FINAL REPORT

to

THE FLORIDA DEPARTMENT OF TRANSPORTATION
RESEARCH CENTER

on Project

"Impact of Lane Closures on Roadway Capacity, Phase 2"

FDOT Contract BDK77-977-18 (UF Project 93879)

January 2014

University of Florida
Transportation Research Center
Department of Civil and Coastal Engineering

DISCLAIMER

SI (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

This project is a follow-up to Florida Department of Transportation (FDOT) research project BD545-61, "Impact of Lane Closures on Roadway Capacity" (specifically, Part A: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure and Part C: Modeling Diversion Propensity at Work Zones). In this previous project, the primary objective was to update the procedure in the Plans Preparation Manual (PPM), Volume 1, Section 10.14.7 (2006), for two-lane roadways. Field data collection was not included in the previous project; thus, the results were based strictly on simulation data from the FlagSim simulation program.

The primary objective of this project was to update the two-lane roadway with a lane closure analysis procedure developed under the previous project, based on calibrating the FlagSim simulation program to field data. An additional aspect of this that was not considered in the BD545-61 project was to account for the effect of grade on the work zone performance measures. An additional project objective was to update the RTF estimation method developed under the BD545-61 project, as necessary, based on measured traffic demands (before and during) at work zone field sites.

Field data were collected at three sites and used to calibrate the FlagSim program. FlagSim was then used to generate the data used to update the models contained in the analysis procedure developed under the previous project. Local area traffic demand data were also used to update the RTF estimation model.

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EXECUTIVE SUMMARY

This project is a follow-up to Florida Department of Transportation (FDOT) research project BD545-61, "Impact of Lane Closures on Roadway Capacity" (specifically, Part A: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure and Part C: Modeling Diversion Propensity at Work Zones). In this previous project, the primary objective was to update the procedure in the Plans Preparation Manual (PPM), Volume 1, Section 10.14.7 (2006), for two-lane roadways. Field data collection was not included in the previous project; thus, the results were based strictly on simulation data from the FlagSim simulation program.

Before the preceding research project, the FDOT developed an analysis procedure for two-lane roadways with a lane closure that was a relatively simple deterministic procedure, with rough approximations for work zone capacity and other important parameter values. Through the previous project (BD545-61), a new analysis procedure was developed that is sensitive to the major factors that influence work zone performance measures. However, the main limitation from the BD545-61 project was the lack of field data to use for calibrating the various simulation parameters.

Another aspect of the BD545-61 project was to develop a method to estimate the amount of traffic diversion that occurs at a work zone location. The previous analysis procedure in the PPM included the "Remaining Traffic Factor" (RTF) term. This term accounts for "The percentage of traffic that will not be diverted onto other facilities during a lane closure" (FDOT, 2006 PPM). The value to use for this input was left strictly to the analyst's judgment, as there was no method or quantitative guidance provided. Again, since field data were not available in the BD545-61 project, a stated preference (SP) survey, via telephone, approach was used to develop a method to estimate that amount of traffic diversion that will occur at a work zone site.

The primary objective of this project was to update the two-lane roadway with lane closure analysis procedure developed under the previous project based on calibrating the FlagSim simulation program to field data. An additional aspect of this that was not considered in the BD545-61 project was to account for the effect of grade on the work zone performance measures. An additional project objective was to update the RTF estimation method developed under the BD545-61 project, as necessary, based on measured traffic demands (before and during) at field sites.

Field data were collected from three sites. Two of these sites were in fairly rural locations, which featured longer lane closure lengths and lower demand volumes. The third site was less rural in nature and featured shorter lane closures and higher demand volumes. All three sites were located in the north-central Florida region. From the field data, values for factors critical to the calibration of FlagSim were determined, such as startup lost time, saturation headway, travel speed through the work zone, flagging right-of-way changing behavior, etc.

After FlagSim was calibrated to the field conditions, it was then used to generate the data used to update the models contained in the analysis procedure developed under the previous project. Specifically, models for average work zone travel speed, average saturation headway, total queue delay, and maximum queue length were updated. The models were updated in the analysis worksheet tool.

The RTF task aimed to refine the estimation model proposed in Phase 1 using field-observed diversion data. The binary Logit model developed in Phase 1 was calibrated based on SP survey data, and SP data tend to overestimate the diversion rate in work zones. The aggregate traffic data collected in a work zone on SR-20 confirmed this phenomenon. A simplistic methodology is adopted primarily due to limitations in data availability and quality. The constant coefficient associated with the original route is adjusted to fix the overestimation problem while retaining the preference structure of the estimated route choice model. The recalibrated model was incorporated into the RTF modeling framework proposed in Phase 1 by updating the route choice model.

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CHAPTER 1
INTRODUCTION

This project is a follow-up to Florida Department of Transportation (FDOT) research project BD545-61, "Impact of Lane Closures on Roadway Capacity" (specifically, Part A: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure and Part C: Modeling Diversion Propensity at Work Zones). In this previous project, the primary objective was to update the procedure in the Plans Preparation Manual (PPM), Volume 1, Section 10.14.7 (2006), for two-lane roadways. Field data collection was not included in the previous project; thus, the results were based strictly on simulation data from the FlagSim simulation program (described in Appendix C).

Some material in this report is repeated from the previous project report to minimize the need to reference the previous report, starting with an overview of two-lane roadway lane closure configuration and operations. Two-lane roadway work zone configurations consist of a single lane that accommodates both directions of flow, in an alternating pattern, as illustrated in Figure 1.

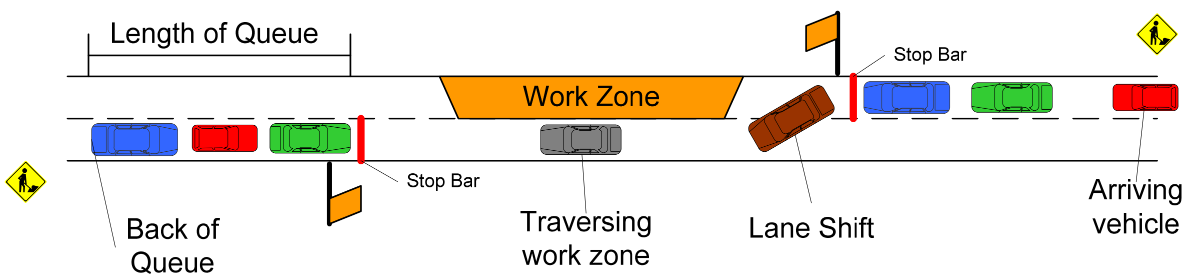


Figure 1: Two-lane work zone operated with flagging control

These work zones typically employ a flagging control person (i.e., someone who operates a sign that gives motorists instructions to stop or proceed) at both ends to regulate the flow of traffic through the work zone. In some situations (usually where the lane closure is long or there are a large number of driveways), a lead vehicle, called a pilot car, may be required to lead the platoon of vehicles through the work zone.

Significant delay is incurred by motorists due to the lost time that accrues while the opposing direction has the right-of-way. Additionally, both directions incur lost time when there is a change in the right-of-way as the last vehicle that received the right-of-way must traverse the entire length of the work zone; therefore, all vehicles must wait until the last vehicle has passed the opposite stop location. The queue discharge process is similar to the operation of a signalized intersection, but the queue discharge rate may be lower due to driver caution and various work zone factors and activities.

Changing of the right-of-way is rarely performed in an optimal manner. Flag persons are not trained on how to switch the right-of-way in such a manner as to minimize delay, or otherwise optimize some particular performance measure (Evans, 2006). Generally, flag persons change the flow direction due to queue and cycle length. The queue at the beginning of the "green" period discharges at the saturation flow rate. After the initial queue dissipates, flag persons usually extend the green to allow for vehicles still arriving. This extension time can be lowered if there is a significant queue in the opposite direction. At this point, the flow through the work zone will drop to the arrival rate. The arrival rate can be significantly lower than the queue discharge rate on low volume roadways, thus increasing the overall average delay if vehicles are queuing at the opposite approach (Cassidy and Son, 1994).

The typical performance measures for evaluating a work zone with flagging operations are:

- Capacity – maximum vehicle throughput
- Delay – time spent not moving, or at a slower speed than desired
- Queue length – vehicle arrivals minus vehicle departures for a specified length of time

Problem Statement

Since there is not a single accepted national standard for analyzing work zone operations and estimating performance measures, such as might be provided by the Highway Capacity Manual (HCM) (TRB, 2010), transportation agencies are tasked with developing their own methods or adopt/adapt ones from existing methods. Before the preceding research project, the FDOT developed an analysis procedure for two-lane roadways with a lane closure that was a relatively simple deterministic procedure, with rough approximations for work zone capacity and other important parameter values. Through the previous project (BD545-61), a new analysis procedure was developed that is sensitive to the major factors that influence work zone performance measures. However, the main limitation from the BD545-61 project was the lack of field data to use for calibrating the various simulation parameters. While some of these parameters were set based on results of field data collection at signalized intersections from a previous FDOT research project (BD545-51, Washburn and Cruz-Casas, 2007), it is likely that there are still a number of significant differences in the queue accumulation and discharge process at two-lane roadway lane closure sites. Furthermore, the extent to which conditions within the work zone might further reduce drivers' desired speed, relative to the posted speed, was not known. Another aspect of the BD545-61 project was to develop a method to estimate the amount of traffic diversion that occurs at a work zone location. The previous analysis procedure in the PPM included the 'Remaining Traffic Factor' (RTF) term. This term accounts for "The percentage of traffic that will not be diverted onto other facilities during a lane closure." (FDOT, 2006 PPM) The value to use for this input was left strictly to the analyst's judgment, as there was no method or quantitative guidance provided. Again, since field data were not available in the BD545-61 project, a stated preference (SP) survey, via telephone, approach was used to develop a method to estimate that amount of traffic diversion that will occur at a work zone site.

Research Objective and Supporting Tasks

The primary objective of this project was to update the two-lane roadway with lane closure analysis procedure developed under the previous project based on calibrating the FlagSim simulation program to field data. An additional aspect of this that was not considered in the BD545-61 project was to account for the effect of grade on the work zone performance measures. An additional project objective was to update the RTF estimation method developed under the BD545-61 project, as necessary, based on measured traffic demands (before and during) at field sites. The tasks that were conducted to support completion of the objectives were as follows:

- Collected work zone operations data at three lane closure sites in north-central Florida.
- Reduced and analyzed the field operations data.
- Developed models for estimating work zone travel speed and saturation headway based on the field data.
- Calibrated various FlagSim input parameters to yield a good match between simulated work zone traffic operations and field work zone operations.
- Incorporated a new truck acceleration model into FlagSim (the same model used in FDOT Project BDK77-977-15) and updated truck characteristics in FlagSim based on analysis of weigh-in-motion (WIM) data from several two-lane highway sites.
- Developed models for estimating work zone travel speed, saturation headway, queue delay, and queue length based on simulation data.
- Revised the analysis procedure spreadsheet developed under the previous project to reflect the updated models developed in this project.
- Collected local area traffic demand data at each field site, before and during the lane closure, (this was performed by FDOT staff) and analyzed the data.
- Updated the RTF estimation model based on the field site local area traffic counts.

Document Organization

The remaining chapters in this report are organized as follows. Chapter 2 provides a brief overview of the results of the preceding project as well as an overview of the original FDOT PPM procedure (this material is repeated from the BD545-61 project report). Readers interested in other research efforts and/or analysis tools applicable to two-lane roadways with a lane closure should consult Chapter 2 of the BD545-61 project report. Chapter 3 describes the field site data collection, analysis, and model development. Chapter 4 describes the simulation calibration effort, the incorporation of the effect of grade, and the development of the final models to be incorporated into the analysis spreadsheet tool. Chapter 5 provides a step-by-step overview of the analysis procedure. Chapter 6 describes the results of the RTF task.

CHAPTER 2
REVIEW OF PREVIOUS FDOT ANALYSIS METHODS

This chapter presents a summary of the original FDOT PPM analysis procedure for two-lane roadways with a lane closure and a summary of the results of the previous project (BD545-61).

Original FDOT PPM Analysis Procedure

The FDOT developed a lane closure analysis procedure for use with all road type classes. The procedure is in the Plans Preparation Manual (PPM), Volume I, Section 10.14.7 (2006). The procedure can analyze two-lane two-way work zones. In order to accommodate flagging operations, the procedure attempts to determine the peak hour volume and the restricted capacity. From these two values, the time during when lane closures can occur without creating excessive delays is determined.

This procedure's main limitation is that capacity is an input, and the given capacities were not specific to two-lane work zones. With capacity not based on a flagging work zone value, the procedure quite likely will be unable to model the field conditions accurately. Another limitation with modeling flagging operations with this procedure is that it is based on only the ratio of green time to the cycle length. This assumption does not take in to account the differences in delays of flagging operations, such as the lost time due to the traversing the work zone, startup lost time, and the variation of extended green time.

The capacity is adjusted by the work zone factor (WZF) shown in Table 1. The WZF is used instead of a calculated travel time based on a typical speed. All of the lost time is also incorporated in to the WZF. This is a simplistic adjustment to incorporate these important factors. The travel time through the work zone is an easy calculation, which would make a logical factor. One of the problems is the WZF is not adjusted by speed and is not documented by what speed the factor is based on. This is an important question, as speeds through a work zone can be quite different for an intense construction operation like chip and seal versus a less intense operation such as shoulder work.

Table 1. FDOT PPM Analysis Method Work Zone Factor (WZF)

WZL (ft.)	WZF	WZL (ft.)	WZF	WZL (ft.)	WZF
200	0.98	2200	0.81	4200	0.64
400	0.97	2400	0.8	4400	0.63
600	0.95	2600	0.78	4600	0.61
800	0.93	2800	0.76	4800	0.59
1000	0.92	3000	0.74	5000	0.57
1200	0.9	3200	0.73	5200	0.56
1400	0.88	3400	0.71	5400	0.54
1600	0.86	3600	0.69	5600	0.53
1800	0.85	3800	0.68	5800	0.51
2000	0.83	4000	0.66	6000	0.5

The FDOT PPM lane closure analysis procedure is as follows:

1. Select the appropriate capacity (c) from the table below:

   LANE CLOSURE CAPACITY TABLE

   Capacity (c) of an Existing 2-Lane-Converted to 2-Way, 1-Lane=1400 veh/h

   Capacity (c) of an Existing 4-Lane-Converted to 1-Way, 1-Lane=1800 veh/h

   Capacity (c) of an Existing 6-Lane-Converted to 1-Way, 1-Lane=3600 veh/h

   Therefore, for a two-lane highway work zone, the capacity (c) is 1400 veh/h.

2. The restricted capacity (RC) is then calculated taking into consideration the following factors:

   TLW = Travel Lane Width

   LC = Lateral Clearance. This is the distance from the edge of the travel lane to the obstruction (e.g., Jersey barrier)

   WZF = Work Zone Factor. This factor is proportional to the length of the work zone. It is only used in the procedure for two-lane two-way work zones.

OF = Obstruction Factor. This factor reduces the capacity of the travel lane if the one of the following factors violates their constraints: TLW less than 12 ft and LC less than 6 ft.

G/C = Ratio of green time to cycle time. This factor is applied when the lane closure is through or within 600 ft of a signalized intersection.

ADT = Average Daily Trips. This value is used to calculate the design hourly volume.

The RC for roadways without signals is calculated as follows:

$$\text{RC (Open Road)} = \text{c} \times \text{OF} \times \text{WZF} \quad [1]$$

If the work zone is through or within 600 feet of a signalized intersection, then RC is determined by applying the following additional calculation.

$$\text{RC (Signalized)} = \text{RC (Open Road)} \times \text{G/C} \quad [2]$$

If Peak Traffic Volume ≤ RC, there is no restriction on the lane closure. That is, if the peak traffic volume is less than or equal to the restricted capacity, the work zone lane closure can be implemented at any time during the day.

If Peak Traffic Volume > RC, calculate the hourly percentage of ADT at which a lane closure will be permitted.

$$\text{Open Road\%} = \frac{RC(OpenRoad)}{ATC \times D \times PSCF \times RTF} \quad [3]$$

where

ATC = Actual Traffic Counts. The hourly traffic volumes for the roadway during the desired time period.
D = Directional distribution of peak hour traffic on multilane roads. This factor does not apply to a two-lane roadway converted to two-way, one-lane.
PSCF = Peak Season Conversion Factor
RTF = Remaining Traffic Factor. The percentage of traffic that will not be diverted onto other facilities during a lane closure.
Signalized% = (Open Road %) × (G/C)

Plot the 24-hour traffic, relative to capacity, to determine when a lane closure is permitted.

Revised Analysis Procedure through FDOT Project BD545-61

Overall Analysis Procedure

As described above, the original FDOT analysis procedure in the PPM is fairly simple and considers a limited number of factors. Consequently, there is a very limited range of field conditions for which this method will yield reasonably accurate results. Furthermore, the only output from the method is work zone capacity. The objective of project BD545-61was to develop an analysis procedure for two-lane roadway work zones (with a lane closure) that was more robust, both in terms of inputs and outputs, than the FDOT's current PPM method. The FDOT also had the requirement that this new procedure still be easy to use.

A custom microscopic simulation program, FlagSim, was used to generate the data used in the development of the models contained in the new analysis procedure. Specifically, models were developed to estimate work zone travel speed, saturation headway, queue delay, and queue length, as follows.

$$WorkZoneSpd_i = 4.608474 + 0.706381 \times PostedSpd_i + 0.000601 \times Min((L \times 5280), 10560) - 0.1063336 \times HV_i \quad [4]$$

where

$WorkZoneSpd_i$ = estimated average travel speed of vehicles through the work zone for direction *i* (mi/h)
$PostedSpd_i$ = the posted speed, or maximum desirable travel speed of vehicles, through the work zone for direction *i* (mi/h)
L = work zone length (mi)
HV_i = percentage of heavy vehicles in the traffic stream for direction *i*

$$h_{sat\_i} = 1.92 \times \left(1 - 0.00516(Min(speed_i, 45) - 45)\right) \times \left(1 + \left(\frac{HV_i}{100}\right) \times (2.37 - 1)\right) \quad [5]$$

where

h_{sat_i} = saturation headway for direction *i* (s/veh)
$speed_i$ = average travel speed downstream of stop bar for direction *i* (veh/h)

HV_i = percentage of heavy vehicles in the traffic stream for direction *i*

$$TotalQDelay_i = -0.276980 \times (g_i / C)(\%) + 0.242061 \times (v/s)_i(\%) + 0.003387 \times C + 0.148503 \times g_i - 0.001376 \times HV_i \times g_i \quad [6]$$

where

$TotalQDelay_i$ = total queue delay for a 1-hr time period for direction *i* (veh-hr)
(g_i/C) = average effective green time to average cycle length ratio for direction *i* (expressed as a percentage)
$(v/s)_i$ = volume to saturation flow rate ratio for direction *i* (expressed as a percentage)
C = average cycle length (sec)
g_i = average green time for direction *i* (sec)
HV_i = percentage of heavy vehicles in the traffic stream for direction *i*

$$MaxQueueLength_i = -0.616983 \times (g_i / C)(\%) + 0.598965 \times (v/s)_i(\%) + 0.0006855 \times C + 0.299197 \times g_i - 0.003199 \times HV_i \times g_i \quad [7]$$

where

$MaxQueueLength_i$ = average maximum queue length per cycle for direction *i* (veh/cycle)
Other terms are as previously defined.

The analysis procedure also employs calculation elements consistent with the analysis of signalized intersections. This procedure is much more robust than the original PPM procedure, and the results match well with the simulation data. The analysis procedure was implemented into an easy-to-use spreadsheet format. Screen captures of the analysis spreadsheet are shown in Figure 2 and Figure 3.

Two-Lane, Two-Way, Work Zone Analysis Worksheet
Florida Department of Transportation
(08/19/10)

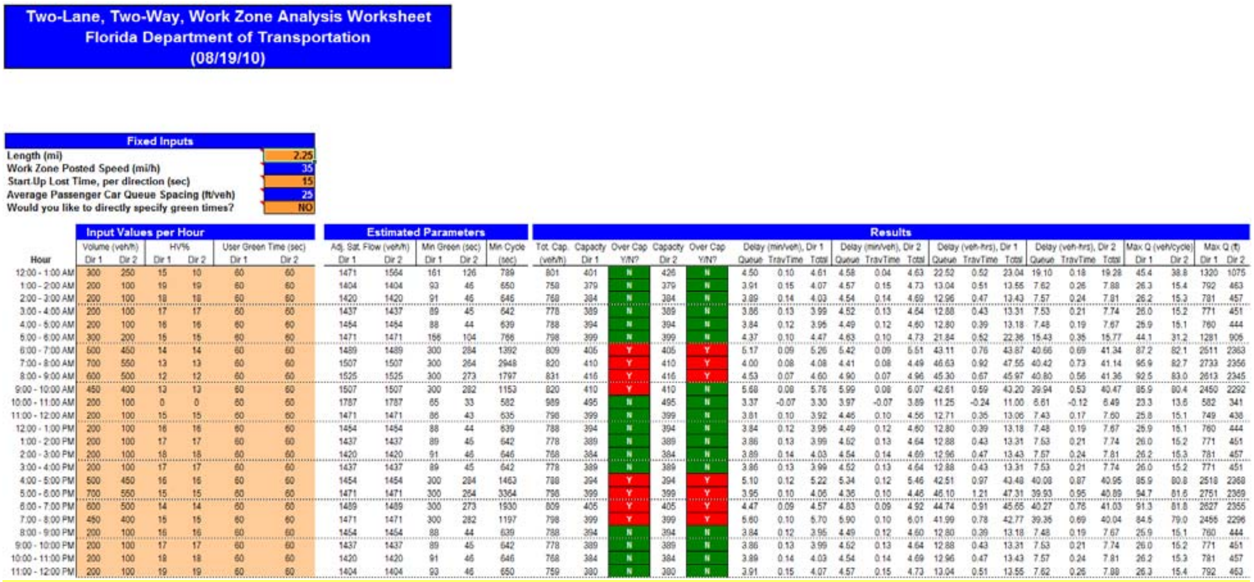
Input Variables	
Length (mi)	2.25
Work Zone Posted Speed (mi/h)	35
Start-Up Lost Time, per direction (sec)	15
Heavy Vehicles (%), Peak Direction	15
Heavy Vehicles (%), Off-Peak Direction	10
Volume (veh/h), Peak Direction	300
Volume (veh/h), Off-Peak Direction	250
Average Passenger Car Queue Spacing (ft/veh)	25
Would you like to directly specify green times?	NO
User Defined Peak Green Time (sec)	
User Defined Off-Peak Green Time (sec)	

Measures of Effectiveness	Peak Direction	Off-Peak Direction	Total
Capacity (veh/hr)	401	426	826
	Under Capacity	Under Capacity	Under Capacity
Delay in Queue (min/veh)	4.50	4.58	4.54
Work Zone Travel Time Delay (min/veh)	0.10	0.04	0.08
Total Delay (min/veh)	4.61	4.63	4.62
Delay in Queue (veh-hrs)	22.52	19.10	41.62
Work Zone Travel Time Delay (veh-hrs)	0.52	0.18	0.70
Total Delay (veh-hrs)	23.04	19.28	42.32
Maximum Queue Length (veh/cycle)	45.4	38.8	
Maximum Queue Length (ft)	1320	1075	

Estimated Parameters	
Adjusted Saturation Flow Rate (veh/h), Peak Dir	1471
Adjusted Saturation Flow Rate (veh/h), Off-Peak Dir	1564
Minimum Green Time (sec), Peak Direction	161
Minimum Green Time (sec), Off-Peak Direction	126
Minimum Cycle Length (sec)	789
Effective Vehicle Queue Spacing (ft/veh), Peak Dir	29.1
Effective Vehicle Queue Spacing (ft/veh). Off-Peak Dir	27.7

Notes:
MOE values in the "Total" column reflect volume weighted (by direction) averages where appropriate
Only the values in the colored cells in the "Input Variables" section should be edited by the user

Figure 2. Analysis worksheet tool developed in FDOT project BD545-61 screen capture (1-hour analysis)



Two-Lane, Two-Way, Work Zone Analysis Worksheet
Florida Department of Transportation
(08/19/10)

Fixed Inputs	
Length (mi)	2.25
Work Zone Posted Speed (mi/h)	35
Start-Up Lost Time, per direction (sec)	15
Average Passenger Car Queue Spacing (ft/veh)	25
Would you like to directly specify green times?	NO

	Input Values per Hour						Estimated Parameters				
	Volume (veh/h)		HV%		User Green Time (sec)		Adj. Sat. Flow (veh/h)		Min Green (sec)		Min Cycle
Hour	Dir 1	Dir 2	Dir 1	Dir 2	Dir 1	Dir 2	Dir 1	Dir 2	Dir 1	Dir 2	(sec)
12:00 - 1:00 AM	300	250	15	10	60	60	1471	1564	161	126	789
1:00 - 2:00 AM	200	100	19	19	60	60	1404	1404	93	46	650
2:00 - 3:00 AM	200	100	18	18	60	60	1420	1420	91	46	646
3:00 - 4:00 AM	200	100	17	17	60	60	1437	1437	89	45	642
4:00 - 5:00 AM	200	100	16	16	60	60	1454	1454	88	44	639
5:00 - 6:00 AM	300	200	15	15	60	60	1471	1471	166	104	766
6:00 - 7:00 AM	500	450	14	14	60	60	1489	1489	300	284	1392
7:00 - 8:00 AM	700	550	13	13	60	60	1507	1507	300	264	2948
8:00 - 9:00 AM	600	500	12	12	60	60	1525	1525	300	273	1797
9:00 - 10:00 AM	450	400	13	13	60	60	1507	1507	300	282	1153
10:00 - 11:00 AM	200	100	0	0	60	60	1787	1787	65	33	582
11:00 - 12:00 AM	200	100	15	15	60	60	1471	1471	86	43	635
12:00 - 1:00 PM	200	100	16	16	60	60	1454	1454	88	44	639
1:00 - 2:00 PM	200	100	17	17	60	60	1437	1437	89	45	642
2:00 - 3:00 PM	200	100	18	18	60	60	1420	1420	91	46	646
3:00 - 4:00 PM	200	100	17	17	60	60	1437	1437	89	45	642
4:00 - 5:00 PM	500	450	16	16	60	60	1454	1454	300	284	1463
5:00 - 6:00 PM	700	550	15	15	60	60	1471	1471	300	264	3364
6:00 - 7:00 PM	600	500	14	14	60	60	1489	1489	300	273	1930
7:00 - 8:00 PM	450	400	15	15	60	60	1471	1471	300	282	1197
8:00 - 9:00 PM	200	100	16	16	60	60	1454	1454	88	44	639
9:00 - 10:00 PM	200	100	17	17	60	60	1437	1437	89	45	642
10:00 - 11:00 PM	200	100	18	18	60	60	1420	1420	91	46	646
11:00 - 12:00 PM	200	100	19	19	60	60	1404	1404	93	46	650

	Results										
	Tot. Cap.	Capacity	Over Cap	Capacity	Over Cap	Delay (min/veh), Dir 1			Delay (min/veh), Dir 2		
Hour	(veh/h)	Dir 1	Y/N?	Dir 2	Y/N?	Queue	TravTime	Total	Queue	TravTime	Total
12:00 - 1:00 AM	801	401	N	426	N	4.50	0.10	4.61	4.58	0.04	4.63
1:00 - 2:00 AM	758	379	N	379	N	3.91	0.15	4.07	4.57	0.15	4.73
2:00 - 3:00 AM	768	384	N	384	N	3.89	0.14	4.03	4.54	0.14	4.69
3:00 - 4:00 AM	778	389	N	389	N	3.86	0.13	3.99	4.52	0.13	4.64
4:00 - 5:00 AM	788	394	N	394	N	3.84	0.12	3.95	4.49	0.12	4.60
5:00 - 6:00 AM	798	399	N	399	N	4.37	0.10	4.47	4.63	0.10	4.73
6:00 - 7:00 AM	809	405	Y	405	Y	5.17	0.09	5.26	5.42	0.09	5.51
7:00 - 8:00 AM	820	410	Y	410	Y	4.00	0.08	4.08	4.41	0.08	4.49
8:00 - 9:00 AM	831	416	Y	416	Y	4.53	0.07	4.60	4.90	0.07	4.96
9:00 - 10:00 AM	820	410	Y	410	N	5.68	0.08	5.76	5.99	0.08	6.07
10:00 - 11:00 AM	989	495	N	495	N	3.37	-0.07	3.30	3.97	-0.07	3.89
11:00 - 12:00 AM	798	399	N	399	N	3.81	0.10	3.92	4.46	0.10	4.56
12:00 - 1:00 PM	788	394	N	394	N	3.84	0.12	3.95	4.49	0.12	4.60
1:00 - 2:00 PM	778	389	N	389	N	3.86	0.13	3.99	4.52	0.13	4.64
2:00 - 3:00 PM	768	384	N	384	N	3.89	0.14	4.03	4.54	0.14	4.69
3:00 - 4:00 PM	778	389	N	389	N	3.86	0.13	3.99	4.52	0.13	4.64
4:00 - 5:00 PM	788	394	Y	394	Y	5.10	0.12	5.22	5.34	0.12	5.46
5:00 - 6:00 PM	798	399	Y	399	Y	3.95	0.10	4.06	4.36	0.10	4.46
6:00 - 7:00 PM	809	405	Y	405	Y	4.47	0.09	4.57	4.83	0.09	4.92
7:00 - 8:00 PM	798	399	Y	399	Y	5.60	0.10	5.70	5.90	0.10	6.01
8:00 - 9:00 PM	788	394	N	394	N	3.84	0.12	3.95	4.49	0.12	4.60
9:00 - 10:00 PM	778	389	N	389	N	3.86	0.13	3.99	4.52	0.13	4.64
10:00 - 11:00 PM	768	384	N	384	N	3.89	0.14	4.03	4.54	0.14	4.69
11:00 - 12:00 PM	759	380	N	380	N	3.91	0.15	4.07	4.57	0.15	4.73

	Results (cont.)									
	Delay (veh-hrs), Dir 1			Delay (veh-hrs), Dir 2			Max Q (veh/cycle)		Max Q (ft)	
Hour	Queue	TravTime	Total	Queue	TravTime	Total	Dir 1	Dir 2	Dir 1	Dir 2
12:00 - 1:00 AM	22.52	0.52	23.04	19.10	0.18	19.28	45.4	38.8	1320	1075
1:00 - 2:00 AM	13.04	0.51	13.55	7.62	0.26	7.88	26.3	15.4	792	463
2:00 - 3:00 AM	12.96	0.47	13.43	7.57	0.24	7.81	26.2	15.3	781	457
3:00 - 4:00 AM	12.88	0.43	13.31	7.53	0.21	7.74	26.0	15.2	771	451
4:00 - 5:00 AM	12.80	0.39	13.18	7.48	0.19	7.67	25.9	15.1	760	444
5:00 - 6:00 AM	21.84	0.52	22.36	15.43	0.35	15.77	44.1	31.2	1281	906
6:00 - 7:00 AM	43.11	0.76	43.87	40.66	0.69	41.34	87.2	82.1	2511	2363
7:00 - 8:00 AM	46.63	0.92	47.55	40.42	0.73	41.14	95.9	82.7	2733	2356
8:00 - 9:00 AM	45.30	0.67	45.97	40.80	0.56	41.36	92.5	83.0	2613	2345
9:00 - 10:00 AM	42.61	0.59	43.20	39.94	0.53	40.47	85.9	80.4	2450	2292
10:00 - 11:00 AM	11.25	-0.24	11.00	6.61	-0.12	6.49	23.3	13.6	582	341
11:00 - 12:00 AM	12.71	0.35	13.06	7.43	0.17	7.60	25.8	15.1	749	438
12:00 - 1:00 PM	12.80	0.39	13.18	7.48	0.19	7.67	25.9	15.1	760	444
1:00 - 2:00 PM	12.88	0.43	13.31	7.53	0.21	7.74	26.0	15.2	771	451
2:00 - 3:00 PM	12.96	0.47	13.43	7.57	0.24	7.81	26.2	15.3	781	457
3:00 - 4:00 PM	12.88	0.43	13.31	7.53	0.21	7.74	26.0	15.2	771	451
4:00 - 5:00 PM	42.51	0.97	43.48	40.08	0.87	40.95	85.9	80.8	2518	2368
5:00 - 6:00 PM	46.10	1.21	47.31	39.93	0.95	40.89	94.7	81.6	2751	2369
6:00 - 7:00 PM	44.74	0.91	45.65	40.27	0.76	41.03	91.3	81.8	2627	2355
7:00 - 8:00 PM	41.99	0.78	42.77	39.35	0.69	40.04	84.5	79.0	2455	2296
8:00 - 9:00 PM	12.80	0.39	13.18	7.48	0.19	7.67	25.9	15.1	760	444
9:00 - 10:00 PM	12.88	0.43	13.31	7.53	0.21	7.74	26.0	15.2	771	451
10:00 - 11:00 PM	12.96	0.47	13.43	7.57	0.24	7.81	26.2	15.3	781	457
11:00 - 12:00 PM	13.04	0.51	13.55	7.62	0.26	7.88	26.3	15.4	792	463

Figure 3. Analysis worksheet tool developed in FDOT project BD545-61 screen capture (24-hour analysis)

While it was felt that the results of this project (BD545-61) provided significant improvements over the existing FDOT PPM procedure, there were several areas that were identified that could benefit from additional research, as follows:

- One obvious limitation to the results of this project is the lack of field data for verification/validation of several aspects of the simulation program. Although certain parameter values used in the simulation program were compared for consistency to field data values obtained from the Cassidy and Son research (1994), most of their field sites utilized a pilot car; thus, their parameter values may not be directly comparable to sites that do not use a pilot car. Field data should be collected at several sites, under only flagging control, to confirm the following factors:
  - Saturation flow rates and/or capacities
    - What are typical values, and how do they differ due to traffic stream composition?
    - Are they different by direction, e.g., due to the required lane shift in one direction?
  - Travel speeds through the work zone
    - Are they related to, or independent of, posted speed limits?
    - Are they different by direction due to the lane crossover at the beginning of the work zone? Son (1994) states from their literature review that vehicles in the blocked travel direction usually have lower speeds than the opposite direction.
  - Startup lost time
    - What are typical values?

        - Are they different by direction?
    - Flagging methods
        - Is a gap-out strategy ever applied, and if so, how?
        - Is a maximum green time used, and if so, what value?
        - Is a green time extension used, and if so, what value?

Remaining Traffic Factor (RTF) Task

When estimating the hourly traffic demand, the FDOT PPM procedure applies a "Remaining Traffic Factor" (RTF) to the observed hourly traffic demand without the lane closure. The RTF accounts for possible traffic diversion during the lane closure. However, no guidance has been offered on how to obtain the value of the RTF in the PPM.

The purposes of this research task were twofold. First, diversion behaviors at work zones were modeled in a discrete choice modeling framework. A stated preference survey was carried out to obtain the data on drivers' diversion propensity from work zones. By calibrating a Logit model with the data, we identified three major factors that influence drivers' diversion decisions, namely, travel time, work zone location, and weather condition. For other factors, such as trip purpose and drivers' social economic characteristics, we found no evidence that they are important in drivers' decision making about diversion at work zones. The calibrated model provides us with more insight on drivers' work zone diversion behaviors and may be used to forecast diversion rates or be incorporated into a work zone traffic analysis tool.

Second, we proposed two procedures, namely open-loop and closed-loop, to apply the calibrated binary Logit model to estimate the RTF. The former directly applies the choice model without considering the feedback of remaining and diverted flows on travel times. It may be more appropriate to be used for a short-term work zone lane closure. The latter applies the notion of equilibrium to maintain the consistency between travel times and flows at different routes. Therefore, it may better replicate the situation at a long-term work zone. Based on the combinations of the weather condition and work zone location, four Fisk's stochastic user equilibrium models have been formulated, which can be solved by the Excel solver to compute the RTF. An Excel tool was developed to facilitate the computation, screen captures of which are shown below in Figure 4 and Figure 5.

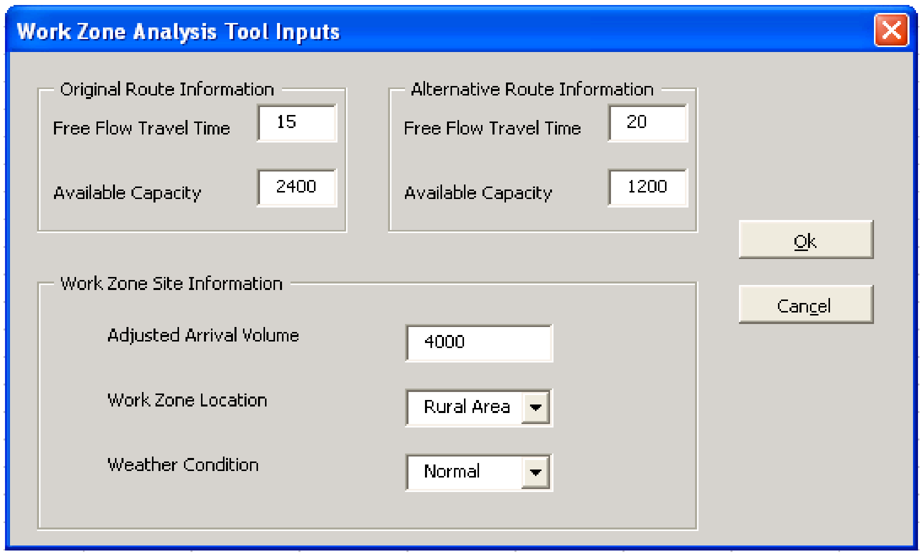


Figure 4. RTF estimation spreadsheet tool developed in FDOT project BD545-61 screen capture (1)

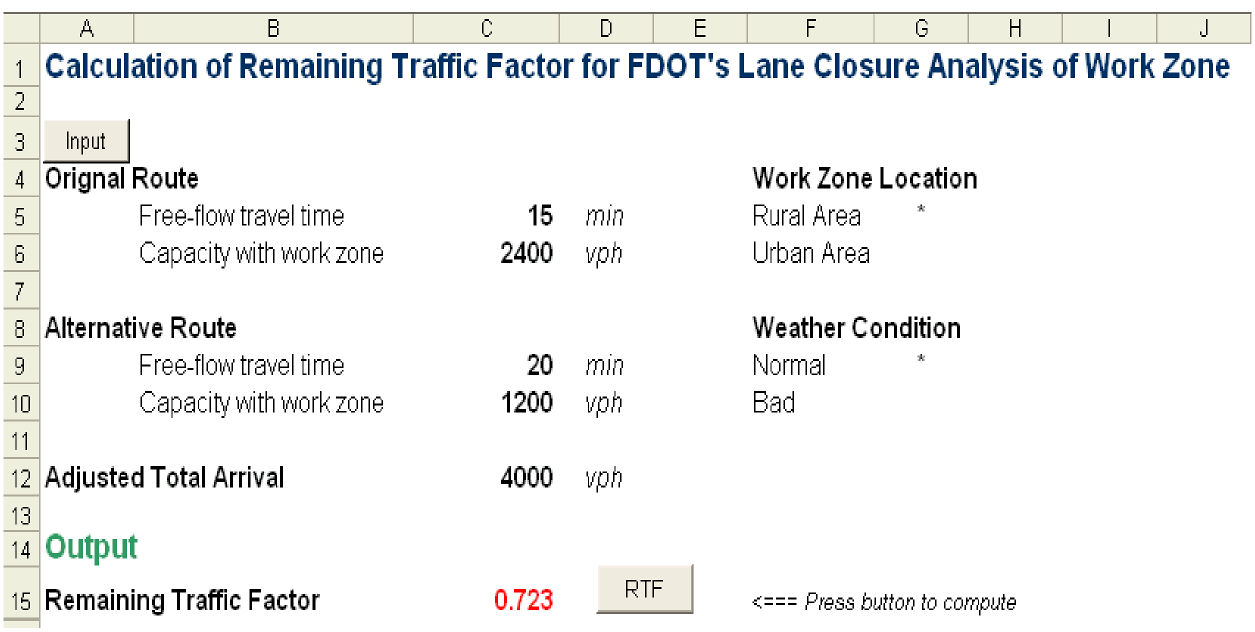


Figure 5. RTF estimation spreadsheet tool developed in FDOT project BD545-61 screen capture (2)

CHAPTER 3

FIELD DATA COLLECTION AND ANALYSIS

This chapter describes the data requirements for calibration of the FlagSim simulation program. This is followed by discussion on the sites where data were collected, the data collection procedure undertaken, and a brief description of the data collected at these sites. The data processing procedure is then described, and results from this processing are presented and discussed. Lastly, the work zone speed and saturation headway models developed from the field data are presented.

Data Requirements

In order to calibrate the FlagSim simulation program to field conditions, it was first necessary to identify what type of data were necessary to perform this task. Based on the simulation program internal models and possible outputs from this program, the following data parameters were identified:

- Length of lane closure
- Posted speed in work zone
- Posted speed of work zone approach
- Travel time of each vehicle through work zone for each phase
- Vehicle type of each vehicle entering the work zone per phase
- Number of vehicles entering the work zone per phase
- Average speed of vehicles in the work zone per phase
- "Green" time per phase
- Startup lost time per phase
- Queue delay per phase
- Queue length per phase
- Saturation headway per phase

- Type of flagging control used at the lane closure

These parameters collectively comprise the inputs and outputs of the FlagSim program. In addition, it was also necessary to obtain some data regarding traffic operations within the lane closure. Specifically, how traffic operations were impacted by construction taking place in the work zone.

Description of Study Sites

To facilitate the calibration of the FlagSim program, it was necessary to identify several study sites that provided different traffic characteristics and work zone conditions. Ultimately, field data were collected from three sites. Two of these sites were in fairly rural locations, which featured longer lane closure lengths and lower demand volumes. The third site was less rural in nature and featured shorter lane closures and higher demand volumes. The general location of these sites is indicated in Figure 6. Each of these sites is discussed in more detail in the following sections.

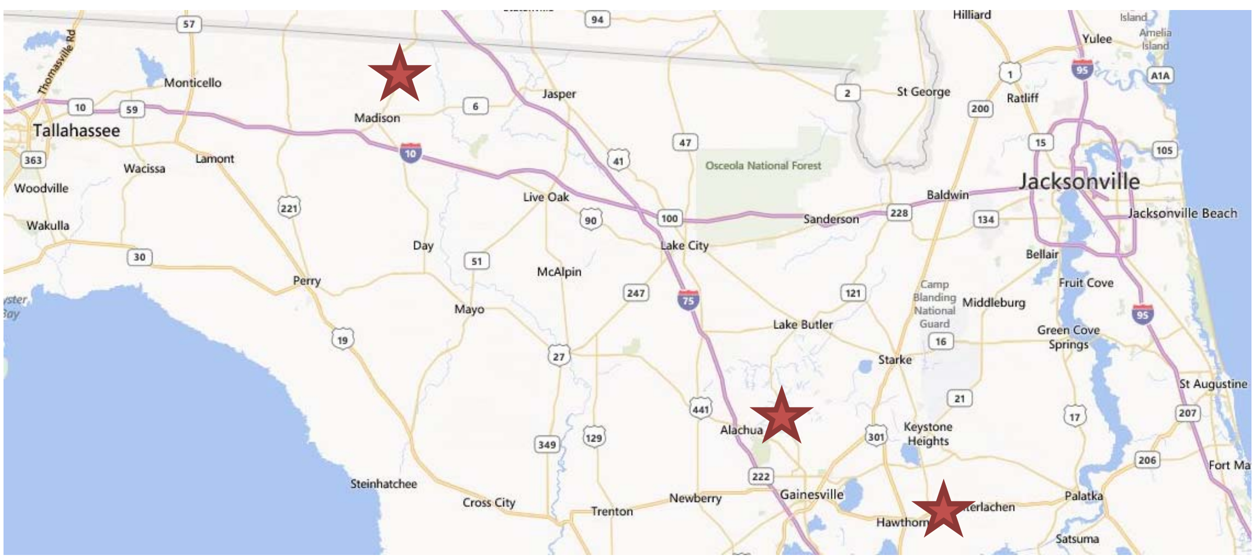


Figure 6. Work zone site locations

Site 1 Description

The first field site identified was located on SR-145 between the cities of Madison, FL and the Florida/Georgia border. This road is a frequent logging route and features a large percentage of heavy vehicles. It is more rural in nature, and the total AADT on this road was approximately 2000 in 2010. The length of lane closures on this roadway varied between 1.29 and 1.95 miles. The distance weighted average of the posted speed in these lane closures was mainly 55 mi/h, while one lane closure had an average posted speed of 60 mi/h. Construction activities consisted mainly of milling and resurfacing. Figure 7 shows a general map of the location of the construction along this road. It should also be noted that a few access roads are located along this stretch of road and had some contribution to the traffic through the lane closures. These roads primarily provide access to residential neighborhoods.

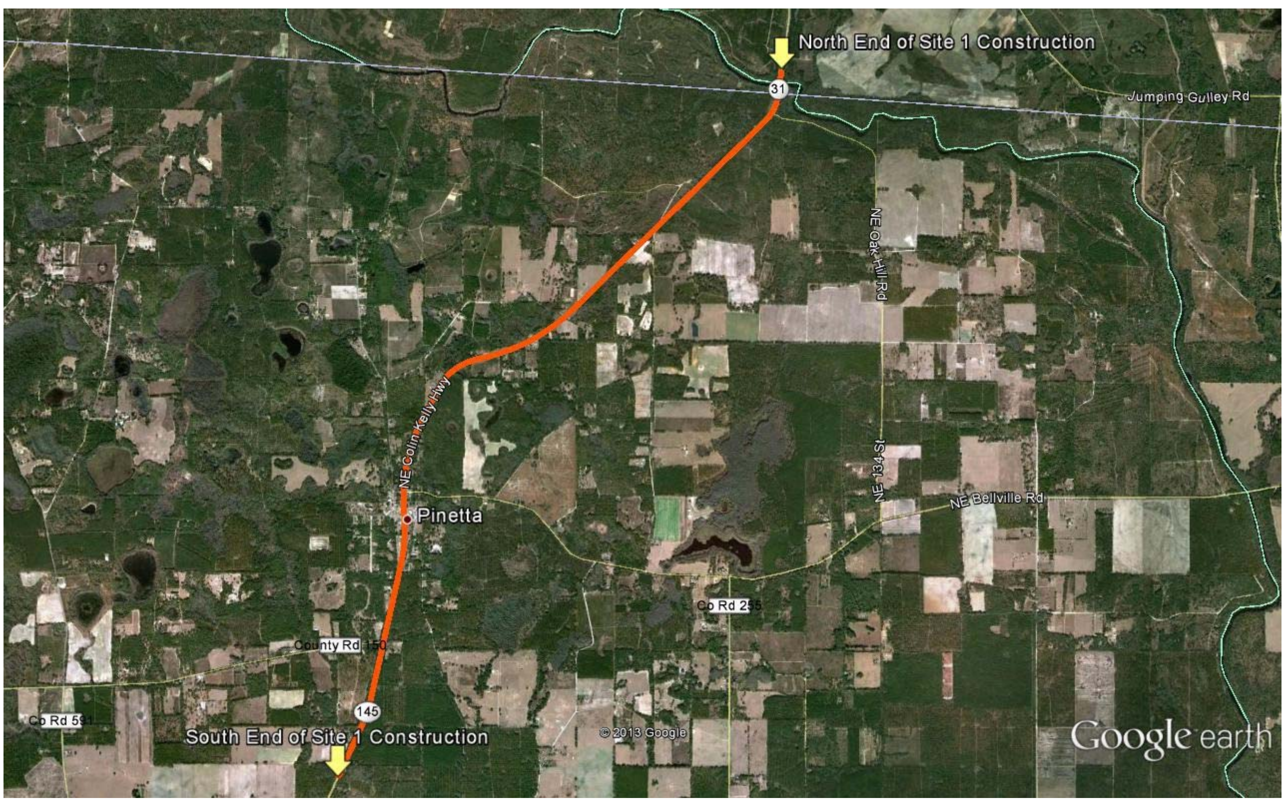


Figure 7. Extent of construction along SR-145 (site 1)

Site 2 Description

The second field site identified was located on SR-235 between the cities of Alachua, FL and La Crosse, FL. This road is more rural in nature, and the total AADT on this road was approximately 2800 in 2010. The length of lane closures on this roadway varied between 1.63 and 2.00 miles. The distance weighted average of the posted speed in these lane closures was 55 mi/h. Construction activities consisted mainly of milling and resurfacing. Occasional access roads are located along this stretch of road. These roads primarily provide access to more rural residences although a couple provided access to religious institutions. Figure 8 shows a map of where construction was being performed along this stretch of road.

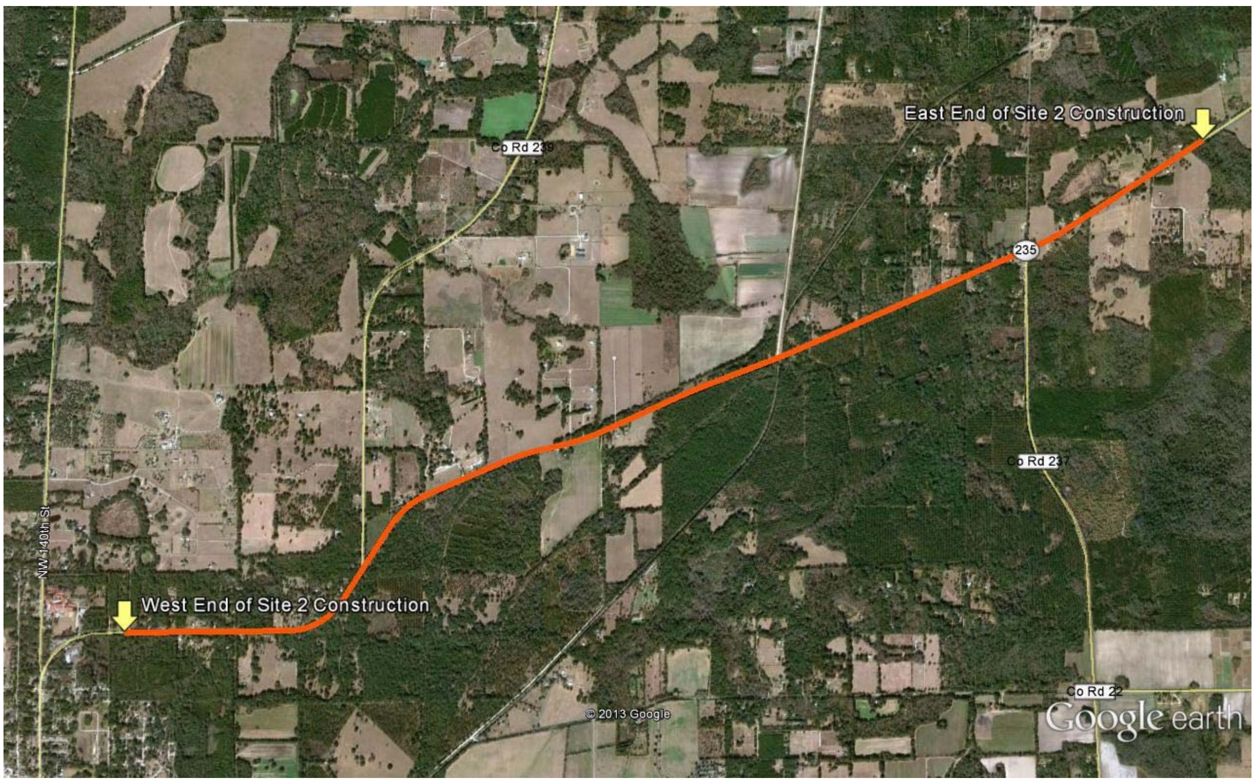


Figure 8. Extent of construction along SR-235 (site 2)

Site 3 Description

The third field site identified was located on SR-20 between the city of Hawthorne, FL and the intersection of SR-20 and SR-21. This road is heavily trafficked by commuters in the both the morning and afternoon. As a result, this road is less rural in nature during these peak periods and features larger volumes of traffic compared to sites 1 and 2. The total AADT on this road was approximately 8200 in 2010. The length of lane closures on this roadway varied between 0.74 and 1.63 miles with only one lane closure being over 1 mile. The distance weighted average of the posted speed in these lane closures was mainly 55 mi/h, while one lane closure had an average posted speed of 50 mi/h. Construction activities performed at this site primarily consisted of shoulder reconstruction and sodding. Figure 9 shows a map of the location of the construction along this road. Occasional access roads are located along this stretch of road. These roads can serve as alternate routes to the nearby city of Hawthorne and SR-21.

Figure 9. Extent of construction along SR-20 (site 3)

Data Collection Procedure

To obtain adequate data for calibration of the FlagSim simulation program, it was desirable to obtain approximately 4 hours of data each day for 4 different days at each of the three study sites. Due to the microscopic nature of the data required for this study, video was selected as the method by which to collect the data. For each study site, stationary cameras were placed at each end of the lane closures to observe vehicles entering and exiting the work zone, queuing at the work zone, and flagging operations. The video feed was recorded to an external hard drive recorder which was secured in a Pelican case next to the camera. Both the camera and hard drive recorder were powered by a single 12-volt battery. An example of the type of equipment and set up used to collect the data is shown in Figure 10.

Figure 10. Video camera and external hard drive recorder setup used for data collection

In addition to obtaining data at the entrances to the work zones, it was also desirable to obtain some data on the traffic operations within the lane closure. In order to obtain information about these traffic operations, an instrumented Honda Pilot was driven through the work zone along with regular traffic. This vehicle was equipped with cameras that recorded video of each trip that was made through the work zone. This video was used to obtain information about other factors within the work zone, such as available lane width, construction activity, and construction vehicle presence that may have a significant impact on vehicles' travel times through the work zone. It was desired to record approximately 12 trips through the work zone (6 in each direction) for each couple of hours of data collection at each site. Figure 11 shows the instrumented vehicle used for the data collection.

Figure 11. Instrumented Honda Pilot used to collect data inside work zone

Description of Data Obtained from Study Sites

Video from Stationary Cameras

A total of 34.5 hours of data was obtained from the three study sites. Data for site 1 were collected on 10/25/2011, 10/27/2011, and 10/28/2011. Approximately 4 hours of data was collected on 10/25/2011 and 10/27/2011, while 3 hours of data were collected on 10/28/2011. Figure 12 shows a frame capture from one of the videos recorded at this site.

Figure 12. Entrance to work zone at site 1 on 10/25/2011

Data for site 2 were collected on 02/01/2012, 02/03/2012, 02/06/2012, 02/08/2012, and 02/09/2012. Unfortunately, the data collected on 02/01/2012 did not prove useful as it contained very minimal amounts of traffic (only 1 to 3 vehicles in queue). This very low traffic demand does not lend itself well to reliable calibration of the FlagSim program. As a result, these data was not used for the purposes of this project. Approximately 13.5 hours of data were collected on the remaining three days at the site. Specifically, 6, 2.5, 1.5, and 3.5 hours of data were collected on 02/03/2012, 02/06/2012, 02/08/2012, and 02/09/2012, respectively. Figure 13 shows a frame capture from one of the videos recorded at this site.

Figure 13. Entrance to work zone at site 2 on 2/3/2012

Data were collected from site 3 on 01/21/2013, 01/23/2013, 01/24/2013, and 01/25/2013. Because this site featured shorter lane closures, it was necessary for the construction crew to move the location of the lane closure more frequently as the construction progressed throughout the day. As a result, the length and location of the lane closure varied throughout each day. Approximately 10 hours of data were collected at this site. Specifically, 2, 2.5, 3, and 2.5 hours of data were collected on 01/21/2013, 01/23/2013, 01/24/2013, and 01/25/2013, respectively. Figure 14 shows a frame capture from one of the videos recorded at this site.

Figure 14. Entrance to work zone at site 3 on 1/25/2013

Video from Instrumented Honda Pilot

A total of 117 trips were made through the various work zones at the three sites. Fifty-one trips were made at site 1, 29 trips were made at site 2, and 37 trips were made at site 3. Figure 15, Figure 16, and Figure 17 show frame captures from the in-vehicle videos recorded at sites 1, 2, and 3, respectively.

Figure 15. Video from instrumented Honda Pilot at site 1 on 10/25/2011

Figure 16. Video from instrumented Honda Pilot at site 2 on 2/9/2012

Figure 17. Video from instrumented Honda Pilot at site 3 on 1/24/2013

Data Processing

Once the data had been collected at a lane closure site, it was necessary to process these data to obtain the information needed for the calibration of FlagSim. This processing required watching the videos from both the stationary cameras as well as from the instrumented Honda Pilot. Pertinent information from these videos was recorded into Excel spreadsheets. The data items that were obtained from these two video sources are discussed in the following sections.

Before proceeding with the discussion, the following definitions are provided for several terms used throughout the remainder of this report:

- *Green time*: "Green" time, which means "go time", is the time during which, for a given travel direction, the flag person's paddle/sign is displaying 'slow'. The total green time is calculated as the difference in time from when the flag person changes the paddle/sign from 'stop' to 'slow' and back to 'stop'. The definition of this term as used in this study is consistent with the definition of 'displayed green time' in signalized intersection analysis.

- *Red time*: "Red" time, which means "stopped time", is the time during which, for a given travel direction, the flag person's paddle/sign is displaying 'stop'. The total red time is calculated as the difference in time from when the flag person changes the paddle/sign from 'slow' to 'stop' and back to 'slow'. The definition of this term as used in this study is consistent with the definition of 'displayed red time' in signalized intersection analysis.

- *Phase time*: The phase time was calculated as the green time plus the time it takes the last vehicle to enter the work zone during the displayed green to exit the work zone. More generally, this is referred to as green time plus work zone travel time. There were some cases where the flag person allowed one or more vehicles to enter the work zone after he/she turned the paddle/sign to 'stop'. In these cases, the time that the flag person changed the flag to 'stop' was changed to the time that the last vehicle entered the work zone. However, this was not done in cases where the vehicle(s) that entered after the paddle/sign had been changed to 'stop' were associated with the construction activities (i.e., the vehicle did not exit the work zone during that phase).

- *Lost time*: As used in this study, the definition of total lost time for a phase is consistent with the definition as used in signalized intersection analysis—that is, the time during which vehicles for a given approach/direction are not moving. This lost time is typically separated into a 'startup' lost time component and a 'clearance' lost time component. The startup lost time is considered to be the difference between the time when the front bumper of the last vehicle to exit the work zone crosses the stop bar and the time when the front bumper of the first vehicle of the opposing direction enters the work zone. The clearance lost time is considered to be the travel time through the lane closure area of the last vehicle for the opposing direction to enter the work zone, for a given phase.

- *Cycle time*: The cycle time (or length) is calculated as the difference in time from when the flag person for a given travel direction changes the paddle/sign from 'stop' to 'slow' to 'stop' and back to 'slow' again. This is equivalent to the phase time for one travel direction plus the phase time for the opposing travel direction.

Data from Stationary Camera Video

Some of the parameters outlined in the data requirements section were obtained from the stationary camera videos. An Excel spreadsheet was used to organize data for each travel direction for each day and site. An example of the type of Excel spreadsheet created for the stationary camera video data is shown in Appendix A. The data are organized for each phase observed from the video recordings. For each phase, certain information was recorded in order to obtain data for the parameters outlined in the data requirements section. This section discusses how such information was used to determine values for the parameters in the data requirements section. A discussion on what type of flagging control was employed in the field is also discussed.

Displayed paddle/sign indication change times

The time at which a flag person for a given travel direction change the displayed indication ('slow' or 'stop') was recorded. This allowed several of the above-defined time-related definitions to be calculated.

Vehicle type and work zone travel time

A record of each vehicle that entered the work zone was created. Each record contained the vehicle's work zone entry time and work zone exit time (for those vehicles that exited the work zone). Using the work zone entry and exit times of the vehicle, the work zone travel time for the vehicle was obtained. The vehicle was also classified as either a passenger car (PC), small truck

(ST), medium truck (MT), or large truck (LT). Pictures showing how the truck categories were classified can be found in Appendix B.

Average speed of vehicles in the work zone per phase

The work zone travel times for all vehicles entering the work zone during a given phase were averaged. This average work zone travel time was then used along with the length of the lane closure to determine the average speed of vehicles through the work zone for the phase.

Number of vehicles entering the work zone per phase

The time when each flag person switched their paddle/sign was recorded. From this information and the work zone entry time for each vehicle, the number of vehicles entering the work zone for each phase could be determined. It was also possible to determine how many vehicles of each different vehicle classification (e.g., passenger car, small truck) entered the work zone during each phase.

Startup lost time

The amount of startup lost time is a function of several factors. The first delay occurs as the last vehicle exiting the work zone travels from the work zone exit point to a safe distance in order to allow the next direction of vehicles to proceed. The exiting vehicle must maneuver the lane switch area and pass the first few vehicles queued. Second, additional time is needed for the flag person to switch their paddle/sign, such as the time it takes the flag person to determine when the work zone is clear. Finally, there is lost time for the first vehicle reacting to the change of the sign, similar to vehicles' startup lost time at a signalized intersection.

The startup lost time for each phase was calculated by taking the difference between the time the first vehicle in queue entered the work zone and the time the last vehicle traveling in the opposing direction exited the work zone. If the last vehicle traveling in the opposing direction exited after the flag person changed the paddle/sign to 'slow', the startup lost time calculation was modified. In this case, the startup lost time was calculated by taking the difference between the time the first vehicle in queue entered the work zone and the time the flag person changed the paddle/sign to 'slow'.

The mean and standard deviation of the startup lost time was determined for each site. These values are shown in Table 2. From this table, it can be seen that the first two sites had larger means and standard deviations than the third site. This is likely a result of the longer lane closures at these sites. Since these sites were more rural in nature and had longer lane closures, the amount of time that some drivers were waiting to enter the work zone was in the order of 4 to 7 minutes. As a result, some drivers were not paying as much attention to the flag person and took a little more time to start up after the flag person changed the paddle/sign to 'slow.' This resulted in larger startup lost time values compared to those obtained from the third site, which had shorter lane closures and was less rural in nature.

Table 2. Startup Lost Time Values Determined for Each Site

Site #	**Startup Lost Time**	
	Mean (s)	**Std. Dev. (s)**
1	14.73	10.56
2	15.18	11.56
3	10.00	4.75

Queue length

The queue length for each phase and direction was obtained by simply counting the number of vehicles in queue prior to the flag person changing the paddle/sign to 'slow'.

Saturation headway

The saturation headway for each phase and direction was obtained by using the work zone entry times of the first eight vehicles in queue. Specifically, this value was calculated by taking the difference between the work zone entry times of the first and eighth vehicle in queue and dividing by the number of headways between the first and eighth vehicle.

Type of flagging control employed

After watching the videos from the stationary cameras, it seemed as though most flag persons were using a 'distance gap out' mechanism to judge when to switch the travel direction right-of-way. The main input for this type of flagging control in FlagSim is the mean distance gap out value. From watching the videos, it was difficult to determine the distance gaps that the flag persons were using to control their paddle/sign. Therefore, the mean distance gap out value could not be determined with much accuracy. The time gaps associated with the distance gaps that the flag persons used, however, could be easily determined from the videos. While it is unrealistic for a flag person to directly employ a 'time gap out' method in the field, since the flag person would have to constantly look at a timing device, the use of a time gap out flagging control would allow for the best calibration of the FlagSim program. Therefore, a time gap out flagging control was used in place of a distance gap out flagging control for calibration of the FlagSim program.

In order to use this time gap out flagging control for the FlagSim calibration, it was necessary to determine the mean and standard deviation of the time gap out values used by the flag persons. The mean time gap out value was determined using a critical gap procedure. Specifically, Raff's critical gap method (1950) was used, which required the use of the gaps the flag persons accepted as well as rejected. This is the same method used to identify critical gap acceptance values for the unsignalized intersection analysis procedure in the HCM.

An accepted gap was calculated by taking the difference between the work zone entry times of two consecutive vehicles that entered the work zone during the same phase. Each phase contained multiple accepted gaps if more than two vehicles entered the work zone during the phase. A rejected gap was calculated for a given phase by taking the difference between the time the first vehicle arrived at the work zone after the flag person changed the paddle/sign to 'slow' and the time the last vehicle in the phase entered the work zone. There was only one rejected gap per phase.

Rather than estimating the time gap out values to the nearest second, it was determined that it would be more beneficial to estimate the time gap out values to the nearest 5 seconds. This was because the actual values of the accepted and rejected gap values were only accurate within a couple of seconds, since the work zone entry times could only be obtained from the videos to the nearest second. Therefore, the accepted and rejected gap values were placed into 5 second bins between 0 and 60 seconds. Values greater than or equal to 60 seconds were placed into a separate bin, since a very small number of gaps greater than or equal to 60 seconds were accepted by the flag persons.

After the accepted and rejected gaps were placed into these bins, the critical time gap out value was determined. A graph was created to show the cumulative number of accepted gaps and rejected gaps for the different bins. From this graph the critical time gap out value was determined by looking at the point where these cumulative curves intersected. This value was used as the mean time gap out value in FlagSim. Since the critical time gap out value was only accurate within 5 seconds, it was decided that a standard deviation of 5 seconds was appropriate for the time gap out value.

Critical time gap out values were determined for each site. These values are shown in Table 3. From this table, it can be seen that the first two sites had a larger mean critical time gap out value as compared to the third site. This is likely a result of the longer lane closures and smaller traffic demands at sites 1 and 2. Because the lane closures were longer and not as many vehicles needed to enter the work zone, the flag persons would generally allow any late arriving vehicles to enter the work zone, even if the vehicles were a good distance away from the work zone. This in turn increased some of the accepted gap values, which resulted in a larger critical gap. The graphs that were used to obtain the critical gap values for each site are shown in Figure 18, Figure 19, and Figure 20. The data used to create these plots can be found in Appendix A.

Table 3. Critical Time Gap Out Values Determined for Each Site

Site #	Critical Time Gap Out	
	Mean (s)	Std. Dev. (s)
1	30	5
2	30	5
3	25	5

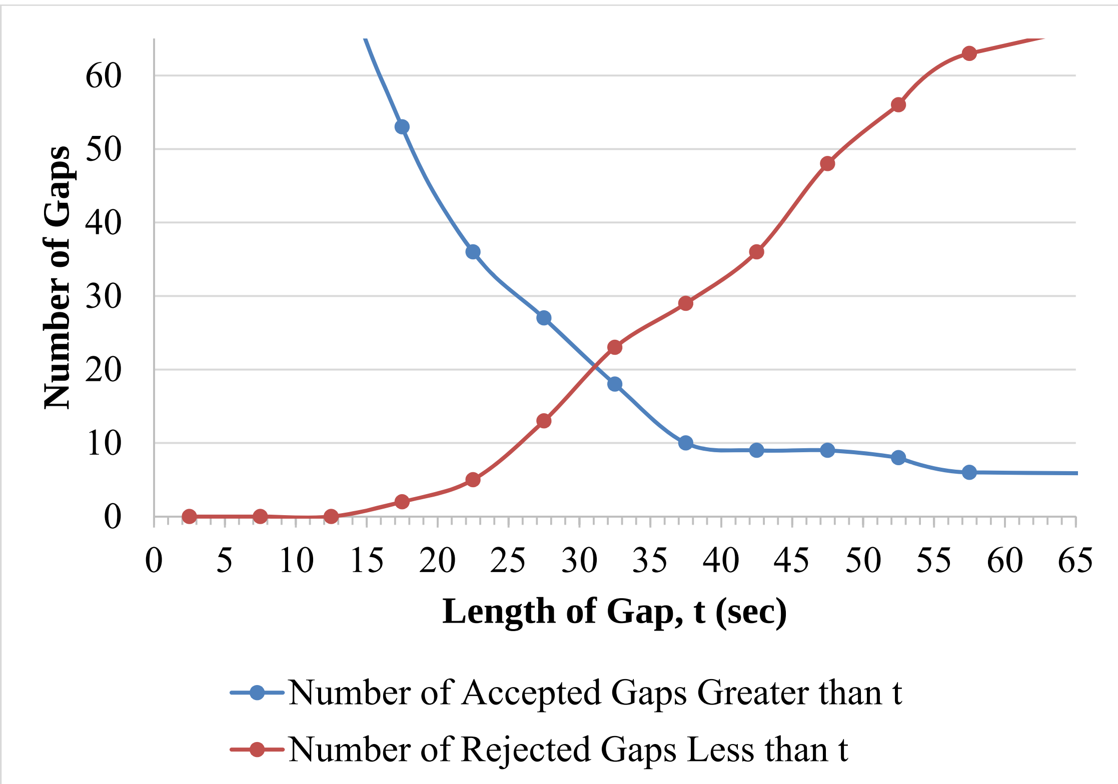


Figure 18. Critical gap for site 1

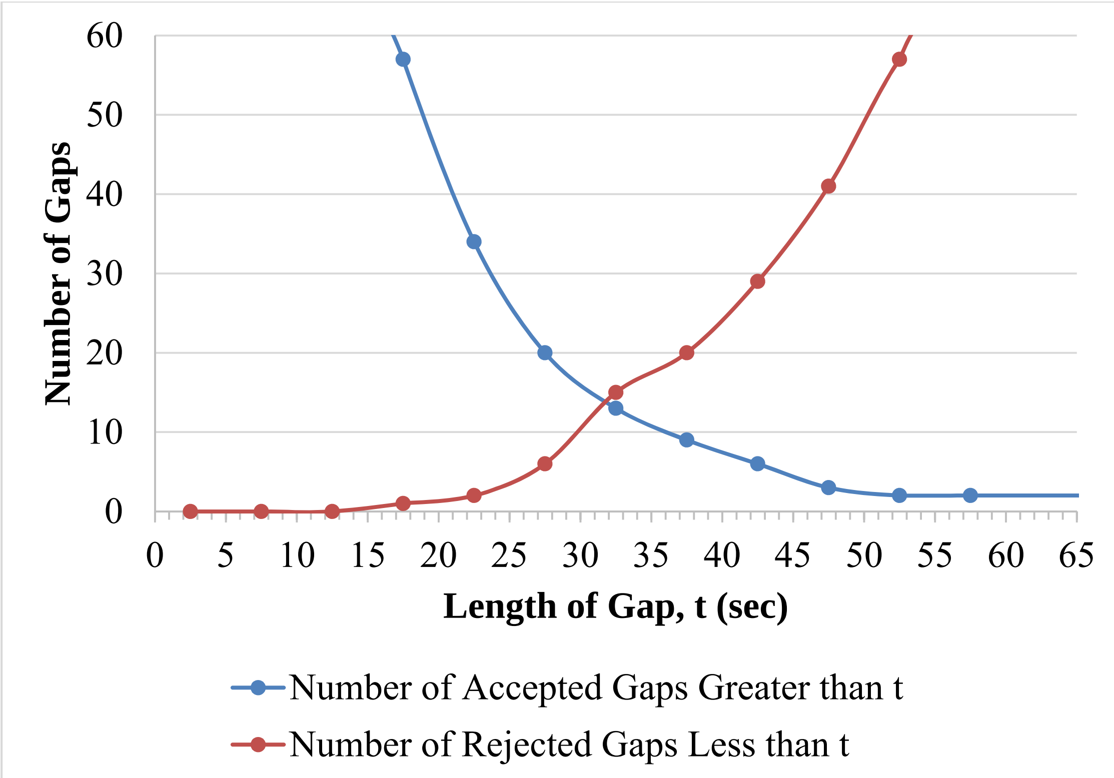


Figure 19. Critical gap for site 2

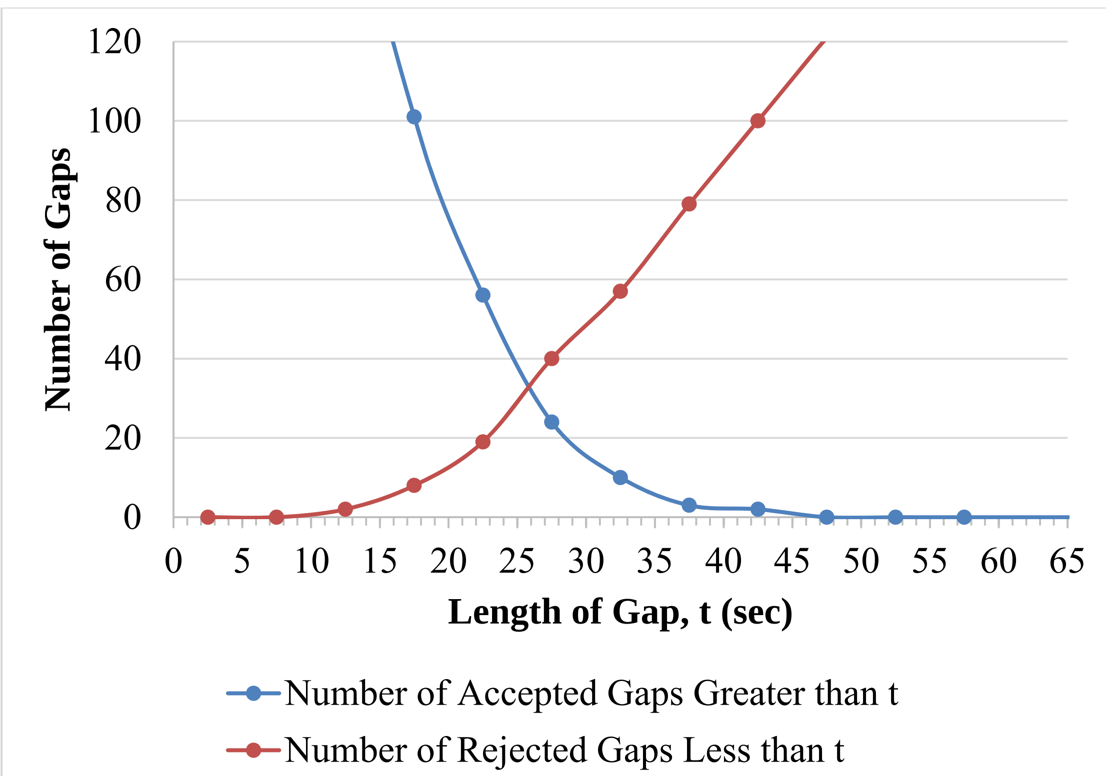


Figure 20. Critical gap for site 3

Video from Instrumented Vehicle

Video of trips made through the work zone in the instrumented Honda Pilot were used to ascertain information about different factors within the work zone that may have an impact on traffic operations in the work zone. Specifically, it was desirable to determine what factors may have an impact on vehicles' speeds through the work zone. From watching the videos, it was observed that the following factors may have influenced vehicles' speeds:

- Effective lane width – the width of the pavement available for vehicles to drive on (includes paved shoulders)
- Construction activity – level of construction activity taking place (e.g., milling and resurfacing, shoulder work, sodding)
- Construction vehicle presence – number of stationary construction vehicles parked on the closed lane in close proximity to vehicles traveling on the open lane
- Travel direction of closed lane – whether drivers will have to travel in the "opposing" lane through the work zone
- Percentage of construction vehicles entering the work zone – the percent of construction vehicles that entered the work zone during a phase but did not exit

Information about the first four factors above was determined from the instrumented Honda Pilot video. Information about the last factor, percentage of construction vehicles entering the work zone, was determined from both the stationary camera video and instrumented Honda Pilot video. An Excel spreadsheet was used to organize information about each of these factors for all recorded trips through the work zone. A screenshot of this spreadsheet can be found in Appendix A. The type of information obtained for each of these factors is discussed below in its respective section.

Effective lane width

Based on observations from the videos, it was hypothesized that as the lane width available to drivers in the work zone decreased, the average speed of vehicles in the work zone also decreased. Therefore, this effective lane width was recorded for each trip made through the work zone by the instrumented Honda Pilot. It was difficult to determine a precise numeric value for the effective lane width from the videos, so this variable was categorized into three general levels (narrow, medium, and wide).

Narrow lane widths were assigned for lanes that had no, or a very narrow, shoulder and cones placed inside the lane. Figure 21 shows an example of a narrow effective lane width. Medium lane widths were assigned for lanes that had a small shoulder and cones placed outside the lane or on the centerline. Medium lane widths were also assigned for lanes that had a relatively wide shoulder and cones placed inside the lane. Figure 22 shows an example of a medium effective lane width. Wide lane widths were classified for a lane with a relatively wide shoulder and cones placed outside the lane or on the centerline. Wide lane widths were also assigned for lanes that had a narrow shoulder but cones placed outside the lane. Figure 23 shows an example of a wide effective lane width.

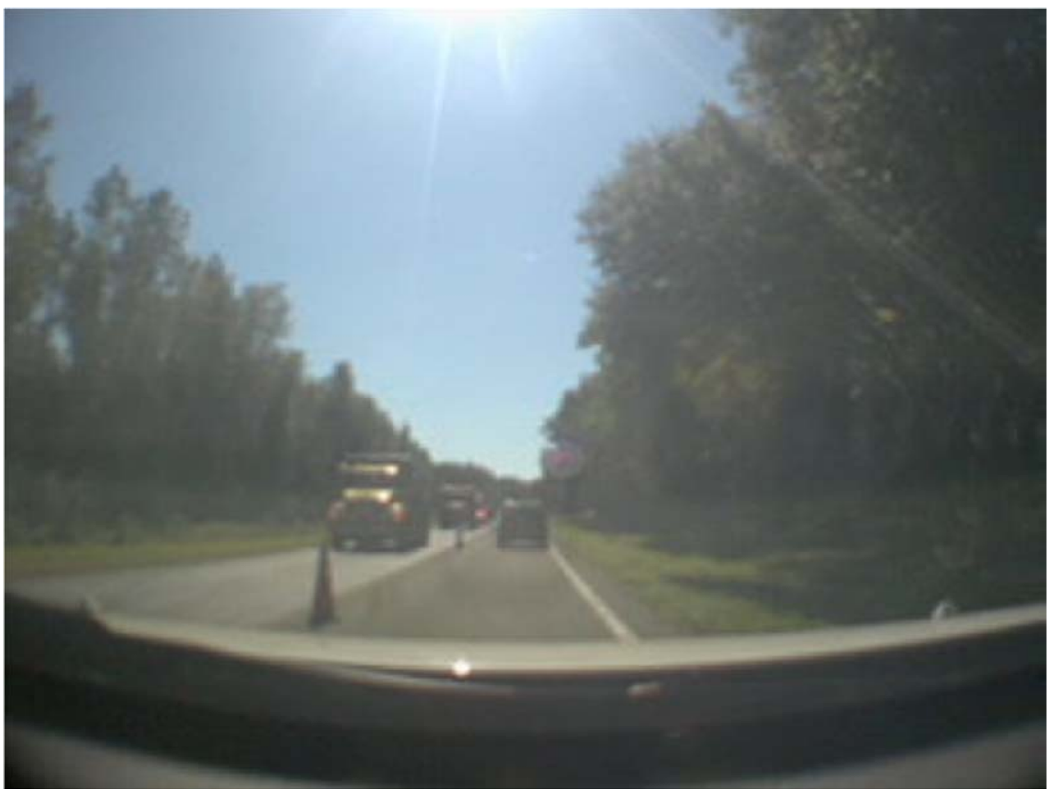


Figure 21. Example of narrow effective lane width from site 1


Figure 22. Example of medium effective lane width from site 2

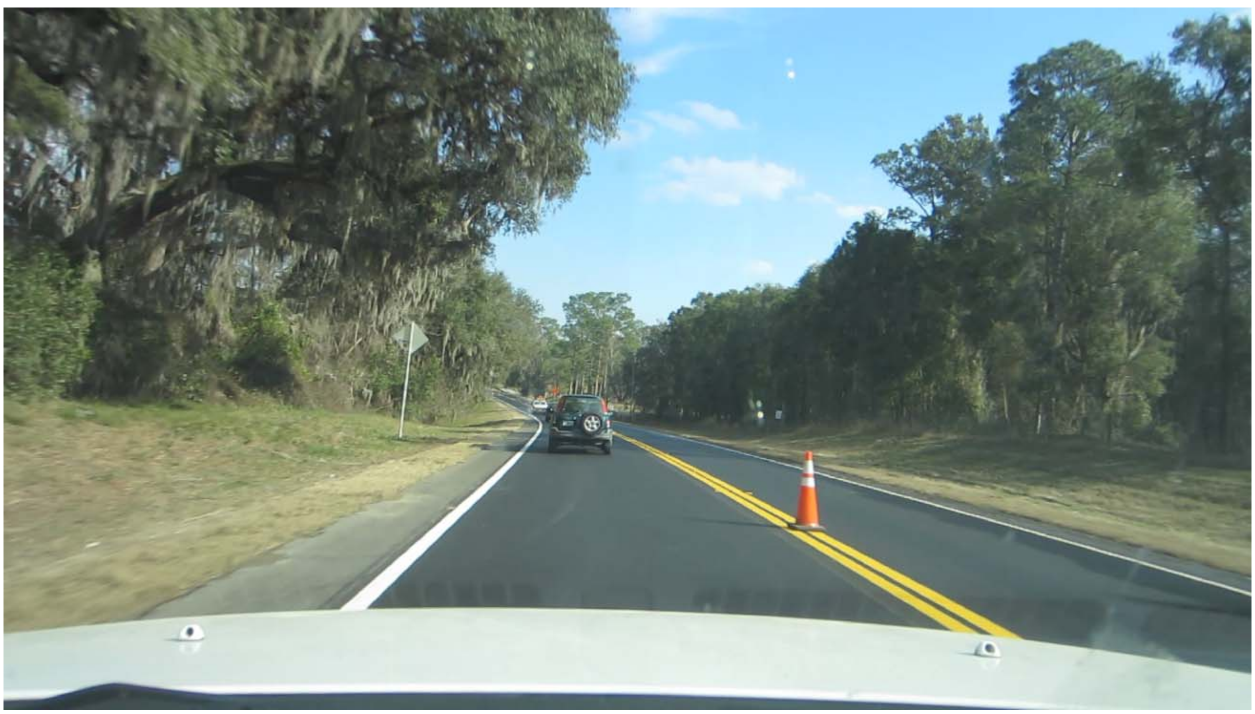


Figure 23. Example of wide effective lane width from site 3

Construction activity

The construction activity in the work zone also appeared to have an effect on vehicles' speeds in the work zone. Therefore, the construction activity was recorded for each trip through the work zone. Since a numeric value was not able to be put on the construction activity, three different categorical levels were used for this variable (low, medium, and high). Low construction activity was considered for activities such as sodding, shoulder work, or any other activity that required few construction vehicles or equipment to operate close to the open travel lane. Medium construction activity was considered for activities such as milling or resurfacing or any other activity that required several construction vehicles or pieces of equipment to operate close to the open travel lane. High construction activity considered for activities such as both milling and resurfacing taking place at the same time or any other activity that required a large number of construction vehicles or equipment to operate close to the open travel lane.

Construction vehicle presence

The number of stationary construction vehicles that were in proximity to the open travel lane was also thought to have some effect on vehicles' speeds in the work zone. Since some construction vehicles (e.g., dump trucks, rolling equipment) would sit on the closed travel lane in close proximity to the open travel lane, it was thought that drivers may tend to slow down when driving past these vehicles. This could lead to lower average speeds in the work zone. The presence of construction vehicles was recorded for each trip made with the instrumented Honda Pilot. Developing a precise numeric value for this factor was not practical; thus, three different categorical levels were used (low, medium, and high). Low construction vehicle presence was defined as having very few construction vehicles in the work zone, and if there were vehicles, they were not close to the open travel lane. Medium construction vehicle presence was defined as having a few construction vehicles in the work zone. These were mainly pickup trucks or other smaller pieces of construction equipment, but there could be a few larger construction vehicles (e.g., dump trucks). A few of these construction vehicles would be close to the open travel lane, but the majority would not. High construction vehicle presence was defined as having a large number of construction vehicles in the work zone. These vehicles would consist of larger construction vehicles (e.g., dump trucks, semi-tractor trailers), and many of these vehicles would be in close proximity to the open travel lane.

Travel direction of closed lane

If a driver is traveling on the lane that is closed, he/she will have to temporarily switch lanes and travel on the opposing lane when proceeding through the work zone. Since drivers are not accustomed to driving in the opposite lane, they may be more cautious when proceeding through the work zone. As a result, the average speed of vehicles in the work zone may be slightly lower for the travel direction with the closed lane as opposed to the direction with the open lane. The travel direction of the closed lane was recorded for each of the trips through the work zone in the Honda Pilot.

Percentage of construction vehicles entering the work zone

When watching some of the videos, vehicles associated with the construction activities (e.g., dump trucks) were seen departing from the open travel lane and moving onto the closed travel lane to help with the construction activities. Before these vehicles moved off the open travel lane and onto the closed travel lane, they usually decelerated, sometimes causing the vehicles traveling behind them to slow down. As a result, the travel times of these vehicles may have been extended due to this impedance by the construction vehicles. Information about how many of these construction vehicles entered the work zone was not able to be accurately determined from the instrumented Honda Pilot videos. Fortunately, this information could be obtained from the stationary camera video. Therefore, the construction vehicles which entered the work zone but did not exit were identified for each phase. These vehicles were temporarily assigned a classification of CV, for construction vehicle, within the spreadsheet data logs. The percentage of construction vehicles that entered the work zone was then determined for each of the trips the Honda Pilot made through the work zone. It should be noted that most of the construction vehicles that entered the work zone and did not exit were dump trucks.

Models from Field Data

Two models were estimated from the field data—one for average travel speed through the work zone and one for the average saturation headway of vehicles discharging from a queue into the work zone.

Work Zone Speed Model

With the impact to the overall cycle length due to the lost time caused by traversing the work zone, the estimation of the work zone travel speed must be as accurate as possible. A regression analysis was performed on all of the data recorded from the Honda Pilot trips through the work zone (92 trips). The resulting model formulation is shown in Eq. 8.

$$\begin{aligned} WorkZoneSpd_i &= 0.4611 - 0.4694 \times \%HV_i - 12.9068 \times LW\_Narrow - 8.2328 \times LW\_Medium \\ &+ 0.8501 \times PostedSpd - 1.33 \times TravelDirClosedLane - 0.0590 \times NumVeh_i \\ &- 2.5092 \times ConstAct\_MedHigh + 0.5310 \times \%HV_i \times LW\_Narrow + 0.2993 \times \%HV_i \times LW\_Medium \end{aligned} \quad [8]$$

where

$WorkZoneSpd_i$ = average travel speed of vehicles through the work zone for phase *i* (mi/h)
$\%HV_i$ = percentage of heavy vehicles in the traffic stream for phase *i*
LW_Narrow = 1 if the effective lane width is narrow, 0 otherwise
LW_Medium = 1 if the effective lane width is medium, 0 otherwise
PostedSpd = the posted speed limit through the work zone (mi/h)
TravelDirClosedLane = 1 if vehicles are traveling in the direction of the closed lane (i.e., they perform a lane shift when entering and exiting work zone), 0 otherwise
$NumVeh_i$ = the number of vehicles entering the work zone for phase *i*

ConstAct_MedHigh = 1 if the level of construction activity in the work zone is medium or high, 0 otherwise

The signs of the variables are all as expected. When interpreting coefficient signs, keep in mind that some variables appear more than once in the equation (e.g., %HV and lane widths), and that some terms are interactions (e.g., the last two terms). All of the non-intercept terms were significant at the 95% or better confidence level, except for the *NumVeh* term, which was significant at the 90% confidence level and the *ConstAct_MedHigh* term, which was significant at the 85% confidence level. The adjusted R^2 value of the model is 0.684. Given all of the variability in the field data, this moderate level of model fit was expected.

Saturation Headway Model

One of the key parameters to all of the calculations in the analysis procedure is saturation headway. This measure refers to the time headway between vehicles when departing from a standing queue when the traffic signal (or flag person's paddle/sign in this case) turns green. A regression analysis was performed on all of the phase data recorded from the field for phases that had at least 8 vehicles in queue at the start of the phase (358 phases). The resulting model formulation is shown in Eq. 9.

$$\bar{h}_{sat\_i} = 2.9817 + 0.0127 \times \%ST_i + 0.0417 \times \%MT_i + 0.0487 \times \%LT_i \qquad [9]$$

where

$\bar{h}_{sat\_i}$ = average saturation headway for phase *i* (s/veh)
$\%ST_i$ = percentage of small trucks in the traffic stream for phase *i*
$\%MT_i$ = percentage of medium trucks in the traffic stream for phase *i*
$\%LT_i$ = percentage of large trucks in the traffic stream for phase *i*

The signs of the variables are all as expected, and all of the terms were significant at the 95% or better confidence level. The adjusted R^2 value of the model is 0.627. Again, given all of the variability in the field data, this moderate level of model fit was expected.

CHAPTER 4
SIMULATION ANALYSIS AND RESULTS

This chapter describes the simulation aspect of this project. Because a wide range of input conditions were not obtained from the field sites described in the previous chapter, it was necessary to use simulation to be able to analyze the performance of two-lane roadways with a lane closure across a wide range of conditions (e.g., length of lane closure, traffic demand, work zone posted speed, etc.). The main purpose of the field data was to identify the appropriate values for the various settings that affect the behavior of the vehicles and flagging operations in the simulation program.

Two-lane work zones are unique in their operation. In order to model the operations reasonably accurately, a simulation program must have the following capabilities at a minimum:

- model the flagging control method used in the field
- model vehicle arrivals at the work zone
- model vehicles discharging from the stop line
- model heavy vehicles, in addition to passenger cars
- model vehicles traveling through the work zone
- record various simulation results in order to allow for the following performance measures to be calculated, such as
    - queue delay
    - travel time delay due to reduced speeds
    - queue length
    - capacity

Most, if not all, existing commercially available simulation packages do not explicitly provide for modeling work zones on two-lane roadways, nor are they easily configured for such modeling, particularly because of the unique aspects of flagging control. The FlagSim simulation program was used for the simulation aspects of this project. This program was also used for the predecessor project to this one; however, it has undergone a number of enhancements since that time. A detailed overview of the program is provided in the Users Guide, which is included in Appendix C of this report.

Calibration

The calibration effort consisted of initially setting the various driver and vehicle parameters in FlagSim to values consistent with observations from the field data and/or other data sources. A large number of simulation runs, with a range of input conditions consistent with the range of input conditions observed in the field, were then made. The simulation results for average work zone travel speed and average saturation headway were then compared to the field values. This process was repeated many times, with small revisions made to one or more of the driver parameters each time. The driver parameter values that resulted in the best fit of the simulation data to the field data were retained for further use in the FlagSim simulation runs. The vehicle parameters were not varied from their initial settings. The vehicle and driver parameters are accessed through the 'Advanced Vehicle/Driver Parameters' screen in FlagSim (see Users Guide in Appendix C). These parameters and their settings are described in the remainder of this section.

Vehicle Parameters

Vehicle Dimensions (length, width, height)

The three truck classifications discussed in the previous chapter were generally matched to the standard FHWA classifications as follows:

- Small Truck—Class 5 and 6
- Medium Truck—Class 8
- Large Truck—Class 9, 11, and 12

The dimensions of the three truck types were set accordingly. The passenger car dimensions were based on common sedan-type vehicle—specifically a Honda Civic. The selected dimensions are shown in Table 4.

Maximum Acceleration

Maximum acceleration is not an input to FlagSim. FlagSim now uses a full vehicle dynamics modeling approach to determine the maximum acceleration of a vehicle. This model takes into account the vehicle's physical (such as frontal area, drag coefficient, and weight) and drivetrain (such as engine output and transmission gearing) characteristics to determine the tractive effort available to accelerate the vehicle at every time step during the simulation. This approach also allows roadway grade to be accounted for, as this affects the grade resistance in the acceleration calculations. This approach for modeling maximum acceleration is described in more detail in the FlagSim Users Guide (see Appendix C).

Vehicle Weight

For another FDOT research project (BDK77-977-15), weigh-in-motion (WIM) data were obtained for numerous locations across the state for a recent 3.5 year period. Of the 24 WIM data collection locations, three of these stations were located on two-lane highways. The data from these three sites were used to establish weight values for the three truck types. The passenger car weight was based on the vehicle manufacturer's data specification sheet. The selected weights are shown in Table 4.

Drag Coefficient

The drag coefficient values were set according to guidance in Mannering and Washburn (2012) (see Chapter 2).

Maximum Torque and Power

The maximum engine torque and power were set according to the values established through FDOT Project BDK77-977-15. These values are shown in Table 5.

Transmission Gear Ratios

The transmission gear ratios were set according to the values established through FDOT Project BDK77-977-15. The reader is referred to that project report for the specific values.

Maximum Deceleration

Typically achievable maximum deceleration rates as shown in Table 5 were used. However, since these deceleration rates usually only occur in emergency braking situations, they rarely are utilized in a FlagSim simulation.

Table 4. Vehicle Type Physical Characteristics

Vehicle Type	Length (ft)	Width (ft)	Height (ft)	Weight (lb)	Drag Coeff.
Passenger car	14.6	5.7	4.5	3060	0.33
Small truck	30	7	10	17000	0.55
Medium truck	45	8	10	36000	0.66
Large truck	68.5	9	10	53000	0.66

Table 5. Vehicle Type Drivetrain Characteristics

Vehicle Type	Max Torque (ft-lb)	Max Power (hp)	Max Decel (ft/s^2)
Passenger car	139	197	-19
Small truck	660	300	-15
Medium truck	1650	485	-15
Large truck	1650	485	-15

Driver Parameters

Desired Acceleration

The desired acceleration rates were set as 3.8 ft/s^2, 2.5 ft/s^2, 2.0 ft/s^2, and 2.0 ft/s^2 for passenger cars, small trucks, medium trucks, and large trucks, respectively. These values were consistent with in-vehicle GPS data from other studies and observations from the field videos.

Desired Deceleration

Values of 10 and 11 ft/s^2 have been identified as appropriate for non-emergency braking situations (Mannering and Washburn, 2012). A value of 11 ft/s^2 was used for passenger cars. Since truck drivers are usually a little less tolerant of having to decelerate, slightly lower values were used—9 ft/s^2, 8 ft/s^2, and 7 ft/s^2 for small, medium, and large trucks, respectively.

Desired Speed %

The base desired speed value is a function of factors such as posted speed limit, construction activity, effective lane width, and direction of closed lane. This desired speed % input specifies the percentage difference from the base desired speed value that a driver will desire to travel when not constrained by other vehicles. To identify these values, the average speeds through work zone of the different vehicles types were calculated. Values were calculated for all vehicles traveling through the work zone, just the vehicles not considered to be in a following mode (using a headway threshold of 6 seconds), and just the lead vehicle of each platoon of vehicles traveling through the work zone. After examination of all the values, it was felt that the values based on just the lead vehicles of platoons were the most reliable. From these measurements, values of 7.5%, 0%, -3%, and -5% were set for passenger cars, small trucks, medium trucks, and large trucks, respectively. In other words, passenger car drivers will travel 7.5% above the base desired speed value, on average, while large truck drivers will travel 5% below the base desired speed value, on average.

Desired Headway

The desired following headway values were set as 1.5 s, 2.25 s, 2.75 s, and 3.0 s for passenger cars, small trucks, medium trucks, and large trucks, respectively.

Stop Gap

This input specifies the distance between the rear bumper of a lead vehicle and the front bumper of a trail vehicle, while at a stop (i.e., in a queue waiting to enter the work zone). The stop gap values were set as 12 ft, 16 ft, 20 ft, and 22 ft for passenger cars, small trucks, medium trucks, and large trucks, respectively.

Other Input Values

Other inputs necessary to run the simulations for the calibration, as well as all subsequent simulations are as follows.

Flag Control Settings

- Flagging method: As discussed in Chapter 3, the 'time gap out' flagging method was employed in FlagSim. Based on the field results of gap out times, it was decided to use a mean gap out time of 30 seconds (with a standard deviation of 5 seconds) for 'rural' conditions, which were considered to be sites with lane closures of one mile or greater and posted speed limits greater than 40 mi/h, and a mean gap out time of 25 seconds (with a standard deviation of 5 seconds) for all other conditions.

- Startup lost time: As for the gap out times, two different sets of times were used for rural and non-rural conditions. For rural conditions, a mean startup lost time of 15 seconds (with a standard deviation of 10 seconds) was used, and for all other conditions a mean startup lost time of 10 seconds (with a standard deviation of 5 seconds) was used.

- Minimum green time: This value was set to 5 seconds. This variable is essentially a non-factor when the time gap out flagging method is used.

- Maximum green time: This value was set to 300 seconds. Most field phases were considerably shorter than this, but a few phases reached as high as 290 seconds.

Vehicle Distribution

While a variety of total truck percentages were run as part of the overall set of simulation runs, the relative percentages of small, medium, and large trucks were varied only at two levels. Based on the field data, the small, medium, and large truck percentage splits used were 20, 35, and 45, respectively, for rural conditions. For non-rural conditions, the small, medium, and large truck percentage splits used were 45, 20, and 35, respectively.

Approach Roadway Length

The approach roadway length was set to 1.5 miles, which was sufficient to accommodate the queuing for nearly all simulation scenarios. Any simulation runs that resulted in a queue length equal to the approach roadway length (FlagSim will only report queue lengths up to the length of the approach roadway length) were removed from the data set.

Approach Roadway Posted Speed

The approach roadway posted speed was set to the same value as the work zone posted speed.

Work Zone Travel Delay Threshold Speed

The work zone travel delay threshold speed is set to the work zone posted speed. Vehicles traveling less than this speed in the work zone accumulate travel delay.

Queue Delay Threshold Speed

The queue delay threshold speed is set to 10 mi/h. Vehicles traveling less than this speed on the approach roadway accumulate queue delay.

Simulation Duration

A 5-minute warm-up period and a 60-minute simulation period were used for each simulation run.

Results

The calibration results between FlagSim and the field data for average work zone travel speed were based on a total of 1012 individual phases that covered a wide range of inputs. A linear regression analysis of the two sets of values produced an adjusted R^2 value of 0.732.

The calibration results between FlagSim and the field data for average saturation headway were based on a total of 845 individual phases that covered a wide range of inputs. A linear regression analysis of the two sets of values produced an adjusted R^2 value of 0.852.

Again, any driver parameter values different from the values given above resulted in lower R-squared values. Overall, this level of calibration between the field data and FlagSim is quite reasonable given the considerable variability in the field conditions.

Simulation-Based Models

With the appropriate values set for the various driver parameters and other input variables through the calibration effort, the final models to be used in the analysis procedure were then developed. These models consisted of work zone travel speed, saturation headway, queue delay, and queue length.

Work Zone Speed Model

The work zone speed model was based on results for over 17,000 one-hour simulation runs that covered a wide range of inputs. A regression analysis of all the simulation results yielded the model formulation shown in Eq. 10.

$$\begin{aligned} WorkZoneSpd_i &= 2.7481 - 0.1246 \times \%HV_i - 11.5697 \times LW\_Narrow \\ &- 7.3768 \times LW\_Medium + 0.0577 \times \%HV_i \times LW\_NarrowMedium \\ &- 2.1289 \times ConstAct\_MedHigh - 0.6907 \times TravelDirClosedLane \\ &- 0.0004 \times (\mathrm{Min}(WZLen \times GradeProp_i), 300) + 0.7492 \times PostedSpd \end{aligned} \quad [10]$$

where

$WorkZoneSpd_i$ = average travel speed of vehicles through the work zone for direction *i* (mi/h)
$\%HV_i$ = percentage of heavy vehicles in the traffic stream for direction *i*
LW_Narrow = 1 if the effective lane width is narrow, 0 otherwise
LW_Medium = 1 if the effective lane width is medium, 0 otherwise
LW_NarrowMedium = 1 if the effective lane width is narrow or medium, 0 otherwise
ConstAct_MedHigh = 1 if the level of construction activity in the work zone is medium or high, 0 otherwise
TravelDirClosedLane = 1 if vehicles are traveling in the direction of the closed lane (i.e., they perform a lane shift when entering and exiting work zone), 0 otherwise
WZLen = length of the work zone (ft)
$GradeProp_i$ = grade proportion (i.e., %grade/100) in direction *i* (downhill grades should be entered as zero)
PostedSpd = the posted speed limit through the work zone (mi/h)

This model is generally consistent with the field data based model, with a few small differences. The field model included a term for the number of vehicles entering the work zone during a phase, although this variable was only marginally significant. Given the controlled entry of vehicles into the work zone, the traffic volume level by itself has much less effect on average travel speed like it does under less controlled traffic flow environments. Furthermore, significant reductions in average travel speed are usually not observed for low to moderate flow rates (of passenger cars only), which is usually the norm for work zone situations. The number of trucks in the traffic stream has a much more significant effect on the work zone average travel speed than the overall traffic demand level. While the number of trucks can be implemented through an interaction term of demand and percent heavy vehicles, the use of the percent heavy vehicles variable individually provides nearly as good of a model fit as the interaction term, and since this model is applied at the simulation period level as opposed to the phase level, the application of this model using just an overall average of heavy vehicle percentage is more straightforward.

The simulation model includes a term for the combination of grade proportion and length of grade. This term is statistically significant in the model, but it has a very small impact on the overall average speed. While steep and/or long grades can have a large effect on truck speeds, average speeds through the work zone are typically only in the 30-40 mi/h range, even for a passenger car only stream. Trucks are usually able to maintain speeds in this range even on moderately steep and/or long grades. Length of grade multiplied by grade proportion is limited to a maximum value of 300, which corresponds approximately to the point at which trucks will reach their crawl speed. The effect of grade was not observed from the field data because all of the study sites had level or very nearly level terrain.

The other difference from the field model is that the narrow and medium effective lane width variables have been combined into one term. All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.960.

Saturation Headway Model

The saturation headway model was based on over 109,000 individual phases that covered a wide range of inputs. A regression analysis of all the simulation results yielded the model formulation shown in Eq. 11.

$$\begin{aligned}\bar{h}_{sat\_i} &= 3.0875 + 0.0180 \times \%ST_i + 0.0276 \times \%MT_i + 0.0379 \times \%LT_i \\ &+ 0.2812 \times GradeProp - 0.0095 \times AvgWZspeed\end{aligned} \quad [11]$$

where

$\bar{h}_{sat\_i}$ = average saturation headway for direction *i* (s/veh)
$\%ST_i$ = percentage of small trucks in the traffic stream for direction *i*
$\%MT_i$ = percentage of medium trucks in the traffic stream for direction *i*
$\%LT_i$ = percentage of large trucks in the traffic stream for direction *i*
$GradeProp_i$ = grade proportion (i.e., %grade/100) in direction *i* (downhill grades should be entered as zero)
AvgWZspeed = average work zone travel speed for direction *i*, as calculated from Eq. 10 or using field-measured speeds (mi/h)

This model is generally consistent with the field data based model, with the difference that two additional terms are included, one for the *GradeProp* variable and one for the *AvgWZspeed* variable. Since the grades at the field sites were generally level, it was not possible to include this variable in the field model. Since FlagSim can now account for the effect of grade on vehicle acceleration, grade was included as a variable in the experimental design, and as expected its effect was found to be statistically significant. Also, given that the field sites had a narrow range of posted speeds (50-60 mi/h), it was not surprising that average work zone travel speed was not found to be significant in the field data based model. With the wider range of work zone posted speeds run in the experimental design for the simulation based models, average work zone travel speed was found to be significant. The coefficient sign is also as expected—higher speeds through the work zone will reduce the saturation headway. All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.792.

Total Queue Delay and Maximum Queue Length Models

The queue delay and queue length models were based on a very large set of simulation scenarios. The variables and ranges of input values used to develop the set of simulation input scenarios are identified in Table 6.

Table 6. Experimental Design for Simulation-Based Models

Variable	Range of Input Values
Length (mi)	0.25-2
Posted Speed (mi/h)	35-55
Grade (%)	0-6
Total Volume (veh/h)	200-1000
D Factor	0.5-0.7
HV %	0-20
Effective Lane Width	Narrow, Medium, Wide
Construction Activity	Low, Medium, High
Lane Closure Direction	Direction 1, Direction 2

Six replications were run for each input scenario. After removing simulation runs that resulted in over-capacity conditions, a total of 7541 simulation runs were used for the development of the queuing models. For the development of queue delay and queue length models in this project, scenarios that yielded volume-to-capacity ratios of 1.2 or greater were removed from the analysis data set. Generally, for over-capacity conditions, simple deterministic queuing equations can be applied to estimate queue delay and queue length.

A regression analysis of all the simulation results yielded the total queue delay model formulation shown in Eq. 12.

$$TotalQDelay_i = -0.56844 \times (g_i / C)(\%) + 0.42799 \times (v/s)_i(\%) + 0.00591 \times C + 0.09670 \times g_i - 0.00064 \times HV_i \times g_i \quad [12]$$

where

$TotalQDelay_i$ = total queue delay for a 1-hr time period for direction *i* (veh-hr)
(g_i /*C*) = average effective green time to cycle length ratio for direction *i* (expressed as a percentage)
$(v/s)_i$ = volume to saturation flow rate ratio for direction *i* (expressed as a percentage)
C = average cycle length (sec)
HV_i = percentage of heavy vehicles in the traffic stream for direction *i*
g_i = average green time for direction *i*

All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.790. A regression analysis of all the simulation results yielded the maximum queue length model formulation shown in Eq. 13.

$$MaxQLength_i = -1.49485 \times (g_i / C)(\%) + 0.65045 \times (v/s)_i(\%) + 0.01432 \times C + 0.35359 \times g_i - 0.00138 \times HV_i \times g_i \quad [13]$$

where

$MaxQLength_i$ = average maximum queue length per cycle for direction *i* (veh/cycle)
Other terms are as defined previously

All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.738. These two models have the same formulation, but with differing coefficient values, as expected. It should be noted that the use of queue delay in this study represents an intermediate measure of delay. The value of queue delay will fall between the measure of stop delay (where delay is only accumulated when vehicle velocity equals zero) and the measure of control delay (where delay is accumulated for a vehicle any time its velocity is less than what the average running speed would be without the control).

CHAPTER 5
ANALYSIS PROCEDURE OVERVIEW

This chapter provides a step-by-step overview of the analysis procedure that is implemented into the spreadsheet tool.

Step 1: Enter input values

The analyst needs to enter values for the following inputs:

- Traffic demand for each direction
- Percentage of small trucks, medium trucks, and large trucks for each direction
- Roadway grade for each direction
- Length of work zone
- Field measured or estimated work zone travel speed
- If work zone travel speed is field measured
  - Work zone travel speed by direction
- If work zone travel speed is estimated
  - Work zone posted speed
  - Effective lane width
  - Level of construction activity
  - Travel direction with lane closure
- Startup lost time (or can use default value)
- Green time (or can use calculated minimum value)

Step 2: Calculate the work zone average travel speed

This step is skipped if the analyst enters field-measured average work zone travel speeds.

$$\begin{aligned} WorkZoneSpd_i = {} & 2.7481 - 0.1246 \times \%HV_i - 11.5697 \times LW\_Narrow \\ & - 7.3768 \times LW\_Medium + 0.0577 \times \%HV_i \times LW\_NarrowMedium \\ & - 2.1289 \times ConstAct\_MedHigh - 0.6907 \times TravelDirClosedLane \\ & - 0.0004 \times (\text{Min}(WZLen \times GradeProp_i), 300) + 0.7492 \times PostedSpd \end{aligned} \quad [14]$$

where

$WorkZoneSpd_i$ = average travel speed of vehicles through the work zone for direction *i* (mi/h)
$\%HV_i$ = percentage of heavy vehicles in the traffic stream for direction *i*
LW_Narrow = 1 if the effective lane width is narrow, 0 otherwise
LW_Medium = 1 if the effective lane width is medium, 0 otherwise
LW_NarrowMedium = 1 if the effective lane width is narrow or medium, 0 otherwise
ConstAct_MedHigh = 1 if the level of construction activity in the work zone is medium or high, 0 otherwise

TravelDirClosedLane = 1 if vehicles are traveling in the direction of the closed lane (i.e., they perform a lane shift when entering and exiting work zone), 0 otherwise
WZLen = length of the work zone (ft)
$GradeProp_i$ = grade proportion (i.e., %grade/100) in direction *i* (downhill grades should be entered as zero)
PostedSpd = the posted speed limit through the work zone (mi/h)

Step 3: Calculate average saturation headway

$$\begin{aligned}\bar{h}_{sat\_i} &= 3.0875 + 0.0180 \times \%ST_i + 0.0276 \times \%MT_i + 0.0379 \times \%LT_i \\ &+ 0.2812 \times GradeProp - 0.0095 \times AvgWZspeed\end{aligned} \qquad [15]$$

where

$\bar{h}_{sat\_i}$ = average saturation headway for direction *i* (s/veh)
$\%ST_i$ = percentage of small trucks in the traffic stream for direction *i*
$\%MT_i$ = percentage of medium trucks in the traffic stream for direction *i*
$\%LT_i$ = percentage of large trucks in the traffic stream for direction *i*
$GradeProp_i$ = grade proportion (i.e., %grade/100) in direction *i* (downhill grades should be entered as zero)
AvgWZspeed = average work zone travel speed for direction *i*, as calculated from Eq. 10 or using field-measured speeds (mi/h)

Step 4: Calculate saturation flow rate

$$s_i \text{ (veh/h)} = \frac{3600 \text{ (s/h)}}{\bar{h}_{sat\_i} \text{ (s/veh)}} \qquad [16]$$

Step 5: Calculate cycle length

$$PT_i = \frac{wzlen}{speed_i} + g_i + SLT_i \qquad [17]$$

where

PT_i = phase time direction *i* (s)
wzlen = length of the work zone (ft)
$speed_i$ = average work zone travel speed, as calculated from Eq. 14 or using field-measured speed, for direction *i* (ft/s)
g_i = green time for direction *i* (s)
SLT = startup lost time—elapsed time between last vehicle to exit work zone and time when flag person turns paddle/sign to "Slow" for other direction

$$C = PT_1 + PT_2 \qquad [18]$$

where

C = cycle length (sec)

Initially, the green time used in Eq. 17 will use a maximum green time (determine by the analyst) in order to determine whether the work zone will operate below are above capacity, as discussed in the next step. If it is determined the work zone will operate under capacity, then the calculation for phase time will use either the analyst-entered green time or a calculated minimum green time, as determined from Eqs. 20 and 21.

It should be noted that to be entirely accurate, the value for the $speed_i$ variable used to calculate the phase time for direction *i* should be the speed of the last vehicle to enter the work zone in direction *i*. The use of the average work zone travel speed from Eq. 14 will create some error, but this error is minimal.

Step 6: Calculate capacity

Capacity can be calculated with the standard equation used for signalized intersection analysis (TRB, 2010), as shown in Eq. 19.

$$c_i = s_i \times {g_i}/{C} \qquad [19]$$

where

c_i = capacity of the work zone in direction *i* (veh/h)
s_i = saturation flow rate for direction *i* (veh/h)
(g_i/C) = effective green time to cycle length ratio for direction *i*

To determine if the work zone will operate under capacity (i.e., conditions do not result in continually building queue lengths) for the given configuration, it is suggested to calculate Eq. 17 using the maximum green time (default is 300 seconds). The resulting capacity from Eq. 19 can then be compared to the input volume (by direction) to determine if none, either, or both directions are under or over capacity. If one or both directions are over capacity, an alternative work zone configuration should be considered; otherwise, delays and queue lengths will quickly become intolerable to motorists. Generally, for over-capacity conditions, simple deterministic queuing equations can be applied to estimate queue delays and queue lengths.

If the work zone is under capacity, the standard formula for calculating the minimum cycle length can be applied (TRB, 2010), shown in Eq. 20.

$$C_{min} = \frac{L \times X_c}{X_c - \left[\left(\frac{v}{s} \right)_1 + \left(\frac{v}{s} \right)_2 \right]} \qquad [20]$$

where

C_{min} = minimum necessary cycle length (sec)
L = total lost time for cycle (sec)
X_c = critical v/c ratio for the work zone
$(v/s)_i$ = flow ratio for direction i

Note again that the total lost time includes the startup and clearance lost times. Here it assumed the critical v/c ratio, X_c, is 1.0. Eq. 21 (TRB, 2010) can be applied to proportion the green times to the two directions of travel.

$$g_i = \left(\frac{v}{s} \right)_i \left(\frac{C}{X_i} \right) \qquad [21]$$

where

g_i = effective green time for phase (direction) i
$(v/s)_i$ = flow ratio for direction i
C = cycle length in seconds
X_i = v/c ratio for direction i (again, assumed to be 1.0)

It should be noted that the use of minimum cycle length, and corresponding green times, calculated from equations 20 and 21 do not necessarily lead to minimum delay values. These values just ensure that all the vehicles queued during the red period for a direction are served during the subsequent green period. It was beyond the scope of this project to develop optimal timing strategies, that is, timing guidelines that would minimize the value of specific performance measures, such as vehicle delay. Thus, for an under-capacity situation, the calculation procedure implemented in the spreadsheet tool uses equations 20 and 21 to determine the minimum cycle length and minimum green times to apply for the queue delay and queue length estimation models.

<u>Step 7: Calculate total queue delay</u>

$$\begin{aligned} TotalQDelay_i &= -0.56844 \times (g_i / C)(\%) + 0.42799 \times (v/s)_i (\%) + 0.00591 \times C \\ &+ 0.09670 \times g_i - 0.00064 \times HV_i \times g_i \end{aligned} \quad [22]$$

where

$TotalQDelay_i$ = total queue delay for a 1-hr time period for direction i (veh-hr)
(g_i /C) = effective green time to cycle length ratio for direction i (expressed as a percentage)
$(v/s)_i$ = volume to saturation flow rate ratio for direction i (expressed as a percentage)
C = cycle length (sec)
HV_i = percentage of heavy vehicles in the traffic stream for direction i
g_i = green time for direction i

<u>Step 8: Calculate maximum queue length</u>

$$\begin{aligned} MaxQLength_i &= -1.49485 \times (g_i / C)(\%) + 0.65045 \times (v/s)_i (\%) + 0.01432 \times C \\ &+ 0.35359 \times g_i - 0.00138 \times HV_i \times g_i \end{aligned} \quad [23]$$

where

$MaxQLength_i$ = average maximum queue length per cycle for direction i (veh/cycle)
Other terms are as defined previously

CHAPTER 6
RTF TASK

Introduction

The FDOT Plans Preparation Manual contains a chapter (Chapter 10) titled "Work Zone Traffic Control" that discusses a lane closure analysis procedure to calculate the restricted capacity for roadway segments with lane closures. The calculated capacity is compared with the estimated hourly traffic demand to determine the time of day/night that the lane(s) can be closed. The procedure employs a remaining traffic factor (RTF), which denotes the percentage of travelers choosing not to divert, to estimate the hourly traffic demand through the work zone. The estimation of RTF plays a critical role in the lane closure analysis. However, no guidance has been provided on obtaining the value of the RTF in the current manual.

Phase 1 of the project titled “Impact of Lane Closures on Roadway Capacity, Part C: Modeling Diversion Propensity at Work Zones” investigates drivers’ diversion behaviors at work zones and estimates the RTF within the framework of discrete choice modeling. A binary Logit model was calibrated based on the route choice data obtained through a stated preference (SP) survey, considering 11 potential attributes that may contribute to drivers’ diversion decisions. The model calibration procedure identifies three major factors influencing the diversion behavior, namely travel time, work zone location, and weather condition. No statistical evidence was found to support the hypothesis that the remaining eight factors are important to drivers’ diversion decision at work zones. Table 7 summarizes the coefficient specification of the final calibrated model obtained from the Phase 1 study.

Table 7. Final RTF Model Specification

Explanatory Variables	Original Route		Alternative Route	
	Param.	*t* stat	Param.	*t* stat
Constant	-0.5013	-2.0800	--	--
Travel time	-0.1416	-10.1580	-0.1416	-10.1580
Location	0.7220	2.8440	--	--
Weather conditions	0.3959	1.5840	--	--
Number of cases	436			
Log likelihood at convergence	-201.3115			
LL for no-coefficient model	-302.2122			
Rho^2	0.3339			
Adjusted Rho^2	0.3277			

The negative sign associated with the travel time coefficient indicates that travelers prefer routes with shorter travel time, given other factors being equal. The positive sign associated with the location coefficient implies that travelers tend to stay on the original route in rural areas. This behavior can be explained by the fact that fewer alternative routes are generally available in rural areas than in urban ones. Furthermore, it could be more difficult for travelers to obtain updated travel information in rural areas. The sign of the weather coefficient is also positive, and it can be interpreted that travelers are more likely to divert when encountering bad weather. Intuitively, travel time reliability in work zone decreases in bad weather conditions and safety becomes one of the prominent concerns.

The Phase 1 study also proposes two estimation procedures to apply the calibrated binary Logit model to estimate the RTF, namely open- and closed-loop procedures. The former directly applies the model without considering the feedback of remaining and diverted flows on travel times while the latter applies the notion of traffic equilibrium and attempts to maintain the consistency between travel times and flows on different routes. As traffic equilibrium may not be achieved in a short time, the open-loop procedure may be more appropriate for short-term work zones while the closed-loop procedure may be closer to actual diversion rates at long-term work zones. Therefore, the calibrated model from Phase 1 not only provides us more insights on the diversion behavior in work zone but also serves as the basis for developing analytic tools for work zone analysis.

That being said, the model calibration in Phase 1 was solely based on the SP survey data. It is widely known that respondents in SP surveys tend to over-predict their own responses. As a result, the calibrated model may overestimate the diversion rate and subsequently underestimate the RTF. One indication of that is the sign of the constant associated with the original route is negative (-0.5013) in Table 7. This implies that even when the travel times are equal, drivers are still inclined to divert, which may not be necessarily consistent with actual behaviors observed at work zones. Indeed, Hensher et al. (2005) pointed out that SP data often provide good estimates about the preference trade-offs that decision makers make but will not, unless by chance, reflect the true aggregate shares observed in the real world.

Methodology

The objective of this study is to further refine the choice model obtained in Phase 1 using field observed traffic data. One commonly adopted approach in the literature is to combine the actual choices made by individual travelers (i.e., revealed preference (RP) data) and SP survey data to address the validity issue of SP data and improve the accuracy of parameter estimates, see, e.g., Ben-Akiva et al. (1994) and Hensher et al. (2005). However, the integration of RP and SP data is only made possible when both data sources are available. Considering the time and budget limitations faced by this study, there are not enough resources to conduct another survey to collect RP data of individual travelers. Therefore, the data collection task in Phase 2 only records aggregate choice data instead of disaggregate route choices made by travelers.

To fully explore the limited data collected, the model refinement task in this phase focuses on calibrating the alternative-specific constants of the choice model estimated in Phase 1. By calibrating the constant term of the discrete choice model using the aggregate choice data collected in this phase, the inflated diversion rate can be adjusted to reproduce the actual diversion rate observed in the field. Meanwhile, the preference structure of the estimated choice model is also retained (Hensher et al., 2005).

Data Collection

It is difficult to exactly measure the number of vehicles diverting to alternative routes in a work zone construction site. In this study, tube detectors were strategically deployed in the road network surrounding a work zone. Traffic counts before and during the work zone construction were collected, and the difference between them was used to approximate the actual diversion rate in the field. The locations of the vehicle detectors were intended to cover major potential detours as well as the work zone site. Our research team initially identified three work zones located in both rural and urban areas. However, only one work zone site produced relatively reliable traffic counts and was adopted for the model recalibration in this study. It is also worth mentioning that limited useful data greatly restrict data analysis options available to us, but they justify the simplified model recalibration methodology proposed in the previous section.

The remaining parts of this section describe the work zone site and data collection work. The work zone is located on SR-20 near Hawthorne in Alachua County. Figure 24 illustrates the locations of the work zone site and loop detectors deployed. The work zone construction site is located just east of detector 1 shown in this figure. Detector 1 is intended to count traffic through the work zone site, while detectors 2 to 4 are used to capture traffic volumes on potential detour routes.

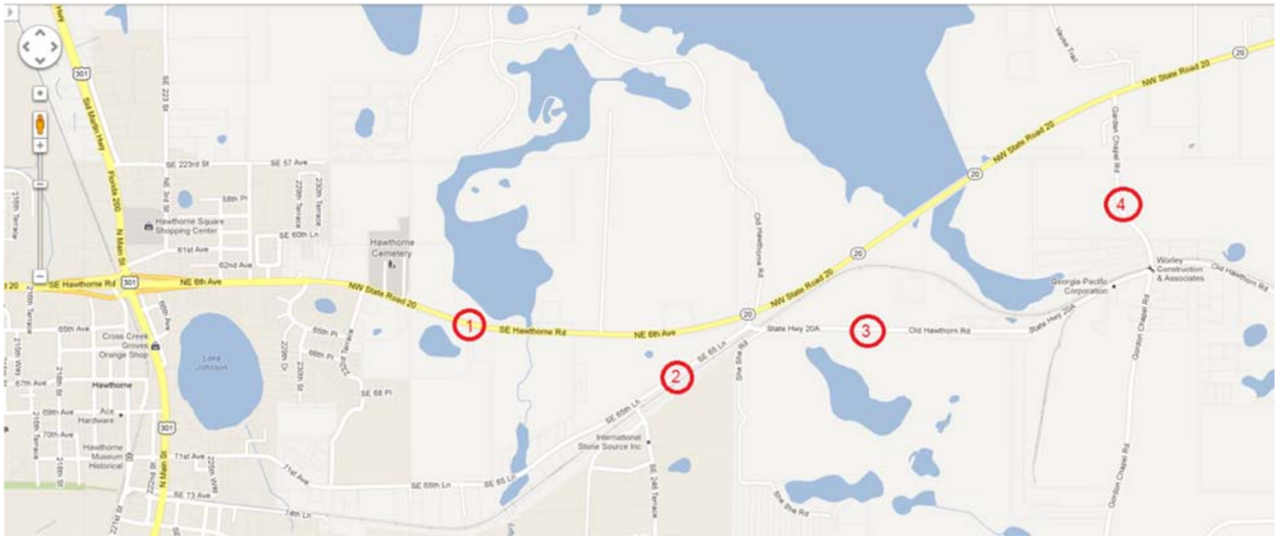


Figure 24. SR-20 work zone site

Traffic counts for both before- and during-construction periods were collected for three consecutive days in December 2012 and February 2013, respectively. Weather conditions during both periods were normal. Westbound traffic counts were collected and are shown in Table 8.

Table 8. Before and During Construction Traffic Counts (Westbound)

	Before Construction (veh/day)				During Construction (veh/day)			
Date	Dec-18	Dec-19	Dec-20	Average	Feb-19	Feb-20	Feb-21	Average
Detector 1	3410	3568	3576	3518	3136	3292	3406	3278
Detector 2	270	286	264	273	339	259	274	291
Detector 3	33	42	33	36	66	53	50	56
Detector 4	445	440	415	433	396	374	393	388

It is estimated that roughly 240 vehicles (6.8%) diverted during the work zone construction time assuming the total travel demand remains the same before and during construction. Table 8 also shows that more traffic passed through detectors 2 and 3 during the construction time as expected. For detector 4, slightly fewer vehicles actually used this segment during the construction time, which indicates that travelers may have already diverted to detours upstream of this segment, which is not accounted for by the deployed detectors. Traffic counts of different days have been averaged to reduce the influence of daily demand variation, however, the impact of seasonal demand variation cannot be eliminated since the before- and during-construction traffic counts were collected two months apart.

Travel delays due to work zone construction directly influence travelers' diversion decisions. A flag person on each end of the work zone controlled the construction site. Only vehicles from one direction were allowed to enter the work zone site at a time while vehicles from the other direction have to wait in queue. Therefore, the primary source of travel delay experienced by travelers is the queuing delay before vehicles actually enter the work zone site. In this study, data obtained from video were used to estimate the queuing delay. Queuing delays for 518 vehicles were extracted from video obtained at the construction site on February 21. Table 9 shows the average queuing delays experienced by travelers.

Table 9. Average Queuing Delay (Westbound)

Length of Lane Closure (miles)	Posted Speed in Work Zone (mi/h)	Average Queuing Delay (s/veh)
0.904	55	206.52

Data Analysis

The utility functions of original (*O*) and alternative (*A*) routes obtained in Phase 1 are as follows:

$$U_O = -0.5013 - 0.1416TT_O + 0.7220L_O + 0.3959W_O + \varepsilon_O \qquad [24]$$

$$U_A = -0.1416TT_A + \varepsilon_A \qquad [25]$$

where

TT = travel time
L is a binary variable indicating the location of the work zone ($L = 1$ for rural work zone and $L = 0$ otherwise)
W is a weather condition binary variable ($W = 1$ for normal weather conditions and $W = 0$ for bad weather conditions).

Based on the binary Logit model, the diversion rate can be calculated using the following equation:

$$P(A) = \frac{e^{U_A}}{e^{U_A} + e^{U_O}} = \frac{1}{1 + e^{(U_O - U_A)}} \qquad [26]$$

If the above equation is adopted in estimating the diversion rate for the work zone on SR-20, the estimated diversion rate is 24.90%. It is evident that the observed diversion rate (6.8%) is much lower than the estimated one, which coincides with the literature that models based on SP data tend to over-predict users' responses. Following the methodology discussed previously, the constant coefficient associated with the original route, β_O, is adjusted to solve the overestimation problem. Essentially, β_O is treated as an unknown variable instead of a known constant and the diversion rate, $P(A)$, is set to equal to 6.8%. The equation to calculate the diversion rate is used to solve for an adjusted β_O, and $\beta_O = 1.013$. Therefore, the new utility function for the original route can be recalibrated as:

$$U_O = 1.1013 - 0.1416TT_O + 0.7220L_O + 0.3959W_O + \varepsilon_O \qquad [27]$$

and the utility function for the alternative route remains unchanged. The sign of β_O changed from negative in Phase 1 to positive. The newly recalibrated model implies that travelers have a general preference towards the original route and are not willing to divert to alternative routes, all things being equal.

Summary

This task aimed to refine the RTF model proposed in Phase 1 using field observed diversion data. The binary Logit model developed in Phase 1 was calibrated based on SP survey data, and SP data tend to overestimate the diversion rate in work zones. The aggregate traffic data collected in a work zone on SR-20 confirm this phenomenon. A simplistic methodology is adopted primarily due to limitations in data availability and quality. The constant coefficient associated with the original route is adjusted to fix the overestimation problem while retaining the preference structure of the estimated route choice model. The recalibrated model was incorporated into the RTF modeling framework proposed in Phase 1 by updating the route choice model.

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APPENDIX A

DATA COLLECTED FROM FIELD SITES

Table A-1. Accepted and Rejected Gap Data for Determining Critical Gap at Site 1

Gap Interval (sec)	Midpoint of Gap Interval (t) (sec)	Number of Gaps Accepted Greater than t	Number of Gaps Rejected Less than t
0 - 4.9	2.5	380	0
5 - 9.9	7.5	173	0
10 - 14.9	12.5	83	0
15 - 19.9	17.5	53	2
20 - 24.9	22.5	36	5
25 - 29.9	27.5	27	13
30 - 34.9	32.5	18	23
35 - 39.9	37.5	10	29
40 - 44.9	42.5	9	36
45 - 49.9	47.5	9	48
50 - 54.9	52.5	8	56
55 - 59.9	57.5	6	63
>= 60	300	4	164

Table A-2. Accepted and Rejected Gap Data for Determining Critical Gap at Site 2

Gap Interval (sec)	Midpoint of Gap Interval (t) (sec)	Number of Gaps Accepted Greater than t	Number of Gaps Rejected Less than t
0 - 4.9	2.5	507	0
5 - 9.9	7.5	203	0
10 - 14.9	12.5	85	0
15 - 19.9	17.5	57	1
20 - 24.9	22.5	34	2
25 - 29.9	27.5	20	6
30 - 34.9	32.5	13	15
35 - 39.9	37.5	9	20
40 - 44.9	42.5	6	29
45 - 49.9	47.5	3	41
50 - 54.9	52.5	2	57
55 - 59.9	57.5	2	67
>= 60	300	2	207

Table A-3. Accepted and Rejected Gap Data for Determining Critical Gap at Site 3

Gap Interval (sec)	Midpoint of Gap Interval (t) (sec)	Number of Gaps Accepted Greater than t	Number of Gaps Rejected Less than t
0 - 4.9	2.5	1259	0
5 - 9.9	7.5	354	0
10 - 14.9	12.5	180	2
15 - 19.9	17.5	101	8
20 - 24.9	22.5	56	19
25 - 29.9	27.5	24	40
30 - 34.9	32.5	10	57
35 - 39.9	37.5	3	79
40 - 44.9	42.5	2	100
45 - 49.9	47.5	0	121
50 - 54.9	52.5	0	140
55 - 59.9	57.5	0	146
>= 60	300	0	210

	A	B	C	D	E	F	G	H	I
1	***EB Traffic***	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**
2	Time Last EB Veh from Previous Phase Enters WZ	Not Recorded	9:41:13 AM	9:46:10 AM	9:50:16 AM	9:55:13 AM	11:36:44 AM	11:41:52 AM	11:46:28 AM
3	Time 1st EB Veh Arrives at WZ	Not Recorded	9:42:17 AM	9:47:01 AM	9:51:05 AM	9:56:15 AM	11:37:33 AM	11:42:24 AM	11:47:03 AM
4	Period with No Queue at WZ (sec)	Not Recorded	64	51	49	62	49	32	35
5	Queue Delay of 1st Queued Veh (sec)	Not Recorded	212	131	217	146	174	193	239
6	Time Last WB Veh Exits WZ	9:40:40 AM	9:45:44 AM	9:48:59 AM	9:54:35 AM	9:58:33 AM	11:40:22 AM	11:45:34 AM	11:50:50 AM
7	Number of Vehs In Queue	5	8	5	6	5	10	16	12
8	Distance between 1st Queued Veh and Flag (ft)	6	8	15	5	20	3	2	2
9	Time Flag Changes to Slow	9:40:41 AM	9:45:46 AM	9:49:05 AM	9:54:38 AM	9:58:35 AM	11:40:23 AM	11:45:32 AM	11:51:00 AM
10	Time Flag Changes to Stop	9:41:35 AM	9:47:00 AM	9:50:25 AM	9:55:18 AM	9:59:29 AM	11:41:56 AM	11:46:33 AM	11:52:26 AM
11	Green Time (sec)	54	74	80	40	54	93	61	86
12	Total Lost Time (sec)	11	5	13	7	8	5	5	12
13	Number of PC that Entered WZ	5	6	11	7	9	16	15	17
14	Number of ST that Entered WZ	0	2	0	0	1	1	1	0
15	Number of MT that Entered WZ	0	0	0	0	0	0	1	0
16	Number of LT that Entered WZ	1	0	0	1	0	1	1	1
17	Number of CV that Entered WZ	0	0	0	0	0	0	0	0
18	Number of Vehs that Entered WZ	6	8	11	8	10	18	18	18
19	Number of Entering Vehs that Exited WZ	6	8	11	8	10	18	18	17
20	Time between 8th Veh in Queue (or Last Queued Veh) and 1st Veh Entry Time (sec)	19	21	13	14	11	23	20	28
21	Saturation Headway (sec/veh)	4.750	3.000	3.250	2.800	2.750	3.286	2.857	4.000
22	Avg Work Zone Travel Time (min)	1.600	1.279	1.461	1.356	1.238	1.307	1.420	1.409
23	Std Dev Work Zone Travel Time (min)	0.054	0.049	0.177	0.079	0.024	0.115	0.063	0.083
24	Avg Speed in Work Zone (mi/h)	33.750	42.215	36.971	39.816	43.607	41.303	38.018	38.330
25	1st Veh Entry Time	9:40:51 AM	9:45:49 AM	9:49:12 AM	9:54:42 AM	9:58:41 AM	11:40:27 AM	11:45:37 AM	11:51:02 AM
26	1st Veh Type	PC	PC	PC	PC	PC	PC	PC	PC
27	1st Veh Description	white car	black pick up truck	gold car	dark SUV	Chevy tahoe	black SUV	silver car	dark gray SUV
28	1st Veh Exit Time	9:42:32 AM	9:47:05 AM	9:50:51 AM	9:56:02 AM	9:59:54 AM	11:41:51 AM	11:47:07 AM	11:52:19 AM
29	1st Veh WZ Travel Time (min)	1.68	1.27	1.65	1.33	1.22	1.40	1.50	1.28
30	2nd Veh Entry Time	9:40:55 AM	9:45:54 AM	9:49:15 AM	9:54:46 AM	9:58:43 AM	11:40:30 AM	11:45:39 AM	11:51:05 AM
31	2nd Veh Type	LT	PC	PC	PC	PC	PC	PC	PC

EB 1-21-2013 | WB 1-21-2013

Figure A-1: Example of Excel spreadsheet for video data from stationary cameras

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Video File Name	Site #	Date	Travel Direction	Phase #	Vehicle #	Start Video Time	End Video Time	Avg. Travel Time in WZ for Phase (min)	Avg. Speed in WZ for Phase (mi/h)	Number of Vehicles that Entered WZ	Percent Heavy Vehicles that Entered WZ	Percent Construction Vehicles that did not Exit WZ	Level of Construction Activity in WZ	Level of Construction Vehicle Presence in WZ	Effective Lane Width	Posted Speed in WZ (mi/h)	Travel Direction of Closed Lane	Is traveling in Direction of Closed Lane (0 = false, 1 = true)
2	LC1	1	10/25/11	Northbound	N/A	ıey ente	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	2	2	2	55	Northbound	1
3	LC2	1	10/25/11	Southbound	N/A	hicle in c	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	2	2	2	55	Northbound	0
4	LC3	1	10/25/11	Northbound	N/A	ueue fro	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	2	2	2	55	Northbound	1
5	LC4	1	10/25/11	Southbound	1	et inside	N/A	N/A	2.853	36.81	9	33.33	11.11	2	2	2	55	Northbound	0
6	LC5	1	10/25/11	Northbound	8	9	N/A	N/A	-99.000	-99.00	16	25.00	-99.00	3	3	2	55	Northbound	1
7	LC6	1	10/25/11	Southbound	9	ıe. Enter	N/A	N/A	3.163	33.19	8	62.50	25.00	3	3	2	55	Northbound	0
8	LC7&8	1	10/25/11	Northbound	11	15	N/A	N/A	3.126	33.59	15	20.00	6.67	3	2	2	55	Northbound	1
9	LC7&8	1	10/25/11	Southbound	11	7	N/A	N/A	2.883	36.42	9	11.11	0.00	3	2	2	55	Northbound	0
10	LC9	1	10/25/11	Northbound	12	11	N/A	N/A	3.003	34.96	11	18.18	9.09	3	2	2	55	Northbound	1
11	LC10	1	10/25/11	Southbound	18	4	N/A	N/A	3.102	33.85	11	45.45	18.18	3	3	2	55	Northbound	0
12	LC11-12-13	1	10/25/11	Northbound	19	11	N/A	N/A	3.439	30.53	14	35.71	0.00	3	3	2	55	Northbound	1
13	LC11-12-13	1	10/25/11	Southbound	19	17	N/A	N/A	3.013	34.85	18	22.22	5.56	3	3	2	55	Northbound	0
14	LC11-12-13	1	10/25/11	Northbound	20	12	N/A	N/A	3.079	34.10	12	25.00	0.00	3	3	2	55	Northbound	1
15	LC14	1	10/25/11	Southbound	N/A	N/A	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	3	2	2	55	Northbound	0
16	LC15	1	10/27/11	Southbound	2	1	N/A	N/A	3.040	38.43	8	12.50	0.00	2	2	2	60	Northbound	0
17	LC16	1	10/27/11	Northbound	3	12	N/A	N/A	3.257	35.87	14	14.29	14.29	2	1	2	60	Northbound	1
18	LC17	1	10/27/11	Southbound	4	2	N/A	N/A	2.926	39.92	7	28.57	0.00	2	2	2	60	Northbound	0
19	LC18	1	10/27/11	Northbound	5	14	N/A	N/A	3.368	34.69	22	22.73	4.55	3	2	2	60	Northbound	1
20	LC19	1	10/27/11	Southbound	8	5	N/A	N/A	2.900	40.28	10	30.00	0.00	2	2	2	60	Northbound	0
21	LC20	1	10/27/11	Northbound	9	18	N/A	N/A	3.511	33.28	18	27.78	16.67	2	2	2	60	Northbound	1
22	LC21	1	10/27/11	Southbound	10	4	N/A	N/A	2.829	41.30	7	28.57	0.00	2	2	2	60	Northbound	0
23	LC22	1	10/27/11	Northbound	12	15	N/A	N/A	3.374	34.62	18	33.33	11.11	2	3	2	60	Northbound	1
24	LC23	1	10/27/11	Southbound	15	8	N/A	N/A	2.940	39.73	15	13.33	0.00	2	3	2	60	Northbound	0
25	LC24	1	10/27/11	Southbound	21	5	N/A	N/A	3.567	32.75	15	26.67	0.00	3	2	2	60	Northbound	0
26	LC25	1	10/27/11	Northbound	23	1	N/A	N/A	3.116	37.49	18	11.11	0.00	3	2	2	60	Northbound	1
27	LC26	1	10/27/11	Southbound	24	12	N/A	N/A	3.628	32.20	13	23.08	0.00	3	2	2	60	Northbound	0
28	LC27	1	10/27/11	Northbound	25	10	N/A	N/A	3.570	32.73	13	38.46	15.38	3	2	2	60	Northbound	1

TRC Vehicle Video Data

Figure A-2: Example of Excel spreadsheet for video data from instrumented Honda Pilot

APPENDIX B

PICTURES OF VEHICLE TYPES BY CATEGORY

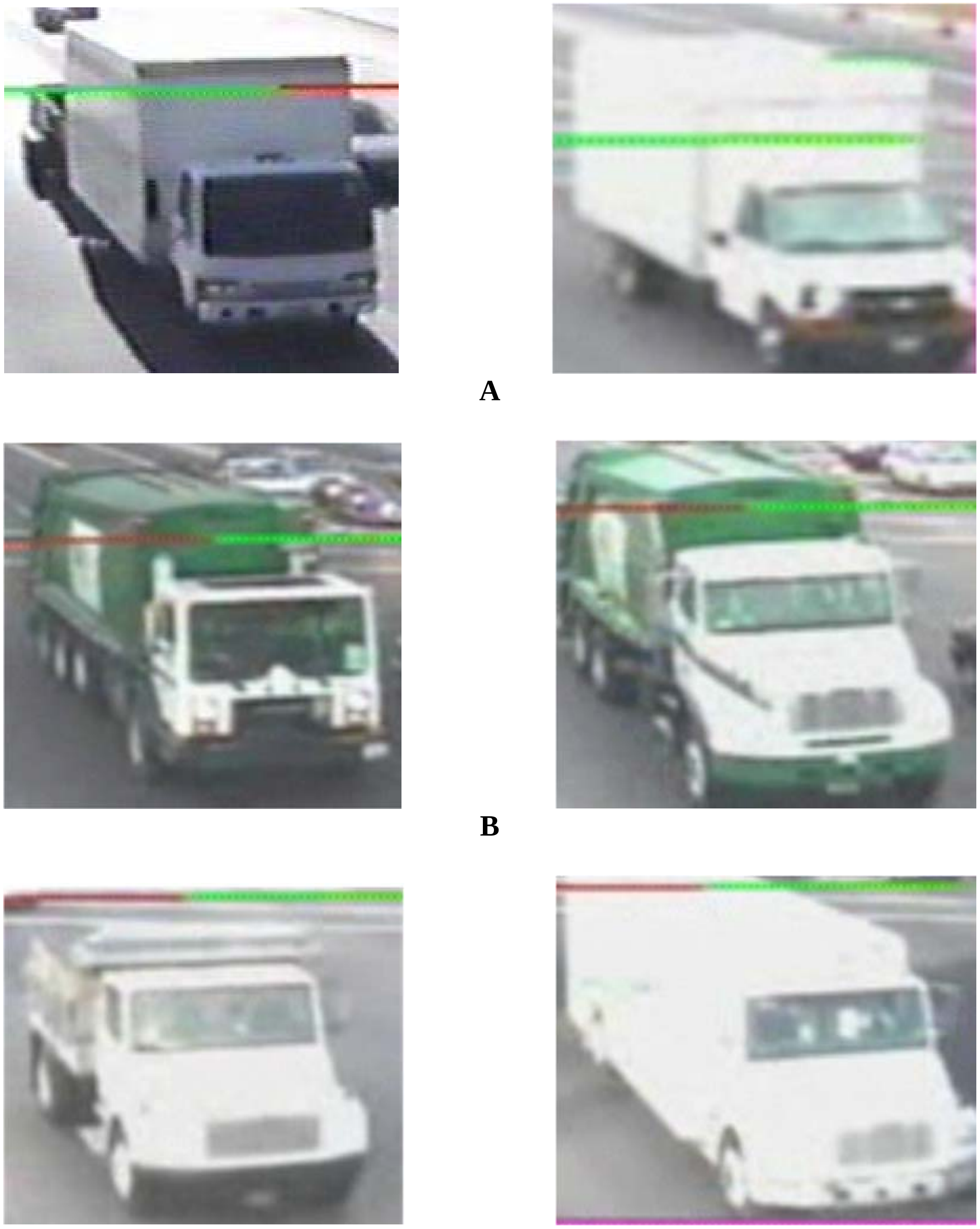

Figure B-1. Small trucks. A) Panel truck. B) Garbage truck. C) Two-axle single-unit dump truck. D) Small delivery truck. E) Passenger cars with trailers

E

Figure B-1. Continued

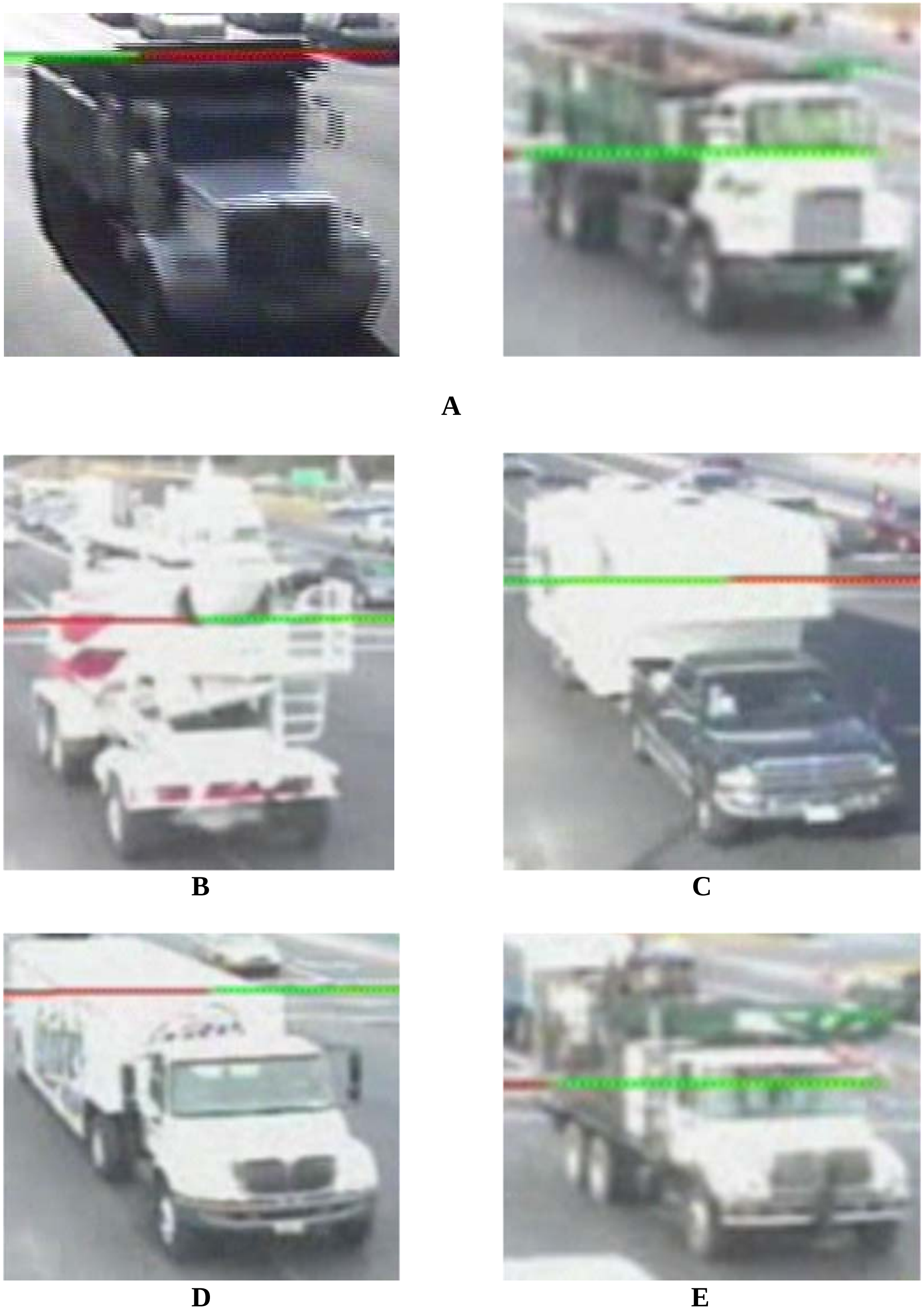

Figure B-2. Medium trucks. A) Three-axle single-unit dump truck. B) Concrete mixer. C) Passenger car with trailer using fifth wheel. D) Delivery truck. E) Single-unit cargo truck.

A

B

Figure B-3. Large trucks. A) Tractor plus trailer. B) Tractor plus flatbed. C) Buses.

C

Figure B-3. Continued

APPENDIX C
FLAGSIM USERS GUIDE