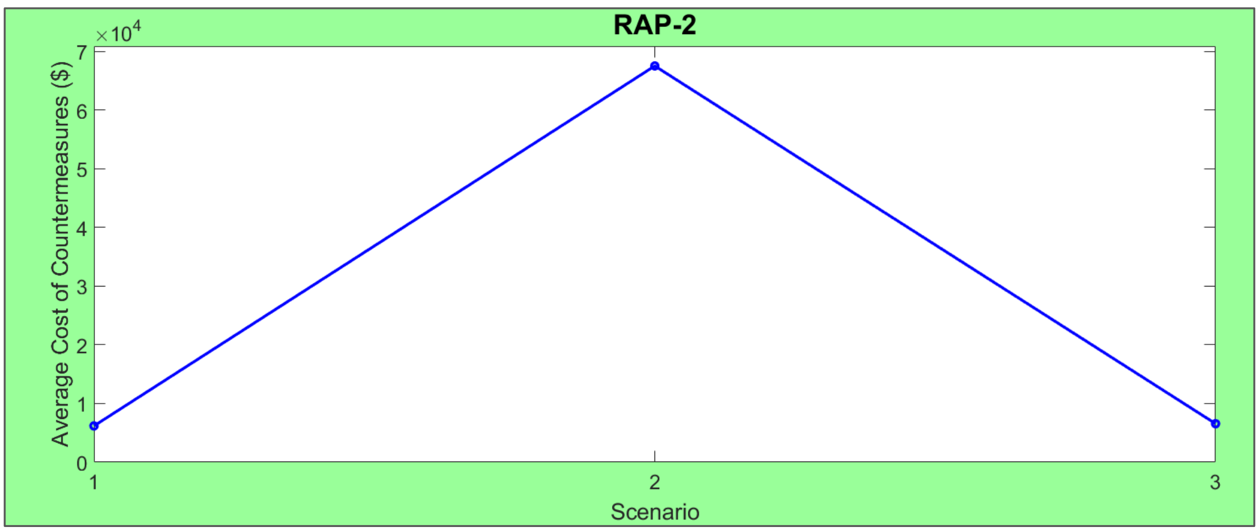



**Figure 129** The average cost of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #4).

On the contrary, the average installation cost of the countermeasures, which were selected by **RAP-2** for the private highway-rail grade crossings in scenario 2, exceeded $67,500. Such a high installation cost can be explained by the fact that only a small percentage (<1.00%) of private highway-rail grade crossings were gated highway-rail grade crossings based on the FRA crossing inventory database. Therefore, the majority of private highway-rail grade crossings were not eligible for the low-cost countermeasures. Finally, the average installation cost of the countermeasures, which were selected by **RAP-2** for the highway-rail grade crossings in scenario 3, did not exceed $7,000. Thus, the average installation cost of countermeasures, obtained for scenario 1, was close to the average installation cost of countermeasures, obtained for scenario 3. Although the highway-rail grade crossings, which were selected for upgrading by

**RAP-2** in scenario 3, consisted of both types of crossings, most of them were public and, hence, were eligible for implementation of the low-cost countermeasures.

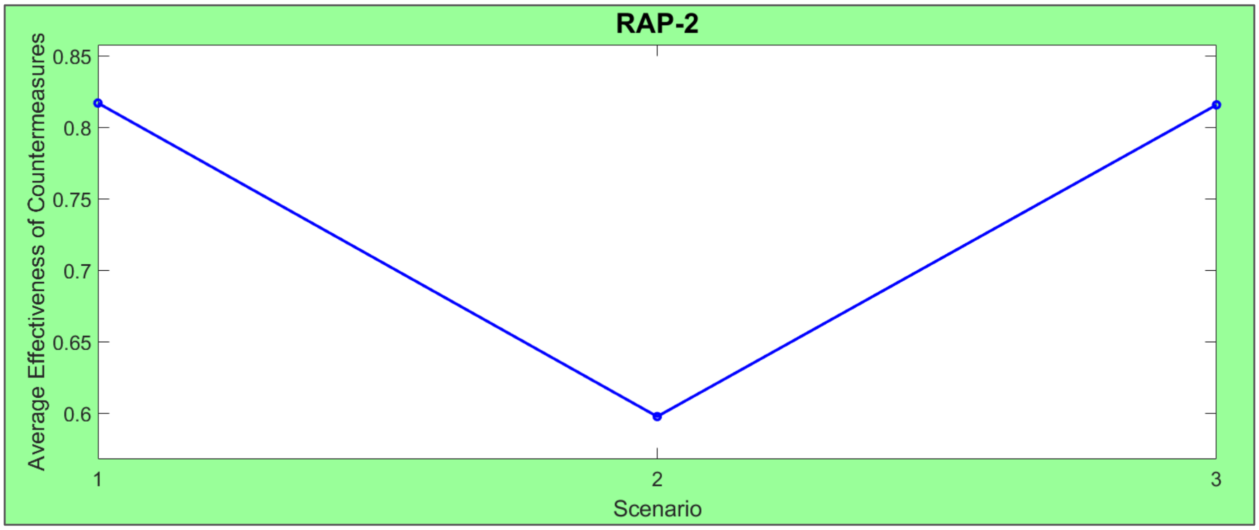



**Figure 130** The average effectiveness of countermeasures implemented at the highway-rail grade crossings selected for upgrading by **RAP-2** (analysis #4).

Furthermore, based on the information presented in Figure 130, it can be concluded that the PSR heuristic consistently selected the countermeasures with higher effectiveness factors for the crossing type scenarios 1 and 3. The lowest average effectiveness factor was higher than 0.81 for the crossing type scenarios 1 and 3. The countermeasures with lower effectiveness factors were recorded for the crossing type scenario 2, as most of the private highway-rail grade crossings were not eligible for the low-cost countermeasures with fairly high effectiveness factors. Such a particular selection of countermeasures for the considered crossing type scenarios can be also explained by the nature of the proposed PSR heuristic, as it aims to select the countermeasures with the highest hazard severity reduction-to-cost ratios at the most hazardous public highway-rail grade crossings in the State of Florida.

### 11.5. Consideration of Additional Criteria throughout Resource Allocation

The Florida Priority Index Formula, which was developed as a part of this project, uses the following fields from the FRA crossing inventory database in order to prioritize the highway-rail grade crossings in the State of Florida for upgrades.

- Field “CrossingID” – crossing inventory number;
- Field “WdCode” – warning device code;
- Field “Aadt” – annual average daily traffic (AADT) count;
- Field “DayThru” – total daylight through trains;
- Field “NghtThru” – total night time through trains;
- Field “TotalSwt” – total switching trains;
- Field “MaxTtSpd” – maximum timetable speed;
- Field “MainTrk” – number of main tracks;
- Field “OthrTrk” – number of other tracks;
- Field “HwyClassCD” – functional classification of road at crossing (0 = rural; 1 = urban);

- Field “AwdIDate” – installation date of current active warning devices;
- Field “PosXing” – crossing position (1 = at grade; 2 = railroad under; 3 = railroad over); and
- Field “TypeXing” – crossing type (2 = private; 3 = public).

The aforementioned fields are further utilized to derive the following attributes of the highway-rail grade crossings:

- Field “PF” – protection factor;
- Field “TotalTrains” – total number of trains (daylight through + night time through + switching);
- Field “ThruTrains” – total number of through trains (daylight through + night time through);
- Field “TotTracks” – number of main and other tracks;
- Field “AH5” – 5-year accident history;
- Field “A” – accident history parameter;
- Field “FPI” – the Florida Priority Index;
- Field “OverallHaz” – overall hazard at a highway-rail grade crossing;
- Field “FatHaz” – fatality hazard at a highway-rail grade crossing;
- Field “CasHaz” – casualty hazard at a highway-rail grade crossing;
- Field “InjHaz” – injury hazard at a highway-rail grade crossing; and
- Field “PropHaz” – property damage hazard at a highway-rail grade crossing.

All the aforementioned attributes are used to rank highway-rail grade crossings for safety improvement projects. In practice, however, some other factors could also be considered for prioritization of highway-rail grade crossings, which may include, but are not limited to, the following (the field names were adopted from the FRA crossing inventory database):

*Traffic Control Device Information*

- Field “HwynrSig” – does nearby highway intersection have traffic signals? (1 = yes; 2 = no);
- Field “MonitorDev” – highway monitoring devices (0 = none; 1 = yes-photo/video recording; 2 = yes-vehicle presence detection);
- Field “PaveMrkIDs” – pavement markings (0 = none; 1 = stop lines; 2 = railroad crossing symbols; 3 = dynamic envelope); and
- Field “PrempType” – highway traffic signal preemption (1 = simultaneous; 2 = advance).

*Location and Classification Information*

- Field “DevelTypID” – type of land use (11 = open space; 12 = residential; 13 = commercial; 14 = industrial; 15 = institutional; 16 = farm; 17 = recreational; 18 = railroad yard);
- Field “TypeTrnSrvcIDs” – type of train service (11 = freight; 12 = intercity passenger; 13 = commuter; 14 = transit; 15 = shared use transit; 16 = tourist/other); and
- Field “Whistban” – quiet zone (0 = no; 1 = 24 hour; 2 = partial; 3 = Chicago excused).

*Physical Characteristics Information*

- Field “HwyNear” – intersecting roadway within 500 feet? (1 = yes; 2 = no);
- Field “HwyPved” – is roadway/pathway paved? (1 = yes; 2 = no);
- Field “Illumina” – is crossing illuminated? (1 = yes; 2 = no);
- Field “TraficLn” – number of traffic lanes crossing railroad;
- Field “XAngle” – smallest crossing angle (1 = 0° – 29°; 2 = 30° – 59°; 3 = 60° – 90°); and
- Field “XSurfaceIDs” – crossing surface (11 = timber; 12 = asphalt; 13 = asphalt and timber; 14 = concrete; 15 = concrete and rubber; 16 = rubber; 17 = metal; 18 = unconsolidated; 19 = composite; 20 = other [specify]).

*Public Highway Information*

- Field “HwySpeed” – highway speed limit;
- Field “PctTruk” – estimated percent trucks; and
- Field “SchlBsCnt” – average number of school bus count per day.

For this analysis, the 25 most hazardous public highway-rail grade crossings in the State of Florida for the year of 2018 were determined using the Florida Priority Index Formula. Note that all the 6,089 public highway-rail grade crossings in the State of Florida were considered to determine the 25 most hazardous public highway-rail grade crossings.

Along with the FPI values, other attributes of highway-rail grade crossings can be taken into account to rank highway-rail grade crossings for safety improvement projects. The funding authority (e.g., FDOT) may focus on certain characteristics, such as traffic control device information, location and classification information, physical characteristics information, public highway information, and others. Table 86 presents the additional traffic control device information as well as the location and classification information for the 25 most hazardous public highway-rail grade crossings in the State of Florida, while Table 87 highlights some of their physical characteristics and the public highway information. While focusing on the existing traffic control devices, the funding authority may consider various fields from the FRA crossing inventory database to prioritize highway-rail grade crossings, including “HwynrSig”, “MonitorDev”, “PaveMrkIDs”, and “PrempType”. For instance, the highway-rail grade crossing “273057E” was ranked 7$^{th}$ based on the FPI values. The value of the field “HwynrSig” for this highway-rail grade crossing was “2”, which means its nearby highway intersection had no traffic signals. On the other hand, the highway-rail grade crossing “628177F” was ranked 4$^{th}$ based on the FPI values, whereas the highway intersection near that crossing had traffic signals. Therefore, if the field “HwynrSig” is considered throughout resource allocation, then the highway-rail grade crossing “273057E”, which was ranked 7$^{th}$ based on the FPI values, should be upgraded before the highway-rail grade crossing “628177F”, which was ranked 4$^{th}$ based on the FPI values.

The information regarding location and classification of highway-rail grade crossings is conveyed in various fields of the FRA crossing inventory database, including “DevelTypID”, “TypeTrnSrvcIDs”, and “Whistban”. For instance, the field “DevelTypID” discloses the information related to the type of land use at the location of highway-rail grade crossings. If the funding authority decides to prioritize highway-rail grade crossings located in commercial areas (as commercial areas typically accommodate more individuals than other areas), then the field

“DevelTypID” should be considered for the prioritization process. The highway-rail grade crossing, which was ranked as 3rd based on the FPI values (i.e., the highway-rail grade crossing “272938M”), was in a commercial setting, while the highway-rail grade crossing, which was ranked as 2nd based on the FPI values (i.e., the highway-rail grade crossing “273062B”), was placed in an industrial setting. Hence, if the funding authority decides to prioritize highway-rail grade crossings in commercial locations, then the highway-rail grade crossing “272938M” (ranked 3rd) should be upgraded before the highway-rail grade crossing “273062B” (ranked 2nd).

The physical characteristics of highway-rail grade crossings are highlighted in various fields of the FRA crossing inventory database, including “HwyNear”, “HwyPved”, “Illumina”, “TraficLn”, “XAngle”, and “XSurfaceIDs”. The field “TraficLn”, for example, refers to the number of traffic lanes crossing a given railroad. Among the 25 most hazardous public highway-rail grade crossings in the State of Florida, the highway-rail grade crossing “628183J” (ranked 5th) and the highway-rail grade crossing “628290Y” (ranked 21st) had the highest number of highway traffic lanes that crossed the associated railroads. As highways with more lanes generally attract more traffic, they could have a higher chance of experiencing accidents. So, the highway-rail grade crossings, which are ranked as 5th and 21st based on the FPI values, should receive priority, if the funding authority considers the field “TraficLn” throughout resource allocation. Furthermore, the field “Illumina” refers to the lighting condition of a highway-rail grade crossing (i.e., if a highway-rail grade crossing is illuminated or not). The values of “Illumina” for the highway-rail grade crossings, which were ranked 1st (i.e., the highway-rail grade crossing “273155V”) and 2nd (i.e., the highway-rail grade crossing “273062B”), were set to be “2” in the FRA crossing inventory database. Hence, these highway-rail grade crossings were not illuminated. The high hazard values at these highway-rail grade crossings could be due to the lack of illumination. An installation of adequate lighting devices at the hazardous highway-rail grade crossings that do not have illumination could be more effective alternative (in terms of both installation cost and safety improvements) than installation of typical countermeasures, which were highlighted in section 7.4.2 of this report (e.g., flashing lights, gates, barrier curbs, etc.).

The public highway information related to highway-rail grade crossings is provided in various fields of the FRA crossing inventory database, including “HwySpeed”, “PctTruk”, and “SchlBsCnt”. The state and local administrations often place more importance on school bus count, which is represented by the field “SchlBsCnt”, throughout resource allocation among highway-rail grade crossings. It can be observed that the highway-rail grade crossing “628282G”, which was ranked 11th based on the FPI values, had the highest school bus count per day (94 school buses) among the 25 most hazardous public highway-rail grade crossings in the State of Florida. Therefore, the highway-rail grade crossing “628282G” could be moved higher in the priority list if the funding authority directly accounts for the number of school buses, traversing highway-rail grade crossings, throughout resource allocation.

**Table 86** The additional attributes of the 25 most hazardous public highway-rail grade crossings (traffic control device information and location and classification information).

| Rank | CrossingID | Traffic Control Device Information | | | | Location and Classification Information | | |
|---|---|---|---|---|---|---|---|---|
| | | HwynrSig | MonitorDev | PaveMrkIDs | PrempType | DevelTypID | TypeTrnSrvcIDs | Whistban |
| 1 | 273155V | 2 | 0 | 0 | N/R | 13 | 11 | N/R |
| 2 | 273062B | 2 | 0 | 1,2 | N/R | 14 | 11 | N/R |
| 3 | 272938M | 2 | 0 | 1,2 | N/R | 13 | 11 | N/R |
| 4 | 628177F | 1 | N/R | 1,2 | N/R | 13 | 11,12,13 | 1 |
| 5 | 628183J | 1 | N/R | 1,2 | 1 | 13 | 11,12,13 | 1 |
| 6 | 628191B | 1 | N/R | 1,2 | N/R | 13 | 11,12,13 | 0 |
| 7 | 273057E | 2 | 0 | 1,2 | N/R | 14 | 11 | N/R |
| 8 | 628139W | 1 | N/R | 1,2 | N/R | 11 | 11,12,13 | 1 |
| 9 | 628160C | 1 | N/R | 1,2 | N/R | 13 | 11,12,13 | 1 |
| 10 | 628163X | 1 | N/R | 1,2 | N/R | 13 | 11,12,13 | 1 |
| 11 | 628282G | 1 | N/R | 1,2 | 1 | 15 | 11,12,13 | 1 |
| 12 | 628118D | 1 | N/R | 1,2 | N/R | 12 | 12,13 | 1 |
| 13 | 628186E | 1 | N/R | 1,2 | 1 | 13 | 11,12,13 | 0 |
| 14 | 628155F | 2 | N/R | 1,2 | N/R | 14 | 11,12,13 | 1 |
| 15 | 628320N | 1 | N/R | 1,2 | 1 | 13 | 11,12,13 | 0 |
| 16 | 628169N | 2 | N/R | 1,2 | N/R | 11 | 11,12,13 | 1 |
| 17 | 621538J | 2 | N/R | 1,2 | N/R | 13 | 11,12,13 | 1 |
| 18 | 628168G | 1 | N/R | 1,2,3 | N/R | 13 | 11,12,13 | 1 |
| 19 | 628165L | 1 | N/R | 1,2 | N/R | 12 | 11,12,13 | 1 |
| 20 | 628272B | 1 | N/R | 1,2 | 1 | 13 | 11,12,13 | 0 |
| 21 | 628290Y | 1 | N/R | 1,2 | N/R | 13 | 11,12,13 | 1 |
| 22 | 628144T | 2 | N/R | 1,2 | N/R | 13 | 11,12,13 | 1 |
| 23 | 628167A | 1 | 0 | 1,2 | 1 | 13 | 11,12,13 | 1 |
| 24 | 628274P | 1 | N/R | 1,2 | 1 | 14 | 11,12,13 | 1 |
| 25 | 628378W | 1 | N/R | 1,2 | N/R | 13 | 11,13 | 0 |

Note:
N/R – Not Reported.

**Table 87** The additional attributes of the 25 most hazardous public highway-rail grade crossings (physical characteristics and public highway information).

| Rank | CrossingID | Physical Characteristics | | | | | | Public Highway Information | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | HwyNear | HwyPved | Illumina | TraficLn | XAngle | XSurfaceIDs | HwySpeed | PctTruk | SchlBsCnt |
| 1 | 273155V | 2 | 1 | 2 | 1 | 3 | 12 | 5 | 0 | N/R |
| 2 | 273062B | 2 | 1 | 2 | 2 | 2 | 12 | 25 | 99 | N/R |
| 3 | 272938M | 1 | 1 | 1 | 2 | 3 | 14 | 20 | 99 | N/R |
| 4 | 628177F | 1 | 1 | 1 | 6 | 3 | 16 | 45 | 3 | 63 |
| 5 | 628183J | 1 | 1 | 1 | 8 | 3 | 14 | 35 | 11 | 19 |
| 6 | 628191B | 1 | 1 | 1 | 6 | 3 | 14 | 45 | 4 | 31 |
| 7 | 273057E | 2 | 1 | 1 | 4 | 3 | 14 | 25 | 99 | 3 |
| 8 | 628139W | 1 | 1 | 1 | 4 | 3 | 14 | 35 | 3 | 51 |
| 9 | 628160C | 1 | 1 | N/R | 4 | 3 | 14 | 40 | 0 | 21 |
| 10 | 628163X | 1 | 1 | 1 | 6 | 3 | 14 | 45 | 1 | 13 |
| 11 | 628282G | 1 | 1 | N/R | 6 | 3 | 14 | 40 | 4 | 94 |
| 12 | 628118D | 1 | 1 | 1 | 4 | 3 | 16 | 30 | 0 | 37 |
| 13 | 628186E | 1 | 1 | 1 | 6 | 3 | 15 | 45 | 3 | 25 |
| 14 | 628155F | 2 | 1 | N/R | 5 | 3 | 14 | 35 | 4 | 11 |
| 15 | 628320N | 1 | 1 | N/R | 5 | 3 | 15 | 30 | 8 | 54 |
| 16 | 628169N | 1 | 1 | 1 | 6 | 3 | 14 | 45 | 12 | 50 |
| 17 | 621538J | 1 | 1 | N/R | 3 | 3 | 15 | 30 | 0 | 5 |
| 18 | 628168G | 1 | 1 | 1 | 6 | 3 | 15 | 45 | 45 | 15 |
| 19 | 628165L | 1 | 1 | 1 | 7 | 3 | 14 | 40 | 0 | 28 |
| 20 | 628272B | 1 | 1 | N/R | 6 | 3 | 15 | 45 | 3 | 32 |
| 21 | 628290Y | 1 | 1 | 1 | 8 | 3 | 15 | 35 | 5 | 80 |
| 22 | 628144T | 1 | 1 | N/R | 4 | 3 | 16 | 35 | 3 | 22 |
| 23 | 628167A | 1 | 1 | 1 | 6 | 3 | 14 | 40 | 35 | 5 |
| 24 | 628274P | 1 | 1 | N/R | 6 | 3 | 16 | 45 | 3 | 35 |
| 25 | 628378W | 1 | 1 | N/R | 4 | 3 | 14 | 30 | 0 | 12 |

Note:
N/R – Not Reported.

## 12. CONCLUSIONS AND FUTURE RESEARCH EXTENSIONS

The State of Florida has been recognized for its freight mobility and increasing volumes of international trade. The movement of freight within and outside the state is a major contributor to its economy. A significant portion of freight handled in the State of Florida is transported by rail. Along with the growing demand for rail-freight transportation, safety at the highway-rail grade crossings has posed a significant challenge to the Florida Department of Transportation (FDOT). Accidents at highway-rail crossings may result in negative externalities, including loss of lives, severe injuries, release of hazardous materials, property damage, etc. A significant number of accidents have been reported at the highway-rail grade crossings in the State of Florida over the years, which highlights the necessity of safety improvement projects at certain crossings. The main objective of this project was to develop methodologies and decision support tools that can improve safety at the highway-rail grade crossings in the State of Florida, considering the available budget constraints.

Throughout the literature review that was conducted as a part of this project, a variety of formulae have been identified, which are used to predict the number of accidents or estimate hazard indexes at highway-rail grade crossings (the number of accidents and hazard indexes are further used to rank highway-rail grade crossings for safety improvement projects). The existing nationally recognized accident and hazard prediction formulae, which were identified throughout the review of literature, include the following: (1) the Coleman-Stewart Model; (2) the NCHRP Report 50 Accident Prediction Formula; (3) the New Hampshire Hazard Index Formula; (4) the Peabody-Dimmick Formula; and (5) the U.S. DOT Accident Prediction Formula. The accident and hazard prediction formulae were categorized into two groups, including the following: (1) absolute formulae (which predict the number of accidents over a time period and the number of accidents that can be prevented if specific safety improvement measures are implemented); and (2) relative formulae (which provide a measure of a relative hazard and may be used to rank highway-rail grade crossings).

A total of four accident prediction models and nine hazard prediction models have been analyzed for the highway-rail grade crossings in the State of Florida. The most hazardous highway-rail grade crossings in the State of Florida were selected in order to evaluate the candidate accident and hazard prediction models. The most hazardous highway-rail grade crossings were represented by the following types of highway-rail grade crossings: (a) the highway-rail grade crossings that experienced at least one accident between the year of 2007 and the year of 2017 (a total of 489 highway-rail grade crossings); (b) 50 active highway-rail grade crossings with the highest exposure value but without accidents between the year of 2007 and the year of 2017; and (c) 50 passive highway-rail grade crossings with the highest exposure value but without accidents between the year of 2007 and the year of 2017. Note that the exposure of a given highway-rail grade crossing was estimated as a product of the number of vehicles per day and the number of trains per day. The candidate accident and hazard prediction models were compared using the following approaches: (1) chi-square formula; (2) grouping of crossings based on the actual accident data; and (3) Spearman rank correlation coefficient.

Based on the performed analysis, the Modified Texas Priority Index Formula (or “the Florida Priority Index Formula”) was recommended to rank the highway-rail grade crossings in the State of Florida for safety improvement projects. The Florida Priority Index Formula assesses a potential hazard of a given highway-rail grade crossing based on the average daily traffic volume, average daily train volume, train speed, protection factor, and accident history parameter. Unlike the canonical Texas Priority Index Formula, the Florida Priority Index Formula computes the accident history parameter based on the total number of accidents in the last five years or since the year of last improvement (in case there was an upgrade). On the other hand, the canonical Texas Priority Index Formula ignores the upgrades that were performed at a given highway-rail grade crossing throughout the accident history estimations.

Moreover, as a part of this project, two optimization models were developed for improving safety at the highway-rail grade crossings in the State of Florida. Both optimization models were designed to assist the FDOT personnel with selection of the highway-rail grade crossings for upgrading and identification of the appropriate upgrading type. The first optimization model (which was referred to as the **RAP-1** mathematical model) aimed to minimize the overall hazard at the highway-rail grade crossings, while the second optimization model (which was referred to as the **RAP-2** mathematical model) aimed to minimize the overall hazard severity at the highway-rail grade crossings. Consideration of severity throughout development of the optimization models is critical, since a significant number of fatalities are reported every year at the highway-rail grade crossings in the State of Florida. A set of solution algorithms were proposed for the **RAP-1** and **RAP-2** mathematical models. The Profitable Hazard Reduction (PHR) heuristic was found to be the most promising solution algorithm for the **RAP-1** mathematical model, while the Profitable Severity Reduction (PSR) heuristic was found to be the most promising solution algorithm for the **RAP-2** mathematical model. The PHR heuristic selects the highway-rail grade crossings for upgrading and determines the appropriate upgrading type based on the hazard reduction-to-cost ratios. On the other hand, the PSR heuristic selects the highway-rail grade crossings for upgrading and determines the appropriate upgrading type based on the hazard severity reduction-to-cost ratios.

In order to assist the FDOT personnel with resource allocation among the highway-rail grade crossings in the State of Florida, a standalone application, "HRX Safety Improvement", was designed. The standalone application is able to estimate the potential hazard values of the highway-rail grade crossings in the State of Florida based on the Florida Priority Index Formula. The Federal Railroad Administration's (FRA) crossing inventory database and the FRA highway-rail grade crossing accident database are used to provide necessary inputs regarding the physical and operational characteristics of highway-rail grade crossings during the estimations of Florida Priority Index values for these highway-rail grade crossings. Furthermore, the standalone application "HRX Safety Improvement" is able to conduct resource allocation among the most hazardous highway-rail grade crossings with the aim to minimize the overall hazard at the highway-rail grade crossings or the overall hazard severity at the highway-rail grade crossings. The latter objectives are achieved by employing the PHR heuristic and the PSR heuristic, respectively.

The research, conducted as a part of this project, can be extended in the following directions:

- Develop custom statistical models for assessing hazard severity of the highway-rail grade crossings in the State of Florida (i.e., the expected fatality hazard, injury hazard, and property damage hazard).
- Design custom simulation models that emulate collisions between highway vehicles and passing trains at highway-rail grade crossings. Such models could be further used to accurately assess the impacts of collisions on the passengers inside highway vehicles and trains.
- Consider application of multiple countermeasures at a given highway-rail grade crossing throughout resource allocation.
- Develop a multi-objective framework, capturing a conflicting nature of certain objectives throughout resource allocation among highway-rail grade crossings (e.g., maximize the total number of passing trains and passing vehicles versus minimize the overall hazard).
- Evaluate the developed PHR and PSR heuristic algorithms against the alternative solution methodologies (e.g., metaheuristic algorithms – Evolutionary Algorithms, Differential Evolution, Particle Swarm Optimization, Whale Swarm Optimization, Ant Colony Optimization, Bee Colony Optimization, Tabu Search, Variable Neighborhood Search, Simulated Annealing, etc.).
- Incorporate hybridization techniques within the developed PHR and PSR heuristic algorithms (i.e., certain sub-problems could be solved to the global optimality).
- Apply the proposed resource allocation methodology to the highway-rail grade crossings located in other states.

## REFERENCES

1. Akbar, M.M., Rahman, M.S., Kaykobad, M., Manning, E.G. and Shoja, G. C. (2006). Solving the multidimensional multiple-choice knapsack problem by constructing convex hulls. *Computers & Operations Research*, 33(5), pp. 1259-1273.

2. Andonov, R., Poirriez, V. and Rajopadhye, S. (2000). Unbounded knapsack problem: Dynamic programming revisited. *European Journal of Operational Research*, 123(2), pp. 394-407.

3. Austin, R.D. and Carson, J.L. (2002). An alternative accident prediction model for highway-rail interfaces. *Accident Analysis and Prevention*, 34(1), pp. 31-42.

4. Barcia, P. and Holm, S. (1988). A revised bound improvement sequence algorithm. *European Journal of Operational Research*, 36(2), pp. 202-206.

5. Battiti, R. and Tecchiolli, G. (1992). Parallel biased search for combinatorial optimization: Genetic Algorithms and Tabu Search. *Microprocessors and Microsystems*, 16(7), pp. 351-367.

6. Bazgan, C., Hugot, H. and Vanderpooten, D. (2009). Solving efficiently the 0–1 multi-objective knapsack problem. *Computers & Operations Research*, 36(1), pp. 260-279.

7. Bowman, B.L. (1994). *Assessment of the State of Alabama Rail-Highway Safety Program*. [online] Montgomery, Alabama. Available at: http://www.eng.auburn.edu/files/centers/hrc/Multimodal%20Transportation.pdf [Accessed 01 Oct 2018].

8. Cabot, A.V. (1970). An enumeration algorithm for knapsack problems. *Operations Research*, 18(2), pp. 306-311.

9. Chadwick, S., Zhou, N. and Saat, M.R. (2014). Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S. *Safety Science*, 68, pp. 128-137.

10. Chang, C.S., Wang, W., Liew, A.C., Wen, F.S. and Srinivasan, D. (1995). Genetic algorithm based bicriterion optimization for traction substations in DC railway system. In: *Proceedings of the IEEE Conference on Evolutionary Computation*. [online] Perth, Australia: IEEE, pp. 11-16. Available at: https://ieeexplore.ieee.org/document/489111 [Accessed 01 Oct 2018].

11. Chang, T.J., Meade, N., Beasley, J.E. and Sharaiha, Y.M. (2000). Heuristics for cardinality constrained portfolio optimisation. *Computers & Operations Research*, 27(13), pp.1271-1302.

12. Chekuri, C. and Khanna, S. (2005). A polynomial time approximation scheme for the multiple knapsack problem. *SIAM Journal on Computing*, 35(3), pp. 713-728.

13. Cook, S. (2006). *The P versus NP Problem*. [online] Oxford, U.K.: Clay Mathematics Institute. Available at: http://www.claymath.org/sites/default/files/pvsnp.pdf [Accessed 21 Dec 2018].

14. Dammeyer, F. and Voss, S. (1991). *Application of Tabu Search strategies for solving multiconstraint zero–one knapsack problems*. Working Paper. Technische Hochschule Darmstadt.

15. DeviantArt (2018). *Railroad crossing gate*. [online] Available at: https://www.deviantart.com/willm3luvtrains/art/Railroad-Crossing-Gate-Signal-2-646117031 [Accessed 21 Dec 2018].

16. Drexl, A. (1988). A Simulated Annealing approach to the multiconstraint zero-one knapsack problem. *Computing*, 40(1), pp. 1-8.

17. Dueck, G. and Scheuer, T. (1990). Threshold Accepting: a general purpose optimization algorithm appearing superior to Simulated Annealing. *Journal of Computational Physics*, 90(1), pp. 161-175.
18. Dueck, G. and Wirsching, J. (1989). *Threshold Accepting Algorithms for multi-constraint 0-1 knapsack problems*. IBM Deutschland GmbH. Heidelberg Scientific Center.
19. Dulebenets, M.A. (2012). *Highway-rail grade crossing identification and prioritizing model development*. Master Thesis. The University of Memphis.
20. Dulebenets, M.A. (2017). A Novel Memetic Algorithm with a deterministic parameter control for efficient berth scheduling at marine container terminals. *Maritime Business Review*, 2(4), pp. 302-330.
21. Dulebenets, M.A. (2018a). Application of evolutionary computation for berth scheduling at marine container terminals: Parameter tuning versus parameter control. *IEEE Transactions on Intelligent Transportation Systems*, 19(1), pp. 25-37.
22. Dulebenets, M.A. (2018b). A Diploid Evolutionary Algorithm for sustainable truck scheduling at a cross-docking facility. *Sustainability*, 10(5), p. 1333.
23. Dulebenets, M.A. (2018c). A comprehensive evaluation of weak and strong mutation mechanisms in Evolutionary Algorithms for truck scheduling at cross-docking terminals. *IEEE Access*, 6, pp. 65635-65650.
24. Dulebenets, M.A. (2019). A Delayed Start Parallel Evolutionary Algorithm for just-in-time truck scheduling at a cross-docking facility. *International Journal of Production Economics*, 212, pp. 236-258.
25. Dulebenets, M.A., Kavoosi, M., Abioye, O.F. and Pasha, J. (2018). A Self-Adaptive Evolutionary Algorithm for the berth scheduling problem: Towards efficient parameter control. *Algorithms*, 11(7), p. 100.
26. Dulebenets, M.A., Moses, R., Ozguven, E.E. and Vanli, A. (2017). Minimizing carbon dioxide emissions due to container handling at marine container terminals via Hybrid Evolutionary Algorithms. *IEEE Access*, 5, pp. 8131-8147.
27. Dulebenets, M.A., Pasha, J., Abioye, O.F., Kavoosi, M., Ozguven, E.E., Moses, R., Boot, W.R. and Sando, T. (2019). Exact and heuristic solution algorithms for efficient emergency evacuation in areas with vulnerable populations. *International Journal of Disaster Risk Reduction*, 39, pp. 1-18.
28. Eiben, A.E. and Smith, J.E. (2015). *Introduction to Evolutionary Computing*. 2nd ed. Berlin: Springer-Verlag Berlin Heidelberg.
29. Elzohairy, Y. and Benekohal, R. (2000). *Evaluation of Expected Accident Frequency Formulas for Rail-Highway Highway-Rail Grade Crossings*. [online] Urbana, Illinois. Available at: http://www.idot.illinois.gov/Assets/uploads/files/Transportation-System/Research/Illinois-Transportation-Research-Center/2000.09.01%20-%20Evaluation%20of%20Expected%20Accident%20Frequency%20Formulas%20for%20Rail-Highway%20Crossings%20-%20VC-HR1%20FY98.pdf [Accessed 24 Sept 2018].
30. ePermitTest (2018). *Railroad crossing gate*. [online] Available at: https://www.epermittest.com/road-signs/railroad-crossing-gate-lights [Accessed 21 Dec 2018].
31. Faghri, A. and Demetsky M. (1986). *Evaluation of Methods for Predicting Rail-Highway Highway-Rail Grade Crossing Hazards*. [online] Charlottesville, Virginia. Available at: http://www.virginiadot.org/vtrc/main/online_reports/pdf/86-r32.pdf [Accessed 24 Sept 2018].

32. FDOT (2010). *The Florida Rail System Plan: Investment Element*. [online] Available at: http://www.fdot.gov/rail/PlanDevel/Documents/FinalInvestmentElement/A-2010FLRailPlan-InvestmentElement.pdf [Accessed 24 Sept 2018].
33. FDOT (2011). *Florida's Highway-Rail Grade Crossing Safety Action Plan*. [online] Available at: http://www.fdot.gov/rail/FCSAP0811.pdf [Accessed 24 Sept 2018].
34. FDOT (2015). *Florida Transportation Trends & Conditions*. [online] Available at: http://www.fdot.gov/planning/trends/pg15.pdf [Accessed 24 Sept 2018].
35. FHWA (2003). *Manual on Uniform Traffic Control Devices*. [online] Available at: https://mutcd.fhwa.dot.gov/pdfs/2003r1r2/mutcd2003r1r2complet.pdf [Accessed 27 Oct 2018].
36. FICO (2019). *FICO® Xpress Optimization*. [online] Available at: https://www.fico.com/en/products/fico-xpress-optimization [Accessed 06 Jan 2019].
37. FRA (2010). *Accident Prediction and Resource Allocation Procedure Normalizing Constants 2010*. [online] Available at: https://www.fra.dot.gov/Elib/Document/1488 [Accessed 02 Oct 2018].
38. FRA (2011a). *FRA Guide for Preparing Accident/Incident Reports*. [online] Available at: https://safetydata.fra.dot.gov/OfficeofSafety/ProcessFile.aspx?doc=FRAGuideforPreparingAccIncReportspubMay2011.pdf [Accessed 15 Oct 2018].
39. FRA (2011b). *Highway-Rail Grade Crossing Accident/Incident. Form FRA F 6180.57*. Accident Downloads on Demand. Data File Structure and Field Input Specifications.
40. FRA (2015). *FRA Instructions for Electronic Submission of U.S. DOT Crossing Inventory Data Grade Crossing Inventory System (GCIS) v2.0*. U.S. Department of Transportation. Federal Railroad Administration. Office of Railroad Safety.
41. FRA (2016). *FRA Data Dictionary for External Use Grade Crossing Inventory System (GCIS) v2.5.0.0*. U.S. Department of Transportation. Federal Railroad Administration. Office of Railroad Safety.
42. FRA (2018a). *Accident/Incident Data*. [online] Available at: https://safetydata.fra.dot.gov/OfficeofSafety/publicsite/on_the_fly_download.aspx [Accessed 06 Oct 2018].
43. FRA (2018b). *FRA Office of Safety Analysis*. [online] Available at: https://safetydata.fra.dot.gov/OfficeofSafety/default.aspx [Accessed 16 Oct 2018].
44. Franke, T., Ho, T. and Christie, C. (2012). The Chi-Square test: often used and more often misinterpreted. *American Journal of Evaluation*, 33(3), pp. 448-458.
45. Fréville, A. (2004). The multidimensional 0–1 knapsack problem: An overview. *European Journal of Operational Research*, 155(1), pp. 1-21.
46. GAMS (2019). *Cutting Edge Modeling*. [online] Available at: https://www.gams.com/ [Accessed 11 Jan 2019].
47. Gilmore, P.C. and Gomory, R.E. (1966). The theory and computation of knapsack functions. *Operations Research*, 14(6), pp. 1045-1074.
48. Glover, F. and Kochenberger, G.A. (1996). Critical Event Tabu Search for Multidimensional Knapsack Problems. In: I.H. Osman, J.P. Kelly, eds., *Meta-Heuristics*, 1st ed. Springer: Boston, pp. 407-427.
49. Green, C.J. (1967). *Two algorithms for solving independent multidimensional knapsack problems*. Management Sciences Report, no. 110, Carnegie institute of Technology, Graduate School of Industrial Administration, Pittsburgh, USA
50. Güntzer, M.M. and Jungnickel, D. (2000). Approximate minimization algorithms for the 0/1 knapsack and subset-sum problem. *Operations Research Letters*, 26(2), pp. 55-66.

51. Hanafi, S., Fréville, A. and El Abdellaoui, A. (1996). Comparison of heuristics for the 0–1 multidimensional knapsack problem. In: I.H. Osman, J.P. Kelly, eds., *Meta-Heuristics*, 1st ed. Springer: Boston, pp. 449-465.
52. Hans, Z., Albrecht, C., Johnson, P. and Nlenanya, I. (2015). *Development of Railroad Highway Grade Highway-Rail Grade Crossing Consolidation Rating Formula*. [online] Ames, Iowa. Available at: https://lib.dr.iastate.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1061&context=intrans_techtransfer [Accessed 24 Sept 2018].
53. Ibaraki, T. (1987). Enumerative Approaches to Combinatorial Optimization - Part II. *Annals of Operations Research*, 11.
54. IBM (2019). *IBM ILOG CPLEX Optimization Studio*. [online] Available at: https://www.ibm.com/products/ilog-cplex-optimization-studio [Accessed 07 Jan 2019].
55. Iowa DOT (2006). *Use of a benefit-cost ratio to prioritize projects for funding*. [online] Ames, Iowa. Available at: https://www.iowadot.gov/iowarail/assistance/130/130SelectionProcess_final.pdf [Accessed 24 Sept 2018].
56. Isaka S. (1983). *Double relaxation dynamic programming methods for the multi-dimensional knapsack problem*. Master Thesis. Kyoto University.
57. Karp, R.M. (1972). Reducibility among combinatorial problems. In: R.E. Miller, J.W. Thatcher, J.D. Bohlinger, eds., *Complexity of computer computations*, 1st ed. Springer: Boston, pp. 85-103.
58. Khuri, S., Bäck, T. and Heitkötter, J. (1994). The zero/one multiple knapsack problem and Genetic Algorithms. In: *Proceedings of the 1994 ACM symposium on applied computing*. [online] Phoenix, Arizona: ACM, pp. 188-193. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.51.2713&rep=rep1&type=pdf [Accessed 01 Oct 2018].
59. Kulik, A. and Shachnai, H. (2010). There is no EPTAS for two-dimensional knapsack. *Information Processing Letters*, 110(16), pp. 707-710.
60. Laerd Statistics (2018). *Spearman's rank-order correlation*. [online] Available at: https://statistics.laerd.com/statistical-guides/spearmans-rank-order-correlation-statistical-guide.php [Accessed 12 Dec 2018].
61. Land, A.H. and Doig, A.G. (1960). An automatic method of solving discrete programming problems. *Econometrica: Journal of the Econometric Society*, 28(3), pp. 497-520.
62. Lima, R. (2010). *IBM ILOG CPLEX What is inside of the box?* [online] Pittsburgh, Pennsylvania. Available at: http://egon.cheme.cmu.edu/ewo/docs/rlima_cplex_ewo_dec2010.pdf [Accessed 24 Sept 2018].
63. Lin, P., Wang, Z., Vasili, A. and Schultz, D. (2017). *A Pilot Study for Preventing Incorrect Turns at Highway-Rail Grade Crossings*. [online] Tampa, Florida. Available at: https://rosap.ntl.bts.gov/view/dot/36342 [Accessed 24 Sept 2018].
64. Lorie, J.H. and Savage, L.J. (1955). Three problems in rationing capital. *The Journal of Business*, 28(4), pp. 229-239.
65. Marsten, R.E. and Morin, T.L. (1976). *MMPD, a computer code for solving multiconstraint knapsack problems in integer variables*. User's Guide. Operations Research Center, MIT, Cambridge, MA.
66. Mathews, G.B. (1896). On the partition of numbers. *Proceedings of the London Mathematical Society*, 1(1), pp. 486-490.

67. MathWorks (2019a). *MATLAB*. [online] Available at: https://www.mathworks.com/ [Accessed 09 Jan 2019].
68. MathWorks (2019b). *MATLAB Runtime*. [online] Available at: https://www.mathworks.com/products/compiler/matlab-runtime.html [Accessed 05 June 2019].
69. McHugh, M. (2013). The Chi-Square test of independence. *Biochemia Medica*, 23(2), pp. 143-149.
70. Mysore, V. (2013). Florida Statewide Multi-Modal Freight Model. In: *14th TRB National Transportation Planning Applications Conference*. Columbus, Ohio: TRB.
71. Nemhauser, G.L. and Ullmann, Z. (1969). Discrete dynamic programming and capital allocation. *Management Science*, 15(9), pp. 494-505.
72. Nemhauser, G.L., Savelsbergh, M.W. and Sigismondi, G.C. (1994). MINTO, a mixed INTeger optimizer. *Operations Research Letters*, 15(1), pp. 47-58.
73. Ohlsson, M., Peterson, C. and Söderberg, B. (1993). Neural Networks for optimization problems with inequality constraints: the knapsack problem. *Neural Computation*, 5(2), pp. 331-339.
74. Pisinger, D. (2007). The quadratic knapsack problem – a survey. *Discrete Applied Mathematics*, 155(5), pp. 623-648.
75. Qureshi, M., Virkler, M., Bernhardt, K., Spring, G., Avalokita, S., Yathapu, N., Chilukuri, V., King, T. and Gibbons, K. (2003). *Highway Rail Highway-Rail Grade Crossing Project Selection*. [online] Rolla, Missouri. Available at: https://library.modot.mo.gov/RDT/reports/Ri01010/RDT03017.pdf [Accessed 24 Sept 2018].
76. Ryan, C. and Mielke, A. (2017). *Development of Revised Grade Highway-Rail Grade Crossing Hazard Index Model*. [online] Carson City, Nevada. Available at: https://www.nevadadot.com/home/showdocument?id=9133 [Accessed 24 Sept 2018].
77. Senju, S. and Toyoda, Y. (1968). An approach to linear programming with 0-1 variables. *Management Science*, 15, pp. 196-207.
78. Shih, W. (1979). A Branch and Bound Method for the multiconstraint zero-one knapsack problem. *Journal of the Operational Research Society*, 30(4), pp. 369-378.
79. Sperry, B., Naik, B. and Warner, J. (2017). *Evaluation of grade crossing hazard ranking models*. [online] Columbus, Ohio. Available at: http://www.dot.state.oh.us/engineering/OTEC/2017Presentations/75/Sperry_75.pdf [Accessed 24 Sept 2018].
80. Statistics How To (2018a). *Chi-Square Statistic: How to Calculate It / Distribution*. [online] Available at: from https://www.statisticshowto.datasciencecentral.com/probability-and-statistics/chi-square/ [Accessed 11 Sept 2018].
81. Statistics How To (2018b). *Spearman Rank Correlation (Spearman's Rho): Definition and How to Calculate it*. [online] Available at: https://www.statisticshowto.datasciencecentral.com/spearman-rank-correlation-definition-calculate/ [Accessed 11 Sept 2018].
82. Statistics Solutions (2018). *Using Chi-Square Statistic in Research*. [online] Available at: https://www.statisticssolutions.com/using-chi-square-statistic-in-research/ [Accessed 11 Sept 2018].
83. Thesen, A. (1975). A Recursive Branch and Bound Algorithm for the multidimensional knapsack problem. *Naval Research Logistics*, 22(2), pp. 341-353.
84. Toyoda, Y. (1975). A simplified algorithm for obtaining approximate solutions to zero-one programming problems. *Management Science*, 21(12), pp. 1417-1427.

85. U.S. Census (2015). *Florida Demographic Information*. [online] Available at: http://www.arcgis.com/home/item.html?id=61a30fb3ea4c43e4854fbb4c1be57394#data [Accessed 07 Jun 2018].
86. U.S. Census (2018). *US States - Ranked by Population 2018*. [online] Available at: http://worldpopulationreview.com/states/ [Accessed 04 Oct 2018].
87. U.S. DOT (1991). *Federal-Aid Policy Guide: Part 924 - Highway Safety Improvement Program*. [online] Available at: https://www.fhwa.dot.gov/legsregs/directives/fapg/cfr0924.htm [Accessed 19 Oct 2018].
88. U.S. DOT (2007). *Rail-Highway Grade Crossing Handbook*. [online] Available at: https://www.fra.dot.gov/Elib/Document/1464 [Accessed 24 Sept 2018].
89. U.S. DOT (2014). *GradeDec.NET Reference Manual*. [online] Available at: https://www.fra.dot.gov/Elib/Document/14852 [Accessed 24 Sept 2018].
90. U.S. GPO (2006). *United States Code, 2006 Edition, Supplement 2, Title 49 - TRANSPORTATION*. [online] Available at: https://www.gpo.gov/fdsys/pkg/USCODE-2008-title49/pdf/USCODE-2008-title49.pdf [Accessed 16 Oct 2018].
91. Van Leeuwen, J. (1990). *Algorithms and Complexity. Handbook of Theoretical Computer Science*. 1st ed. Netherlands: Elsevier.
92. Weingartner, H.M. and Ness, D.N. (1967). Methods for the solution of the multidimensional 0/1 knapsack problem. *Operations Research*, 15(1), pp. 83-103.
93. Weissmann, A.J., Weissmann, J., Kunisetty, J.L., Warner, J., Park, E., Sunkari, S., Protopapas, A. and Venglar, S. (2013). *Integrated Prioritization Method for Active and Passive Highway-Rail Crossings*. [online] San Antonio, Texas. Available at: https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6642-1.pdf [Accessed 24 Sept 2018].
94. Wikipedia (2018a). *NP-hardness*. [online] Available at: https://en.wikipedia.org/wiki/ NP-hardness [Accessed 21 Oct 2018].
95. Wikipedia (2018b). *Knapsack problem*. [online] Available at: https://en.wikipedia.org/wiki/Knapsack_problem [Accessed 21 Oct 2018].
96. Witzgall, C. (1975). *Mathematical methods of site selection for Electronic Message Systems (EMS)*. [online] Washington, D.C. Available at: https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir75-737.pdf [Accessed 24 Sept 2018].
97. Xiong, D., Zhao, F., Chow, L. and Chung, S. (2007). *Integrating Data and Models for Analysis of Freight Movement on Multimodal Transportation Systems for Florida*. [online] Knoxville, Tennessee. Available at: http://www.fsutmsonline.net/images/uploads/reports/FDOT_BD015_13_rpt.pdf [Accessed 24 Sept 2018].

**APPENDICES**

## Appendix A. U.S. DOT Accident Prediction Factor Values for Highway-Rail Grade Crossings with Different Warning Devices

U.S. DOT Accident Prediction Factor Values for Highway-Rail Grade Crossings with Passive Warning Devices

| K | "c" x "t" | EI | Main | MT | Day Thru | DT | Highway Paved | HP | Maximum Timetable | MS | Highway Type | HT | Highway Lanes | HL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0* | 1.00 | 0 | 1.00 | 0 | 1.00 | 1 (yes) | 1.00 | 0 | 1.00 | 01&11 | 1.00 | 1 | 1.00 |
| | 1 - 5 | 2.22 | 1 | 1.23 | 1 | 1.27 | 2 (no) | 0.54 | 5 | 1.04 | 02&12 | 0.90 | 2 | 1.00 |
| | 6 - 10 | 3.30 | 2 | 1.52 | 2 | 1.38 | | | 10 | 1.08 | 06&14 | 0.82 | 3 | 1.00 |
| | 11 - 20 | 4.24 | 3 | 1.87 | 3 | 1.45 | | | 15 | 1.12 | 07&16 | 0.74 | 4 | 1.00 |
| | 21 - 30 | 5.01 | 4 | 2.31 | 4 | 1.50 | | | 20 | 1.17 | 08&17 | 0.67 | 5 | 1.00 |
| | 31 - 50 | 5.86 | 5 | 2.85 | 5 | 1.55 | | | 25 | 1.21 | 09&19 | 0.61 | 6 | 1.00 |
| | 51 - 80 | 6.89 | 6 | 3.51 | 6 | 1.58 | | | 30 | 1.26 | | | 7 | 1.00 |
| | 81 - 120 | 7.95 | | | 7 | 1.61 | | | 35 | 1.31 | | | 8 | 1.00 |
| | 121 - 200 | 9.29 | | | 8 | 1.64 | | | 40 | 1.36 | | | 9 | 1.00 |
| | 201 - 300 | 10.78 | | | 9 | 1.67 | | | 45 | 1.41 | | | | |
| | 301 - 400 | 12.06 | | | 10 | 1.69 | | | 50 | 1.47 | | | | |
| | 401 - 500 | 13.11 | | | 11-20 | 1.78 | | | 55 | 1.53 | | | | |
| | 501 - 600 | 14.02 | | | 21-30 | 1.91 | | | 60 | 1.59 | | | | |
| | 601 - 700 | 14.82 | | | 31-40 | 2.00 | | | 65 | 1.65 | | | | |
| | 701 - 1000 | 16.21 | | | 41-60 | 2.09 | | | 70 | 1.71 | | | | |
| | 1001 - 1300 | 17.93 | | | | | | | 75 | 1.78 | | | | |
| | 1301 - 1600 | 19.37 | | | | | | | 80 | 1.85 | | | | |
| | 1601 - 2000 | 20.81 | | | | | | | 85 | 1.92 | | | | |
| | 2001 - 2500 | 22.42 | | | | | | | 90 | 2.00 | | | | |
| | 2501 - 3000 | 23.97 | | | | | | | | | | | | |
| | 3001 - 4000 | 25.98 | | | | | | | | | | | | |
| | 4001 - 6000 | 29.26 | | | | | | | | | | | | |
| | 6001 - 8000 | 32.73 | | | | | | | | | | | | |
| | 8001 - 10000 | 35.59 | | | | | | | | | | | | |
| | 10001 - 15000 | 39.71 | | | | | | | | | | | | |
| | 15001 - 20000 | 44.43 | | | | | | | | | | | | |
| | 20001 - 25000 | 48.31 | | | | | | | | | | | | |
| | 25001 - 30000 | 51.65 | | | | | | | | | | | | |
| | 30001 - 40000 | 55.98 | | | | | | | | | | | | |
| | 40001 - 50000 | 60.87 | | | | | | | | | | | | |
| | 50001 - 60000 | 65.08 | | | | | | | | | | | | |
| | 60001 - 70000 | 68.81 | | | | | | | | | | | | |
| | 70001 - 90000 | 73.74 | | | | | | | | | | | | |
| | 90001 - | 79.44 | | | | | | | | | | | | |
| | 110001 - | 84.42 | | | | | | | | | | | | |
| | 130001 - | 91.94 | | | | | | | | | | | | |
| | 180001 - | 100.92 | | | | | | | | | | | | |
| | 230001 - | 109.94 | | | | | | | | | | | | |
| | 300001 - | 118.87 | | | | | | | | | | | | |

General Form of Basic Accident Prediction Formula: a = K x El x MT x DT x HP x HT x HL

"c" x "t" = Number of highway vehicles per day, "c", multiplied by total train movements per day, "t"

El = Exposure index factor
MT = Main tracks factor
DT = Day thru trains factor
HP = Highway paved factor
MS =Maximum timetable speed factor
HT = Highway type factor
HL = Highway lanes factor

* Less than one train per day
** See Table 16 for definition of highway type codes

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

U.S. DOT Accident Prediction Factor Values for Highway-Rail Grade Crossings with Flashing Light Warning Devices

| K | "c" x "t" | EI | Main | MT | Day Thru | DT | Highway Paved | HP | Maximum Timetable | MS | Highway Type | HT | Highway Lanes | HL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0* | 1.00 | 0 | 1.00 | 0 | 1.00 | 1 (yes) | 1.00 | 0 | 1.00 | 01&11 | 1.00 | 1 | 1.00 |
| | 1 - 5 | 2.27 | 1 | 1.11 | 1 | 1.09 | 2 (no) | 1.00 | 5 | 1.00 | 02&12 | 1.00 | 2 | 1.15 |
| | 6 - 10 | 2.99 | 2 | 1.24 | 2 | 1.12 | | | 10 | 1.00 | 06&14 | 1.00 | 3 | 1.32 |
| | 11 - 20 | 3.59 | 3 | 1.39 | 3 | 1.14 | | | 15 | 1.00 | 07&16 | 1.00 | 4 | 1.51 |
| | 21 - 30 | 4.17 | 4 | 1.55 | 4 | 1.15 | | | 20 | 1.00 | 08&17 | 1.00 | 5 | 1.74 |
| | 31 - 50 | 4.79 | 5 | 1.72 | 5 | 1.17 | | | 25 | 1.00 | 09&19 | 1.00 | 6 | 1.99 |
| | 51 - 80 | 5.52 | 6 | 1.92 | 6 | 1.18 | | | 30 | 1.00 | | | 7 | 2.29 |
| | 81 - 120 | 6.27 | | | 7 | 1.18 | | | 35 | 1.00 | | | 8 | 2.63 |
| | 121 - 200 | 7.20 | | | 8 | 1.19 | | | 40 | 1.00 | | | 9 | 3.02 |
| | 201 - 300 | 8.22 | | | 9 | 1.20 | | | 45 | 1.00 | | | | |
| | 301 - 400 | 9.07 | | | 10 | 1.20 | | | 50 | 1.00 | | | | |
| | 401 - 500 | 9.77 | | | 11-20 | 1.23 | | | 55 | 1.00 | | | | |
| | 501 - 600 | 10.37 | | | 21-30 | 1.26 | | | 60 | 1.00 | | | | |
| | 601 - 700 | 10.89 | | | 31-40 | 1.28 | | | 65 | 1.00 | | | | |
| | 701 - 1000 | 11.79 | | | 41-60 | 1.30 | | | 70 | 1.00 | | | | |
| | 1001 - 1300 | 12.89 | | | | | | | 75 | 1.00 | | | | |
| | 1301 - 1600 | 13.80 | | | | | | | 80 | 1.00 | | | | |
| | 1601 - 2000 | 14.71 | | | | | | | 85 | 1.00 | | | | |
| | 2001 - 2500 | 15.72 | | | | | | | 90 | 1.00 | | | | |
| | 2501 - 3000 | 16.67 | | | | | | | | | | | | |
| | 3001 - 4000 | 17.91 | | | | | | | | | | | | |
| | 4001 - 6000 | 19.89 | | | | | | | | | | | | |
| | 6001 - 8000 | 21.97 | | | | | | | | | | | | |
| | 8001 - 10000 | 23.66 | | | | | | | | | | | | |
| | 10001 - 15000 | 26.08 | | | | | | | | | | | | |
| | 15001 - 20000 | 28.80 | | | | | | | | | | | | |
| | 20001 - 25000 | 31.02 | | | | | | | | | | | | |
| | 25001 - 30000 | 32.91 | | | | | | | | | | | | |
| | 30001 - 40000 | 35.34 | | | | | | | | | | | | |
| | 40001 - 50000 | 38.06 | | | | | | | | | | | | |
| | 50001 - 60000 | 40.39 | | | | | | | | | | | | |
| | 60001 - 70000 | 42.43 | | | | | | | | | | | | |
| | 70001 - 90000 | 45.11 | | | | | | | | | | | | |
| | 90001 - | 48.18 | | | | | | | | | | | | |
| | 110001 - | 50.85 | | | | | | | | | | | | |
| | 130001 - | 54.84 | | | | | | | | | | | | |
| | 180001 - | 59.56 | | | | | | | | | | | | |
| | 230001 - | 64.25 | | | | | | | | | | | | |
| | 300001 - | 68.86 | | | | | | | | | | | | |

General Form of Basic Accident Prediction Formula: a = K x El x MT x DT x HP x HT x HL

"c" x "t" = Number of highway vehicles per day, "c", multiplied by total train movements per day, "t"

El = Exposure index factor
MT = Main tracks factor
DT = Day thru trains factor
HP = Highway paved factor
MS =Maximum timetable speed factor
HT = Highway type factor
HL = Highway lanes factor

* Less than one train per day
** See Table 16 for definition of highway type codes

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

U.S. DOT Accident Prediction Factor Values for Highway-Rail Grade Crossings with Gate Warning Devices

| K | "c" x "t" | EI | Main Tracks | MT | Day Thru Trains | DT | Highway Paved | HP | Maximum Timetable Speed | MS | Highway Type Code** | HT | Highway Lanes | HL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0* | 1.00 | 0 | 1.00 | 0 | 1.00 | 1 (yes) | 1.00 | 0 | 1.00 | 01&11 | 1.00 | 1 | 1.00 |
| | 1 - 5 | 2.37 | 1 | 1.34 | 1 | 1.00 | 2 (no) | 1.00 | 5 | 1.00 | 02&12 | 1.00 | 2 | 1.11 |
| | 6 - 10 | 3.18 | 2 | 1.79 | 2 | 1.00 | | | 10 | 1.00 | 06&14 | 1.00 | 3 | 1.23 |
| | 11 - 20 | 3.86 | 3 | 2.40 | 3 | 1.00 | | | 15 | 1.00 | 07&16 | 1.00 | 4 | 1.36 |
| | 21 - 30 | 4.51 | 4 | 3.21 | 4 | 1.00 | | | 20 | 1.00 | 08&17 | 1.00 | 5 | 1.51 |
| | 31 - 50 | 5.22 | 5 | 4.29 | 5 | 1.00 | | | 25 | 1.00 | 09&19 | 1.00 | 6 | 1.68 |
| | 51 - 80 | 6.07 | 6 | 5.74 | 6 | 1.00 | | | 30 | 1.00 | | | 7 | 1.86 |
| | 81 - 120 | 6.94 | | | 7 | 1.00 | | | 35 | 1.00 | | | 8 | 2.07 |
| | 121 - 200 | 8.03 | | | 8 | 1.00 | | | 40 | 1.00 | | | 9 | 2.29 |
| | 201 - 300 | 9.23 | | | 9 | 1.00 | | | 45 | 1.00 | | | | |
| | 301 - 400 | 10.25 | | | 10 | 1.00 | | | 50 | 1.00 | | | | |
| | 401 - 500 | 11.08 | | | 11-20 | 1.00 | | | 55 | 1.00 | | | | |
| | 501 - 600 | 11.80 | | | 21-30 | 1.00 | | | 60 | 1.00 | | | | |
| | 601 - 700 | 12.43 | | | 31-40 | 1.00 | | | 65 | 1.00 | | | | |
| | 701 - 1000 | 13.51 | | | 41-60 | 1.00 | | | 70 | 1.00 | | | | |
| | 1001 - 1300 | 14.84 | | | | | | | 75 | 1.00 | | | | |
| | 1301 - 1600 | 15.96 | | | | | | | 80 | 1.00 | | | | |
| | 1601 - 2000 | 17.07 | | | | | | | 85 | 1.00 | | | | |
| | 2001 - 2500 | 18.30 | | | | | | | 90 | 1.00 | | | | |
| | 2501 - 3000 | 19.48 | | | | | | | | | | | | |
| | 3001 - 4000 | 21.00 | | | | | | | | | | | | |
| | 4001 - 6000 | 23.46 | | | | | | | | | | | | |
| | 6001 - 8000 | 26.06 | | | | | | | | | | | | |
| | 8001 - 10000 | 28.18 | | | | | | | | | | | | |
| | 10001 - 15000 | 31.22 | | | | | | | | | | | | |
| | 15001 - 20000 | 34.67 | | | | | | | | | | | | |
| | 20001 - 25000 | 37.49 | | | | | | | | | | | | |
| | 25001 - 30000 | 39.91 | | | | | | | | | | | | |
| | 30001 - 40000 | 43.03 | | | | | | | | | | | | |
| | 40001 - 50000 | 46.53 | | | | | | | | | | | | |
| | 50001 - 60000 | 49.53 | | | | | | | | | | | | |
| | 60001 - 70000 | 52.18 | | | | | | | | | | | | |
| | 70001 - 90000 | 55.67 | | | | | | | | | | | | |
| | 90001 - | 59.68 | | | | | | | | | | | | |
| | 110001 - | 63.16 | | | | | | | | | | | | |
| | 130001 - | 68.41 | | | | | | | | | | | | |
| | 180001 - | 74.63 | | | | | | | | | | | | |
| | 230001 - | 80.85 | | | | | | | | | | | | |
| | 300001 - | 86.98 | | | | | | | | | | | | |

General Form of Basic Accident Prediction Formula: a = K x El x MT x DT x HP x HT x HL

"c" x "t" = Number of highway vehicles per day, "c", multiplied by total train movements per day, "t"

El = Exposure index factor
MT = Main tracks factor
DT = Day thru trains factor
HP = Highway paved factor
MS =Maximum timetable speed factor
HT = Highway type factor
HL = Highway lanes factor

* Less than one train per day
** See Table 16 for definition of highway type codes

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

## Appendix B. U.S. DOT Second Accident Prediction from Initial Prediction and Accident History

U.S. DOT Second Accident Prediction from Initial Prediction and Accident History (1 year of accident data ($T$ = 1))

| Initial Prediction from Basic Model, a | Number of Accidents, N, in T Years | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| 0.00 | 0.000 | 0.048 | 0.095 | 0.143 | 0.190 | 0.238 |
| 0.01 | 0.009 | 0.066 | 0.123 | 0.179 | 0.236 | 0.292 |
| 0.02 | 0.019 | 0.084 | 0.150 | 0.215 | 0.280 | 0.346 |
| 0.03 | 0.028 | 0.102 | 0.176 | 0.250 | 0.324 | 0.398 |
| 0.04 | 0.037 | 0.119 | 0.202 | 0.284 | 0.367 | 0.450 |
| 0.05 | 0.045 | 0.136 | 0.227 | 0.318 | 0.409 | 0.500 |
| 0.06 | 0.054 | 0.153 | 0.252 | 0.351 | 0.450 | 0.550 |
| 0.07 | 0.063 | 0.170 | 0.277 | 0.384 | 0.491 | 0.598 |
| 0.08 | 0.071 | 0.186 | 0.301 | 0.416 | 0.531 | 0.646 |
| 0.09 | 0.079 | 0.202 | 0.325 | 0.447 | 0.570 | 0.693 |
| 0.10 | 0.087 | 0.217 | 0.348 | 0.478 | 0.609 | 0.739 |
| 0.20 | 0.160 | 0.360 | 0.560 | 0.760 | 0.960 | 1.160 |
| 0.30 | 0.222 | 0.481 | 0.741 | 1.000 | 1.259 | 1.519 |
| 0.40 | 0.276 | 0.586 | 0.897 | 1.207 | 1.517 | 1.828 |
| 0.50 | 0.323 | 0.677 | 1.032 | 1.387 | 1.742 | 2.097 |
| 0.60 | 0.364 | 0.758 | 1.152 | 1.545 | 1.939 | 2.333 |
| 0.70 | 0.400 | 0.829 | 1.257 | 1.686 | 2.114 | 2.543 |
| 0.80 | 0.432 | 0.892 | 1.351 | 1.811 | 2.270 | 2.730 |
| 0.90 | 0.462 | 0.949 | 1.436 | 1.923 | 2.410 | 2.897 |
| 1.00 | 0.488 | 1.000 | 1.512 | 2.024 | 2.537 | 3.049 |
| 1.10 | 0.512 | 1.047 | 1.581 | 2.116 | 2.651 | 3.186 |
| 1.20 | 0.533 | 1.089 | 1.644 | 2.200 | 2.756 | 3.311 |
| 1.30 | 0.553 | 1.128 | 1.702 | 2.277 | 2.851 | 3.426 |
| 1.40 | 0.571 | 1.163 | 1.755 | 2.347 | 2.939 | 3.531 |
| 1.50 | 0.588 | 1.196 | 1.804 | 2.412 | 3.020 | 3.627 |
| 1.60 | 0.604 | 1.226 | 1.849 | 2.472 | 3.094 | 3.717 |
| 1.70 | 0.618 | 1.255 | 1.891 | 2.527 | 3.164 | 3.800 |
| 1.80 | 0.632 | 1.281 | 1.930 | 2.579 | 3.228 | 3.877 |
| 1.90 | 0.644 | 1.305 | 1.966 | 2.627 | 3.288 | 3.949 |
| 2.00 | 0.656 | 1.328 | 2.000 | 2.672 | 3.344 | 4.016 |
| 2.10 | 0.667 | 1.349 | 2.032 | 2.714 | 3.397 | 4.079 |
| 2.20 | 0.677 | 1.369 | 2.062 | 2.754 | 3.446 | 4.138 |
| 2.30 | 0.687 | 1.388 | 2.090 | 2.791 | 3.493 | 4.194 |
| 2.40 | 0.696 | 1.406 | 2.116 | 2.826 | 3.536 | 4.246 |
| 2.50 | 0.704 | 1.423 | 2.141 | 2.659 | 3.577 | 4.296 |

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

U.S. DOT Second Accident Prediction from Initial Prediction and Accident History (2 years of accident data ($T$ = 2))

| Initial Prediction from Basic Model, a | Number of Accidents, N, in T Years | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 0.00 | 0.000 | 0.045 | 0.091 | 0.136 | 0.182 | 0.227 | 0.273 | 0.318 | 0.364 |
| 0.01 | 0.009 | 0.063 | 0.116 | 0.170 | 0.223 | 0.277 | 0.330 | 0.384 | 0.438 |
| 0.02 | 0.018 | 0.079 | 0.140 | 0.202 | 0.263 | 0.325 | 0.386 | 0.447 | 0.509 |
| 0.03 | 0.026 | 0.095 | 0.164 | 0.233 | 0.302 | 0.371 | 0.440 | 0.509 | 0.578 |
| 0.04 | 0.034 | 0.110 | 0.186 | 0.263 | 0.339 | 0.415 | 0.492 | 0.568 | 0.644 |
| 0.05 | 0.042 | 0.125 | 0.208 | 0.292 | 0.375 | 0.458 | 0.542 | 0.625 | 0.708 |
| 0.06 | 0.049 | 0.139 | 0.230 | 0.320 | 0.410 | 0.500 | 0.590 | 0.680 | 0.770 |
| 0.07 | 0.056 | 0.153 | 0.250 | 0.347 | 0.444 | 0.540 | 0.637 | 0.734 | 0.831 |
| 0.08 | 0.063 | 0.167 | 0.270 | 0.373 | 0.476 | 0.579 | 0.683 | 0.786 | 0.889 |
| 0.09 | 0.070 | 0.180 | 0.289 | 0.398 | 0.508 | 0.617 | 0.727 | 0.836 | 0.945 |
| 0.10 | 0.077 | 0.192 | 0.308 | 0.423 | 0.538 | 0.654 | 0.769 | 0.885 | 1.000 |
| 0.20 | 0.133 | 0.300 | 0.467 | 0.633 | 0.800 | 0.967 | 1.133 | 1.300 | 1.467 |
| 0.30 | 0.176 | 0.382 | 0.588 | 0.794 | 1.000 | 1.206 | 1.412 | 1.618 | 1.824 |
| 0.40 | 0.211 | 0.447 | 0.684 | 0.921 | 1.158 | 1.395 | 1.632 | 1.868 | 2.105 |
| 0.50 | 0.238 | 0.500 | 0.762 | 1.024 | 1.286 | 1.548 | 1.810 | 2.071 | 2.333 |
| 0.60 | 0.261 | 0.543 | 0.826 | 1.109 | 1.391 | 1.674 | 1.957 | 2.239 | 2.522 |
| 0.70 | 0.280 | 0.580 | 0.880 | 1.180 | 1.480 | 1.780 | 2.080 | 2.380 | 2.680 |
| 0.80 | 0.296 | 0.611 | 0.926 | 1.241 | 1.556 | 1.870 | 2.185 | 2.500 | 2.815 |
| 0.90 | 0.310 | 0.638 | 0.966 | 1.293 | 1.621 | 1.948 | 2.276 | 2.603 | 2.931 |
| 1.00 | 0.323 | 0.661 | 1.000 | 1.339 | 1.677 | 2.016 | 2.355 | 2.694 | 3.032 |
| 1.10 | 0.333 | 0.682 | 1.030 | 1.379 | 1.727 | 2.076 | 2.424 | 2.773 | 3.121 |
| 1.20 | 0.343 | 0.700 | 1.057 | 1.414 | 1.771 | 2.129 | 2.486 | 2.843 | 3.200 |
| 1.30 | 0.351 | 0.716 | 1.081 | 1.446 | 1.811 | 2.176 | 2.541 | 2.905 | 3.270 |
| 1.40 | 0.359 | 0.731 | 1.103 | 1.474 | 1.846 | 2.218 | 2.590 | 2.962 | 3.333 |
| 1.50 | 0.366 | 0.744 | 1.122 | 1.500 | 1.878 | 2.256 | 2.634 | 3.012 | 3.390 |
| 1.60 | 0.372 | 0.756 | 1.140 | 1.523 | 1.907 | 2.291 | 2.674 | 3.058 | 3.442 |
| 1.70 | 0.378 | 0.767 | 1.156 | 1.544 | 1.933 | 2.322 | 2.711 | 3.100 | 3.489 |
| 1.80 | 0.383 | 0.777 | 1.170 | 1.564 | 1.957 | 2.351 | 2.745 | 3.138 | 3.532 |
| 1.90 | 0.388 | 0.786 | 1.184 | 1.582 | 1.980 | 2.378 | 2.776 | 3.173 | 3.571 |
| 2.00 | 0.392 | 0.794 | 1.196 | 1.598 | 2.000 | 2.402 | 2.804 | 3.206 | 3.608 |
| 2.10 | 0.396 | 0.802 | 1.208 | 1.613 | 2.019 | 2.425 | 2.830 | 3.236 | 3.642 |
| 2.20 | 0.400 | 0.809 | 1.218 | 1.627 | 2.036 | 2.445 | 2.855 | 3.264 | 3.673 |
| 2.30 | 0.404 | 0.816 | 1.228 | 1.640 | 2.053 | 2.465 | 2.877 | 3.289 | 3.702 |
| 2.40 | 0.407 | 0.822 | 1.237 | 1.653 | 2.068 | 2.483 | 2.898 | 3.314 | 3.729 |
| 2.50 | 0.410 | 0.828 | 1.246 | 1.664 | 2.082 | 2.500 | 2.918 | 3.336 | 3.754 |

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

U.S. DOT Second Accident Prediction from Initial Prediction and Accident History (3 years of accident data ($T$ = 3))

| Initial Prediction from Basic Model, a | Number of Accidents, N, in T Years | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 0.00 | 0.000 | 0.043 | 0.087 | 0.130 | 0.174 | 0.217 | 0.261 | 0.304 | 0.348 | 0.391 | 0.435 | 0.478 | 0.522 |
| 0.01 | 0.008 | 0.059 | 0.110 | 0.161 | 0.212 | 0.263 | 0.314 | 0.364 | 0.415 | 0.466 | 0.517 | 0.568 | 0.619 |
| 0.02 | 0.017 | 0.074 | 0.132 | 0.190 | 0.248 | 0.306 | 0.364 | 0.421 | 0.479 | 0.537 | 0.595 | 0.653 | 0.711 |
| 0.03 | 0.024 | 0.089 | 0.153 | 0.218 | 0.282 | 0.347 | 0.411 | 0.476 | 0.540 | 0.605 | 0.669 | 0.734 | 0.798 |
| 0.04 | 0.031 | 0.102 | 0.173 | 0.244 | 0.315 | 0.386 | 0.457 | 0.528 | 0.598 | 0.669 | 0.740 | 0.811 | 0.882 |
| 0.05 | 0.038 | 0.115 | 0.192 | 0.269 | 0.346 | 0.423 | 0.500 | 0.577 | 0.654 | 0.731 | 0.808 | 0.885 | 0.962 |
| 0.06 | 0.045 | 0.128 | 0.211 | 0.293 | 0.376 | 0.459 | 0.541 | 0.624 | 0.707 | 0.789 | 0.872 | 0.955 | 1.038 |
| 0.07 | 0.051 | 0.140 | 0.228 | 0.316 | 0.404 | 0.493 | 0.581 | 0.669 | 0.757 | 0.846 | 0.934 | 1.022 | 1.110 |
| 0.08 | 0.058 | 0.151 | 0.245 | 0.338 | 0.432 | 0.525 | 0.619 | 0.712 | 0.806 | 0.899 | 0.993 | 1.086 | 1.180 |
| 0.09 | 0.063 | 0.162 | 0.261 | 0.359 | 0.458 | 0.556 | 0.655 | 0.754 | 0.852 | 0.951 | 1.049 | 1.148 | 1.246 |
| 0.10 | 0.069 | 0.172 | 0.276 | 0.379 | 0.483 | 0.586 | 0.690 | 0.793 | 0.897 | 1.000 | 1.103 | 1.207 | 1.310 |
| 0.20 | 0.114 | 0.257 | 0.400 | 0.543 | 0.686 | 0.829 | 0.971 | 1.114 | 1.257 | 1.400 | 1.543 | 1.686 | 1.829 |
| 0.30 | 0.146 | 0.317 | 0.488 | 0.659 | 0.829 | 1.000 | 1.171 | 1.341 | 1.512 | 1.683 | 1.854 | 2.024 | 2.195 |
| 0.40 | 0.170 | 0.362 | 0.553 | 0.745 | 0.936 | 1.128 | 1.319 | 1.511 | 1.702 | 1.894 | 2.085 | 2.277 | 2.468 |
| 0.50 | 0.189 | 0.396 | 0.604 | 0.811 | 1.019 | 1.226 | 1.434 | 1.642 | 1.849 | 2.057 | 2.264 | 2.472 | 2.679 |
| 0.60 | 0.203 | 0.424 | 0.644 | 0.864 | 1.085 | 1.305 | 1.525 | 1.746 | 1.966 | 2.186 | 2.407 | 2.627 | 2.847 |
| 0.70 | 0.215 | 0.446 | 0.677 | 0.908 | 1.138 | 1.369 | 1.600 | 1.831 | 2.062 | 2.292 | 2.523 | 2.754 | 2.985 |
| 0.80 | 0.225 | 0.465 | 0.701 | 0.944 | 1.183 | 1.423 | 1.662 | 1.901 | 2.141 | 2.380 | 2.620 | 2.859 | 3.099 |
| 0.90 | 0.234 | 0.481 | 0.727 | 0.974 | 1.221 | 1.468 | 1.714 | 1.961 | 2.208 | 2.455 | 2.701 | 2.948 | 3.195 |
| 1.00 | 0.241 | 0.494 | 0.747 | 1.000 | 1.253 | 1.506 | 1.759 | 2.012 | 2.265 | 2.518 | 2.771 | 3.024 | 3.277 |
| 1.10 | 0.247 | 0.506 | 0.764 | 1.022 | 1.281 | 1.539 | 1.798 | 2.056 | 2.315 | 2.573 | 2.831 | 3.090 | 3.348 |
| 1.20 | 0.253 | 0.516 | 0.779 | 1.042 | 1.305 | 1.568 | 1.832 | 2.095 | 2.358 | 2.621 | 2.884 | 3.147 | 3.411 |
| 1.30 | 0.257 | 0.525 | 0.792 | 1.059 | 1.327 | 1.594 | 1.861 | 2.129 | 2.396 | 2.663 | 2.931 | 3.198 | 3.465 |
| 1.40 | 0.262 | 0.533 | 0.804 | 1.075 | 1.346 | 1.617 | 1.888 | 2.159 | 2.430 | 2.701 | 2.972 | 3.243 | 3.514 |
| 1.50 | 0.265 | 0.540 | 0.814 | 1.088 | 1.363 | 1.637 | 1.912 | 2.186 | 2.460 | 2.735 | 3.009 | 3.283 | 3.558 |
| 1.60 | 0.269 | 0.546 | 0.824 | 1.101 | 1.378 | 1.655 | 1.933 | 2.210 | 2.487 | 2.765 | 3.042 | 3.319 | 3.597 |
| 1.70 | 0.272 | 0.552 | 0.832 | 1.112 | 1.392 | 1.672 | 1.952 | 2.232 | 2.512 | 2.792 | 3.072 | 3.352 | 3.632 |
| 1.80 | 0.275 | 0.557 | 0.840 | 1.122 | 1.405 | 1.687 | 1.969 | 2.252 | 2.534 | 2.817 | 3.099 | 3.382 | 3.664 |
| 1.90 | 0.271 | 0.562 | 0.847 | 1.131 | 1.416 | 1.701 | 1.985 | 2.270 | 2.555 | 2.839 | 3.124 | 3.409 | 3.693 |
| 2.00 | 0.280 | 0.566 | 0.853 | 1.140 | 1.427 | 1.713 | 2.000 | 2.287 | 2.573 | 2.860 | 3.147 | 3.434 | 3.720 |
| 2.10 | 0.282 | 0.570 | 0.859 | 1.148 | 1.436 | 1.725 | 2.013 | 2.302 | 2.591 | 2.879 | 3.168 | 3.456 | 3.745 |
| 2.20 | 0.284 | 0.574 | 0.865 | 1.555 | 1.445 | 1.735 | 2.026 | 2.316 | 2.606 | 2.897 | 3.187 | 3.477 | 3.768 |
| 2.30 | 0.286 | 0.578 | 0.870 | 1.161 | 1.453 | 1.745 | 2.037 | 2.329 | 2.621 | 2.913 | 3.205 | 3.497 | 3.789 |
| 2.40 | 0.287 | 0.581 | 0.874 | 1.168 | 1.461 | 1.754 | 2.048 | 2.341 | 2.635 | 2.928 | 3.222 | 3.515 | 3.808 |
| 2.50 | 0.289 | 0.584 | 0.879 | 1.173 | 1.468 | 1.763 | 2.058 | 2.353 | 2.647 | 2.942 | 3.237 | 3.532 | 3.827 |

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

U.S. DOT Second Accident Prediction from Initial Prediction and Accident History (4 years of accident data ($T$ = 4))

| Initial Prediction from Basic Model, a | Number of Accidents, N, in T Years | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 0.00 | 0.000 | 0.042 | 0.083 | 0.125 | 0.167 | 0.208 | 0.250 | 0.292 | 0.333 | 0.375 | 0.417 | 0.458 | 0.500 | 0.542 | 0.583 |
| 0.01 | 0.008 | 0.056 | 0.105 | 0.135 | 0.202 | 0.250 | 0.298 | 0.347 | 0.395 | 0.444 | 0.492 | 0.540 | 0.589 | 0.637 | 0.685 |
| 0.02 | 0.016 | 0.070 | 0.125 | 0.180 | 0.234 | 0.289 | 0.344 | 0.398 | 0.453 | 0.508 | 0.563 | 0.617 | 0.672 | 0.727 | 0.781 |
| 0.03 | 0.023 | 0.083 | 0.144 | 0.205 | 0.265 | 0.326 | 0.386 | 0.447 | 0.500 | 0.568 | 0.629 | 0.689 | 0.750 | 0.811 | 0.871 |
| 0.04 | 0.029 | 0.096 | 0.162 | 0.228 | 0.294 | 0.360 | 0.426 | 0.493 | 0.559 | 0.625 | 0.691 | 0.757 | 0.824 | 0.890 | 0.956 |
| 0.05 | 0.036 | 0.107 | 0.179 | 0.250 | 0.321 | 0.393 | 0.464 | 0.536 | 0.607 | 0.679 | 0.750 | 0.821 | 0.893 | 0.964 | 1.036 |
| 0.06 | 0.042 | 0.118 | 0.194 | 0.271 | 0.347 | 0.424 | 0.500 | 0.576 | 0.653 | 0.729 | 0.806 | 0.882 | 0.958 | 1.035 | 1.111 |
| 0.07 | 0.047 | 0.128 | 0.209 | 0.291 | 0.372 | 0.453 | 0.534 | 0.615 | 0.696 | 0.777 | 0.858 | 0.939 | 1.020 | 1.101 | 1.182 |
| 0.08 | 0.053 | 0.138 | 0.224 | 0.309 | 0.395 | 0.480 | 0.566 | 0.651 | 0.737 | 0.822 | 0.908 | 0.993 | 1.079 | 1.164 | 1.250 |
| 0.09 | 0.058 | 0.147 | 0.237 | 0.327 | 0.417 | 0.506 | 0.596 | 0.686 | 0.776 | 0.865 | 0.955 | 1.045 | 1.135 | 1.224 | 1.314 |
| 0.10 | 0.062 | 0.156 | 0.250 | 0.344 | 0.438 | 0.531 | 0.625 | 0.719 | 0.812 | 0.906 | 1.000 | 1.094 | 1.188 | 1.281 | 1.375 |
| 0.20 | 0.100 | 0.225 | 0.350 | 0.475 | 0.600 | 0.726 | 0.850 | 0.975 | 1.100 | 1.225 | 1.350 | 1.475 | 1.600 | 1.725 | 1.850 |
| 0.30 | 0.125 | 0.271 | 0.417 | 0.563 | 0.708 | 0.854 | 1.000 | 1.146 | 1.292 | 1.437 | 1.583 | 1.729 | 1.875 | 2.021 | 2.167 |
| 0.40 | 0.143 | 0.304 | 0.464 | 0.625 | 0.786 | 0.946 | 1.107 | 1.268 | 1.429 | 1.589 | 1.750 | 1.911 | 2.071 | 2.232 | 2.393 |
| 0.50 | 0.156 | 0.328 | 0.500 | 0.672 | 0.844 | 1.016 | 1.188 | 1.359 | 1.531 | 1.703 | 1.875 | 2.047 | 2.219 | 2.391 | 2.563 |
| 0.60 | 0.167 | 0.347 | 0.528 | 0.708 | 0.889 | 1.069 | 1.250 | 1.431 | 1.611 | 1.792 | 1.972 | 2.153 | 2.333 | 2.514 | 2.694 |
| 0.70 | 0.175 | 0.363 | 0.550 | 0.738 | 0.925 | 1.113 | 1.300 | 1.488 | 1.675 | 1.863 | 2.050 | 2.238 | 2.425 | 2.613 | 2.800 |
| 0.80 | 0.182 | 0.375 | 0.568 | 0.761 | 0.955 | 1.148 | 1.341 | 1.534 | 1.727 | 1.920 | 2.114 | 2.307 | 2.500 | 2.693 | 2.886 |
| 0.90 | 0.188 | 0.385 | 0.583 | 0.781 | 0.979 | 1.177 | 1.375 | 1.573 | 1.771 | 1.969 | 2.167 | 2.365 | 2.563 | 2.760 | 2.958 |
| 1.00 | 0.192 | 0.394 | 0.596 | 0.798 | 1.000 | 1.202 | 1.404 | 1.606 | 1.808 | 2.010 | 2.212 | 2.413 | 2.615 | 2.817 | 3.019 |
| 1.10 | 0.196 | 0.402 | 0.607 | 0.813 | 1.018 | 1.223 | 1.429 | 1.634 | 1.839 | 2.045 | 2.250 | 2.455 | 2.661 | 2.866 | 3.071 |
| 1.20 | 0.200 | 0.408 | 0.617 | 0.825 | 1.033 | 1.242 | 1.450 | 1.658 | 1.867 | 2.075 | 2.283 | 2.492 | 2.700 | 2.908 | 3.117 |
| 1.30 | 0.203 | 0.414 | 0.625 | 0.836 | 1.047 | 1.258 | 1.469 | 1.680 | 1.891 | 2.102 | 2.313 | 2.523 | 2.734 | 2.945 | 3.156 |
| 1.40 | 0.206 | 0.419 | 0.632 | 0.846 | 1.059 | 1.272 | 1.485 | 1.699 | 1.912 | 2.125 | 2.338 | 2.551 | 2.765 | 2.978 | 3.191 |
| 1.50 | 0.208 | 0.424 | 0.639 | 0.854 | 1.069 | 1.285 | 1.500 | 1.715 | 1.931 | 2.146 | 2.361 | 2.576 | 2.792 | 3.007 | 3.222 |
| 1.60 | 0.211 | 0.428 | 0.645 | 0.862 | 1.079 | 1.296 | 1.513 | 1.730 | 1.947 | 2.164 | 2.382 | 2.599 | 2.816 | 3.033 | 3.250 |
| 1.70 | 0.213 | 0.431 | 0.650 | 0.869 | 1.088 | 1.306 | 1.525 | 1.744 | 1.962 | 2.181 | 2.400 | 2.619 | 2.837 | 3.056 | 3.275 |
| 1.80 | 0.214 | 0.433 | 0.655 | 0.875 | 1.095 | 1.315 | 1.536 | 1.756 | 1.976 | 2.196 | 2.417 | 2.637 | 2.857 | 3.077 | 3.293 |
| 1.90 | 0.216 | 0.437 | 0.659 | 0.881 | 1.102 | 1.324 | 1.545 | 1.767 | 1.989 | 2.210 | 2.432 | 2.653 | 2.875 | 3.097 | 3.318 |
| 2.00 | 0.217 | 0.440 | 0.663 | 0.886 | 1.109 | 1.332 | 1.554 | 1.777 | 2.000 | 2.223 | 2.446 | 2.668 | 2.891 | 3114 | 3.337 |
| 2.10 | 0.219 | 0.443 | 0.667 | 0.891 | 1.115 | 1.339 | 1.562 | 1.786 | 2.010 | 2.234 | 2.458 | 2.682 | 2.906 | 3.130 | 3.354 |
| 2.20 | 0.220 | 0.445 | 0.670 | 0.895 | 1.120 | 1.345 | 1.570 | 1.795 | 2.020 | 2.245 | 2.470 | 2.695 | 2.920 | 3.145 | 3.370 |
| 2.30 | 0.221 | 0.447 | 0.673 | 0.899 | 1.125 | 1.351 | 1.577 | 1.803 | 2.029 | 2.255 | 2.481 | 2.707 | 2.933 | 3.159 | 3.385 |
| 2.40 | 0.222 | 0.449 | 0.676 | 0.903 | 1.130 | 1.356 | 1.583 | 1.810 | 2.037 | 2.264 | 2.491 | 2.718 | 2.944 | 3.171 | 3.398 |
| 2.50 | 0.223 | 0.451 | 0.679 | 0.906 | 1.134 | 1.362 | 1.589 | 1.817 | 2.045 | 2.272 | 2.500 | 2.728 | 2.955 | 3.183 | 3.411 |

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

U.S. DOT Second Accident Prediction from Initial Prediction and Accident History (5 years of accident data ($T$ = 5))

| Initial Prediction from Basic Model, a | Number of Accidents, N, in T Years | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 0.00 | 0.000 | 0.040 | 0.080 | 0.120 | 0.160 | 0.200 | 0.240 | 0.280 | 0.320 | 0.360 | 0.400 | 0.440 | 0.480 | | 0.560 |
| 0.01 | 0.008 | 0.054 | 0.100 | 0.146 | 0.192 | 0.238 | 0.285 | 0.331 | 0.377 | 0.423 | 0.469 | 0.515 | 0.562 | | 0.654 |
| 0.02 | 0.015 | 0.067 | 0.119 | 0.170 | 0.222 | 0.274 | 0.326 | 0.378 | 0.430 | 0.481 | 0.533 | 0.585 | 0.637 | | 0.741 |
| 0.03 | 0.021 | 0.079 | 0.136 | 0.193 | 0.250 | 0.307 | 0.364 | 0.421 | 0.479 | 0.536 | 0.593 | 0.650 | 0.707 | | 0.821 |
| 0.04 | 0.028 | 0.090 | 0.152 | 0.214 | 0.276 | 0.338 | 0.400 | 0.462 | 0.524 | 0.586 | 0.648 | 0.710 | 0.772 | | 0.897 |
| 0.05 | 0.033 | 0.100 | 0.167 | 0.233 | 0.300 | 0.367 | 0.433 | 0.500 | 0.567 | 0.633 | 0.700 | 0.767 | 0.833 | | 0.967 |
| 0.06 | 0.039 | 0.110 | 0.181 | 0.252 | 0.323 | 0.394 | 0.465 | 0.535 | 0.606 | 0.677 | 0.748 | 0.819 | 0.890 | | 1.032 |
| 0.07 | 0.044 | 0.119 | 0.194 | 0.269 | 0.344 | 0.419 | 0.494 | 0.569 | 0.644 | 0.719 | 0.794 | 0.869 | 0.944 | | 1.094 |
| 0.08 | 0.048 | 0.127 | 0.206 | 0.285 | 0.364 | 0.442 | 0.321 | 0.600 | 0.679 | 0.758 | 0.836 | 0.915 | 0.994 | | 1.152 |
| 0.09 | 0.053 | 0.135 | 0.218 | 0.300 | 0.382 | 0.465 | 0.517 | 0.629 | 0.712 | 0.794 | 0.876 | 0.959 | 1.041 | | 1.206 |
| 0.10 | 0.057 | 0.143 | 0.229 | 0.314 | 0.400 | 0.486 | 0.571 | 0.657 | 0.743 | 0.829 | 0.914 | 1.000 | 1.086 | | 1.257 |
| 0.20 | 0.089 | 0.200 | 0.311 | 0.422 | 0.533 | 0.644 | 0.756 | 0.867 | 0.978 | 1.089 | 1.200 | 1.311 | 1.422 | | 1.644 |
| 0.30 | 0.109 | 0.236 | 0.364 | 0.491 | 0.618 | 0.745 | 0.873 | 1.000 | 1.127 | 1.255 | 1.382 | 1.509 | 1.636 | | 1.891 |
| 0.40 | 0.123 | 0.262 | 0.400 | 0.538 | 0.677 | 0.815 | 0.954 | 1.092 | 1.231 | 1.369 | 1.508 | 1.646 | 1.785 | | 2.062 |
| 0.50 | 0.133 | 0.280 | 0.427 | 0.573 | 0.720 | 0.867 | 1.013 | 1.160 | 1.307 | 1.453 | 1.600 | 1.747 | 1.893 | | 2.187 |
| 0.60 | 0.141 | 0.294 | 0.447 | 0.600 | 0.753 | 0.906 | 1.059 | 1.212 | 1.365 | 1.518 | 1.671 | 1.824 | 1.976 | | 2.282 |
| 0.70 | 0.147 | 0.305 | 0.463 | 0.621 | 0.779 | 0.937 | 1.095 | 1.253 | 1.411 | 1.568 | 1.726 | 1.884 | 2.042 | | 2.358 |
| 0.80 | 0.152 | 0.314 | 0.476 | 0.638 | 0.800 | 0.962 | 1.124 | 1.286 | 1.448 | 1.610 | 1.771 | 1.933 | 2.095 | | 2.419 |
| 0.90 | 0.157 | 0.322 | 0.487 | 0.652 | 0.817 | 0.983 | 1.148 | 1.313 | 1.478 | 1.643 | 1.809 | 1.974 | 2.139 | | 2.470 |
| 1.00 | 0.160 | 0.328 | 0.496 | 0.664 | 0.832 | 1.000 | 1.168 | 1.336 | 1.504 | 1.672 | 1.840 | 2.008 | 2.176 | | 2.512 |
| 1.10 | 0.163 | 0.333 | 0.504 | 0.674 | 0.844 | 1.015 | 1.185 | 1.356 | 1.526 | 1.696 | 1.867 | 2.037 | 2.207 | | 2.548 |
| 1.20 | 0.166 | 0.338 | 0.510 | 0.683 | 0.855 | 1.028 | 1.200 | 1.372 | 1.545 | 1.717 | 1.890 | 2.062 | 2.234 | | 2.579 |
| 1.30 | 0.168 | 0.342 | 0.516 | 0.690 | 0.865 | 1.039 | 1.213 | 1.387 | 1.561 | 1.735 | 1.910 | 2.084 | 2.258 | | 2.606 |
| 1.40 | 0.170 | 0.345 | 0.521 | 0.697 | 0.873 | 1.048 | 1.224 | 1.400 | 1.576 | 1.752 | 1.927 | 2.103 | 2.279 | | 2.630 |
| 1.50 | 0.171 | 0.349 | 0. 526 | 0.703 | 0.880 | 1.057 | 1.234 | 1.411 | 1.589 | 1.766 | 1.943 | 2.120 | 2.297 | | 2.651 |
| 1.60 | 0.173 | 0.351 | 0.530 | 0.708 | 0.886 | 1.065 | 1.243 | 1.422 | 1.600 | 1.779 | 1.957 | 2.135 | 2.314 | | 2.670 |
| 1.70 | 0.174 | 0.354 | 0.533 | 0.713 | 0.892 | 1.072 | 1. 251 | 1.431 | 1.610 | 1.790 | 1.969 | 2.149 | 2.328 | | 2.687 |
| 1.80 | 0.176 | 0.356 | 0.537 | 0.717 | 0.898 | 1.078 | 1.259 | 1.439 | 1.620 | 1.800 | 1.980 | 2.161 | 2.341 | | 2.702 |
| 1.90 | 0.177 | 0.358 | 0.540 | 0.721 | 0.902 | 1.084 | 1.265 | 1.447 | 1.628 | 1.809 | 1.991 | 2.172 | 2.353 | | 2.716 |
| 2.00 | 0.178 | 0.360 | 0.542 | 0.724 | 0.907 | 1.089 | 1.271 | 1.453 | 1.636 | 1.818 | 2.000 | 2.182 | 2.364 | | 2.729 |
| 2.10 | 0.179 | 0.362 | 0.545 | 0.728 | 0.911 | 1.094 | 1.277 | 1.460 | 1.643 | 1.826 | 2.009 | 2.191 | 2.374 | | 2.740 |
| 2.20 | 0.180 | 0.363 | 0.547 | 0.731 | 0.914 | 1.098 | 1.282 | 1.465 | 1.649 | 1.833 | 2.016 | 2.200 | 2.384 | | 2.751 |
| 2.30 | 0.180 | 0.365 | 0.549 | 0.733 | 0.918 | 1.102 | 1.286 | 1.471 | 1.655 | 1.839 | 2.024 | 2.208 | 2.392 | | 2.761 |
| 2.40 | 0.181 | 0.366 | 0.551 | 0.736 | 0.921 | 1.106 | 1.291 | 1.475 | 1.660 | 1.845 | 2.030 | 2.215 | 2.400 | | 2.770 |
| 2.50 | 0.182 | 0.367 | 0.553 | 0.738 | 0.924 | 1.109 | 1.295 | 1.480 | 1.665 | 1.851 | 2.036 | 2.222 | 2.407 | | 2.778 |

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

# Appendix C. Resource Allocation Procedure Field Verification Worksheet

This worksheet provides a format and instructions for use in field evaluation of crossing to determine if initial recommendations for warning device installations from the Resource Allocation Procedure should be revised. Steps 1 through 5, described below, should be followed in making the determination. In Steps 1 and 3, the initial information (left column) is obtained from office inventory data prior to the field inspection. In Step 4, the decision criteria values are obtained from the Resource Allocation Model printout.

**STEP I: Validate Data used in Calculating Predicted Accidents:**

| Crossing Characteristic | Initial Information | Revised Information |
|---|---|---|
| Crossing Number | | |
| Location | | |
| Existing Warning Device | | |
| Total Trains per Day | | |
| Annual Average Daily Highway Traffic (c) | | |
| Day thru Trains (d) | | |
| Number of Main Tracks (mt) | | |
| Is Highway Paved? (hp) | | |
| Maximum Timetable Speed, mph (ms) | | |
| Highway Type (ht) | | |
| Number of Highway Lanes (hl) | | |
| Number of Years of Accident History (T) | | |
| Number of Accidents in T Years (N) | | |
| Predicted Accident Rate (A) | | |

**STEP 2: Calculate Revised Accident Prediction from DOT Formula if any Data in Step 1 has been Revised.**

Revised Predicted Accidents (A) = ______________________________

**STEP 3: Validate Cost and Effectiveness Data for Recommended Warning Device**

Assumed Effectiveness of Recommended Warning Device (E)__________ Assumed

Cost of Recommended Warning Device (C)
Recommended Warning Device Installation

**STEP 4: Determine if Recommended Warning Device should be Revised if A, E, or C has Changed.**

1. Obtain Decision Criteria Values from Resource Allocation Model. Output:

$DC_1$ = ____ $DC_2$ = ____ $DC_3$ = ____ $DC_4$ = ____

2. Calculate: $R = \frac{\text{Revised A}}{\text{Previous A}} \lozenge \frac{\text{Revised B}}{\text{Previous B}} \lozenge \frac{\text{Revised C}}{\text{Previous C}}$

3. Compare R with Appropriate Decision Criteria as shown Below:

| Existing Passive Crossing (Classes 1, 2, 3, 4) Single Track | | Existing Passive Crossing (Classes 1, 2, 3, 4) Multiple Tracks | | Existing Flashing Light. Crossing (Classes 5, 6, 7) | |
|---|---|---|---|---|---|
| Comparison | Decision | Comparison | Decision | Comparison | Decision |
| $DC_2 < R$ | Gates | $DC3 < R$ | Gates | $DC4 < R$ | Gates |
| $DC_3 < R < DC_2$ | Flashing Lights | $R < DC_3$ | No Installation | $R < DC_4$ | No Installation |
| $R < DC_1$ | No Installation | | | | |

4. Revised Recommended Warning Device Installation*______________________________

**STEP 5: Determine other Characteristics that may Influence Warning Device Installation Decisions**

Multiple tracks where one train/locomotive may obscure vision of another train?
Percent trucks
Passenger train operations over crossing
High speed trains with limited sight distance**
Combination of high speeds & moderately high volumes of highway & railroad traffic **

Either, or any combination of, high vehicular traffic volumes, high numbers of train movements, substantial numbers of school buses or trucks carrying hazardous materials, unusually restricted sight. distance or continuing accident occurrences**

*The cost and effectiveness values for the revised warning device are assumed to change by an amount proportional to the change in these values for the initial recommended warning device as determined in Step 3.

**Gates with flashing lights are the only recommended warning device per 23CFR 646.214(b)(3)(i).

*Source:* Railroad-Highway Grade Crossing Handbook, Second Edition. *Washington, DC: U.S. Department of Transportation, Federal Highway Administration, 1986.*

*Source: U.S. DOT (2007). Rail-Highway Grade Crossing Handbook*

## Appendix D. FRA Crossing Inventory Database Field Description

FRA Crossing Inventory Database Field Description (Crossing Header)

| Field Name | Field Description | Potential Values |
|---|---|---|
| AgencyId | The reporting agency type ID from which the submission originated | 1 = Railroad; 2 = State; 3 = Transit; 4 = FRA Internal |
| CountyCode | The code assigned to each U.S. county | |
| CrossingID | Primary key, also the crossing inventory number | |
| PublishedReportBaseId | Foreign key to the CI_ReportBase table | |
| StateCode | The code assigned to each U.S. state | |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Highway Traffic Control Device)

| Field Name | Field Description | Potential Values |
|---|---|---|
| AdvW10_1 | Count of advance warning signs W10-1 flag | |
| AdvW10_11 | Count of advance warning signs W10-11 flag | |
| AdvW10_12 | Count of advance warning signs W10-12 flag | |
| AdvW10_2 | Count of advance warning signs W10-2 flag | |
| AdvW10_3 | Count of advance warning signs W10-3 flag | |
| AdvW10_4 | Count of advance warning signs W10-4 flag | |
| AdvWarn | Advance warning signs | 0 = none; 1 = W10-1; 2 = W10-2; 3 = W10-3; 4 = W10-4; 11 = W10-11; 12 = W10-12 |
| AwdIDate | Installation date of current active warning devices | |
| AwhornChk | Wayside horn | 1 = yes; 2 = no |

FRA Crossing Inventory Database Field Description (Highway Traffic Control Device) (cont'd)

| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| AwhornlDate | Wayside horn installed on (date) | |
| Bells | Number of bells | |
| Bkl_FlashPost | Mast mounted flashing lights: back lights included | 1 = yes; 2 = no |
| CFlashType | Type of cantilevered (or bridged) flashing light structures | 0 = none; 1 = incandescent; 2 = LED |
| Channel | Channelization devices/medians | 1 = all approaches; 2 = one approach; 3 = median – all approaches; 4 = median – one approach; 5 = none |
| EnsSign | ENS sign displayed | 1 = yes; 2 = no |
| Exempt | EXEMPT signs | 1 = yes; 2 = no |
| FlashNov | Count of cantilevered (or bridged) flashing light structures not over traffic lane | |
| FlashOth | Other flashing lights or warning devices: count | |
| FlashOthDes | Other flashing lights or warning devices: specify type | |
| FlashOv | Count of cantilevered (or bridged) flashing light structures over traffic lane | |
| FlashPai | Total count of flashing light pairs | |
| FlashPost | Mast mounted flashing lights (count) | |
| FlashPostType | Mast mounted flashing lights type | 0 = none; 1 = incandescent; 2 = LED |
| GateConf | Gate configuration | 1 = 2 quad; 2 = 3 quad; 3 = 4 quad |
| GateConfType | Type of gate configuration | 4 = full (barrier) resistance; 6 = median gates |
| GatePed | Count of pedestrian gate arms | |
| Gates | Count of roadway gate arms | |
| HwtrfPsig | Highway traffic pre-signals | 1 = yes; 2 = no |
| HwtrfPsiglndis | Stop line distance (count) | |
| HwtrfPsigsdis | Storage distance (count) | |
| HwynrSig | Does nearby highway intersection have traffic signals? | 1 = yes; 2 = no |
| HwyTrafSignl | Highway traffic signals controlling crossing | 1 = yes; 2 = no |

FRA Crossing Inventory Database Field Description (Highway Traffic Control Device) (cont'd)

| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| Intrprmp | Highway traffic signal interconnection | 1 = not interconnected; 2 = for traffic signals; 3 = for warning signs |
| Led | LED enhanced signs | |
| Low_Grnd | Low ground clearance signs | 1 = yes; 2 = no |
| Low_GrndSigns | Number of low ground clearance signs | |
| MonitorDev | Highway monitoring devices | 0 = none; 1 = yes-photo/video recording; 2 = yes-vehicle presence detection |
| NoSigns | Are there signs or signals? | 1 = yes; 2 = no |
| OthDes1 | Specify type of other MUTCD signs | |
| OthDes2 | Specify type of other MUTCD signs 2 | |
| OthDes3 | Specify type of other MUTCD signs 3 | |
| OthSgn | Other MUTCD signs | 1 = yes; 2 = no |
| OthSgn1 | Number of other MUTCD signs | |
| OthSgn2 | Number of other MUTCD signs 2 | |
| OthSgn3 | Number of other MUTCD signs 3 | |
| PaveMrkIDs | Pavement markings | 0 = none; 1 = stop lines; 2 = RR crossing symbols; 3 = dynamic envelope |
| PrempType | Highway traffic signal preemption | 1 = simultaneous; 2 = advance |
| PrvxSign | Private crossing signs | 1 = yes; 2 = no |
| ReportBaseId | Foreign key to the CI_ReportBase table | |
| Sdl_FlashPost | Mast mounted flashing lights: side lights included | 1 = yes; 2 = no |
| SpecPro | Non-train active warning | 0 = none; 1 = flagging/flagman; 2 = manually operated signals; 3 = watchman; 4 = floodlighting |
| StopStd | Number of STOP signs | |
| XBuck | Number of crossbuck assemblies | |
| YieldStd | Number of YIELD signs | |
| WdCode | Warning device code | |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |

FRA Crossing Inventory Database Field Description (Highway Traffic Control Device) (cont'd)

| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Location and Classification)

| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| BlockNumb | Block number | |
| CityCD | The code assigned to each U.S. city | |
| CntyCD | The code assigned to each U.S. county | |
| DevelTypID | Type of land use | 11 = open space; 12 = residential; 13 = commercial; 14 = industrial; 15 = institutional; 16 = farm; 17 = recreational; 18 = RR yard |
| Highway | Highway type & number | |
| HscoRrid | HSR corridor ID | |
| HwyCont | State contact (telephone number) | |
| Latitude | Latitude | |
| LLsource | Lat/long source | 1 = actual; 2 = estimated |
| Longitude | Longitude | |
| MultFrmsFiled | Do other railroads operate a separate track at crossing? | 1 = yes; 2 = no |
| Nearest | In/near | 0 = in; 1 = near |
| OpenPub | Public access (if private crossing) | 1 = yes; 2 = no |
| PolCont | Emergency notification telephone number | |
| PosXing | Crossing position | 1 = at grade; 2 = RR under; 3 = RR over |
| Railroad | The code associated with the primary operating railroad | |
| ReportBaseId | Foreign key to the CI_ReportBase table | |
| RrCont | Railroad contact (telephone number) | |
| RrID | Line segment | |
| RrMain | The code associated with the parent railroad | |
| RrNarr | Railroad narrative | |
| RrNarr1 | Railroad narrative A | |

FRA Crossing Inventory Database Field Description (Location and Classification) (cont'd)

| Field Name | Field Description | Potential Values |
|---|---|---|
| RrNarr2 | Railroad narrative B | |
| RrNarr3 | Railroad narrative C | |
| RrNarr4 | Railroad narrative D | |
| SameInd | Do other railroads operate over your track at crossing? | 1 = yes; 2 = no |
| SameRr1 | The code associated with the railroad selected in the 1st drop-down list for field I.8 | |
| SameRr2 | The code associated with the railroad selected in the 2nd drop-down list for field I.8 | |
| SameRr3 | The code associated with the railroad selected in the 3rd drop-down list for field I.8 | |
| SameRr4 | The code associated with the railroad selected in the 4th drop-down list for field I.8 | |
| SepInd | Do other railroads operate a separate track at crossing? | 1 = yes; 2 = no |
| SepRr1 | The code associated with the railroad selected in the 1st drop-down list for field I.7 | |
| SepRr2 | The code associated with the railroad selected in the 2nd drop-down list for field I.7 | |
| SepRr3 | The code associated with the railroad selected in the 3rd drop-down list for field I.7 | |
| SepRr4 | The code associated with the railroad selected in the 4th drop-down list for field I.7 | |
| SfxHscoRrid | HSR corridor ID suffix | |
| StateCD | The code assigned to each U.S. states | |
| StNarr | State narrative | |
| StNarr1 | State narrative A | |
| StNarr2 | State narrative B | |
| StNarr3 | State narrative C | |
| StNarr4 | State narrative D | |
| Street | Street or road name | |
| Ttstn | Timetable station | |

FRA Crossing Inventory Database Field Description (Location and Classification) (cont'd)

| Field Name | Field Description | Potential Values |
|---|---|---|
| TtstnNam | Nearest RR timetable station | |
| TypeTrnSrvcIDs | Type of train service | 11 = freight; 12 = intercity passenger; 13 = commuter; 14 = transit; 15 = shared use transit; 16 = tourist/other |
| TypeXing | Crossing type | 2 = private; 3 = public |
| Whistban | Quiet zone | 0 = no; 1 = 24 hour; 2 = partial; 3 = Chicago excused |
| WhistDate | Date established (quiet zone) | |
| XingAdj | Is there an adjacent crossing with a separate number? | 1 = yes; 2 = no |
| XingOwnr | Crossing owner (RR ID) | |
| XngAdjNo | If yes, provide crossing number | |
| XPurpose | Crossing purpose | 1 = highway; 2 = pathway, pedestrian; 3 = station, pedestrian |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Operating Railroad)

| Field Name | Field Description | Potential Values |
|---|---|---|
| Branch | Branch or line name | |
| DayThru | Total daylight thru trains | |
| EMonitorDvce | Event recorder | 1 = yes; 2 = no |
| HealthMonitor | Remote health monitoring | 1 = yes; 2 = no |
| IndustryTrk | Number of industry tracks | |
| Lt1Mov | Check if less than one movement per day | 1 = less than one movement per day; 2 = one or more movements per day |
| Lt1PassMov | Average passenger train count per day: less than one per day | 1 = yes; 2 = no |
| MainTrk | Number of main tracks | |
| MaxSpd | Typical speed range over crossing - max typical speed range over crossing (maximum) | |

FRA Crossing Inventory Database Field Description (Operating Railroad) (cont'd)

| Field Name | Field Description | Potential Values |
|---|---|---|
| MaxTtSpd | Maximum timetable speed | |
| MilePost | RR milepost number | |
| MinSpd | Typical speed range over crossing (minimum) | |
| NghtThru | Total night time thru trains | |
| OperatingRailroadCode | Primary key, the code associated with the primary operating railroad | |
| OperatingRailroadType | Primary key, the type distinguishing whether the operating Railroad is the primary, operate a separate track, or operate over a track | Primary = primary operating railroad; Samerr = operate over your track at crossing; Seprr = operate a separate track at crossing |
| PassCnt | Average passenger train count per day: number per day | |
| PrfxMilePost | RR milepost prefix | |
| ReportBaseId | Foreign key to the CI_ReportBase table | |
| RrDiv | Railroad division or region | |
| RrSubDiv | Railroad subdivision or district | |
| SfxMilePost | RR milepost suffix | |
| Sgnleqp | Is track signaled? | 1 = yes; 2 = no |
| SidingTrk | Number of siding tracks | |
| SpselIDs | Train detection | 0 = none; 11 = constant warning time; 12 = motion detection; 14 = other; 16 = AFO; 17 = PTC; 18 = DC |
| TotalLtr | Total transit trains | |
| TotalSwt | Total switching trains | |
| TransitTrk | Number of transit tracks | |
| WeekTrnMov | How many trains per week? | |
| YardTrk | Number of yard tracks | |
| YearTrnMov | Year of train count data | |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Physical Characteristics)

| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| ComPower | Is commercial power available? | 1 = yes; 2 = no |
| Downst | Does track run down a street? | 1 = yes; 2 = no |
| HwynDist | Approximate intersecting roadway distance (feet) | |
| HwyNear | Intersecting roadway within 500 feet? | 1 = yes; 2 = no |
| HwyPved | Is roadway/pathway paved? | 1 = yes; 2 = no |
| Illumina | Is crossing illuminated? | 1 = yes; 2 = no |
| ReportBaseId | Foreign key to the CI_ReportBase table | |
| TraficLn | Number of traffic lanes crossing railroad | |
| TraflnType | Traffic lane type | 1 = one-way traffic; 2 = two-way traffic; 3 = divided traffic |
| XAngle | Smallest crossing angle | 1 = 0° – 29°; 2 = 30° – 59°; 3 = 60° – 90° |
| XSurfaceIDs | Crossing surface | 11 = timber; 12 = asphalt; 13 = asphalt and timber; 14 = concrete; 15 = concrete and rubber; 16 = rubber; 17 = metal; 18 = unconsolidated; 19 = composite; 20 = other (specify) |
| XSurfDate | Crossing surface installation date | |
| XSurfLength | Crossing surface length | |
| XSurfWidth | Crossing surface width | |
| XSurOthr | Other crossing surface (description) | |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Public Highway)

| Field Name | Field Description | Potential Values |
|---|---|---|
| Aadt | Annual average daily traffic (AADT) count | |
| AadtYear | Annual average daily traffic (AADT) year | |
| EmrgncySrvc | Emergency services route | 1 = yes; 2 = no |
| HwyClassCD | Functional classification of road at crossing: rural or urban | 0 = rural; 1 = urban |
| HwyClassrdtpID | Functional classification of road at crossing: type of highway/roadway (ID) | 11 = interstate; 12 = other freeways and expressways; 13 = other principal arterial; 16 = minor arterial; 17 = major collector; 18 = minor collector; 19 = local |
| HwySpeed | Highway speed limit | |
| HwySpeedps | Highway speed limit: posted or statutory | 1 = posted; 2 = statutory |
| HwySys | Highway system | 1 = interstate highway system; 2 = other national highway system (NHS); 3 = federal aid, not NHS; 8 = non-federal aid |
| LrsMilePost | LRS milepost | |
| LrsRouteid | Linear referencing system (LRS route ID) | |
| PctTruk | Estimated percent trucks | |
| ReportBaseId | Foreign key to the CI_ReportBase table | |
| SchlBsCnt | Average number school bus count per day | |
| SchlBusChk | Regularly used by school buses? | 1 = yes; 2 = no |
| StHwy1 | Is crossing on state highway system? | 1 = yes; 2 = no |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Report Base)

| Field Name | Field Description | Potential Values |
|---|---|---|
| CrossingID | DOT crossing inventory number | |
| CrossingIdSuffix | Crossing ID suffix | |
| MultipleFormsFiled | Multiple forms filed (Boolean) | 1 = yes; 2 = no |
| ParentReportBaseId | Unique ID for all crossings in this table | |
| PostmarkDate | Submission date | |
| ReasonID | Reason for update | 14 = change in data; 15 = new crossing; 16 = closed; 19 = re-open; 20 = date change only; 21 = change in primary operating RR; 22 = admin. correction; 23 = quiet zone update; 24 = no train traffic |
| ReportBaseId | Foreign key to the CI_ReportBase table | |
| ReportingAgencyID | Reporting agency ID | |
| ReportingAgencyTypeID | Reporting agency type ID | 1 = Railroad; 2 = State; 3 = Transit; 4 = FRA Internal |
| ReportStatus | The status of the submission | Bulk Upload Error; Cancelled; Expired; Pending; Published |
| ReportType | Major or minor railroad (used for MFF) | Major = primary operating railroad submitting the full crossing inventory record; Minor = A railroad agency submitting only the railroad and train count data |
| RevisionDate | Revision date | |
| ValidationErrors | Stores all the error code(s) that failed validations | |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Errors)

| Field Name | Field Description | Potential Values |
|---|---|---|
| Code | Primary key, also the unique code assigned to each error | |
| Description | The description of each error message | |
| Section | Stores the section name of the crossing inventory form | Header<br>Part I: Location and Classification Information; Part II: Railroad Information; Part III: Highway or Pathway Traffic Control Device Information; Part IV: Physical Characteristics; Part V: Public Highway Information |
| ShowForMinorReports | Identify whether the error message should be returned for users submitting the short form (railroad data only) | 0 = true; 1 = false |
| ShowForRailroads | Identify whether the error message should be returned for railroad users | 0 = true; 1 = false |
| ShowForStates | Identify whether the error message should be returned for state users | 0 = true; 1 = false |
| SortOrder | Stores the sort order number | |
| Created | Date for which the original error was created | |
| CreatedBy | Username of the user who originally created the records | |
| LastUpdated | Date for which the existing error was modified | |
| LastUpdatedBy | Username of the user who last modified the record | |

FRA Crossing Inventory Database Field Description (Lookups)

| Field Name | Field Description | Potential Values |
|---|---|---|
| Code | The unique code associated with each lookup type | |
| EndDate | The date in which the item is no longer active | |
| ID | Primary key | |
| LookupText | Description of the lookup value | |
| LookupType | The type of lookup | |
| LookupValue | The value the lookup is stored as in the database (compared to what is displayed on the front-end UI) | |

FRA Crossing Inventory Database Field Description (Lookups) (cont'd)

| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| StartDate | The date in which the item was made active | |
| Status | Active/Inactive | 0 = inactive; 1 = active |
| Created | Date for which the original submission was created | |
| CreatedBy | Username of the user who originally submitted the records | |
| LastUpdated | Date for which the existing submission was modified | |
| LastUpdatedBy | Username of the user who last submitted the updated records | |

FRA Crossing Inventory Database Field Description (Reason)

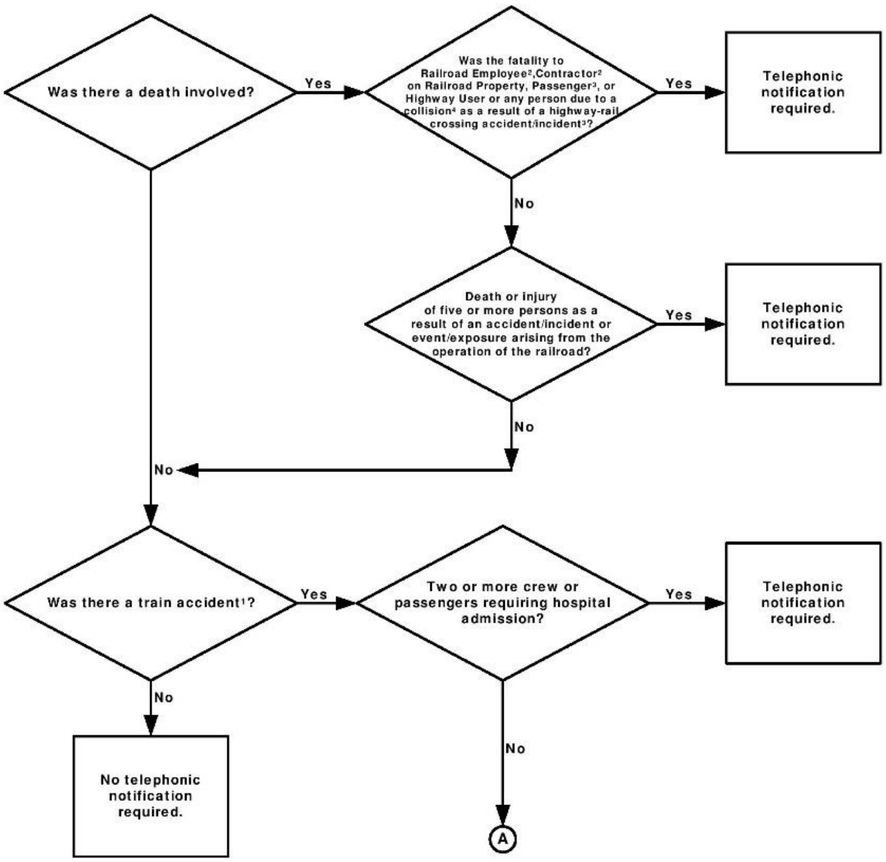
| **Field Name** | **Field Description** | **Potential Values** |
|---|---|---|
| ReasonID | Primary key for this table | |
| Code | Unique code assigned to each item in this table | |
| Descr | The description of each reason for update | |
| StartDate | The date in which the item was made active | |
| EndDate | The date in which the item was made inactive | |
| SortOrder | Username of the user who originally submitted the records | |
| ShowForMinorReports | Identify whether the error message should be returned for users submitting the short form (railroad data only) | 0 = true; 1 = false |
| ShowForRailroads | Identify whether the error message should be returned for railroad users | 0 = true; 1 = false |
| ShowForStates | Identify whether the error message should be returned for state users | 0 = true; 1 = false |

*Source: FRA (2016). FRA Data Dictionary for External Use Grade Crossing Inventory System (GCIS) v2.5.0.0*

## Appendix E. FRA Immediate Telephonic Notification Chart

### Is Telephone Notification Required?

The flowchart below had been designed to allow railroad officials a quick reference for determining if telephonic reporting is required after a train accident, train incident, non train incident or other event. It does not replace the actual rule text. Users of the flow chart are encouraged to review the rule text in Appendix L, § 225.9 Telephonic reports of certain accidents/incidents and other events.

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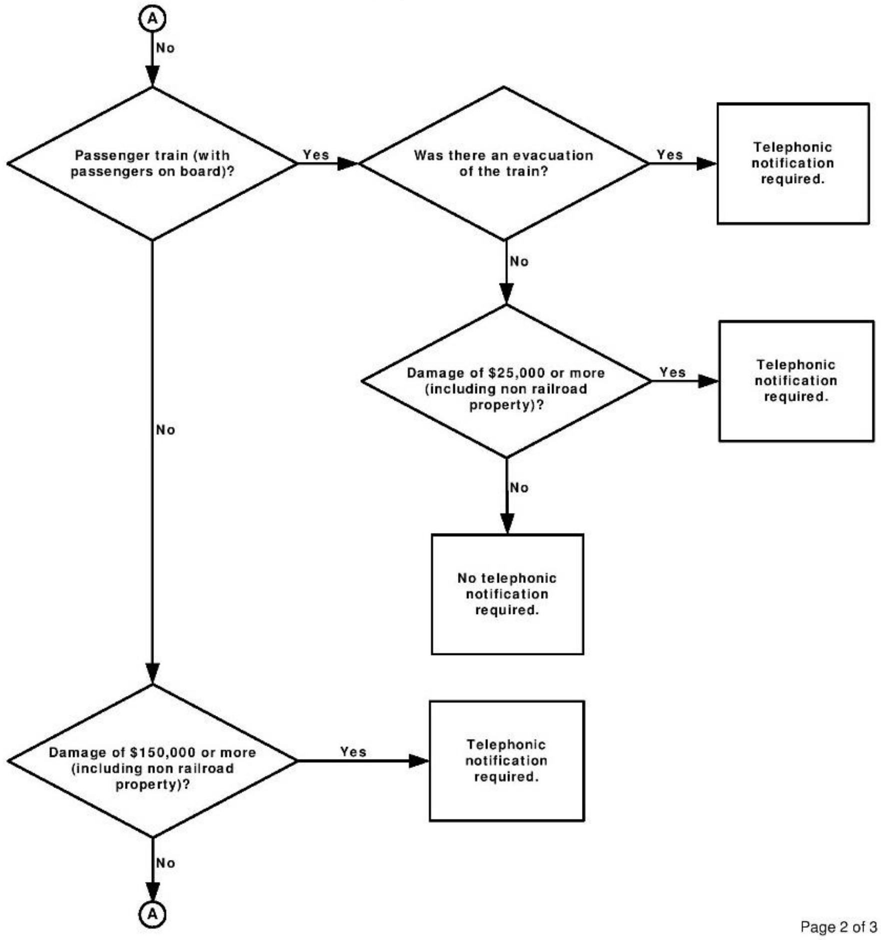
## Is Telephone Notification Required?

(Continued from Previous Page)

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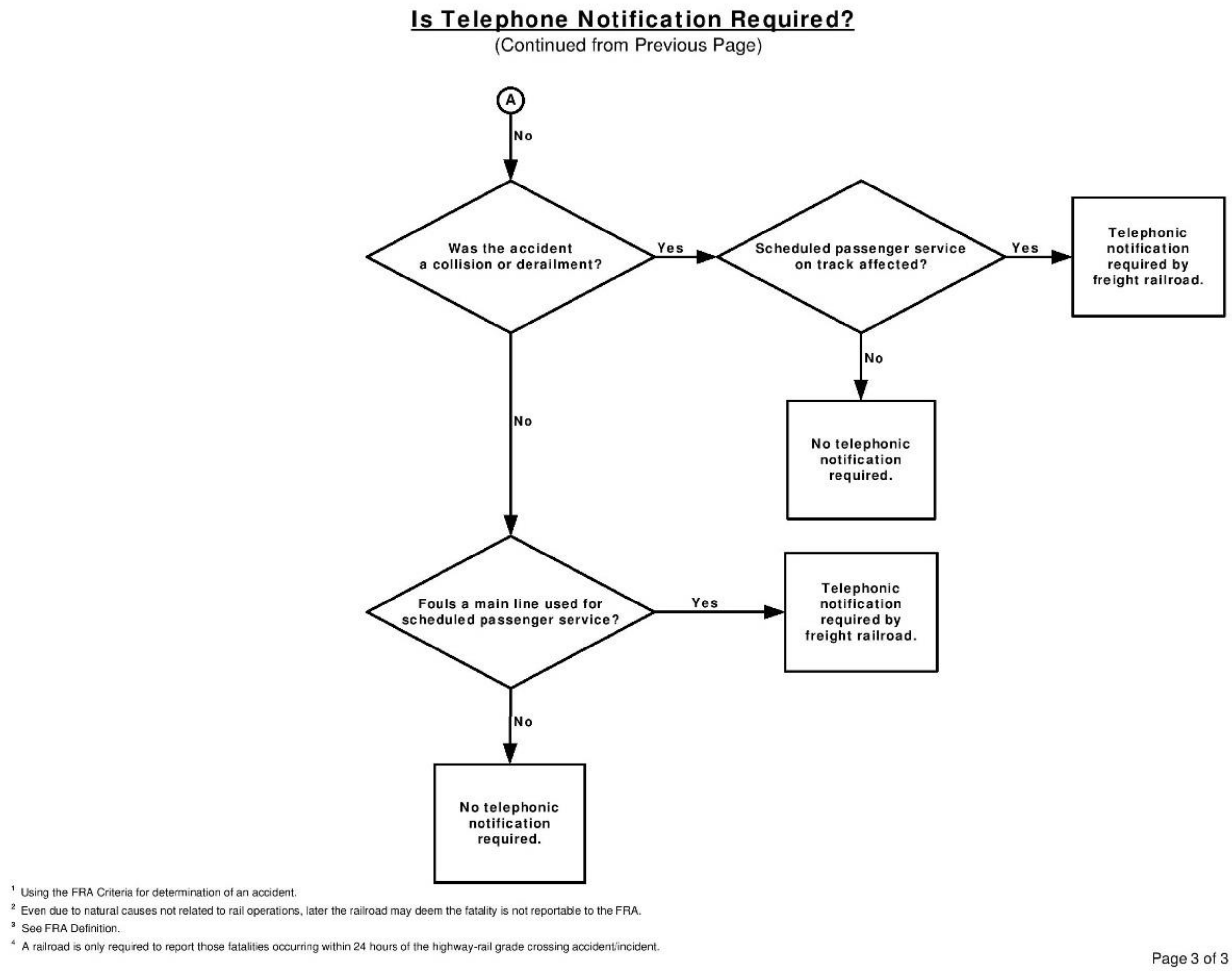


*Source: FRA (2011a). FRA Guide for Preparing Accident/Incident Reports – Appendix M.*

## Appendix F. FRA Highway-Rail Grade Crossing Accident Database Field Description

FRA Highway-Rail Grade Crossing Accident Database Field Description

| Field Name | Field Description | Potential Values | Notes/Conversion |
|---|---|---|---|
| amtrak | Amtrak involvement | | |
| iyr | Year of incident | | |
| imo | Month of incident | | |
| railroad | Railroad code (reporting RR) | | |
| incdtno | Railroad assigned number | | |
| iyr2 | Year of incident | | |
| imo2 | Month of incident | | |
| rr2 | Railroad code (other RR involved) | | |
| incdtno2 | Other railroad assigned number | | |
| iyr3 | Year of incident | | |
| imo3 | Month of incident | | |
| rr3 | Railroad code (RR responsible for track maintenance) | | |
| incdtno3 | RR assigned number | | |
| dummy1 | Blank data expansion field | | |
| casinjrr | # of injured for reporting railroad calculated from F6180.55a's submitted | | |
| gxid | Grade crossing id number | | |
| year | Year of incident | | |
| month | Month of incident | | |
| day | Day of incident | | |
| timehr | Hour of incident | | |
| timemin | Minute of incident | | |
| ampm | Am or pm | | |
| station | Nearest timetable station | | |
| county | County name (see FIPS codes for associated code) | | |

FRA Highway-Rail Grade Crossing Accident Database Field Description (cont'd)

| Field Name | Field Description | Potential Values | Notes/Conversion |
|---|---|---|---|
| state | FIPS state code | | |
| region | FRA designated region | | |
| dummy2 | Blank data expansion field | | |
| city | City name (see FIPS codes for associated code) | | |
| highway | Highway name | | |
| vehspd | Vehicle estimated speed | Blank = unknown | |
| typveh | Highway user | A = auto; B = truck; C = truck-trailer; D = pick-up truck; E = van; F = bus; G = school bus; H = motorcycle; J = other motor vehicle; K = pedestrian; M = other | |
| vehdir | Highway user direction | 1 = north; 2 = south; 3 = east; 4 = west | |
| position | Position of highway user | 1 = stalled or stuck on crossing*; 2 = stopped on crossing; 3 = moving over crossing; 4 = trapped on crossing by traffic*; 5 = blocked on crossing by gates** | *As of June 1, 2011 - name changes<br>**As of June 1, 2011 – new selection – not available before June 1, 2011 |
| rrequip | RR equipment involved | 1 = train (units pulling); 2 = train (units pushing); 3 = train (standing); 4 = car(s) (moving); 5 = car(s) (standing); 6 = light loco(s) (moving); 7 = light loco(s) (standing); 8 = other A = train pulling (RCL); B = train pushing (RCL); C = train standing (RCL); D = EMU Locomotive(s)*; E = DMU Locomotive(s)* | *As of June 1, 2011 – new selection – not available before June 1, 2011 |
| rrcar | Position of car unit in train | | |
| typacc | Circumstance of accident | 1 = rail equipment struck highway user; 2 = rail equipment struck by highway user | |

FRA Highway-Rail Grade Crossing Accident Database Field Description (cont'd)

| Field Name | Field Description | Potential Values | Notes/Conversion |
|---|---|---|---|
| hazard | Entity transporting hazmat | 1 = highway user; 2 = rail equipment; 3 = both; 4 = neither | |
| temp | temperature in degrees Fahrenheit | | |
| visiblty | Visibility | 1 = dawn; 2 = day; 3 = dusk; 4 = dark | |
| weather | Weather conditions | 1 = clear; 2 = cloudy; 3 = rain 4 = fog; 5 = sleet; 6 = snow | |
| typeq | Type of consist | 1 = freight train; 2 = passenger train (pulling)*; 3 = commuter train (pulling)*; 4 = work train; 5 = single car; 6 = cut of cars; 7 = yard/switching; 8 = light loco(s); 9 = maintenance/inspection car;<br>A = special MoW equipment; B = passenger train (pushing)**; C = commuter train (pushing)**; D = EMU**; E = DMU** | *As of June 1, 2011 - name changes<br>**As of June 1 2011 – new selection – not available before June 1, 2011 |
| typtrk | Type of track | 1 = main; 2 = yard; 3 = siding; 4 = industry | |
| trkname | track identification | | |
| trkclas | FRA track class: 1-9, X | | |
| nbrlocos | Number of locomotive units | | |
| nbrcars | Number of cars | | |
| trnspd | Speed of train in miles per hour | Blank = unknown | |
| typspd | Train speed type | E = estimated; R = recorded; Blank = unknown | |
| trndir | Time table direction | 1 = north; 2 = south; 3 = east; 4 = west | |
| signal | Type of signaled crossing warning | If block 32 (crossing) = 01-06, then signal = 1-7 (see back of form 57 for valid entries) | |
| locwarn | Location of warning | 1 = both sides; 2 = side of vehicle approach; 3 = opposite side of vehicle approach | |
| warnsig | Crossing warning interconnected with highway signal | 1 = yes; 2 = no; 3 = unknown | |

FRA Highway-Rail Grade Crossing Accident Database Field Description (cont'd)

| **Field Name** | **Field Description** | **Potential Values** | **Notes/Conversion** |
|---|---|---|---|
| lights | Crossing illuminated by street lights or special lights | 1 = yes; 2 = no; 3 = unknown | |
| standveh | Driver passed highway standing vehicle* | 1 = yes; 2 = no; 3 = unknown | *As of June 1, 2011 - name changes |
| train2 | Highway user went behind or in front of train and struck or was struck by second train* | 1 = yes; 2 = no; 3 = unknown | *As of June 1, 2011 - name changes |
| motorist | Action of highway user* | 1 = went around the gates*; 2 = stopped and then proceeded; 3 = did not stop; 4 = stopped on crossing; 5 = other; 6 = went around/thru temporary barricade (if yes, see instructions)***; 7 = went thru the gate***; 8 = suicide/attempted suicide*** | *As of June 1, 2011 - name changes ***As of June 1 2011 – new selection – field not available before June 1, 2011 |
| view | Primary obstruction of track view | 1 = permanent structure; 2 = standing RR equipment; 3 = passing train; 4 = topography; 5 = vegetation; 6 = highway vehicles; 7 = other; 8 = not obstructed | |
| vehdmg | Highway vehicle property damage in $ | | |
| driver | Driver was | 1 = killed; 2 = injured; 3 = uninjured | |
| inveh | Driver in vehicle | 1 = yes; 2 = no | |
| totkld | Total killed for railroad as reported on F6180.57 | | |
| totinj | Total injured for railroad as reported on F6180.57 | | |
| totocc | Total # of vehicle occupants (including driver)* | | *As of June 1, 2011 - name changes |
| incdrpt | F6180.54 filed | 1 = yes; 2 = no | |
| jointcd | Indicates railroad reporting | | |

FRA Highway-Rail Grade Crossing Accident Database Field Description (cont'd)

| Field Name | Field Description | Potential Values | Notes/Conversion |
|---|---|---|---|
| typrr | Type railroad – ICC categories | 1st position indicates class 1, 2, or 3 railroad | |
| dummy3 | Blank data expansion field | | |
| caskldrr | # killed for reporting RR - calculated from F6180.55a's submitted | | |
| dummy4 | Blank data expansion field | | |
| crossing | Type of warning device at crossing (series of 2-digit codes) | 01 = gates; 02 = cantilever FLS; 03 = standard FLS; 04 = wig wags; 05 = highway traffic signals; 06 = audible; 07 = cross bucks; 08 = stop signs; 09 = watchman; 10 = flagged by crew; 11 = other (specify); 12 = none | |
| narrlen | Length of narrative | | |
| dummy5 | Blank data expansion field | | |
| year4 | 4-digit year of incident | | |
| division | Railroad division | | Blank after May 31, 2011 |
| public | Public crossing | 1 = public; 2 = private | |
| cntycd | FIPS county code | | |
| stcnty | FIPS state and county code | | |
| hzmrlsed | Hazmat released by | 1 = highway user; 2 = rail equipment; 3 = both; 4 = neither; Blank = unknown | |
| hzmname | Name of hazmat released | | |
| hzmqnty | Quantity of hazmat released | | |
| hzmmeas | Measure used in hazmat quantity field | | |
| sigwarnx | Further definition of signal field | If signal = 5-7, then sigwarnx = A-S (see back of form 57 for valid entries) | |
| whistban | Whistle ban in effect | 1 = yes; 2 = no; 3 = not provided; Blank = unknown | Valid from 1997 - May 2011 |

FRA Highway-Rail Grade Crossing Accident Database Field Description (cont'd)

| Field Name | Field Description | Potential Values | Notes/Conversion |
|---|---|---|---|
| drivage | Highway user's age* | Blank = unknown | *As of June 1, 2011 - name changes |
| drivgen | Highway user's gender* | 1 = male; 2 = female; Blank = unknown | *As of June 1, 2011 - name changes |
| pleontrn | Total # of people on train (includes passengers and crew) | Blank = unknown | |
| ssb1 | Special study block 1 | | Valid from 1997 - May 2011 |
| ssb2 | Special study block 2 | | |
| userkld | # of highway-rail crossing users killed as reported by railroad on F6180.57 | | |
| userinj | # of highway-rail crossing users injured as reported by railroad on F6180.57 | | |
| rrempkld | # of railroad employees killed as reported by railroad on F6180.57 | | |
| rrempinj | # of railroad employees injured as reported by railroad on F6180.57 | | |
| passkld | # of train passengers killed as reported by railroad on F6180.57 | | |
| passinj | # of train passengers injured as reported by railroad on F6180.57 | | |
| narr1 | Narrative | | |
| narr2 | Narrative | | |
| narr3 | Narrative | | |
| narr4 | Narrative | | |
| narr5 | Narrative | | |
| subdiv | Railroad subdivision | | Previous field was labeled division |

FRA Highway-Rail Grade Crossing Accident Database Field Description (cont'd)

| Field Name | Field Description | Potential Values | Notes/Conversion |
|---|---|---|---|
| roadcond | Roadway conditions | A = dry; B = wet; C = snow/slush; D = Ice; E = sand, mud, dirt, oil, gravel; F = water (standing, moving) | Previous field (from 1997 - May 2011) was labeled whistban. Starting June 2011 – new field |
| videot | Video taken | 1 = yes; 2 = no | Valid from June 2011 – present |
| videou | Video used | 1 = yes; 2 = no | Valid from June 2011 – present |

*Source: FRA (2011b). Highway-Rail Grade Crossing Accident/Incident. Form FRA F 6180.57. Accident Downloads on Demand. Data File Structure and Field Input Specifications – 06/01/2011*