FINAL REPORT

Operational Performance Models for Freeway Truck-Lane Restrictions

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Prepared for

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EXECUTIVE SUMMARY

Introduction

Highways are designed to facilitate the flow of various modes of traffic including passenger cars, trucks, buses, recreational vehicles, etc. The impacts of these different vehicle types are not uniform, however, creating problems in highway operations and safety. As passenger car volume has increased over the last decade, truck operations have also increased, both in terms of volume and dimension, creating a number of distinct issues that highway planners must address in order to enhance the safety of our highways. A common approach to reducing the impacts of truck traffic on freeways has been to restrict trucks to certain lane(s) to minimize the interaction between trucks and other vehicles and to compensate for their differences in operational characteristics.

Many possible design alternatives for truck-lane restrictions exist. Some use one restricted lane while others use two or more; some restrict trucks to the rightmost lane(s) while others to the leftmost lane(s). The performance of these different truck-lane restriction alternatives differs under different traffic and geometric conditions. Thus, a good estimate of the operational performance of different truck-lane restriction alternatives under prevailing conditions is needed to help make informed decisions on truck-lane restriction alternatives. This study aims to develop operational performance models that can be applied to help identify the most operationally efficient truck-lane restriction alternative on a freeway under prevailing conditions. The operational performance measures examined in this study include average speed, throughput, speed differentials, and lane changes. Prevailing conditions include number of lanes, interchange density, free-flow speeds, volumes, truck percentages, and ramp volumes.

Literature Review

The different types of truck restrictions and their advantages and disadvantages are summarized as follows (Stokes and McCasland, 1986; Carvell et al., 1997):

1. Truck lane restrictions may improve traffic operations and safety by separating slower trucks from faster passenger cars. However, they may cause uneven deterioration of the highway pavement.

2. Restricting trucks from the left-lane(s) removes slower trucks from the faster inner (leftmost) lane(s); however, it causes a concentration of trucks on the right lane(s) and blocks the visibility of signs to drivers in the inner lanes.

3. Restricting trucks from the right-lane(s) requires trucks to use the faster lanes. It is usually used as a temporary measure to prevent pavement deterioration. Since trucks have to shift over to the left lanes, safety concerns arise near interchanges and weigh stations where lane changes are required.

4. Route restrictions are mostly used in urban areas to remove trucks from congested roads or to enhance safety by detouring hazardous material cargo from heavily populated

corridors. However, they may increase the truckers' operating costs by increasing vehicle miles due to greater circuity incurred in travel paths.

5. Time-of-day restrictions prevent trucks from using certain lane(s) or entire facilities during particular time periods. This may force trucks to travel on detour routes with insufficient design standards for increased truck volume, resulting in additional truck-related crashes or delays on these routes. Since most trucks tend to travel during off-peak periods to avoid delays, banning trucks on certain routes may only have marginal effects on freeway operations and safety.

6. Differential speed limits (DSL) are designed to reduce the speed at which trucks are allowed to travel. While some believe that this alternative may reduce crashes involving trucks rear-ending other vehicles, other have argued that DSL increases speed variances and lane changes on roadways, which may, in turn, increase the chances of a crash occurring. The actual benefit of DSL remains questionable and many agencies have removed DSL.

Existing operational and safety studies of truck restrictions have found that:

1. Truck-lane restrictions increase speed differentials and reduce density on steep uphill sections. No significant changes were found for other sections (Hoel and Peek, 1999).

2. No adverse effects of truck restrictions were found with respect to the headways and queue lengths following the impeding trucks (Zavoina *et al.*, 1990); however, unsafe conditions might occur at on-ramp areas with a high percentage of trucks and heavy traffic volume under the combined DSL and lane-restriction situation (Garber and Gadiraju, 1990).

3. Truck-lane restrictions have a positive impact on freeway safety (Vargas 1992; Hoel and Peek 1999).

4. Truck violation rates range between 0% and 10%. Higher compliance rates can be expected for roadways with greater numbers of lanes (Hanscom, 1990; Fitzpatrick *et al.*, 1992; Zavoina *et al.*, 1990 and 1991).

Methodology

Recognizing the difficulty of collecting sufficient data for an empirical modeling procedure that involves a different number of variables, the simulation approach was used to estimate the performance values for various truck-lane restriction alternatives under various traffic and geometric scenarios. Simulation models were developed to replicate the complex interactions among the many variables of interest involved. Both the CORSIM and VISSIM simulation models were examined for their ability to model truck-lane restrictions. Due to a major problem found in the CORSIM model for truck-lane modeling, the VISSIM model was adopted as the simulator for this study.

The VISSIM model was calibrated mainly to replicate the capacity given in the 2000 Highway Capacity Manual (HCM) for various free-flow speeds under the ideal basic freeway section conditions. A program was developed to automate the process of running multiple VISSIM runs and extracting the corresponding output for various input scenarios. Non-linear regression models were then developed to relate the average speed, throughput, number of lane changes, and speed differentials under prevailing conditions. Based on the performance models developed, a simple decision procedure was recommended to select the desired truck-lane restriction alternative for prevailing conditions.

Findings

Based on the analysis of simulated data in this study, it was found that:

1. In general, truck restriction alternatives increase the average speed under low interchange density, low truck volume, and low ramp volume condition. When a freeway corridor is congested with densely spaced interchanges, high truck percentages, or high ramp volumes, truck-lane restrictions reduce the average speed. However, the speed reduction is negligibly small, except when a large number of restricted lanes is used, for example, restricting three out of four total number of lanes. This suggests that restricting an appropriate number of lanes to truck traffic is generally beneficial since it may improve traffic safety without worsening the efficiency of moving traffic.

2. A large number of the restricted lanes resulted in a higher rate of throughput under low truck percentages with sparsely spaced interchanges. A relatively low number of restricted lanes (such as one out of three lanes or one or two out of four and five lanes) generally provide a higher capacity than the non-restriction alternative for truck percentages up to 25%.

3. Statistical analysis shows that the speed differentials between restricted and non-restricted lane groups are significant, and that the magnitude increases as the number of interchanges, ramp volumes, truck percentages, and free-flow speed increases.

4. Truck-lane restrictions significantly reduce the number of lane changes by separating slower vehicles from faster vehicles, thus reducing the necessity of vehicles over-taking one another. Since lane changes are a major cause of crashes, a reduction in lane changes through truck-lane restrictions can potentially improve freeway traffic safety.

5. One-lane truck restriction is suitable for three-, four- and five-lane freeways while two-lane truck restriction is more suitable for four- and five-lane freeway corridors except when the interchange density is high and truck percentage is larger than average.

Recommendations

Although the coefficients of the regression models show a consistent and logical relationship between dependent variable and independent variables, the model validation based on

comparison with the HCM was somewhat limited. Further studies may attempt to validate the simulation results with field data, when they become available.

Due to time constraints, software limitations, and lack of field data, this study has been somewhat limited in scope. It is recommended that further studies focus on the following areas to refine and generalize the models developed in this study:

1. Includes right-lane restrictions, i.e., trucks are not allowed to use the rightmost lane(s). Only left-lane restrictions are modeled in this study.

2. Models exclusive truck lane(s), i.e., passenger cars are not allowed to use the lanes designated for trucks.

3. Models trucks of various dimensions and operating characteristics. The models developed in this study are based on only one average truck type.

4. Incorporates the impact of restriction-compliance with various truck violation rates (i.e., percentage of trucks that use the truck-restricted lane(s)). The models developed in this study assume 100% compliance. It is noted, however, that the current versions of CORSIM and VISSIM do not explicitly model violation rates.

5. Models speed differentials within a traffic stream in the same lane group, in addition to the current model for speed differentials between restricted and non-restricted lane groups.

6. Uses different on- and of-ramp volumes. The models developed in this study assume that the on- and off-ramp volumes are the same. Consequently, the models are not suitable for evaluating corridors with significantly different on- and off-ramp volumes.

7. Considers other configurations of ramps, such as two successive on-ramps, two successive off-ramps, and ramps that form weaving sections.

It is noted that in the latest version of CORSIM that comes with TSIS Version 5.1, the problem described in section 3.1 appears to have been corrected. Accordingly, CORSIM should be reconsidered as a simulator for further studies. The use of CORSIM offers the advantage of applying a simulator that has been calibrated based on the U.S. traffic conditions and driver behaviors. In addition, CORSIM also includes four different types of trucks with calibrated default values for truck dimensions and operating characteristics.

CHAPTER 1
INTRODUCTION

1.1. Motivation

Highways are designed to facilitate the movement of traffic consisting of a variety of modes including passenger cars, trucks, buses, recreational vehicles, and so on. The impacts of these different vehicle types are not uniform, however, creating a need for distinct solutions in terms of highway operations and safety. As passenger-car volume has increased over the last decades, truck operations have also increased, both in terms of volume and dimension, which has created a number of distinct issues that highway planners must address in order to enhance the efficiency and safety of our highways. For the purpose of this study, the Wishart and Hoel (1996) definition is utilized, in which a "truck" is (a) a single-unit or combination vehicle over 10,000 pounds, or (b) any vehicle that has six or more wheels in contact with the road.

One common approach to reducing the impacts of truck traffic on freeways has been to impose certain restrictions on truck movements to minimize the interaction between trucks and other vehicles and to compensate for their differences in operational characteristics. Truck restrictions can come in several forms, including lane restriction, route restriction, time-of-day restriction, and speed restriction (e.g., differential speed limits). Chapter two introduces and reviews these restrictions in detail. Among the different truck restriction alternatives, the separation of trucks from other vehicles through lane restriction is often suggested as a countermeasure in areas that are more susceptible to crashes that involve trucks. In addition to crash reduction, truck-lane restrictions have been used to improve traffic operations and to facilitate the even wear of pavement (Zavoina *et al.,* 1991).

Many design alternatives for truck-lane restrictions exist, including various lane restriction alternatives. Restrictions can be placed on one or more lanes on either the right or left side of the highway. A good estimate of the operational performance of candidate truck-lane restriction alternatives will provide important input for better planning and policy decisions. The operational performance measures considered in this study include average speed, throughput, speed differentials, and lane changes. The prevailing conditions considered include number of lanes, interchange density, free-flow speeds, volumes, and truck percentages. These quantitative models, which relate performance measures to the prevailing roadway conditions, will allow better estimation of the expected performances of different truck restriction methods and, thus, will result in better decision-making. Such models do not currently exist.

1.2. Objectives

This study aims to develop operational performance models that can be applied to help identify the most operationally efficient truck-lane restriction alternative on a freeway under prevailing conditions. These performance models will provide answers to such questions as under what levels of truck and non-truck volumes can a specific truck-lane restriction alternative be justified and what are the expected travel speeds and throughput for the corridor before and after the implementation of a truck restriction method. It is reasonable to assume that improved operations will lead to better safety. The purpose of performance models includes: (a) the ability

to evaluate a proposed truck restriction method before implementation, (b) the ability to re-evaluate an existing method for possible improvements, and (c) the ability to objectively review a method should it become controversial.

1.3. Study Approach

Two types of approaches have been generally used in the literature: (a) field data analysis before and after the implementation of a truck restriction, and (b) computer simulation models. Recognizing the difficulty of collecting sufficient data for empirical modeling able to represent various prevailing conditions, simulation models are used to predict the possible outcome of design alternatives without actually implementing truck-lane restrictions.

1.4. Study Scope

In general, trucks are either restricted from using the leftmost lane(s), or the rightmost lane(s). This study focuses on restrictions under which trucks are not permitted to travel in the fast leftmost lane(s). In addition, the number of freeway lanes is limited to three, four, and five per direction.

1.5. Report Organization

The rest of this report is organized as follows. Chapter two introduces the different types of truck restrictions and provides a review of existing studies. Chapter three introduces the simulation models and describes the general model development procedure. Chapter four summarizes the results from the simulation models. Chapter five presents the performance models for truck-lane restriction alternatives. Finally, Chapter six concludes this report and summarizes the findings.

CHAPTER 2
TRUCK RESTRICTION METHODS

This chapter introduces different truck restrictions, including lane restriction, route restriction, time-of-day restriction, and speed restriction (e.g., differential speed limits), and reviews their effects on traffic operations and safety.

2.1. Lane Restrictions

A truck-restricted lane is defined as a lane that trucks are not allowed to use. Several states have restricted the lanes in which trucks are permitted to travel in order to separate trucks from other traffic. Several types of truck-lane restrictions have been implemented throughout the United States. Expressways will typically restrict trucks to one or two specific lanes, often using either the inside or outside lanes, will restrict truck traffic during certain hours of the day, or will utilize barriers to separate trucks from passenger cars (Wishart and Hoel, 1996).

2.1.1. Restricted from Left Lane(s)

Restricting trucks from the left-lane(s) requires slower trucks to travel in the slower outer (rightmost) lanes. Figure 2-1 shows the lane assignments for restriction from the leftmost lane. This restriction removes trucks from the faster inside lane and may reduce truck speed as well as the psychological impact of trucks on passenger car drivers (Wishart and Hoel, 1996). However, concentrating trucks in the right lane(s) may make the access points (i.e., exit or entrance ramp) unsafe and travel more difficult. Since most signs are posted above the right lane, a high concentration of trucks in the right lane may reduce the visibility of signs to drivers in the inner lane(s) (Stokes and McCasland, 1986). Uneven wear or deterioration of the pavement in the outer lane(s) may also result. Restrictions from the left lane have been implemented on I-95 in Broward County, Florida, and on the Capital Beltway (I-95 and I-495) in Virginia (Hoel and Peek, 1999). In Broward County, for example, three or more axle trucks were banned from the leftmost lane of a 25-mile, 3-lane section (per direction) on I-95 (Vargas, 1992).
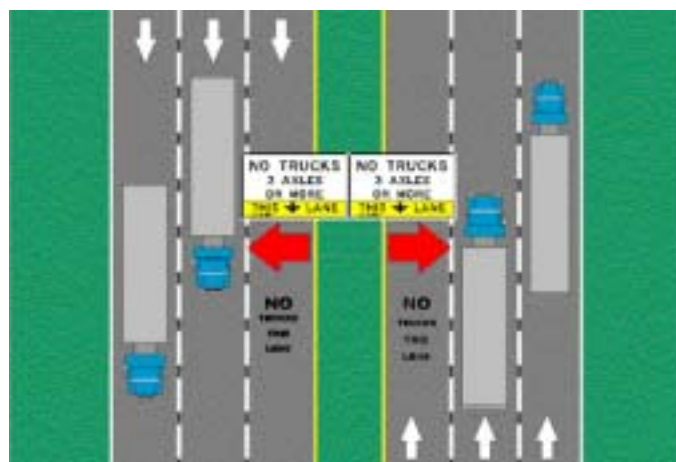
Figure 2-1. Truck Restriction from Leftmost Lane
(source: http://www.doh.dot.state.nc.us/preconstruct/traffic/safety/trucksafety/trucklane/)

2.1.2. Restricted from Right-lane(s)

Another truck-lane restriction is to prohibit trucks from using the rightmost lane(s). This method has been used as a temporary measure to even the wear or deterioration of the pavement and has been implemented on I-90 and I-94 near Madison, Wisconsin (Hanscom, 1990). Since trucks have to shift over to the left lanes, safety concerns arise near interchanges and weigh stations where lane changes are required.

2.1.3. Lane Restrictions with Barriers

A special type of lane restriction involves lanes that are separated by barriers. Two types of separated facilities are discussed in the literature: (a) completely separate roadways for each vehicle type, and (b) one exclusive roadway for either heavy or light vehicles and another roadway for mixed traffic. Figure 2-2 shows the layout of a separated facility implemented along a 33-mile section on the New Jersey Turnpike. It consists of two parallel roadways within the same right of way. A concrete median barrier separates directional flows and a metal beam guardrail separates the inner and outer flows. Trucks and buses are required to travel on the outer roadway, but passenger cars can use either the inner or the outer roadway. About 40% of passenger cars reportedly use the outer lanes. Similarly in California, a section of I-5 north of Los Angeles was reconstructed to provide uninterrupted truck movements by using barriers of this sort (Fitzpatrick *et al*., 1992).
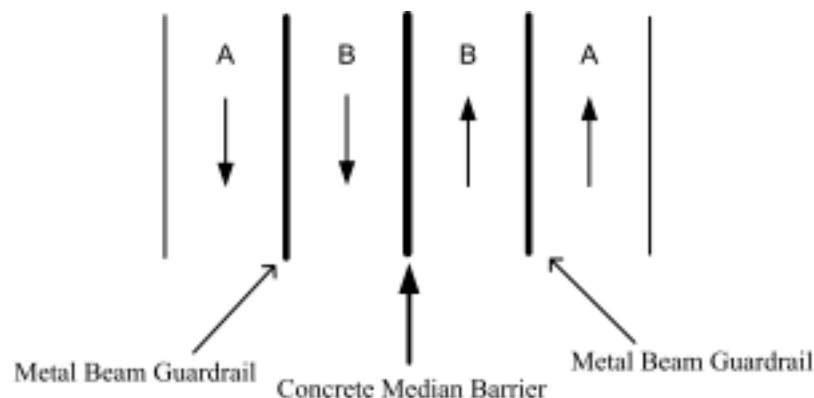
A: Outer lanes – Trucks, buses, and passenger cars
B: Inner lanes – Passenger cars only

Figure 2-2. Conceptual Illustration of Separated Facility in New Jersey Turnpike

In an investigation of the feasibility of an exclusive truck-lane facility in the median area of the I-35 corridor from Dallas to San Antonio, Mason *et al*. (1986) and Middleton *et al*. (1987a, 1987b) recommend constructing an exclusive truck facility for a half-mile long section where the level of service (LOS) was low and the median was wide enough (at least 36 feet) to build the facility.

According to an evaluation by Vidunas and Hoel (1997) using EVFS (Exclusive Vehicle Facilities—an FHWA computer model designed for determining the economic feasibility of

separated truck facilities), the potential benefits of exclusive truck facilities may only be realized in certain situations. EVFS calculates the net present worth and benefit-cost ratio for each alternative that designates existing lanes or provides new additional lane exclusively for trucks. EVFS calculates savings in terms of travel time, vehicle operating cost, injury and property damage, and travel delay. EVFC calculates incurred project costs in terms of engineering and construction costs, right-of-way acquisition, demolition, and periodic pavement maintenance. Based on the results of the pilot study, which was applied to a 31.5-mile segment of I-81 in Virginia, two light-vehicle lanes and one heavy-vehicle lane is a feasible exclusive lane strategy for three-lane highways, while two light-vehicle lanes and two heavy-vehicle lanes are economically beneficial for four-lane highways.

2.2. Route Restrictions

Route restrictions are implemented mainly in urban areas to circumvent truck travel around congested city roads and to prevent them from traveling on routes with inadequate geometric designs. This restriction is often implemented to detour trucks carrying hazardous materials to low population areas. Route restrictions for trucks carrying hazardous cargo are considered beneficial along heavily populated corridors (Stokes and McCasland, 1986). However, route restrictions may increase carriers' operating costs in urban areas due to greater circuity in travel paths, resulting in additional vehicle miles. A good example of route restrictions can be found in Atlanta, Georgia, where through trucks are restricted from using the radial freeways that directly connect to the center of the city (Fitzpatrick *et al*., 1992). In Minneapolis–St. Paul, traffic signs encourage truck traffic to divert to the bypass rather than go through the CBD area on more congested freeways; because this is not a regulatory ban but rather a recommendation, studies find that trucks are not significantly diverted from the more direct routes (Fitzpatrick *et al*., 1992; Wishart and Hoel, 1996).

2.3. Time-of-Day Restrictions

Time-of-day restrictions prevent trucks from using certain lane(s) or entire facilities during particular time periods. In the case of lane restriction regulations in Broward County, as described in section 2.1.1, trucks are restricted from 7:00 am to 7:00 pm. Stokes and McCasland (1986) pointed out that time-of-day restrictions ("banning" trucks) might force trucks to travel on detour routes with insufficient design standards for increased truck volume, resulting in additional truck-related crashes or delays on these routes. In addition, since most trucks tend to travel during off-peak periods to avoid delays, banning trucks on certain routes, especially urban freeways during the peak period, would probably only have marginal effects on freeway operations and safety. Further, time-of-day restrictions could face legal issues and could be difficult to enforce.

In a study of the effects of large trucks on peak-period urban freeway congestion in three California metropolitan areas, Grenzeback *et al*. (1990) found that, for the most part, trucks avoid peak traffic. In the Los Angeles and San Francisco areas, large trucks accounted for 4% of all vehicles during the morning peak and 2.5% of all vehicles during the evening peak. The percentages were significantly lower in San Diego where 1.8% trucks traveled during morning peak and 0.8% during the evening peak. The percentages and absolute numbers of large trucks

were the highest during the midday off-peak period in all three areas. Due to the lower truck volumes on the congested freeways, the authors conclude that a peak-period ban on trucks won't have a significant effect on peak-period congestion, except where the portion of trucks to the total volume was greater than 10% on severely congested freeways. In addition, most of the congestion relief gained from peak-period freeway truck bans, if any, would likely be lost within a short period of time because as peak-period conditions improve, drivers tend to change their travel pattern from the edges of the peak period back to the actual peak periods. Finally, truck bans may increase economic costs and pollution from emissions since they would force trucks to use parallel arterials and shift operations to off-peak periods.

2.4. Differential Speed Limits

Differential speed limits (DSL) are designed to reduce the speed at which trucks are allowed to travel. Because lower speeds require shorter stopping distances for trucks, this alternative may reduce crashes in which trucks rear-end other vehicles. Stokes and McCasland (1986) suggested that, since most truck crashes occur during off-peak periods at relatively high speeds and the performance of passenger cars and trucks differs, a lower speed limit for trucks, with proper enforcement, could be an effective means of reducing traffic crashes.

On the other hand, opponents have argued that DSL increases speed variances and lane changes on roadways, which may, in turn, increase the chances of a crash occurring. Wishart and Hoel (1996) pointed out that some locations had removed DSL after determining that this alternative was ineffective at reducing crashes. A simulation study by Garber and Gadiraju (1990) shows that a combination of right-lane restrictions and DSL skews the speed distribution in the right lane. Since there is a high correlation between the skewness of the speed distribution and the potential of traffic crashes, this combined truck restriction strategy may increase crashes, particularly on highways with a high percentage of trucks. DSL remains a controversial truck restriction strategy; these authors recommend that a more thorough investigation, including before-and-after studies of crash data, be conducted.

2.5. Impacts of Truck Restrictions

Several studies examining the impacts of truck restrictions on speed changes, density, level of service, headway, and safety can be found in the literature, which is reviewed and summarized below.

2.5.1. Speed Changes

The Hanscom (1990) investigation of truck-restriction effects on speed differentials between lanes compares manually collected speed data before and after a restriction was implemented on a three-lane facility (per direction) of I-290 near Chicago. Trucks were restricted from using the leftmost lane of the facility. The author expected that truck-lane restrictions would have an adverse effect on differential speeds between the restricted and non-restricted lanes in that the absence of trucks in the restricted lane (generally the left lane) would increase the speed and the concentration of trucks in the non-restricted lanes would reduce the speed in the corresponding lanes. The increase in differential speeds between lanes is a safety concern because the potential

for traffic crashes increases when vehicles change lanes often (Hanscom, 1990). However, contrary to the expected results, speed differentials between the restricted and unrestricted lanes actually decreased after the implementation of truck restriction. Table 2-1 shows a small average speed reduction due to general increase of traffic volume after truck restriction at both restricted (left) and unrestricted lanes.

Table 2-1. Speed Changes Before and After Trucks were Restricted from Left Lane

	Left Lane (mph)	Right Lanes (mph)	Speed Difference
Before Restriction	62.2	59.3	2.9
After Restriction	60.6	58.4	2.2

(source: Hanscom, 1990)

In order to examine speed changes due to a truck-lane restriction on I-20 near Fort Worth, Texas, Zavoina *et al*. (1991) assessed the data from a system of tapeswitches that was installed across the traffic lanes. This system collected speed data by classification, direction, period (peak or non-peak), and lanes. The arithmetic means of the speeds of each vehicle classification in each lane was examined. In general, the speed change patterns of cars were identical to those of trucks although the variation of cars was smaller than that of trucks. Since the changes were different based on direction (i.e., increase in eastbound but decrease in westbound) and period (i.e., decrease in peak period but increase in off-peak period), the authors could conclude that the changes in speed were due to the truck-lane restriction.

Using the FRESIM microscopic simulation model, Hoel and Peek (1999) evaluated freeway truck-lane restrictions on speed differentials under various scenarios. A total of 24 scenarios were constructed based on two lane-restriction variables (whether or not there were restrictions), three uphill grades (0%, 2%, 4%), and four different initial volume distributions by lane, as follows:

1. An equal distribution across the lanes (33%, 33%, 34%, for the left, center, and right, respectively),
2. A small shift of some vehicles to the right lanes (30%, 35%, 35%),
3. A larger shift of vehicles whereby half of the traffic travels in the middle lane and remaining traffic is evenly distributed between left and right lanes (25%, 50%, 25%), and
4. An estimate of actual distribution (25%, 38%, 37%).

For each scenario, 20 combinations (five values for traffic volume and four for truck percentage) were tested on a hypothetical three-mile section with three lanes in each direction. The volumes ranged from 1,000 to 3,000 vehicles per hour per direction and truck percentages ranged from 10% to 40%. The simulation period was one hour and the free-flow speed was assumed to be 65 mph. A paired sample t-test was used to determine whether or not the differences between data collected before and after the restriction was implemented were significant.

Except for cases involving steep grades, significant speed differentials were not observed. Under steep upgrade conditions, however, the speed differentials generally increased. This behavior is similar to that observed in truck climbing lanes, where slower trucks voluntarily move to climbing lanes and non-truck traffic use all the regular lanes to maintain or less severely reduce

their travel speed. Table 2-2 shows the statistical test results on speed differentials for the various scenarios. Figure 2-3 shows an example of speed differentials for scenario I-U0 and I-R0.

Table 2-2. Statistical Tests on Speed Differentials (α = .05) (source: Hoel & Peek, 1999, p.19)

Scenarios	Calculated t	Critical t	Significant Difference	Result
I-U0 & I-R0	-0.6227	1.729	No	Not changed
I-U2 & I-R2	0.7064	1.729	No	Not changed
I-U4 & I-R4	2.7389	1.729	Yes	Increased
II-U0 & II-R0	-1.3590	1.729	No	Not changed
II-U2 & II-R2	0.7282	1.729	No	Not changed
II-U4 & II-R4	3.8034	1.729	Yes	Increased
III-U0 & III-R0	1.6654	1.729	No	Not changed
III-U2 & III-R2	1.8009	1.729	Yes	Increased
III-U4 & III-R4	2.0908	1.729	Yes	Increased
IV-U0 & IV-R0	1.1598	1.729	No	Not changed
IV-U2 & IV-R2	0.1122	1.729	No	Not changed
IV-U4 & IV-R4	2.6357	1.729	Yes	Increased

Notes: I, II, III, IV denote the initial volume distribution
     I: 33%-33%-34%, II: 30%-35%-35%, III: 25%-50%-25%, IV: 25%-38%-37%
     U, R indicate lane restriction (U: Unrestricted, R: Restricted)
     0, 2, 4 denote uphill grade of 0%, 2%, and 4%, respectively.
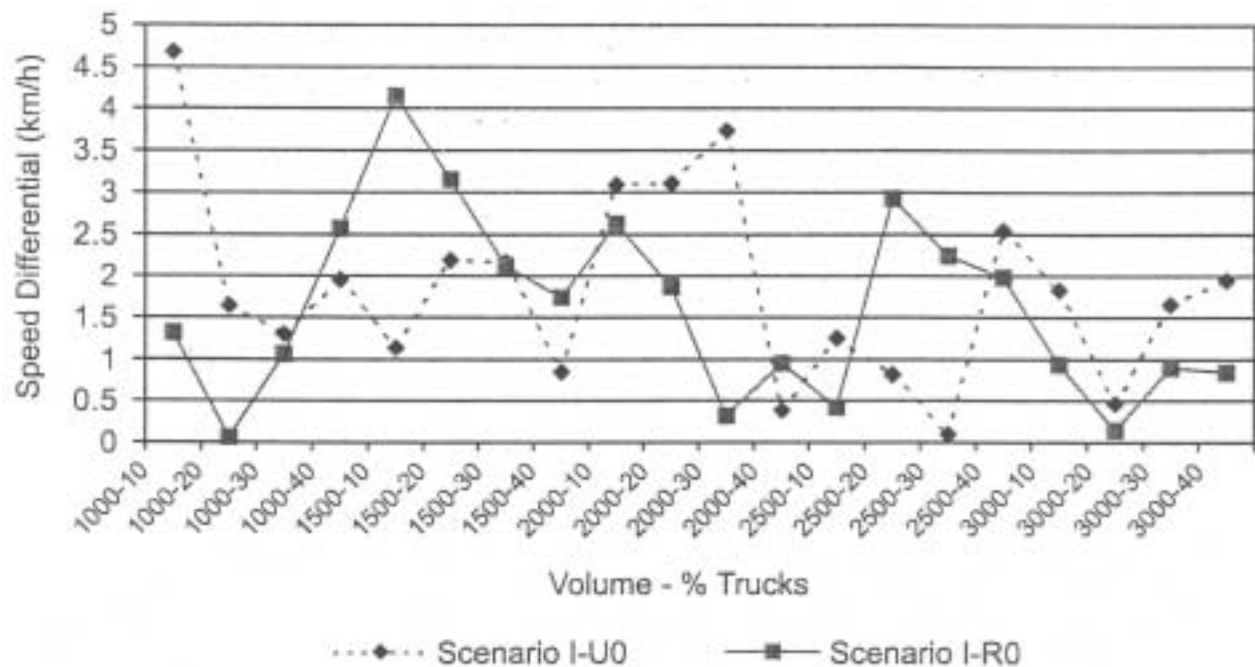
Figure 2-3. Speed Differential for Scenario I-U0 and I-R0
(source: Hoel and Peek, 1999, p. 19)

Using vehicle behavior on an approximately three-mile long section of multilane highway simulated using SIMAN, Garber and Gadiraju (1990) investigated the effect of truck-lane restriction and DSL on speed distribution. Compliance with speed limits was specified in modeling motorist response to posted speed differentials. This information was obtained from existing speed distributions. The truck restriction to the right lane and DSL (differential speed limits) strategy was found to skew the speed distribution. Figure 2-4 shows that the speed is distributed symmetrically without DSL (top), and is skewed with DSL (bottom). Skewness increases as the percentage of trucks in the traffic grows, as shown in Figure 2-5.
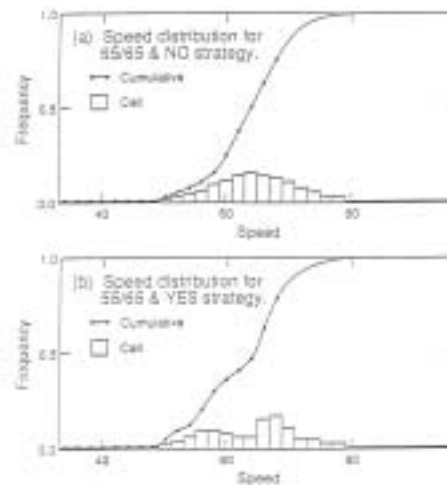
Figure 2-4. Effect of Lane Restriction on Speed Distribution on Right Lane
(source: Garber and Gadiraju, 1990, p. 53)
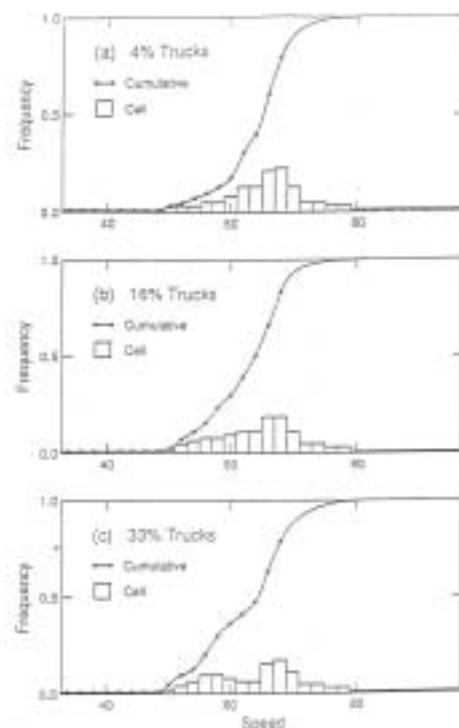
Figure 2-5. Speed Distributions on Right Lane Carrying Different Truck Percentages
(source: Garber and Gadiraju, 1990, p. 53)

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Joshua and Garber (1990) found that the number of truck-involved accidents was expected to increase as speed differentials increase between trucks and other vehicles. Accordingly, DSL may increase the number of truck-involved accidents due to its increase in speed differentials because research has established a relationship between the speed differential and accidents. The chances of being involved in a crash are minimized if the motorist is driving at about the average speed of traffic, as shown in Figure 2-6. The rate at which crashes occur increases substantially when a vehicle travels much faster or slower than the average speed of traffic flow (Stover and Koepke, 1988).
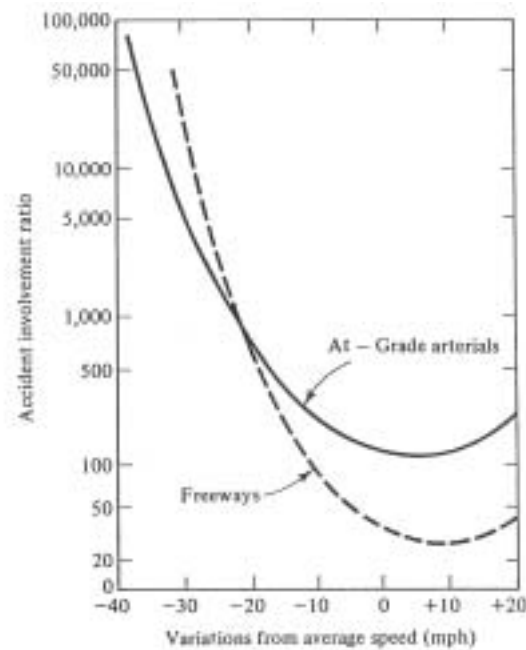
Figure 2-6. Accident Rate per 100 VMT and Speed Differential
(source: Stover and Koepke, 1988, p. 105)

2.5.2. Density and Level of Service

Density is defined as the number of vehicles occupying a given length of highway or lane and is generally expressed as vehicles per mile (vpm) or vehicles per mile per lane (vpmpl). It is the primary characteristic used in determining the level of service (LOS) for a basic freeway section. However, density is difficult to measure directly because its accuracy depends on an elevated vantage point (McShane *et al.*, 1998). Thus, it is generally calculated from speed and flow data, as follows:

$$Density = Flow / Speed \qquad\qquad (2\text{-}1)$$

Hoel and Peek (1999) found that traffic density decreased after the implementation of a truck-lane restriction at steep uphill grade locations because trucks are required to travel in the slower lane to avoid impeding other traffic. Under other conditions, traffic densities were always greater or equal to those without restriction after a restriction was put in place. On the other hand, the LOS was not affected by the truck-lane restrictions but changed only according to the

volume of traffic. Table 2-3 shows the statistical test summary on traffic density changes before and after the truck-lane restriction. Figure 2-7 shows that density increases as the percentage of trucks increases. These results indicate that the truck restriction from the left lane does not significantly affect the LOS of the freeway.

Table 2-3. Statistical Tests on Density ($\alpha = 0.05$)

Scenarios	Calculated t	Critical t	Significant Difference	Result
I-U0 & I-R0	1.6581	1.729	No	Not changed
I-U2 & I-R2	-1.4802	1.729	No	Not changed
I-U4 & I-R4	-1.9613	1.729	Yes	Decrease in density
II-U0 & II-R0	1.9898	1.729	Yes	Increase in density
II-U2 & II-R2	-0.0971	1.729	No	Not changed
II-U4 & II-R4	-2.8107	1.729	Yes	Decrease in density
III-U0 & III-R0	1.1540	1.729	No	Not changed
III-U2 & III-R2	-1.4530	1.729	No	Not changed
III-U4 & III-R4	-3.4742	1.729	Yes	Decrease in density
IV-U0 & IV-R0	2.6237	1.729	Yes	Increase in density
IV-U2 & IV-R2	1.8155	1.729	Yes	Increase in density
IV-U4 & IV-R4	-3.4349	1.729	Yes	Decrease in density

Notes: I, II, III, IV denote the initial volume distribution
      I: 33%-33%-34%, II: 30%-35%-35%, III: 25%-50%-25%, IV: 25%-38%-37%
      U, R indicate lane restriction (U: Unrestricted, R: Restricted)
      0, 2, 4 denote uphill grade of 0%, 2%, and 4%, respectively.

Figure 2-7. Traffic Density for Scenario I-U0 and I-R0
(source: Hoel and Peek, 1999, p. 15)

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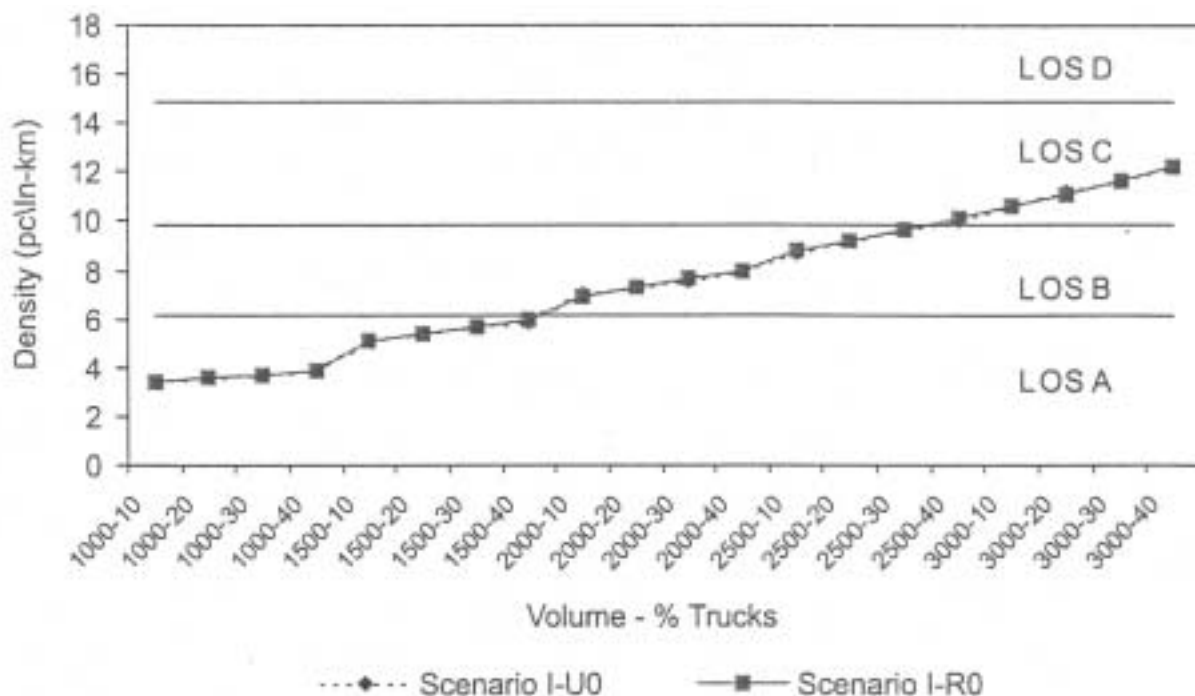## 2.5.3. Headways

While density describes the traffic stream as a whole, microscopic measures such as time headway (or time gap) and space headway describe individual pairs of vehicles within the traffic stream. Zavoina *et al.* (1990) investigated the effects of truck-lane restrictions on time gap, defined as the time lapse between the passing of a fixed point by the rear axle of the leading vehicle and the front axle of the following vehicle. Because this parameter does not incorporate vehicle length, it can provide a more accurate description of how closely vehicles follow one another. The proportion of truck-car pairs in each lane in which time gaps were less than specified values, such as 2.0 and 1.5 seconds, were compared before and after the restriction was implemented using Chi-square tests to evaluate the statistical difference. No significant differences were found for either peak or non-peak periods. As with vehicle speeds, truck-lane restrictions were found to have no significant effect on time gaps. Since the site was in a rural area and the headway was usually greater than five seconds even during the peak period, vehicles were not significantly influenced by the vehicle in front of them after the implementation of the restriction.

In their investigation of the effects of imposing DSL and lane restrictions with respect to the time headways in the right lane, Garber and Gadiraju (1990) found that the imposition of DSL alone does not significantly affect headways. However, when DSL is combined with lane restrictions on the right, a significant decrease in right lane headways was found at sites with high traffic volumes and a high percentage of trucks. This reduction in the number of acceptable gaps available for merging vehicles from entrance ramps creates an unsafe condition called the "barrier effect." The barrier effect might occur at entrance ramp area if the truck percentage is higher than 3.6% and the AADT is greater than 75,000 on six-lane highways.

Hanscom (1990) used time gap analysis to determine the queue length behind the impeding truck. If the time gap is less than a threshold value, the following vehicle is counted as part of the queue. Average flow delay to vehicles impeded by trucks was recorded both at the test and control sites. Although the following vehicle speed reduction was statistically significant, this reduction (less than 1.0 mph) was strongly correlated to the general increase of traffic volume after the restriction was put in place. While a significant reduction in zero queue length was found at the control site, the percentage of trucks with zero queue length was not significantly changed at the test site. This author concluded that the truck-lane restriction to the right two lanes did not increase the queue length behind an impeding truck.

2.5.4. Safety

Although safety is a major reason for truck-lane restrictions, only a few related studies can be found in the literature. Vargas (1992) evaluated the safety effect of the truck-lane restriction implemented in Broward County, Florida. Crash data from the restricted site (Broward County) were compared with those from a non-restricted control site along the same freeway in adjacent Palm Beach County. It was assumed that the truck behavior would not change under the restriction strategy; therefore, the change in percentage of truck crashes to all crash types could be compared both between the two adjacent counties and between time periods (in a before / after design). Three years of crash data were reviewed for the before period (1979-1981) and

two sets of three-year data were used for the after period (1983-1985 and 1986-1988). The study found in truck-involved crashes increased at the control site, but not at the restricted site. Accordingly, lane restrictions were recommended as an effective countermeasure to improve traffic safety.

Garber and Gadiraju (1990) developed simple linear regression models for nine different counties and cities in Virginia to investigate the relationships between crash rate and level of congestion (V/C), expressed as follows:

$$CR = \alpha + \beta(V/C) \tag{2-2}$$

where   CR = crash rate in terms of 100 million VMT,
α, β = model parameters, and
V/C = volume-to-capacity ratio.

The crash involvement rate of trucks (TCR) as a function of truck volume (TVOL), as follows, was modeled to measure the effect of truck strategies:

$$TCR = 8.27 + 0.00278 \times TVOL \tag{2-3}$$

The model shows that the truck restriction strategy would result in the redistribution of truck volume among the lanes and affect the truck crash pattern in each lane. Using hourly traffic volumes from the simulation results, the expected changes in accident rates were tested and no significant changes were found in any of the test cases. Garber and Gadiraju (1990) also found that imposition of DSL and lane restriction did not change the crash rate in the left lane but slightly increased the crash rate in the right lane for both truck-related and all-vehicle crashes. However, these increases were not significant at the 0.05 level.

Hoel and Peek (1999) analyzed the average number of lane changes per vehicle to measure the changes in crash potential and found a relationship between them due to increased interactions between the vehicles. In other words, truck-lane restriction increases the number of lane changes in the flat sections, but significantly decreases lane changes in the uphill sections. The authors suggest that, since trucks were required to travel on the rightmost lanes under the restriction, the number of lane changes probably decreased accordingly under steep grade conditions. Table 2-4 represents the statistical test results of lane changes under various scenarios. As an example, Figure 2-8 shows the number of lane changes per vehicle as a function of general traffic and truck volumes for scenario I-U0 and I-R0.

2.6. Restriction Compliance

The rate of truck compliance to restrictions is usually measured by the percentage of trucks in the restricted lane(s) (i.e., the truck violation rate). Hanscom (1990) assessed the operational effects of truck-lane restrictions through identical behavioral observations at both non-restricted (control) sections and restricted (test) sites on the same highway. The three study sites include two three-lane (per direction) urban-fringe interstates in Chicago, and one rural, two-lane (per direction) interstate in Wisconsin. A high compliance rate was found for the three-lane highway,

where the violation rates were as low as 0.9% and 5.7%. However, the violation rate was higher (10.2%) for the two-lane case, which was attributed to the higher concentration of trucks in a single unrestricted lane. A survey conducted by the Georgia Department of Transportation in 1980 on the truck ban in Atlanta, Georgia showed a comparable violation rate of 5.4% (Fitzpatrick *et al.*, 1992). In another study, Zavoina *et al.* (1990, 1991) analyzed the operational effects of truck-lane restriction on a nine-mile, three-lane (per direction), 3%-upgrade freeway section near Fort Worth, Texas. Truck volumes in the restricted lane decreased significantly after the restriction, and only 3% of trucks violated the restriction without enforcement.

Table 2-4. Statistical Tests on Lane Changes ($\alpha = 0.05$)

Scenarios	Calculated *t*	Critical *t*	Significant Difference	Result
I-U0 & I-R0	3.3438	1.729	Yes	Increased
I-U2 & I-R2	-1.6470	1.729	Yes	Decreased
I-U4 & I-R4	-5.2331	1.729	Yes	Decreased
II-U0 & II-R0	2.4469	1.729	Yes	Increased
II-U2 & II-R2	-1.0633	1.729	No	Not changed
II-U4 & II-R4	-6.6227	1.729	Yes	Decreased
III-U0 & III-R0	0.9053	1.729	No	Not changed
III-U2 & III-R2	-1.8206	1.729	Yes	Decreased
III-U4 & III-R4	-5.5363	1.729	Yes	Decreased
IV-U0 & IV-R0	1.003	1.729	No	Not changed
IV-U2 & IV-R2	-1.1760	1.729	Yes	Decreased
IV-U4 & IV-R4	-7.5298	1.729	Yes	Decreased

Notes: I, II, III, IV denote the initial volume distribution
I: 33%-33%-34%, II: 30%-35%-35%, III: 25%-50%-25%, IV: 25%-38%-37%
U, R indicate lane restriction (U: Unrestricted, R: Restricted)
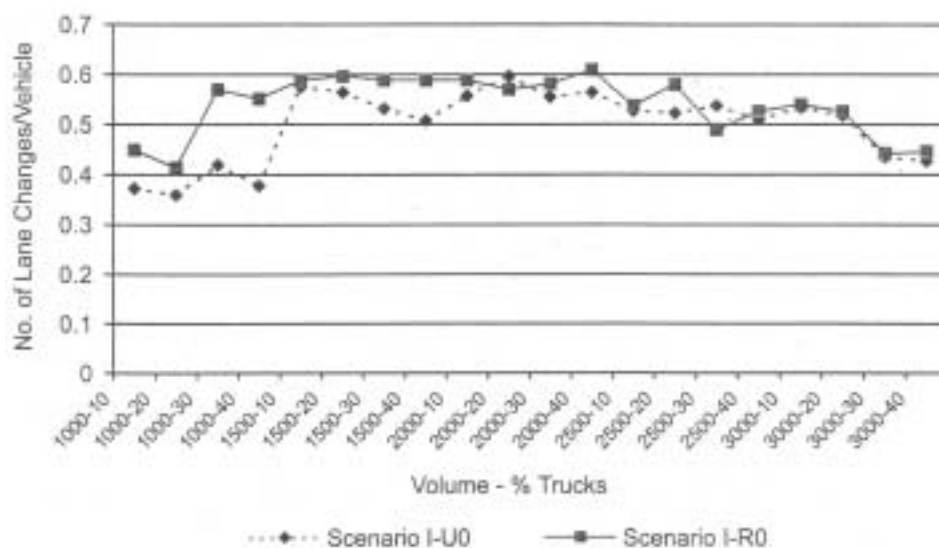0, 2, 4 denote uphill grade of 0%, 2%, and 4%, respectively.

Figure 2-8. Lane Changes for Scenario I-U0 and I-R0
(source: Hoel and Peek 1999, p. 17)

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Koehne *et al*. (1997) developed the following logit model to explain the willingness of truckers and motorists to comply with the truck-lane restrictions implemented in the Washington State Puget Sound region:

$$P_y = \frac{1}{1 + e^{-V_y}}$$ (2-4)

where P_y = the probability of being in favor of truck-lane restriction, and
V_y = the observed portion of the utility derived from favoring truck-lane restriction.

Favorability towards compliance was derived using the following linear utility function:

$$V_y = \alpha + \beta S + \theta D$$ (2-5)

where S = vector of individual's socioeconomic characteristics,
D = vector of individual's observed driving behavior, and
α, β, θ = calibrated parameters.

Indicators including age, number of years employed as a trucker, consequence of restriction violation, cargo type, number of lane changes, and route were utilized for the truckers' favorability model; similar indicators were utilized for the motorists' model. A third model was developed to predict the awareness of motorists of the truck restrictions. These models provide a profile of the "pro" and "con" groups regarding truck-lane restrictions and aim to help administrators to better target their marketing efforts.

2.7. Summary of Findings from Literature Review

Truck-restriction strategies are used to reduce conflicts between trucks and passenger cars on the freeways. The different types of truck restrictions and their advantages and disadvantages can be summarized as follows (Stokes and McCasland, 1986; Carvell *et al*., 1997):

1. Truck lane restrictions may improve traffic operations and safety by separating slower trucks from faster passenger cars. However, they may cause uneven deterioration of the highway pavement.

2. Restricting trucks from the left-lane(s) removes slower trucks from the faster inner (leftmost) lane(s); however, it causes a concentration of trucks on the right lane(s) and blocks the visibility of signs to drivers in the inner lanes.

3. Restricting trucks from the right-lane(s) requires trucks to use the faster lanes. It is usually used as a temporary measure to prevent pavement deterioration. Since trucks have to shift over to the left lanes, safety concerns arise near interchanges and weigh stations where lane changes are required.

4. Route restrictions are mostly used in urban areas to remove trucks from congested roads or to enhance safety by detouring hazardous material cargo from heavily populated

corridors. However, they may increase the truckers' operating costs by increasing vehicle miles due to greater circuity incurred in travel paths.

5. Time-of-day restrictions prevent trucks from using certain lane(s) or entire facilities during particular time periods. This may force trucks to travel on detour routes with insufficient design standards for increased truck volume, resulting in additional truck-related crashes or delays on these routes. Since most trucks tend to travel during off-peak periods to avoid delays, banning trucks on certain routes may only have marginal effects on freeway operations and safety.

6. Differential speed limits (DSL) are designed to reduce the speed at which trucks are allowed to travel. While some believe that this alternative may reduce crashes involving trucks rear-ending other vehicles, other have argued that DSL increases speed variances and lane changes on roadways, which may, in turn, increase the chances of a crash occurring. The actual benefit of DSL remains questionable and many agencies have removed DSL.

Existing operational and safety studies of truck restrictions have found that:

1. Truck-lane restrictions increase speed differentials and reduce density on steep uphill sections. No significant changes were found for other sections (Hoel and Peek, 1999).

2. No adverse effects of truck restrictions were found with respect to the headways and queue lengths following the impeding trucks (Zavoina *et al.*, 1990); however, unsafe conditions might occur at on-ramp areas with a high percentage of trucks and heavy traffic volume under the combined DSL and lane-restriction situation (Garber and Gadiraju, 1990).

3. Truck-lane restrictions have a positive impact on freeway safety (Vargas 1992; Hoel and Peek 1999).

4. Truck violation rates range between 0% and 10%. Higher compliance rates can be expected for roadways with greater numbers of lanes (Hanscom, 1990; Fitzpatrick *et al.*, 1992; Zavoina *et al.*, 1990 and 1991).

CHAPTER 3
MODEL DEVELOPMENT

This chapter describes the process of developing a simulation model for the most common type of truck restriction alternative—the right-lane restriction that prohibits truck traffic from using the left lane(s). Recognizing the difficulty of collecting sufficient data for empirical modeling involving a great number of variables, this study uses the simulation approach to estimate the impacts of various truck-lane restrictions on traffic operations. Simulation can evaluate many possible design alternatives within a reasonable time frame and budget without losing the interdependencies among the many variables. Furthermore, the simulation approach can provide systematic and comprehensive analysis over entire sections of the freeway, including basic, ramp, and weaving sections.

### 3.1. Simulation Model Selection

A number of studies have attempted to compare various simulation models. In general, simulation models are grouped into macroscopic models and microscopic models. FREFLO is a macroscopic freeway simulation model based on relationships between speed, flow, and density. This model evaluates the effects of truck restriction indirectly through changes in capacity (Hoel and Peek, 1999; Smith *et al.*; 1992, Liu *et al.*, 1992). Since performance measures such as number of lane changes and speed differentials can only be derived from detailed vehicle interactions, FREFLO is not a suitable model for this study. Instead, two microscopic simulation models, CORSIM and VISSIM, were considered.

CORSIM (**COR**ridor **SIM**ulation) is a stochastic and microscopic simulation model developed by the U.S. DOT that can simulate traffic operations on both freeways and local streets. It can explicitly simulate truck restrictions (with biased or restricted options) on freeways and individual vehicle movement with various driver types. It is also able to analyze a wide range of traffic, geometric and control variables and provides a rich set of performance measures including lane changes, travel time, delay, speed, density, and fuel consumption. CORSIM uses ASCII file format for input and output files. This facilitates the automated execution of multiple simulation runs with only slight modifications to the input data and the extraction of the output data for further analysis.

VISSIM (**VIS**ual **SIM**ulation) is a behavior-based microscopic traffic simulation model that was developed in Germany (PTV, 2001). It is capable of modeling typical passenger vehicles and trucks for freeways and urban arterials, as well as different modes of surface transit including bus, HOV, and light rail transportation. Like CORSIM, VISSIM uses the ASCII file format for input and output files. VISSIM is also capable of producing output that contains various measures, including delay, queue lengths, speed, density, and lane changes. Unlike CORSIM, VISSIM generates output for individual vehicles, thus speed differentials between passenger cars and trucks after the truck-lane restrictions can be derived from VISSIM output.

During the simulation model selection process, it was discovered that the CORSIM model does not simulate trucks entering truck lane(s) directly when they first enter the network. As shown in Figure 3-1(a), trucks enter from all lanes, even though in this case trucks have been coded to use

only the rightmost lane. Upon entering the network, the trucks would then attempt to perform lane changes to shift to the truck lane(s). At high volumes, these lane changes create a bottleneck that limits the maximum flow rate on the downstream section. Figure 3-1(b) shows that, unlike CORSIM, trucks in VISSIM enter a truck lane directly.
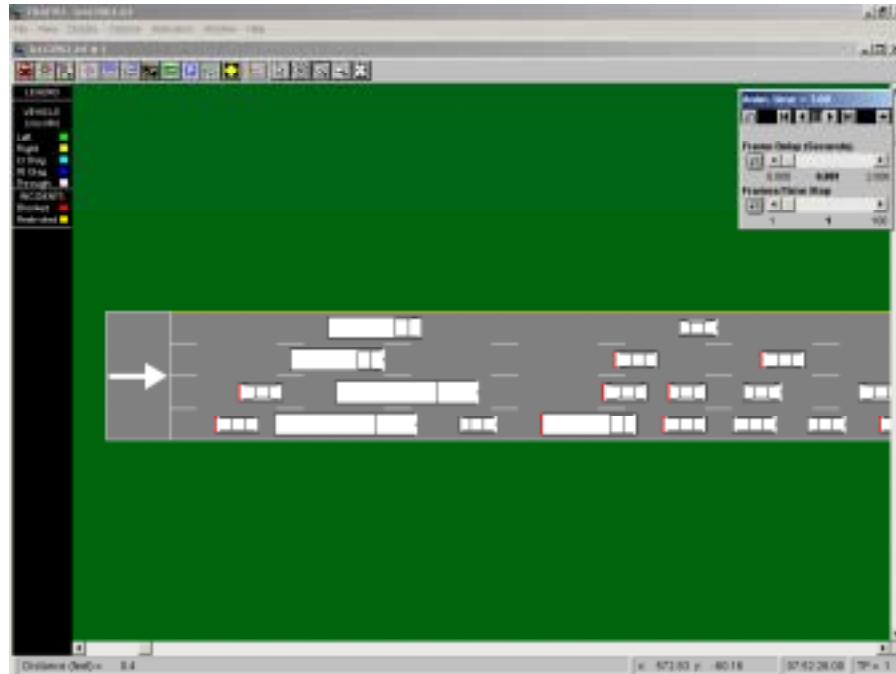
(a) CORSIM : Trucks Enter from All Lanes
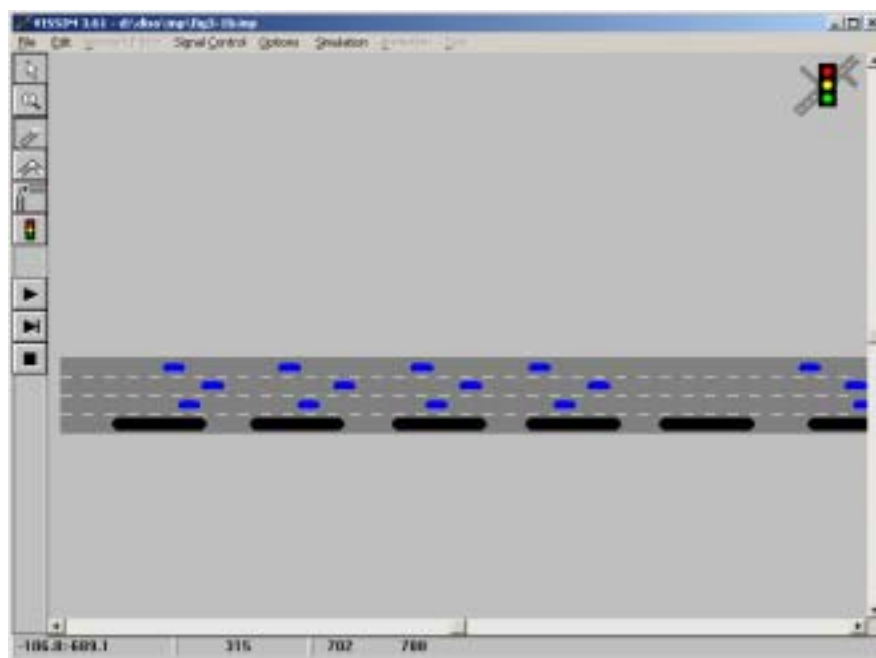
(b) VISSIM : Trucks Enter the Truck Lane Directly

Figure 3-1. Truck Entry Treatments in CORSIM and VISSIM

3.2. VISSIM Limitations

CORSIM provides four default vehicle types including single-unit, semi-trailer with medium load, semi-trailer with full load, and double-bottom trailer. Although VISSIM is more flexible in that it allows a new vehicle type to be defined and added through the "Vehicle Types" menu shown in Figure 3-2, the input is far more complicated than that of CORSIM. It requires input for vehicle performance characteristics that include maximum and desired accelerations, maximum and desired decelerations, weight, power, and vehicle dimensions that include length, shaft length, front gearing, front axle, rear axle, and rear gearing. In the absence of these data, this study uses only the default truck type in VISSIM.

Another limitation of VISSIM has to do with truck compliance. Like CORSIM, VISSIM does not allow a violation rate to be specified to model the percentage trucks that use the restricted lane(s). In other words, the violation rate is assumed 0%, or a 100% compliance rate.

(a) Input for Vehicle Type

(b) Input for Vehicle Dimensions

Figure 3-2. Required VISSIM Input for Defining a New Vehicle Type

3.3. Simulation Model Calibration

Simulations are mathematical simplifications of real-world phenomenon; their capability of replication must be verified prior to application to the real world. Since the default model parameters in VISSIM were not calibrated based on those of the United States, this model calibration step was especially important. Whereas many studies have been done for CORSIM calibration, such as Crowther (2001) and Payne *et al.* (1997), not many works are available for VISSIM calibration. One rare example is the Park and Schneeberger (2003) study, which uses a Latin Hypercube sampling and surface function to calibrate VISSIM model for a coordinated actuated signal system in Virginia.

The heavy vehicle adjustments for the basic freeway segments in the Highway Capacity Manual (HCM) were determined to be the most important functional relationships that the model needs to be able to replicate. It was assumed that the parameters calibrated under these basic conditions were transferable to those of the other conditions. The car-following model parameters of VISSIM were systematically adjusted until they generated results that are as close as those of the HCM maximum service flow rate. This was done by systematically varying the two parameters associated with the Wiedemann 74 car-following model used in VISSIM: "additive part of desired safety distance" and "multiplicative part of desired safety distance." Figures 3-3 (a), (b), and (c) show the calibrated relationship between capacity and truck percentages for different lane freeway. Note that VISSIM parameters were calibrated as close to maximum service flow rate and minimum speed of HCM 2000 as possible.
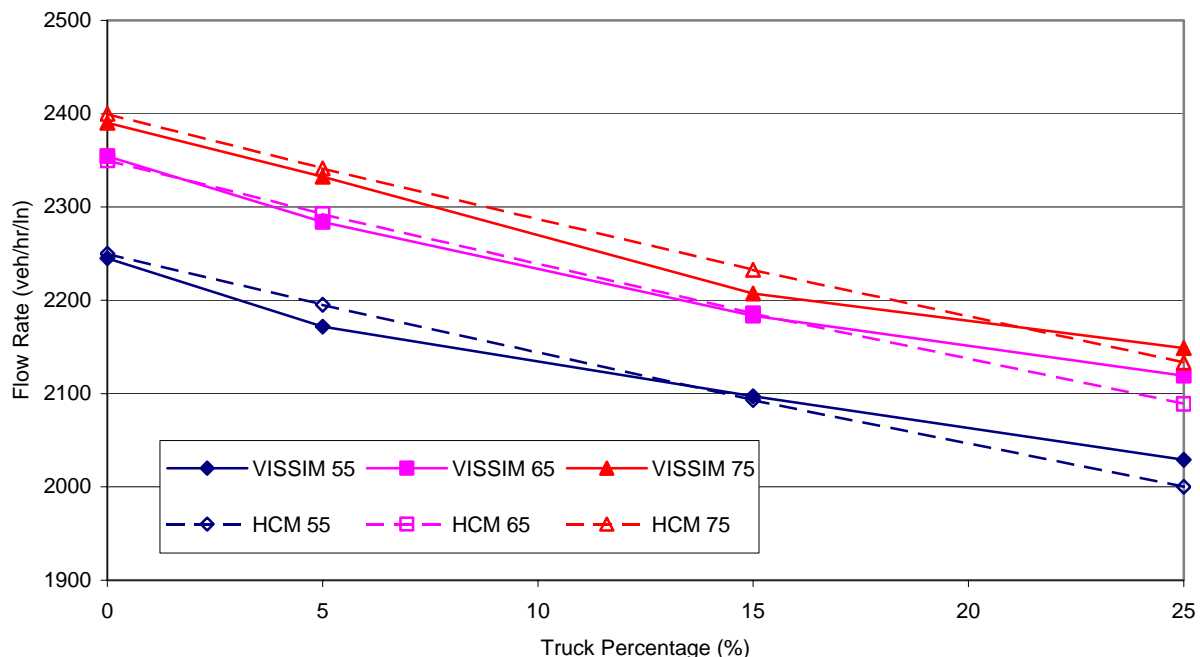
(a) Capacity and Truck Percentages for Three-Lane Corridor
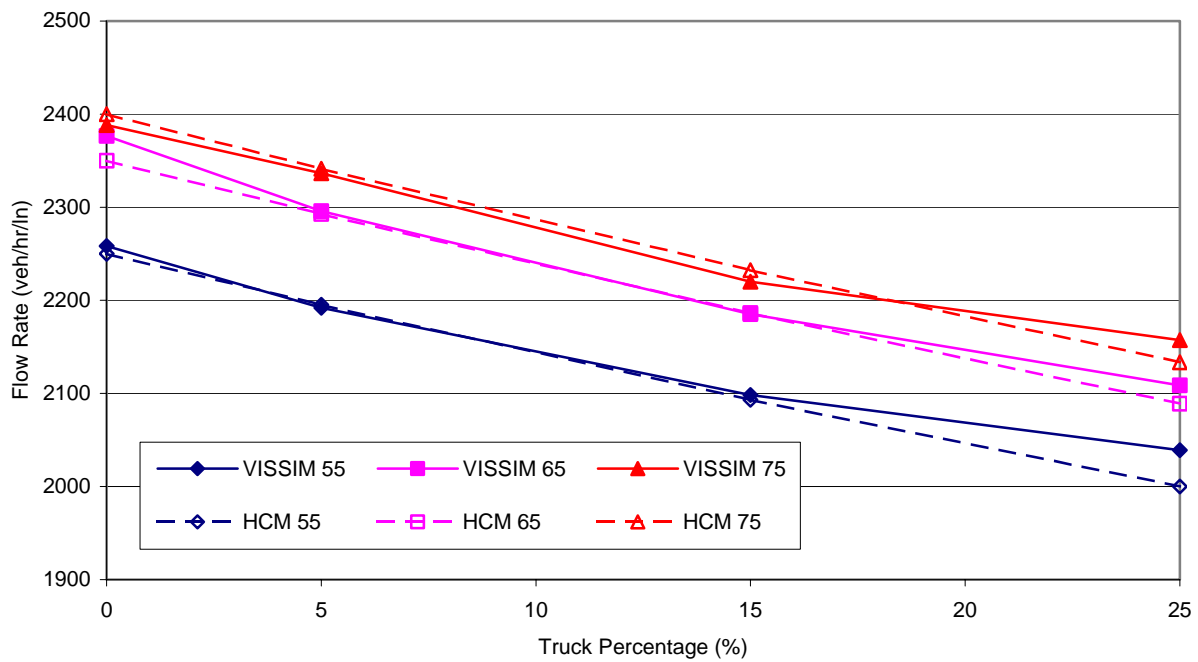
(b) Capacity and Truck Percentages for Four-Lane Corridor
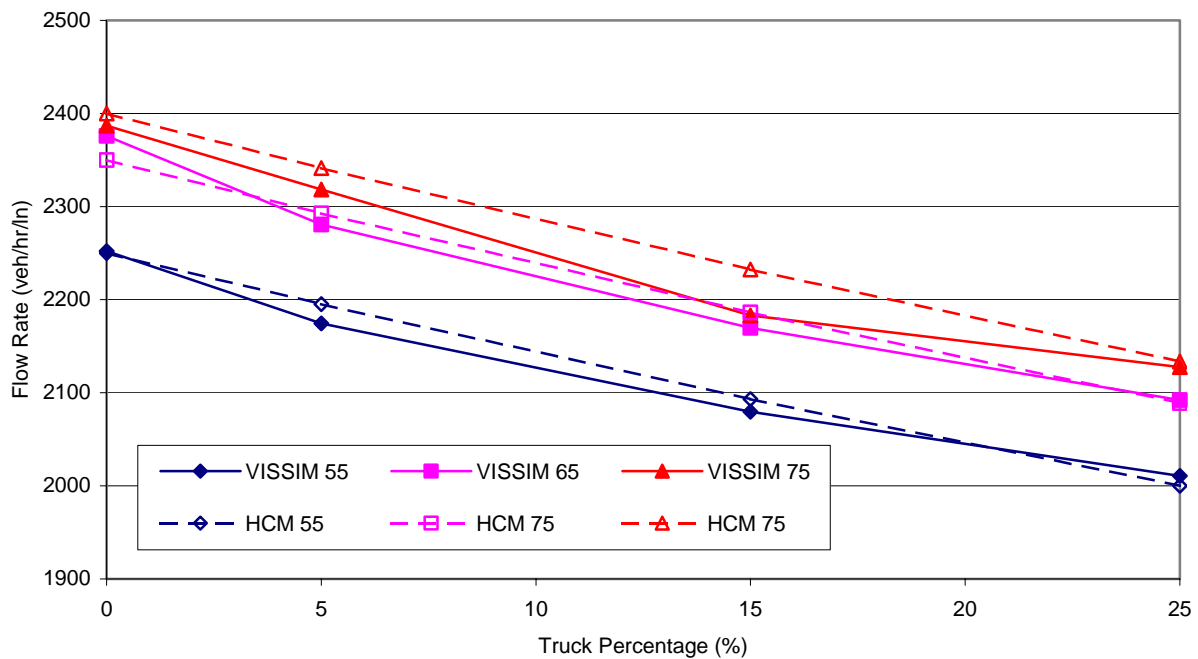
(c) Capacity and Truck Percentages for Five-Lane Corridor

Figure 3-3 Calibration of VISSIM (Capacity and Truck Percentage)

3.4. Simulation Scenarios

After the base simulation model was calibrated, it was modified to model other truck-lane restrictions. A total of 12 different truck-lane restriction alternatives for three-, four-, and five-lane (per direction) freeway corridors, including the non-restricted case, were considered. Figure 3-4 shows the different restriction alternatives for the different number of freeway lanes. Restriction "i" (Ri) denotes that trucks are not allowed to use the leftmost "i" number of lanes. For example, R2 denotes that trucks are not allowed to use the two leftmost lanes. R0 represents the case when there are no lane restrictions. To determine the operational performance changes caused by truck-lane restriction, a base case must be run without any lane restrictions (i.e., Restriction 0 as shown in Figure 3-3).

<figure>

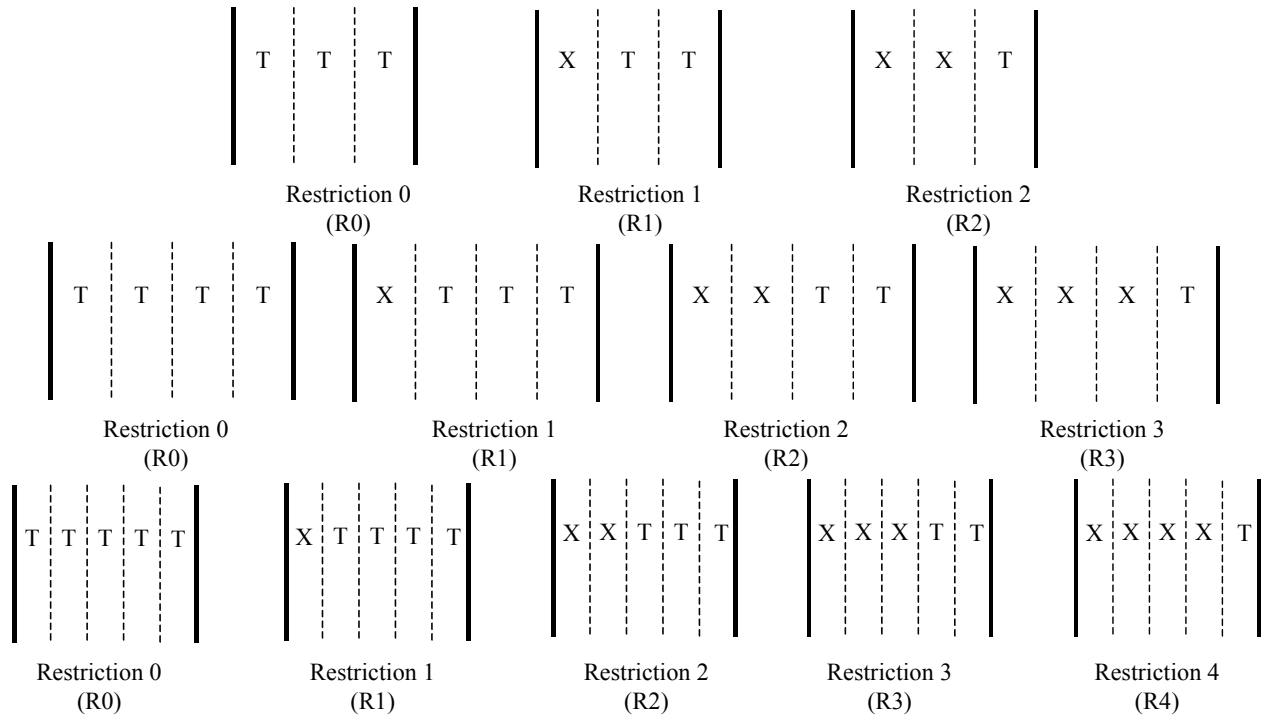| T | T | T | | X | T | T | | X | X | T |

Restriction 0 (R0)   Restriction 1 (R1)   Restriction 2 (R2)

| T | T | T | T | | X | T | T | T | | X | X | T | T | | X | X | X | T |

Restriction 0 (R0)   Restriction 1 (R1)   Restriction 2 (R2)   Restriction 3 (R3)

| T | T | T | T | T | | X | T | T | T | T | | X | X | T | T | T | | X | X | X | T | T | | X | X | X | X | T |

Restriction 0 (R0)   Restriction 1 (R1)   Restriction 2 (R2)   Restriction 3 (R3)   Restriction 4 (R4)

</figure>

X = A truck-restricted lane, i.e., trucks are prohibited from using this lane.
T = A non-truck-restricted lane, i.e., trucks must use this lane.

Figure 3-4. Truck-Lane Restriction Alternatives

Various scenarios were constructed to represent "prevailing conditions," including number of lanes, free-flow speed, volumes, and truck percentage. In addition to these variables, interchange density and ramp volumes were included to investigate the overall performance changes along the freeway corridor. The values simulated for each independent variable are listed in Table 3-1; the different input combinations resulted in 8,541 scenarios. Because some of the input combinations result in infeasible conditions (for example, 100 veh/hr/ln mainline volume and 1,500 veh/hr ramp volume), filters were provided in the program to exclude their simulation runs.

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Table 3-1. Independent Variables and Associated Input Values

Independent Variable	Input Values
Restriction alternatives	3 for 3- lane, 4 for 4-lane, 5 for 5-lane
Number of Lanes Per Direction	3, 4, 5
Free-Flow Speed (mph)	55, 65, 75
Traffic Volume per Lane	100, 600, 1200, 1800, 2000, 2200, 2400
Truck Percentage	0%, 5%, 15%, 25%
Interchange Density (no/mi)	0, 0.5, 1.0, 2.0
Ramp Volume	0, 100, 500, 1000,1500

Due to the stochastic nature of simulation models, each simulation run may generate slightly different outputs. Multiple simulation runs for each scenario are required to overcome such randomness in the simulation outputs and obtain statistically stable results. For this study, five replications were performed for each scenario, resulting in a total of 42,705 simulation runs. Since the initialization period is not explicitly mentioned in VISSIM, the simulation period was set to 4,500 seconds and the data were collected from 900 seconds to 4,500 seconds, for a total of one hour.

3.5. Network Coding and Output

The most demanding element of the development of a traffic simulation model is to code the roadway networks. VISSIM provides a graphical user interface to facilitate creating/editing networks. While most simulation models describe networks as nodes and links, VISSIM uses links and connectors to construct networks, as shown in Figure 3-5. A link represents a one-way, non-branching stretch of roadway where properties such as grade, pavement type, etc. are constant. Connectors are used to model turning possibilities, lane drops, and lane adds.
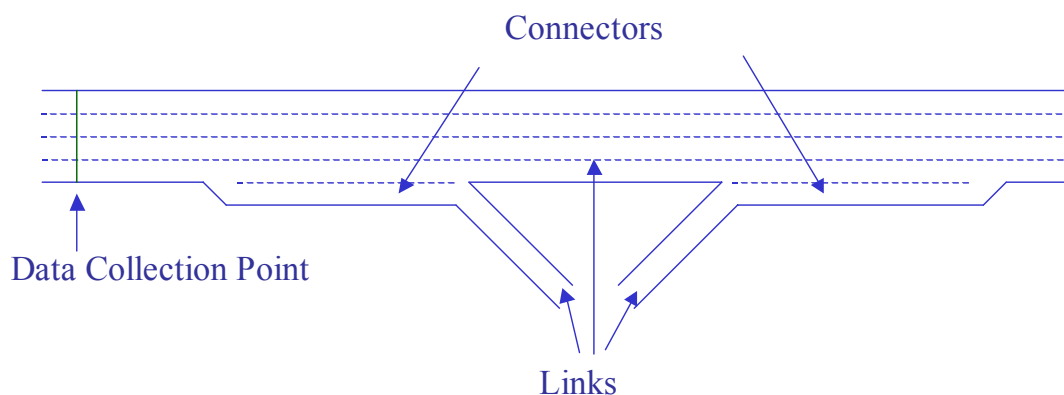
Figure 3-5. Link and Connector of VISSIM Model

A five-mile long corridor is utilized here to evaluate the truck-lane impact on combinations of freeway sections. To do so, the number of diamond interchanges (off-ramp followed by on-ramp) was varied according to interchange density. Note that the distance between the off-ramp and on-ramp link is fixed at 680 feet, which is greater than the 600-foot adequate spacing recommendation in the Traffic Engineering Handbook (ITE, 1992). The length of the

acceleration lane (connector) is set at 1,000 feet and the deceleration lane is set at 700 feet in consideration of the AASHTO required gap acceptance length and taper for smooth traffic operation at the exit and entry areas (AASHTO, 1990). Since the interchange spacing is too close for a density of two interchanges per mile, the full length of auxiliary lane was introduced to replace the separate deceleration and acceleration lanes as shown in Figure 3-6, thereby increasing the number of lanes between the on- and off-ramp points.
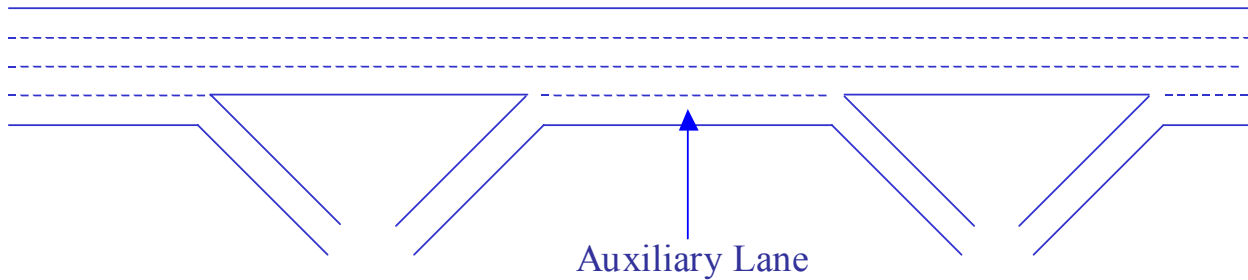
Figure 3-6. Corridor with Two Interchanges per Mile (Interchange Density)

The "Lane Closure" option as shown in Figure 3-7 is used to model truck-lane restriction on specified lanes by selecting the lane and vehicle type(s). It is noted that lane number starts from the rightmost lane, that there is no provision for lane closure violation by trucks in VISSIM.
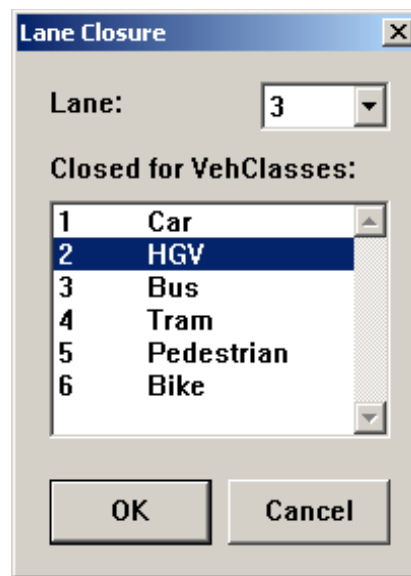
Figure 3-7. Lane Closure Option

VISSIM can produce detailed results on any time interval at user-specified locations by checking the corresponding boxes as shown in Figure 3-8. In this study, the "Data Collection" (based on vehicle counts and spot speed by vehicle type at specified locations), "Lane Change" and "Travel Time" functions are used to generate the travel time data from a one-mile to a three-mile section. Note that VISSIM generates separate output files during a simulation run according to the definition and configuration specific to each evaluation type.

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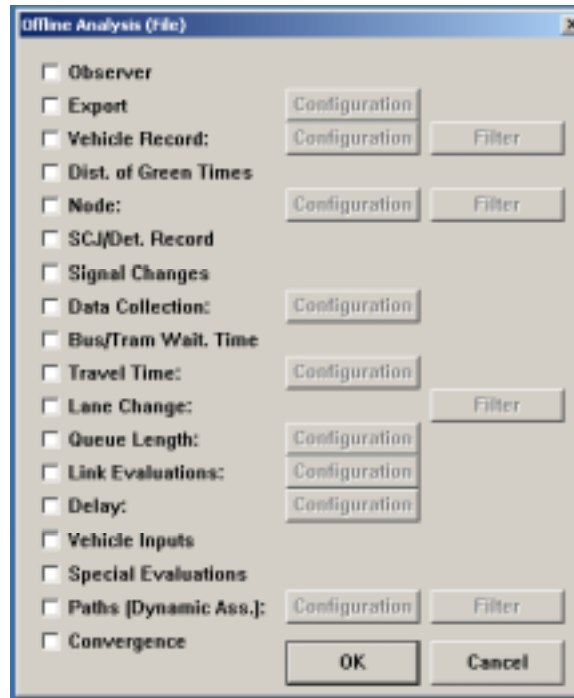
Figure 3-8. Output Selection Screen

3.6. Automated Procedure for Multiple Simulation Runs

In order to investigate the operational performance of truck-lane restriction on freeway corridors under various design and traffic conditions as described in section 3.3, different simulation scenarios must be created by systematically varying the related variables. In addition, multiple simulation runs based on different random number seeds must be performed. Due to the high number of simulation runs, a program was developed to automate the process of performing multiple simulation runs for various scenarios and extracting the appropriate simulation output from each run. In other words, the program performs multiple simulation runs continuously for different combinations of number of lanes, truck restrictions, free-flow speeds, traffic volumes, truck percentages, interchange density, and ramp volume and obtains the simulated performance measures from each run. The automated procedure consists of the following steps:

1. Read the input file for the base network.
2. Modify the base input file for a specific scenario.
3. Run VISSIM for the new input file.
4. Read the VISSIM output file and extract related output for the scenario.
5. Repeat steps 2 to 4 for four additional replications using different random number seeds.
6. Average the output values from each of the five replications.
7. Repeat steps 2 to 6 until all scenarios are simulated.

This automated procedure allows the complete process to be repeated as often as necessary. This is important because the model required fine-tuning several times during the model development process. VISSIM can be run from the DOS command line prompt with simultaneous visual animation.

CHAPTER 4
OPERATIONAL PERFORMANCE ANALYSIS

The Highway Capacity Manual (HCM) (2000) defines a freeway as "a multilane, divided highway with a minimum of two lanes for the exclusive use of traffic in each direction and full control of access without traffic interruption" (p. 5-6). Freeway facilities are composed of three different types of segments: basic freeway segments, ramp segments, and weaving segments. Basic freeway sections are those freeway segments outside the operation impacts of merging, diverging, and/or weaving movements, which cause turbulence in the traffic stream. Since the basic freeway sections handle non-turbulent flows, the operational analysis of this section is relatively straightforward. To achieve the study purpose without losing the generality, different interchange density and ramp volume scenarios were added to the basic freeway section scenarios as explained in the previous chapter. This chapter compares the operational performance of different truck-lane restrictions in terms of average speed based on the two-mile long travel time data, speed differentials between lane groups (restricted and non-restricted lanes), total corridor throughput, and average number of lane changes. The paired sample t-test statistical procedure was used to determine the difference based on the truck-lane restriction for independent variables.

4.1. Speed, Flow and Density

Speed, flow rate and density are the three parameters generally used to macroscopically describe a traffic stream. Equation 4-1 states the relationship between three variables for the uninterrupted traffic flows.

$$Density = \frac{Flow}{Speed} \tag{4-1}$$

Figure 4-1 shows the general relationships among them; the exact calibrations of such relationships vary according to prevailing conditions. Note that any rate of flow less than capacity occurs under two different conditions: (a) high speed and low density, and (b) low speed and high density, as represented by points A and B, respectively in Figure 4-1. While Point A is the desirable operating condition (i.e., stable flow), Point B is observed in the region of forced flow or unstable flow condition. Since the stable flow condition is modeled in this study, speed reduces as flow rate increases.

Although density is a good measure to quantify the traffic demand, it is difficult to measure and usually computed indirectly using the Equation 4-1. The average speed and the maximum flow rate (throughput) are used to represent the macroscopic characteristics in this study.

4.2. Notations

Throughout this chapter, several notations are used in the figures included. These notations, as summarized in Table 4-1, include those for truck-lane restriction alternatives, truck percentages, interchange densities, and ramp volumes. Examples are given in the table to illustrate the

notations.   Note that the layout and the notations for the different truck-lane restriction alternatives are shown in Figure 3-3.
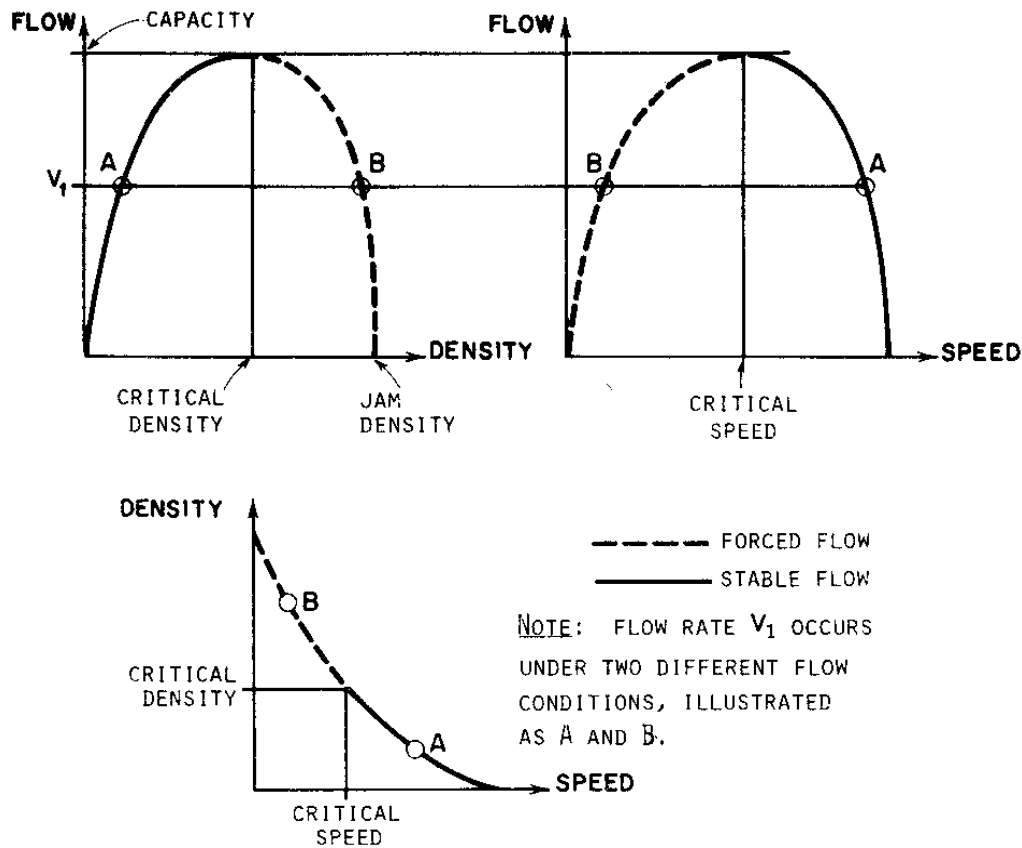
Figure 4-1. Flow, Speed and Density
(source: Traffic Engineering, McShane and Roess)

Table 4-1. Notations

Variable	Notation	Example
Truck-Lane Restriction Alternative	R0, R1, R2, R3, R4	R0: No truck-lane restriction R2: The leftmost two lanes are truck-restricted lanes, i.e., trucks cannot travel on these two lanes.
Truck Percentage	T0, T5, T15, T25	T15: The percentage of trucks in the traffic stream is 15%.
Interchange Density	D0, D0.5, D1, D2	D0.5: The number of interchanges per mile is 0.5, or one interchange in two miles.
Ramp Volume	Rv0, Rv100, Rv500, Rv1000, Rv1500	Rv500: The entrance and exit ramp volumes are 500 vehicles per hour.

4.3. Average Speed

4.3.1. Truck Percentage

Figures 4-2 (a), (b), and (c) show the speed-flow relationships produced by the VISSIM model in which 5%, 15%, and 25% of the traffic flow consist of trucks with 75 mph free-flow speed (FFS) for four-lane freeway basic segment, respectively. This model shows that average speed decreases gradually as flow rate increases. When truck percentages are low or moderate, as in Figures 4-2 (a) and (b), the four restriction alternatives follow nearly the same trajectory and the differences are indistinguishable.

Figure 4-2 (c) illustrates the monotonic decreasing trend also found in Figures 4-2 (a) and (b) until the saturation point. However, when a large number of lanes are restricted (R3), speed drops rapidly and results in lower capacity. Although the differences in terms of speed and capacity are small, the results indicate that the restriction alternatives outperform the non-restriction alternative (R0) in all cases except for a large number of restricted lanes coupled with a high percentage of trucks (R3) as Figure 4-2 (c) illustrates. Similar phenomena occur for the three- and five lane cases as shown in Figures 4-3 (a) and (b).

Figure 4-4 (a) shows speed-flow relationships under the different truck percentages for four-lane freeway corridors with 0.5/mile interchange density, 75 mph FFS, and 500 veh/hr ramp volume. When truck volume is low, the truck-lane restriction alternatives provide a larger capacity and higher speed than the non-restriction alternative, although the difference is quite small. Likewise, for the basic segment case, as previously mentioned, truck-lane restriction does not have any advantage under a very high truck percentage (25%) as shown in the Figures 4-4 (a), (b), and (c).
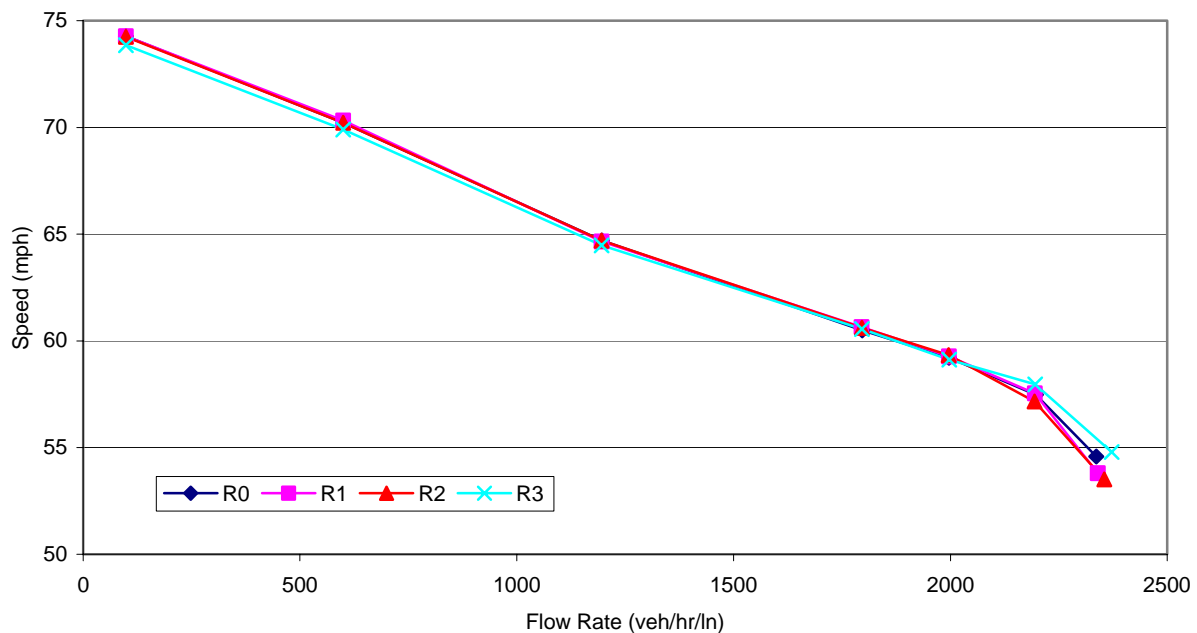
(a) 5% Trucks and 75 mph FFS
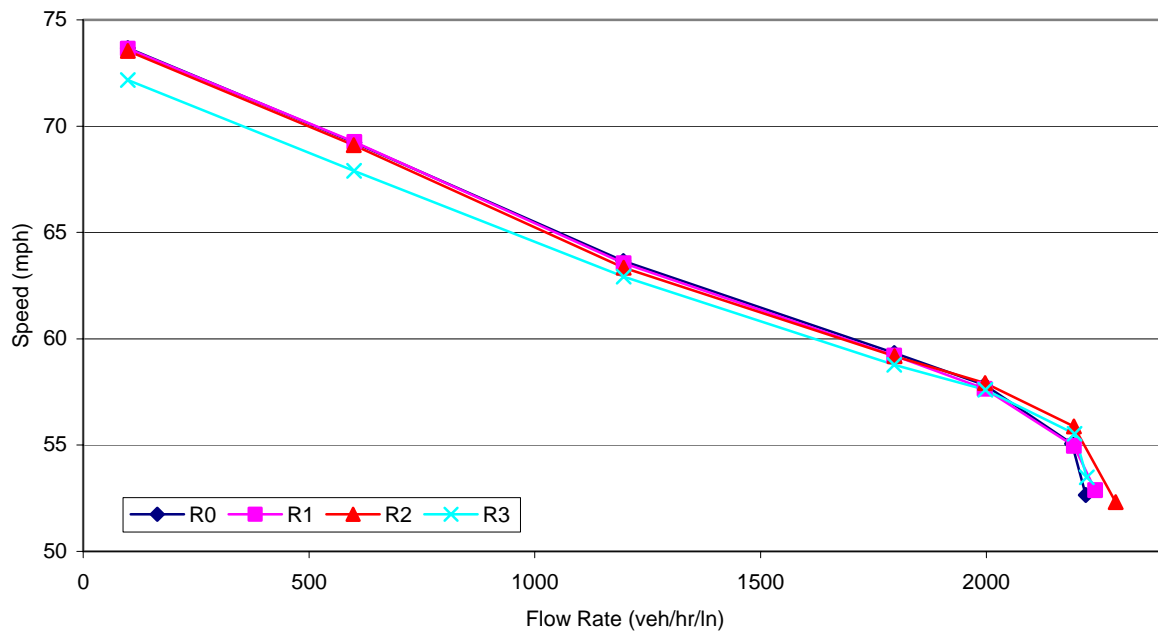
(b) 15% Trucks and 75 mph FFS
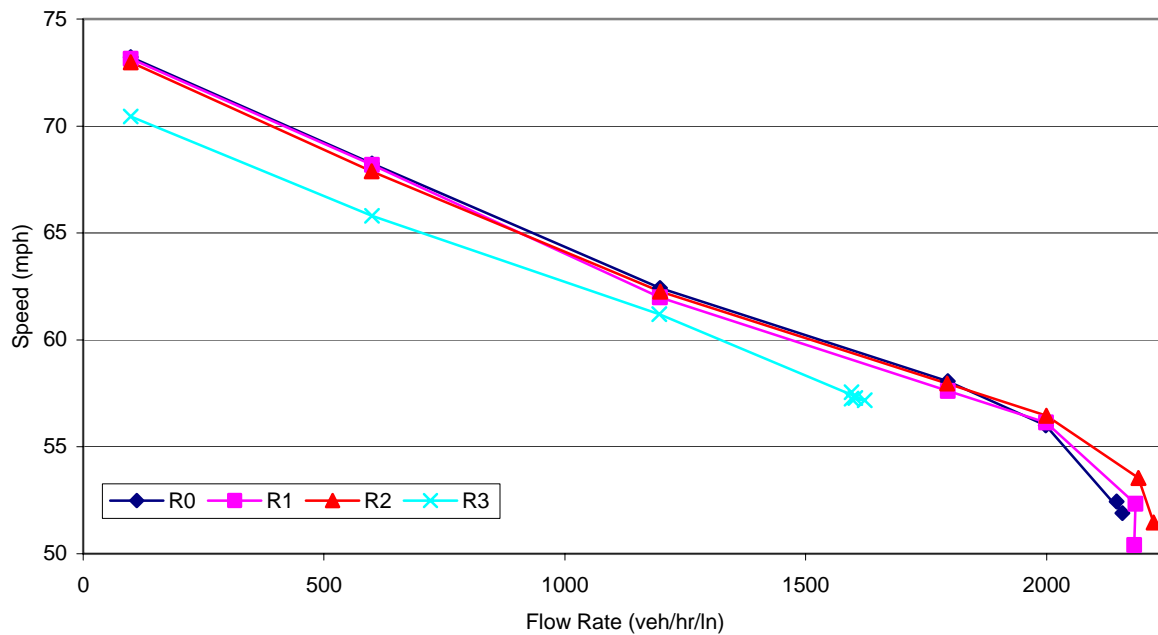
(c) 25% Trucks and 75 mph FFS

Figure 4-2. Speed-Flow Relationship for Four-Lane Case (Basic Segment)
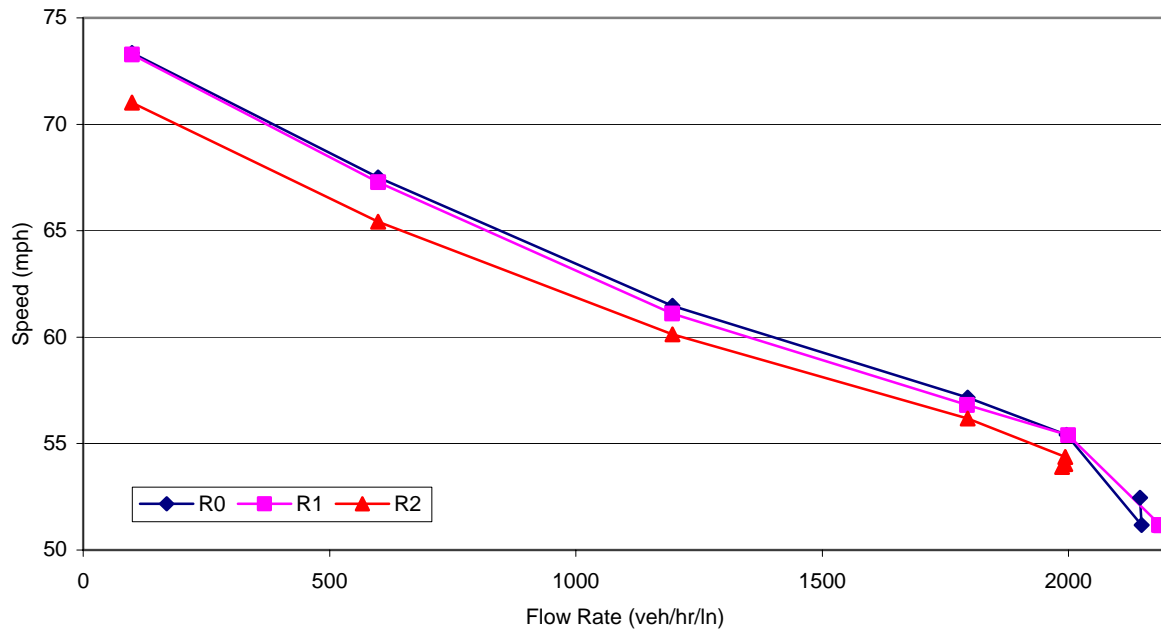
(a) Three-Lane with 25% Trucks and 75 mph FFS
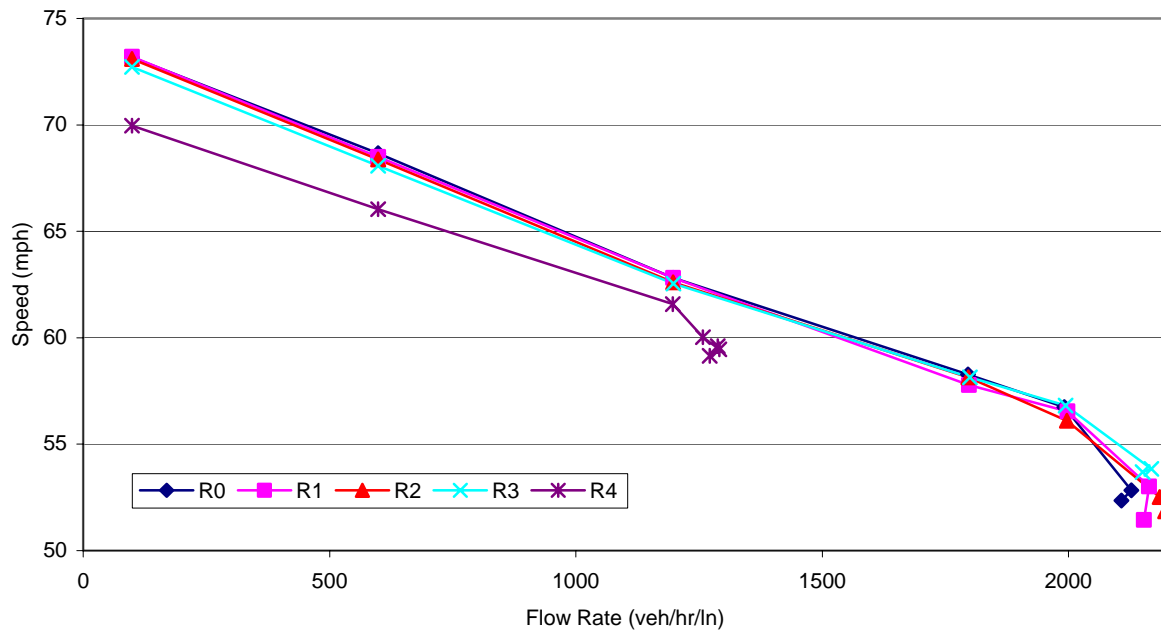
(b) Five-Lane with 25% Trucks and 75 mph FFS

Figure 4-3. Speed-Flow Relationship for Three- and Five-Lane Cases (Basic Segment)

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(a) Four-Lane Corridors

(b) Three-Lane Corridors
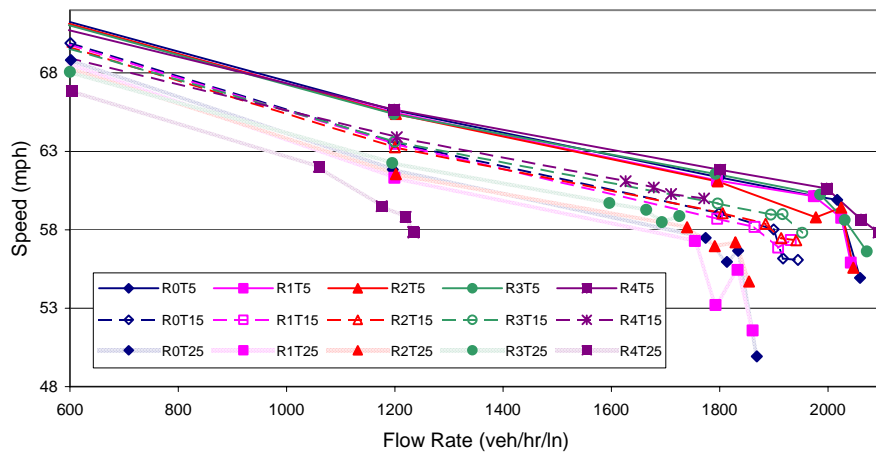
(c) Five-Lane Corridors

**Figure 4-4. Truck Percentages and Speed-Flow Curve
(0.5 Interchange/Mile, 75 mph FFS, and 500 veh/hr Ramp Volume)**

4.3.2. Ramp Volume

Freeways are designed as limited-access facilities in that the locations of the ramps needed to connect them to other highways or to other streets is specifically planned and controlled. These ramps generate turbulenc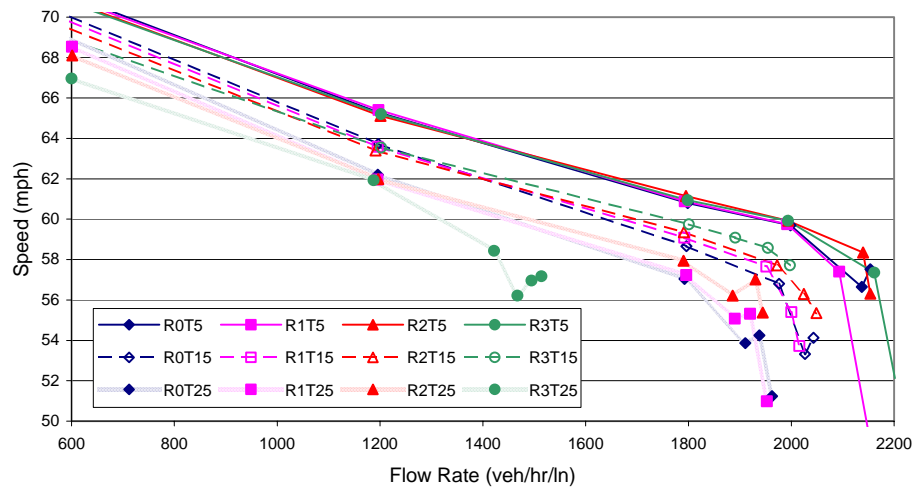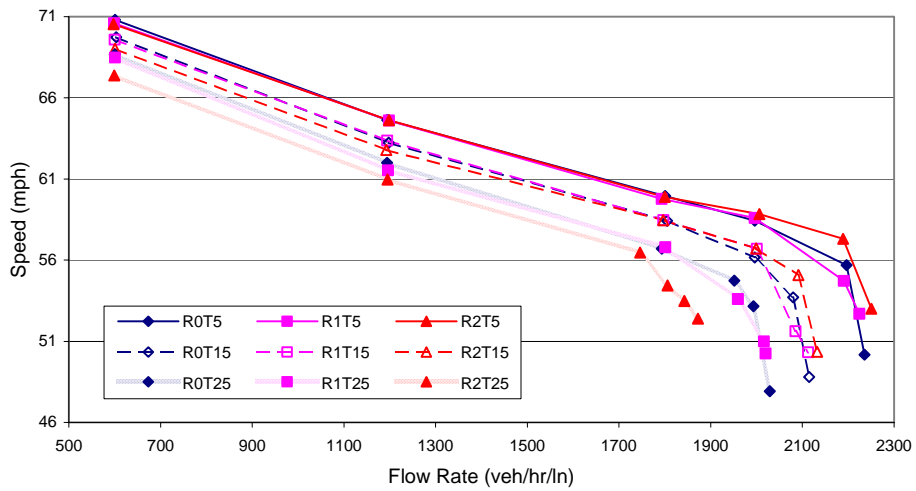e and affect mainline traffic. In this section, ramp effects are investigated by changing the ramp volume under the same truck percentage and interchange densities.

Figure 4-6 shows that the maximum flow rate and speed decrease as ramp volume increases. The truck restriction alternatives outperform non-restriction alternatives when ramp volume is low, as shown in Figure 4-5 (Rv100). However, maximum throughput occurs under the non-restriction alternative when flow rate was increased to reach the congested condition under high ramp volume case (Rv1000). Since the rightmost lane(s) are fully packed with trucks under these restriction alternatives, the model indicates that barrier effects deteriorate mainline traffic quality. Figure 4-5 shows that barrier effects occur when ramp volume is greater than 1000 veh/hr and flow rate approaches 1900 veh/hr/ln under 15% truck percentage. The barrier effects are also found for three- and five-lane freeway as shown in Figures 4-6 (a) and (b). When the ramp volume is moderate (500 veh/hr), restriction alternatives show at least equal performance. However, the speeds fluctuation was found when ramp volume is relatively high (1000 veh/hr or 1500 veh/hr) and under a large number of restricted lanes. This indicates that the system is oversaturated due to truck-lane restriction.
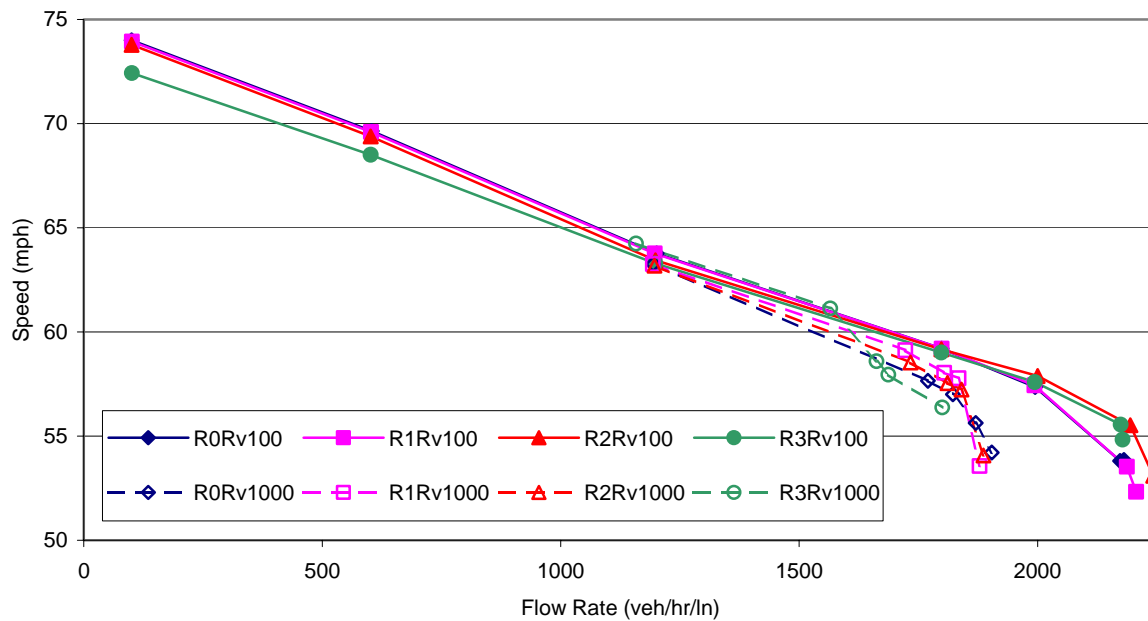
**Figure 4-5. Ramp Volume Effects on Four-Lane Corridors
(15% Trucks, 75 mph FFS, and 0.5/mile Density)**
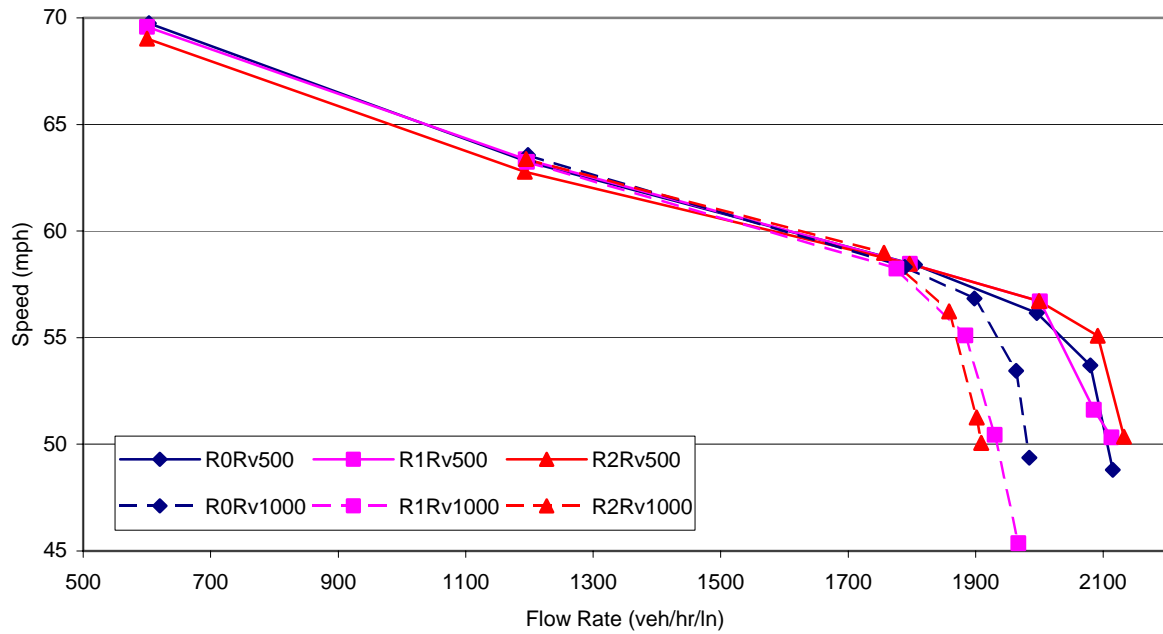
(a) Three-Lane Corridors
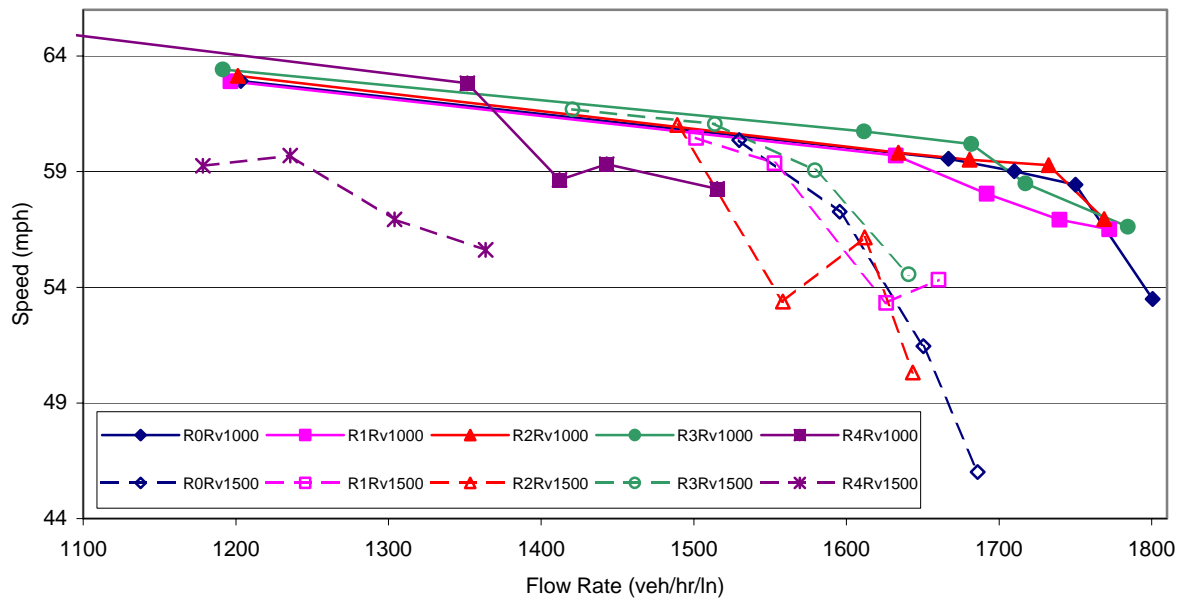
(b) Five-Lane Corridors

**Figure 4-6. Ramp Volume Effects on Speed-Flow Curve
(15% Trucks and 75 mph FFS, and 0.5/mile density)**

4.3.3. Interchange Density

Figures 4-7 (a), (b), (c), and (d) show the speed-flow curves under different interchange densities, truck percentages, and ramp volumes for the four-lane cases. As expected, the average speed decreases as interchange density increases. Figures 4-7 (a) and (b) show that all truck-lane restriction alternatives provide better or nearly equal performances compared to the non-restriction alternative in terms of flow rate and speed under low truck percentage (5%) and medium ramp volume (1000 veh/hr) for all ranges of interchange densities. Hence interchange density does not significantly affect traffic flow under those conditions. However, under a high truck percentage (15%), a high interchange density (2/mile), and a large number of restricted lanes (R3), the corridor reaches the saturated condition rapidly. Figures 4-7 (b) and (d) show that the barrier effects occurred in densely spaced interchange corridors. Note that, in this case, the maximum attainable flow rate under the R3 condition is much lower than the other alternatives. In addition, truck restriction alternatives do not always provide better performance when all three variables (i.e., truck percentage, ramp volume and interchange density), are high, as shown in Figure 4-7 (d). Figures 4-8 (a), (b), and (c) show the speed-flow relationships for the three- and five-lane cases. Barrier effects were also found when the corridor was congested under densely spaced interchanges, high truck percentages, and high ramp volumes. Although the differences are small, the non-restriction alternative (R0) yields higher average speed under these conditions.
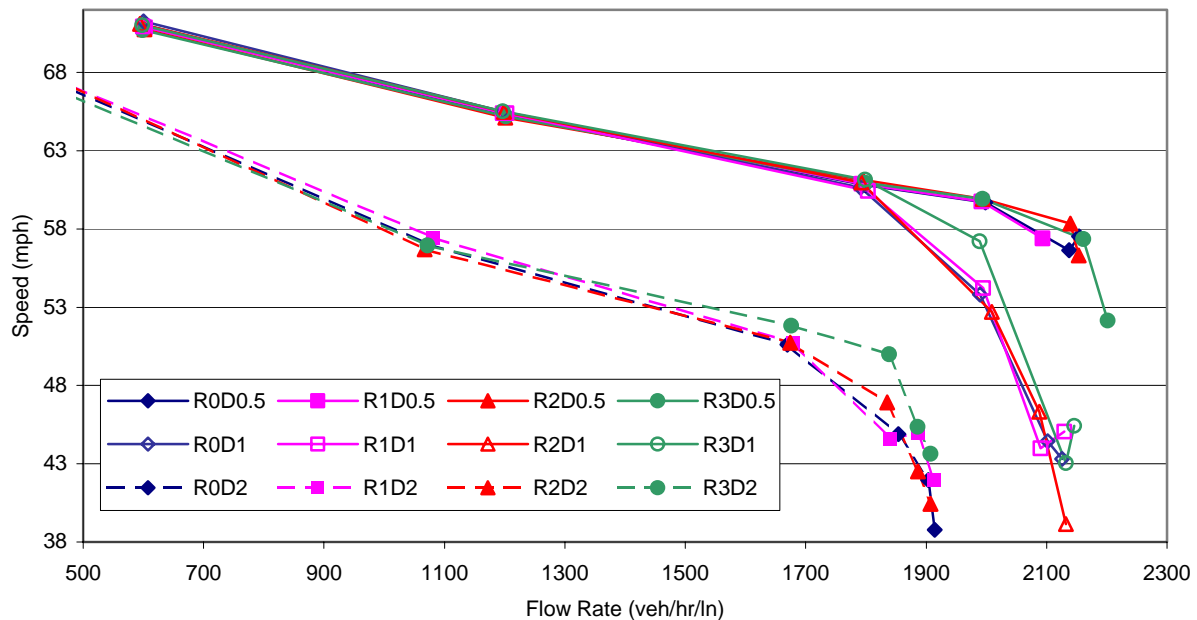
(a) 5% Trucks and 500 veh/hr Ramp Volume
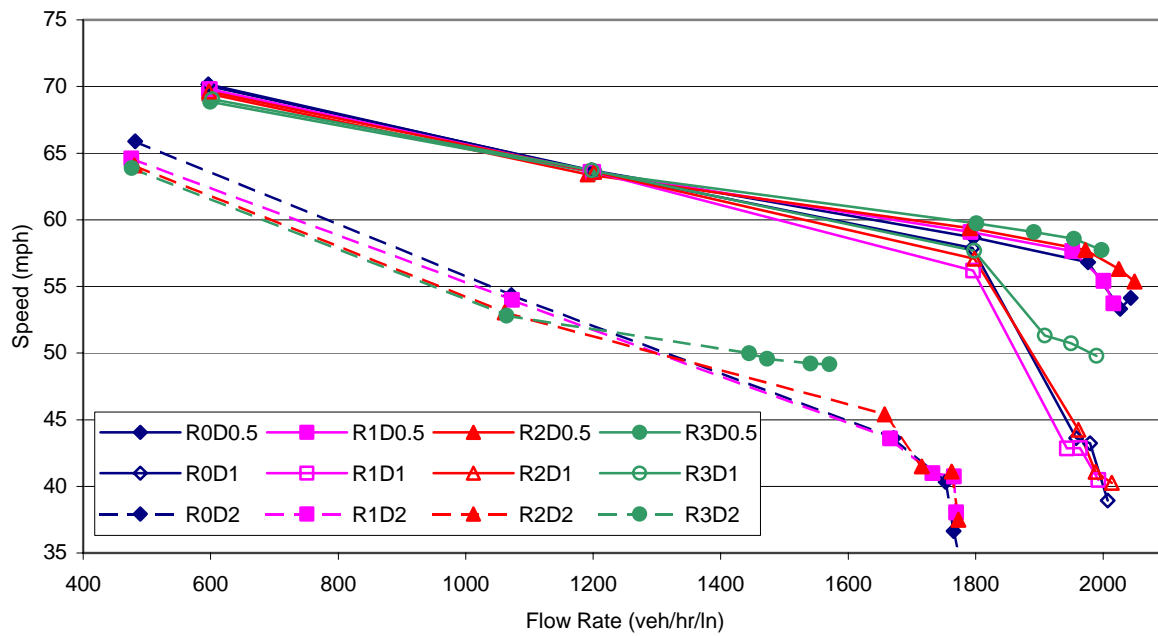
(b) 15% Trucks and 500 veh/hr Ramp Volume
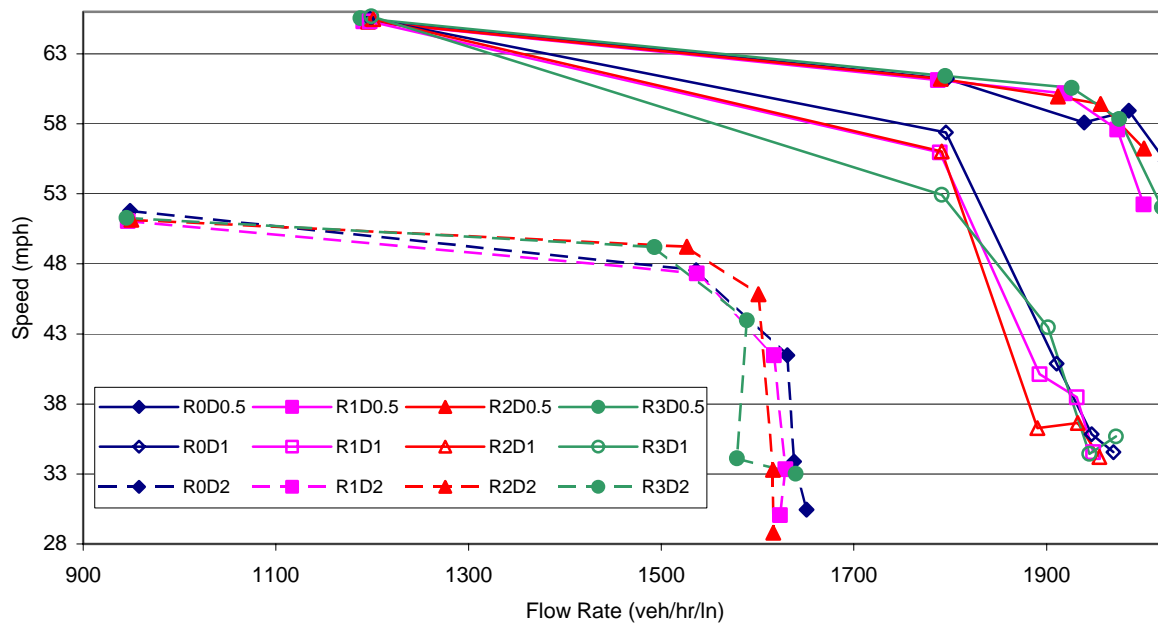
(c) 5% Trucks and 1000 veh/hr Ramp Volume

(d) 15% Trucks and 1000 veh/hr Ramp Volume

Figure 4-7. Interchange Effects for Four-Lane Corridors
(75 mph FFS)
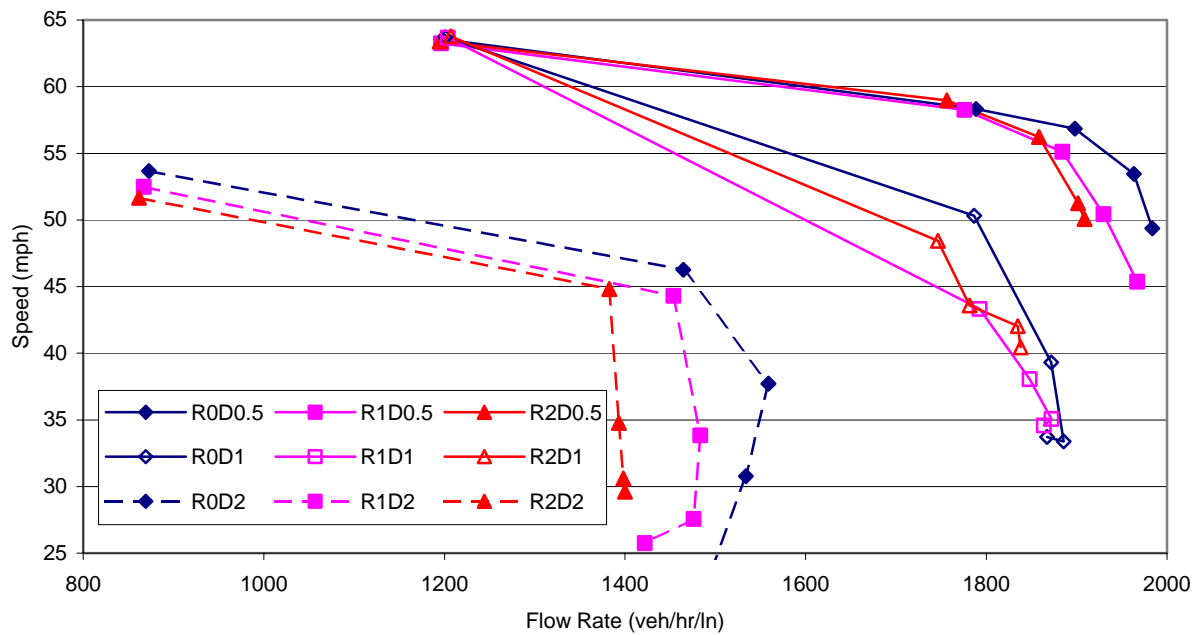
(a) Three-Lane
(15% Trucks, 1000 veh/hr Ramp Volume and 75 mph FFS)

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**(b) Five-Lane
(15% Trucks, 1000 veh/hr Ramp Volume, and 75 mph FFS)**

**(c) Five-Lane
(25% Trucks, 1000 veh/hr Ramp Volume, and 75 mph FFS)**

Figure 4-8. Interchange Effects for Thee-and Five-Lane Corridors

4.4. Speed Differential between Lane Groups

4.4.1. Truck Percentage

A potential adverse effect of truck-lane restriction is increased speed differentials between the lane groups. Speed differentials are defined as the speed difference between the restricted and non-restricted lane groups. The speed-flow relationship for each lane group was evaluated to determine the speed differentials between restricted and non-restricted lane groups. The expectation is that the redistribution of trucks into specific lanes will increase the speed in the restricted lane(s) and decrease the speed in the non-restricted lane(s) where trucks are forced to move and become more concentrated.

Figure 4-9 (a) shows that speed differentials increases as truck percentage increases. In addition, differentials were relatively constant and stable for under-saturated conditions based on either a low number of restricted lane(s) or a lower percentage of trucks. At near-capacity conditions, non-restricted lane flow became unstable, causing the speed of the lane group to drop quickly and increase the speed differential. Since trucks were removed from the restricted lane and the lane operated with unused capacity, the speed in the restricted lanes increased somewhat. In general, these relationships can be illustrated by a U-shaped curve, although options that include a high truck percentage and large number of restrictions do not share this attribute; for example, see R3T25 in Figure 4-9 (a). A similar trend was also found for the three-and five-lane cases, as shown in Figures 4-9 (b) and (c).
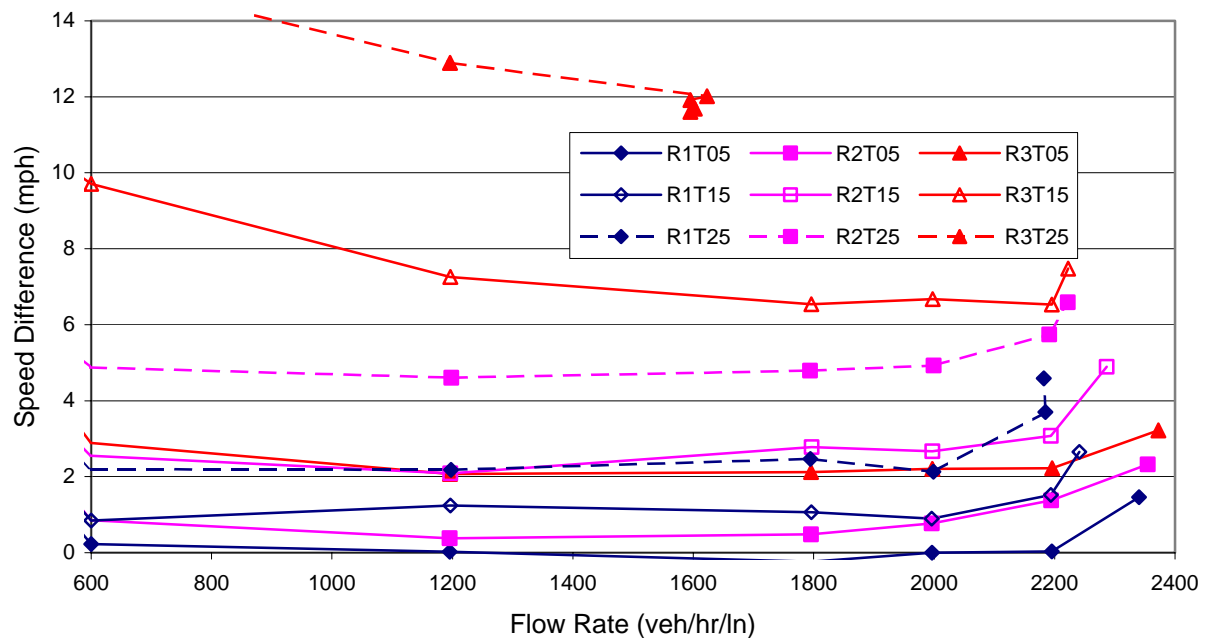
(a) Four-Lane
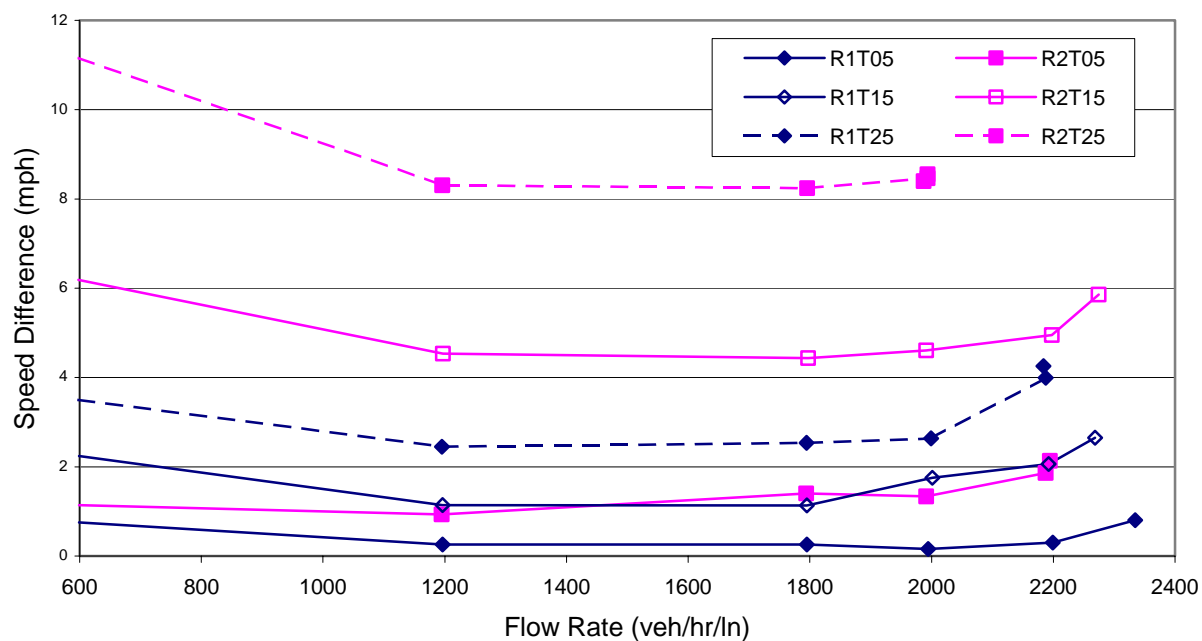
(b) Three-Lane
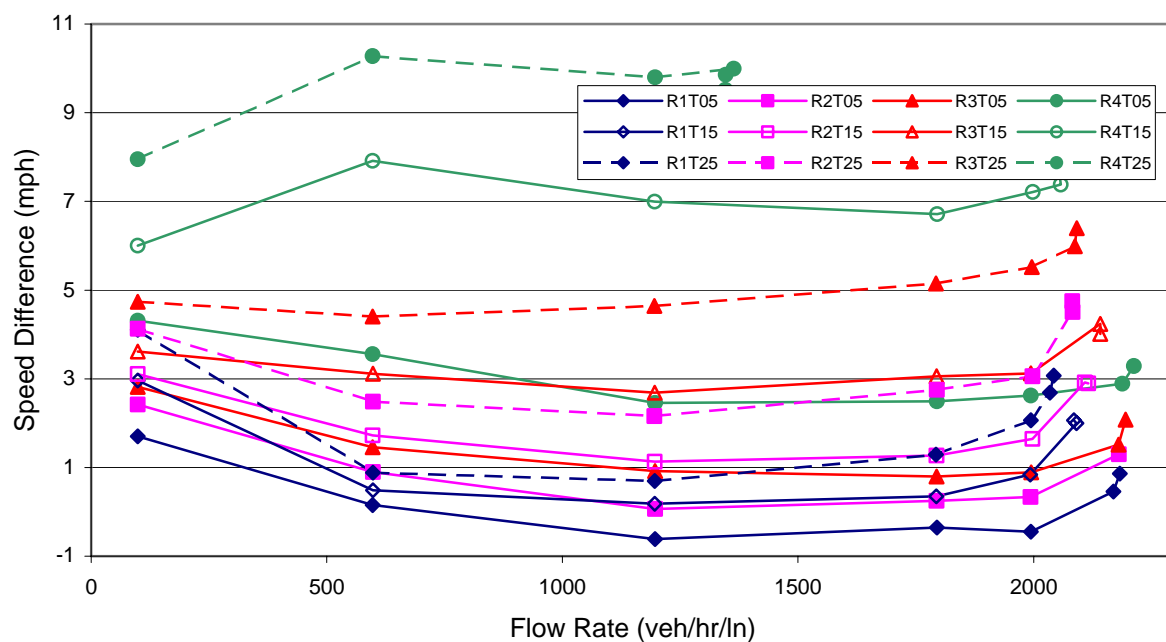
(c) Five-Lane

Figure 4-9. Speed Differentials for Basic Segments
(75 mph FFS)

4.4.2. Ramp Volume and Interchange Density

Figures 4-10 (a) to (d) show that speed differentials decrease as flow rate increases under moderate traffic flow conditions, and increase when flow rate approaches the saturated condition. A monotonic increasing relationship is also found for the severely congested cases due to the high truck percentage and large number of restricted lanes—for example, see R3 in Figures 4-10 (b) to (d). In addition, Figures 4-10 (a) to (d) show that speed differentials increase as interchange density increases. However, U-shaped curves became flat and are rather insensitive to the increase in ramp volume. Since many vehicles attempt to change lanes when approaching their destination, resulting in speed reductions in the non-restriction lane. The range of speed differentials increases as interchange density, ramp volume, or truck percentage increases. Similar trends are also found for the three- and five-lane corridors. Figures 4-11 and 4-12 show the speed differentials under the various traffic conditions for three-and five-lane corridors.
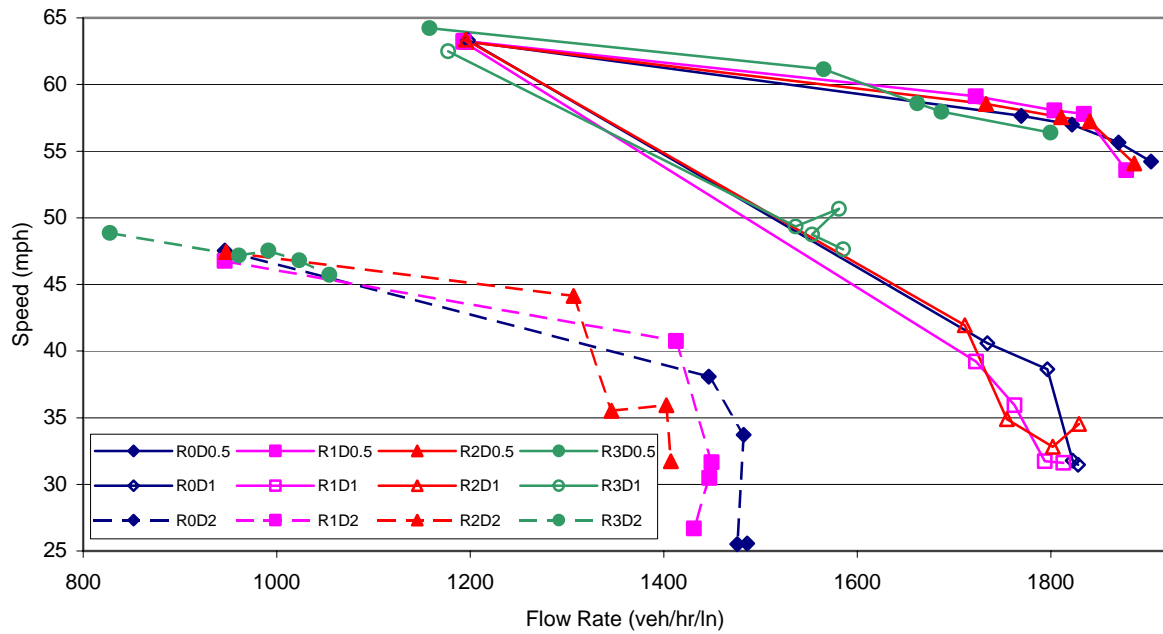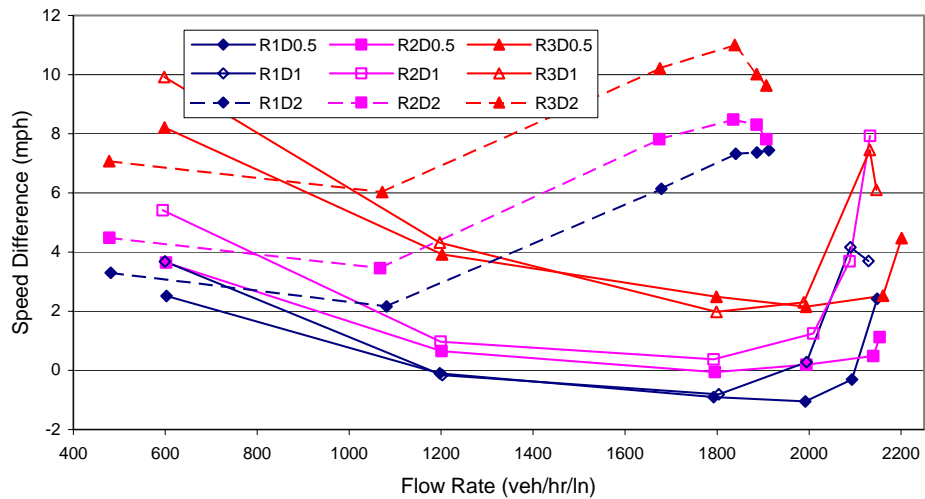

(a) 5% Trucks and 500 veh/hr Ramp Volume
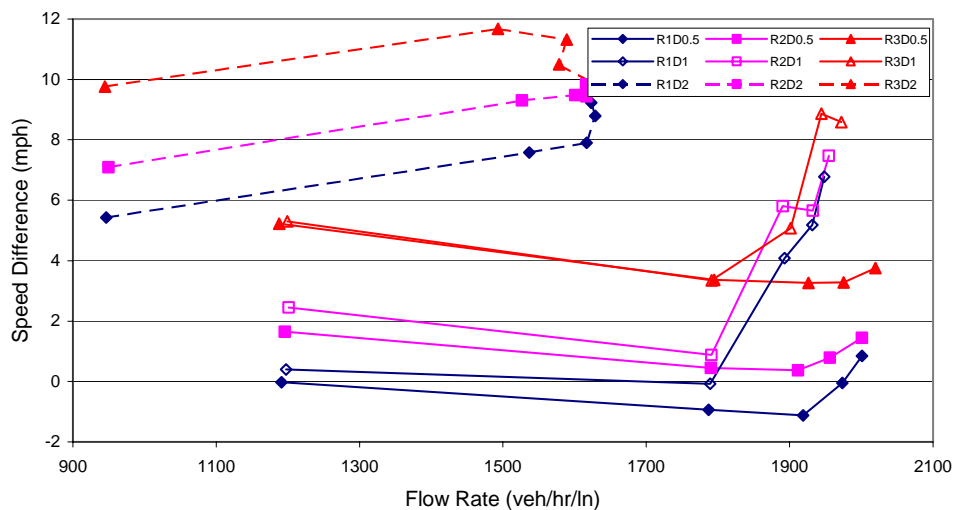
(b) 5% Trucks and 1000 veh/hr Ramp Volume

40
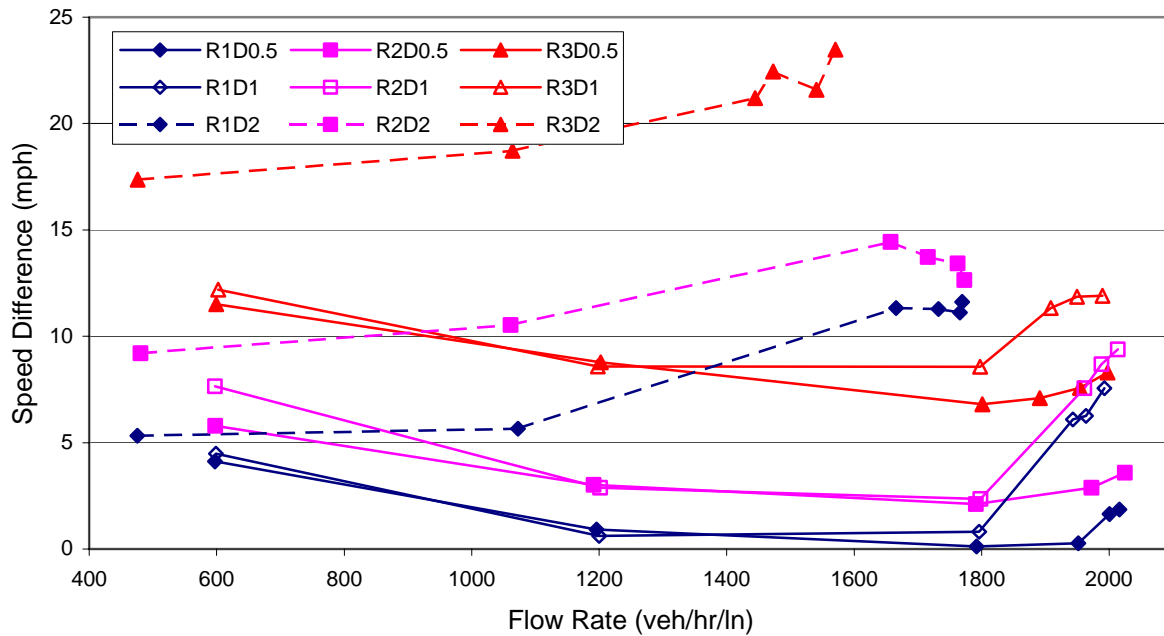
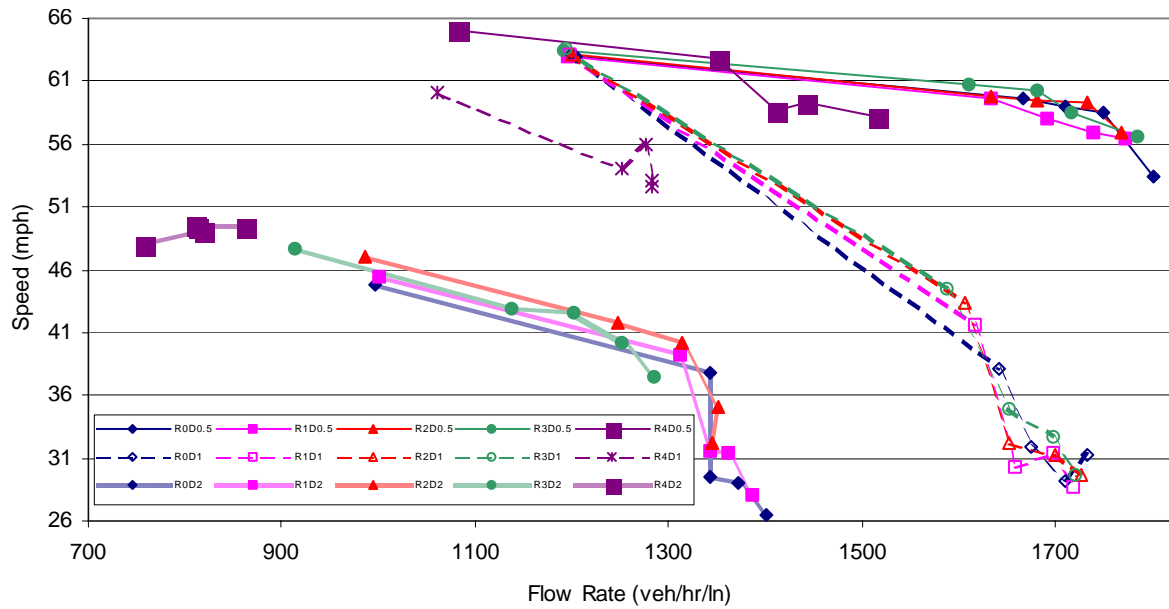**(c) 15% Trucks and 500 veh/hr Ramp Volume**
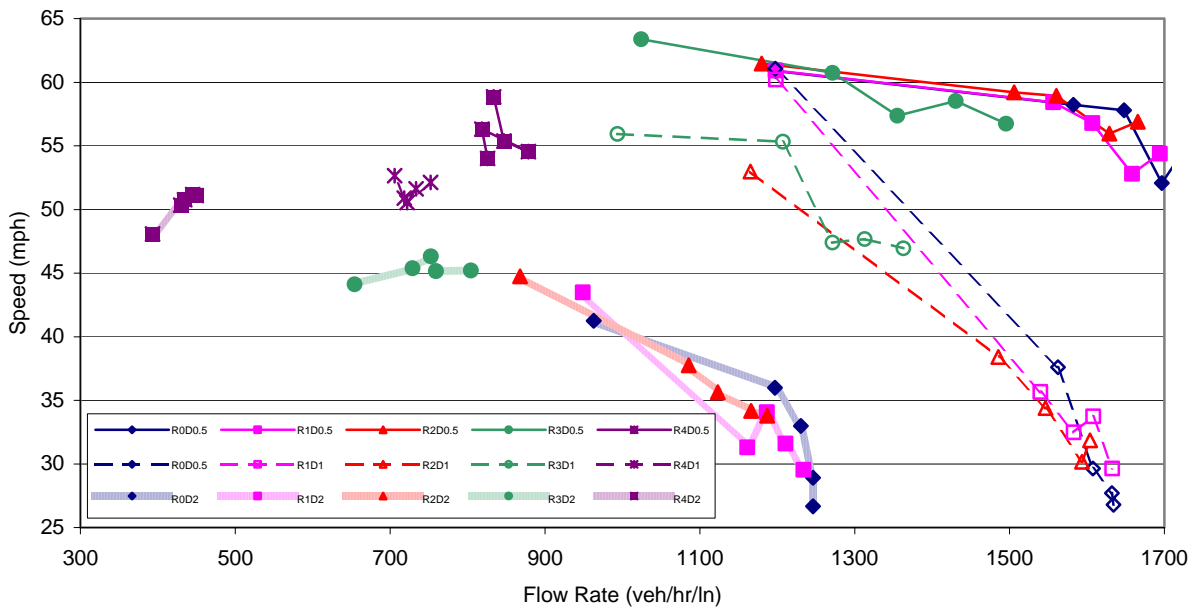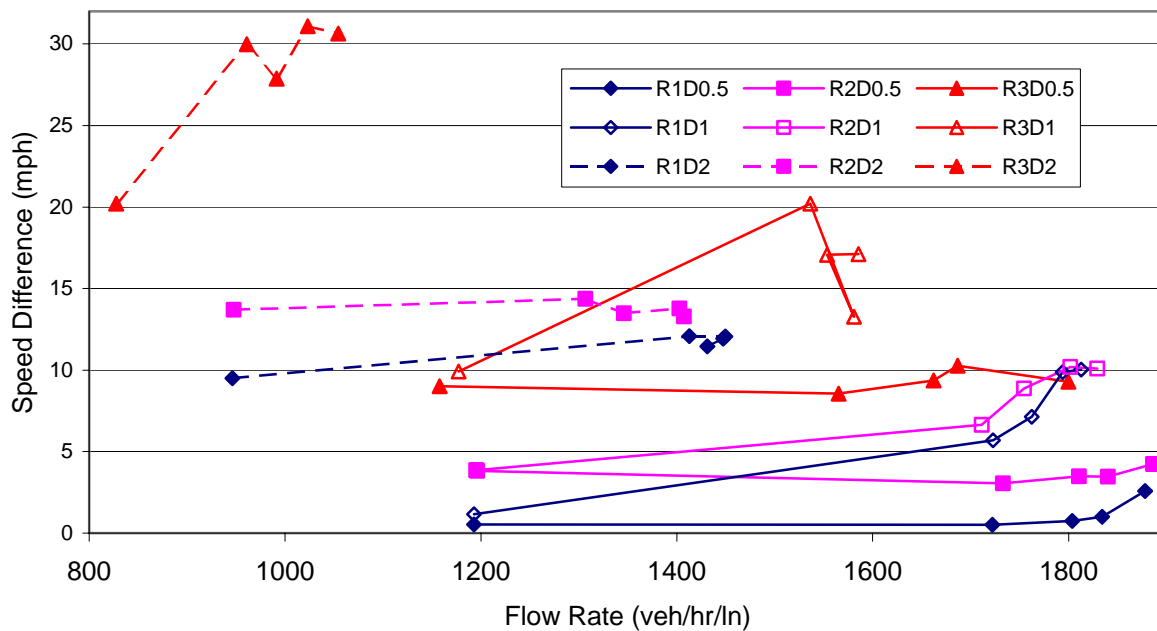

(d) 15% Trucks and 1000 veh/hr Ramp Volume

Figure 4-10. Speed Differentials for Four-Lane Corridors
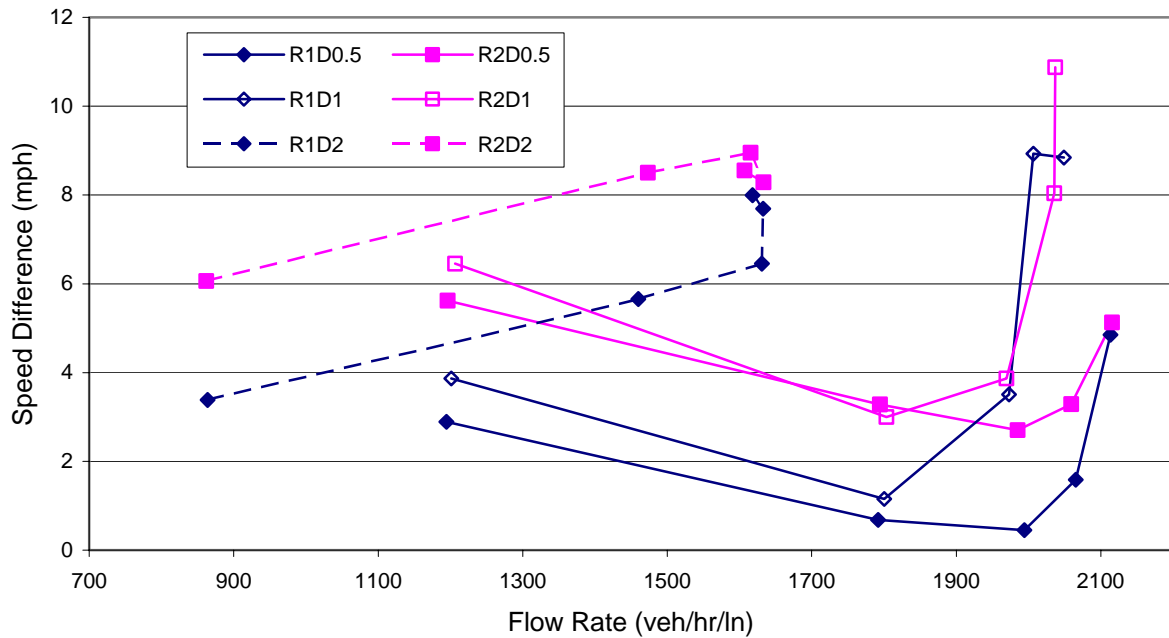
(a) 5% Trucks and 1000veh/hr Ramp Volume
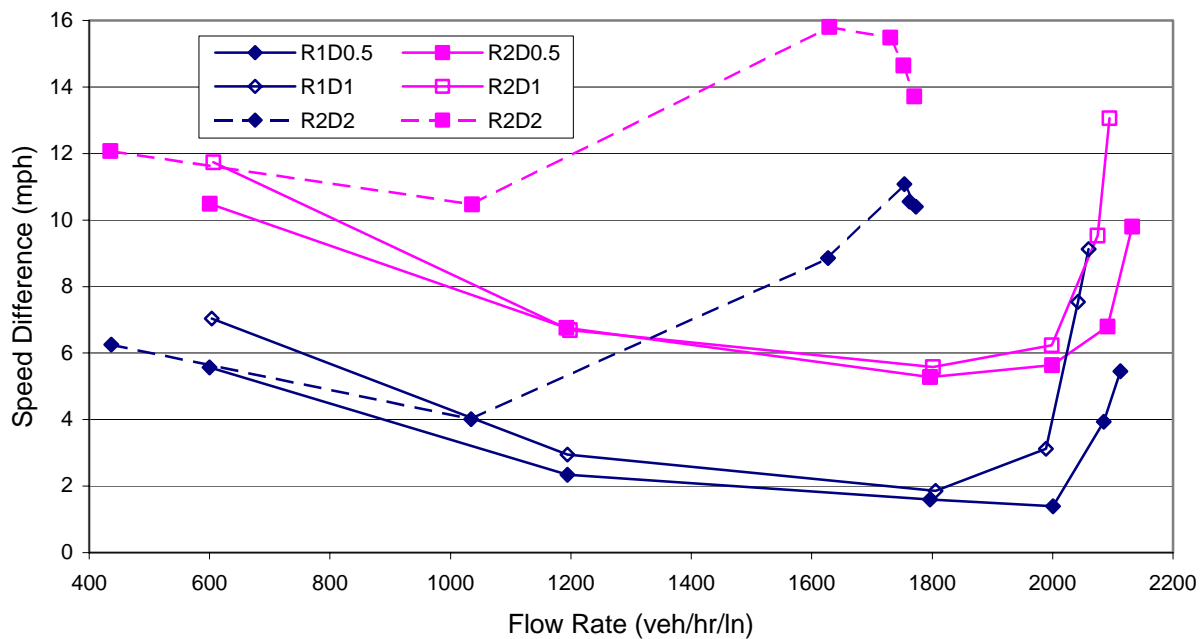
(b) 15% Trucks and 500 veh/hr Ramp Volume

Figure 4-11. Speed Differentials for Three-Lane Corridors
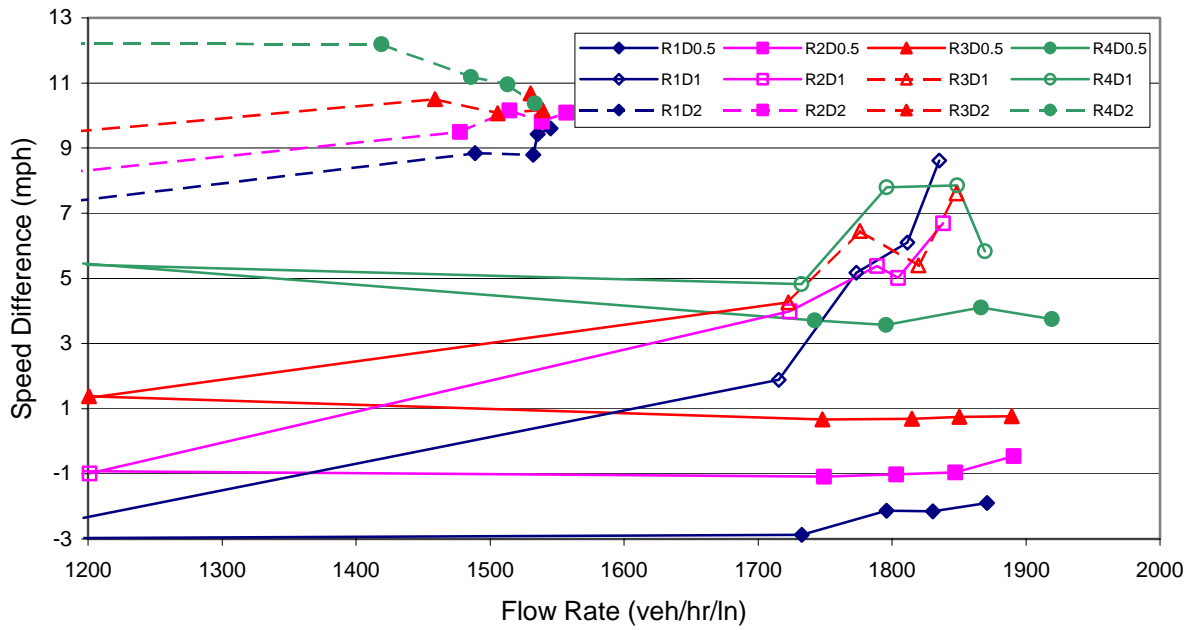
(a) 5% Trucks and 1000 veh/hr Ramp Volume
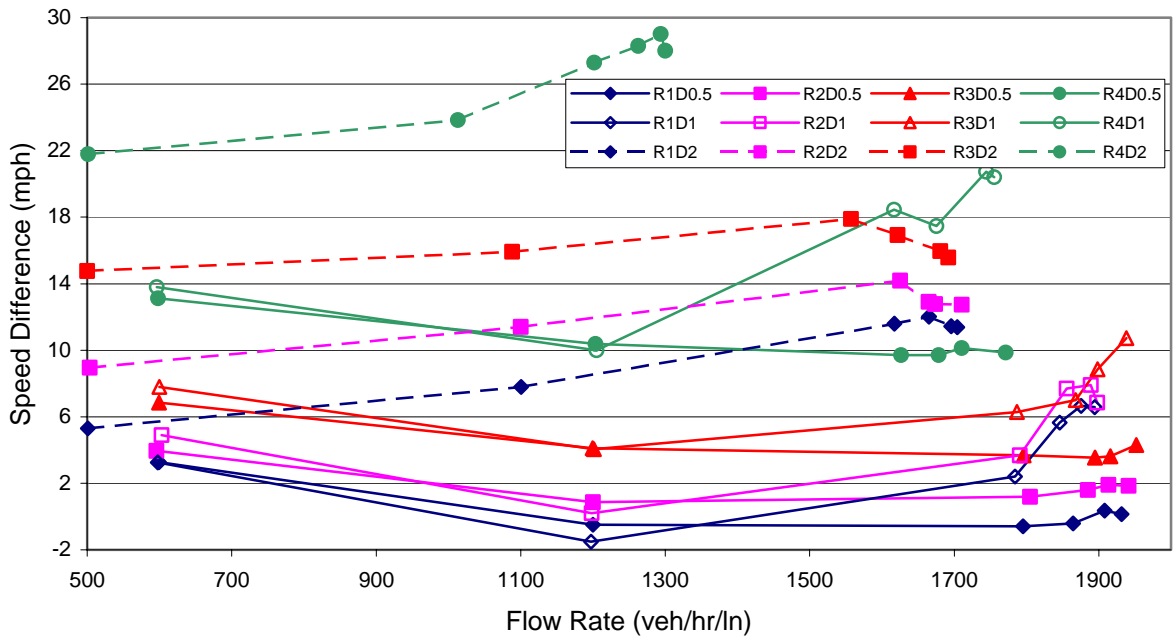
(b) 15% Trucks and 500 veh/hr Ramp Volume

Figure 4-12. Speed Differentials for Five-Lane Corridors

4.4.3. Statistical Analysis of Speed Differential between Lane Groups

Statistical analysis was performed to test for significance in speed differences between lane groups after truck-lane restrictions are implemented by comparing the average lane group speeds. The paired t-test procedure was conducted since each pair, consisting of restricted and non-restricted lane groups, had the same characteristics except for the test condition—the existence of truck traffic. In other words, the truck-restricted lane group was tested against the non-restricted (truck-permitted) lane group. The following hypothesis was assumed and tested for significance:

$$H_0 : \mu_1 = \mu_2 \qquad\qquad H_1 : \mu_1 < \mu_2$$

where μ_1 = average link speed of non-restricted lane group, and
μ_2 = average link speed of truck-restricted lane group.

Tables 4-1, 4-2, and 4-3 show the speed differentials between lane groups for three-, four-, and five-lane corridors with 75 mph FFS respectively. As expected, speed differentials are significant (the restricted lane group speed is greater than that of the non-restricted lane group) for all cases. Since trucks are removed from the restricted lane(s), the restricted lanes maintain higher speeds.

Table 4-2. T-Test Results: Speed Differentials for Three-Lane Corridors

Interchange Density	Rest	μ_1	μ_2	$\mu_2 - \mu_1$	t	Significance	Result	Sample Size
0	R1	59.97	63.17	3.20	4.010	0.001	Different	21
	R2	56.63	63.14	6.51	6.501	0.000	Different	21
0.5	R1	55.44	59.23	10.79	3.791	0.000	Different	66
	R2	51.81	60.11	8.30	12.725	0.000	Different	66
1	R1	47.49	54.10	6.31	11.841	0.000	Different	66
	R2	45.16	55.96	10.79	11.926	0.000	Different	66
2	R1	43.15	51.23	8.09	15.499	0.000	Different	66
	R2	37.79	53.47	15.672	11.444	0.000	Different	66

Table 4-3. T-Test Results: Speed Differentials for Four-Lane Corridors

Interchange Density	Rest	μ_1	μ_2	$\mu_2 - \mu_1$	t	Significance	Result	Sample Size
0	R1	61.05	63.77	2.72	3.768	0.001	Different	21
	R2	59.75	63.96	4.21	5.822	0.000	Different	21
	R3	55.74	64.36	8.62	7.877	0.000	Different	21
0.5	R1	58.32	60.33	2.01	6.270	0.000	Different	66
	R2	57.31	61.32	4.01	11.394	0.000	Different	66
	R3	51.65	62.40	10.75	11.702	0.000	Different	66
1	R1	46.94	52.44	5.49	10.505	0.000	Different	66
	R2	45.11	52.71	7.60	11.454	0.000	Different	66
	R3	42.77	57.60	14.83	11.016	0.000	Different	66
2	R1	42.46	51.34	8.89	16.753	0.000	Different	66
	R2	39.57	51.60	12.03	15.146	0.000	Different	66
	R3	34.10	55.30	21.20	12.845	0.000	Different	66

Table 4-4. T-Test Results: Speed Differentials for Five-Lane Corridors

Interchange Density	Rest	μ_1	μ_2	$\mu_2 - \mu_1$	t	Significance	Result	Sample Size
0	R1	61.50	64.20	2.70	3.355	0.003	Different	21
	R2	60.59	64.40	3.81	4.976	0.000	Different	21
	R3	58.85	64.52	5.67	7.087	0.000	Different	21
	R4	54.63	65.24	10.61	8.967	0.000	Different	21
0.5	R1	59.61	60.66	1.05	2.472	0.016	Different	66
	R2	59.09	61.74	2.65	6.888	0.000	Different	66
	R3	58.04	63.59	5.55	10.844	0.000	Different	66
	R4	51.11	64.22	13.10	12.248	0.000	Different	66
1	R1	45.93	51.29	5.36	9.552	0.000	Different	66
	R2	44.25	50.87	6.62	11.767	0.000	Different	66
	R3	42.75	54.84	12.09	8.439	0.000	Different	66
	R4	40.27	58.95	18.67	11.560	0.000	Different	66
2	R1	41.85	51.37	9.52	18.070	0.000	Different	66
	R2	40.34	51.74	11.39	17.894	0.000	Different	66
	R3	37.36	53.37	16.01	14.331	0.000	Different	66
	R4	31.68	56.25	24.57	14.12	0.000	Different	66

4.5. Throughput

Throughput is defined as the maximum number of vehicles that can go through a freeway corridor under prevailing conditions. The relationships between throughput and various traffic conditions are investigated in this section. If, after the lane restriction is put in place, throughput is greater than the under non-restriction alternative, the restriction may be considered a possible remedy to mitigating the effects of truck traffic on freeway corridors.

4.5.1. Truck Percentage

Figures 4-13 (a), (b), and (c) show a monotonic decreasing relationship between throughput and truck percentage for four-lane basic segments at free-flow speeds (FFS) of 55, 65, and 75 mph, respectively, under various truck-lane restrictions. Severe throughput reductions occur under conditions of high truck percentages (e.g., over 15%) and high number of restricted lanes (e.g., R3), as illustrated in Figures 4-13 (a), (b), and (c). The concentration of trucks in the non-restricted lane(s) after restriction caused congestion on truck-traffic lane(s) and reduced the overall throughput of the corridor. While a higher number of restricted lanes results in larger throughput compared to the non-restriction condition (R0) under low truck percentages, the smaller number of restricted lanes provide more serviceability than the non-restricted alternative (R0) under high truck percentages. This trend also holds for the three- and five-lane cases, as shown in Figures 4-14 (a) and (b), respectively.
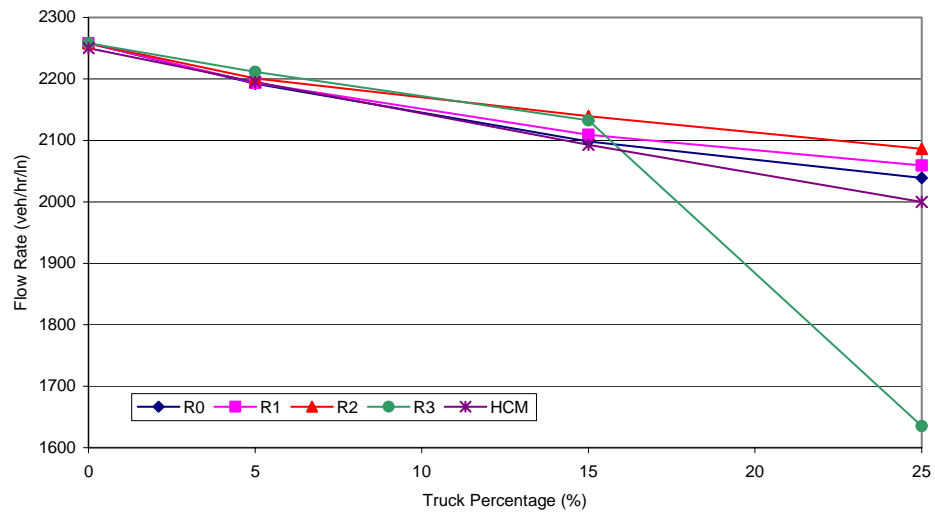
(a) 55 mph FFS
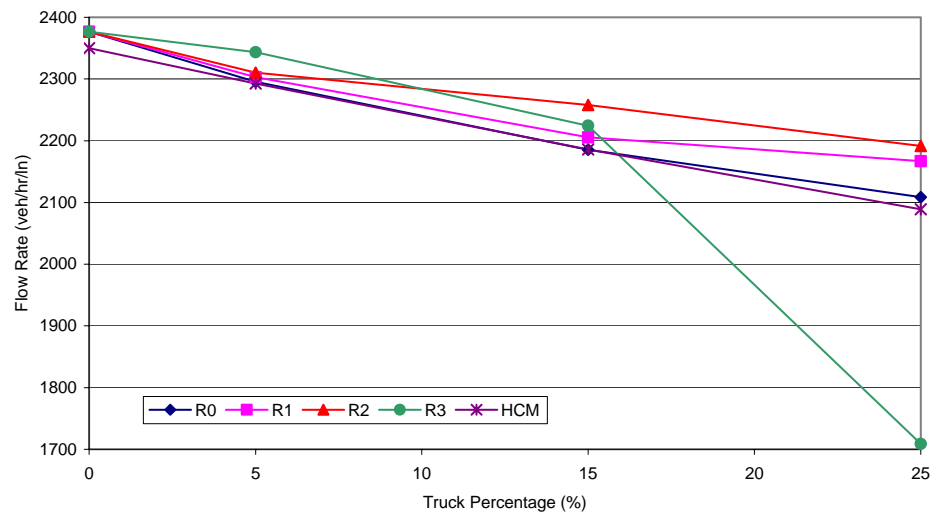
(b) 65 mph FFS
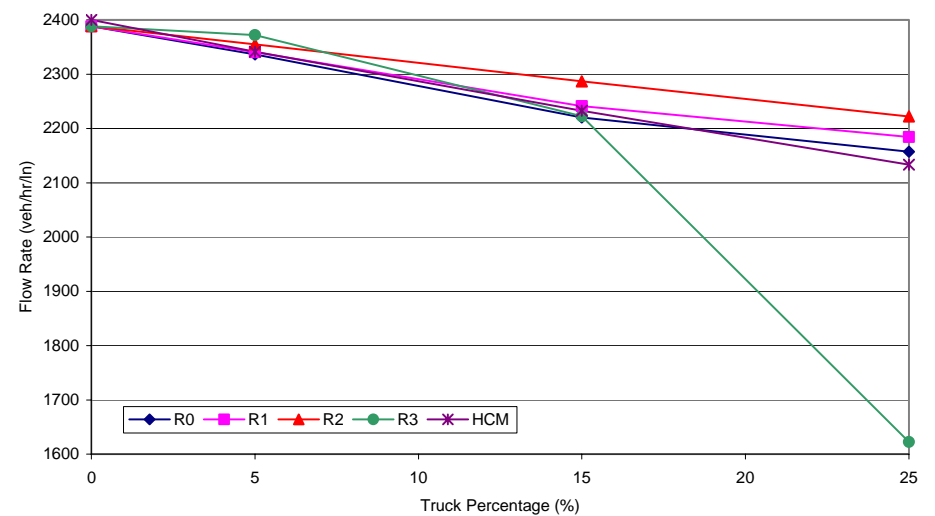
(c) 75 mph FFS

Figure 4-13. Throughput and Truck Percentage for Four-Lane Basic Segment
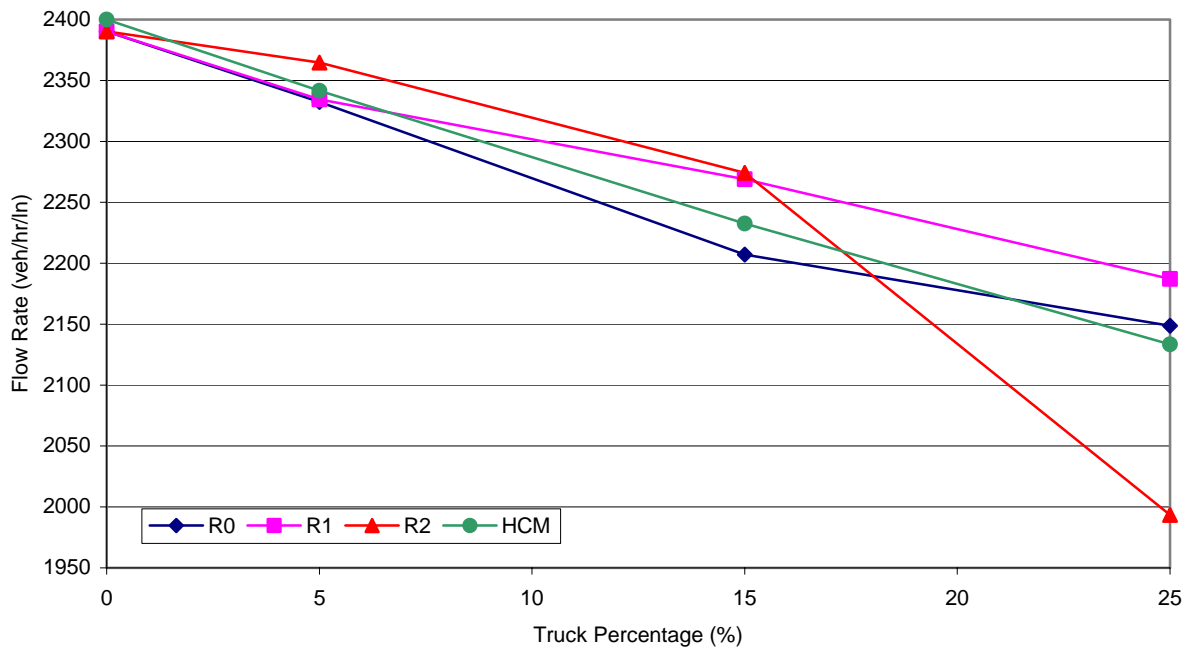
(a) Three-Lane Freeway
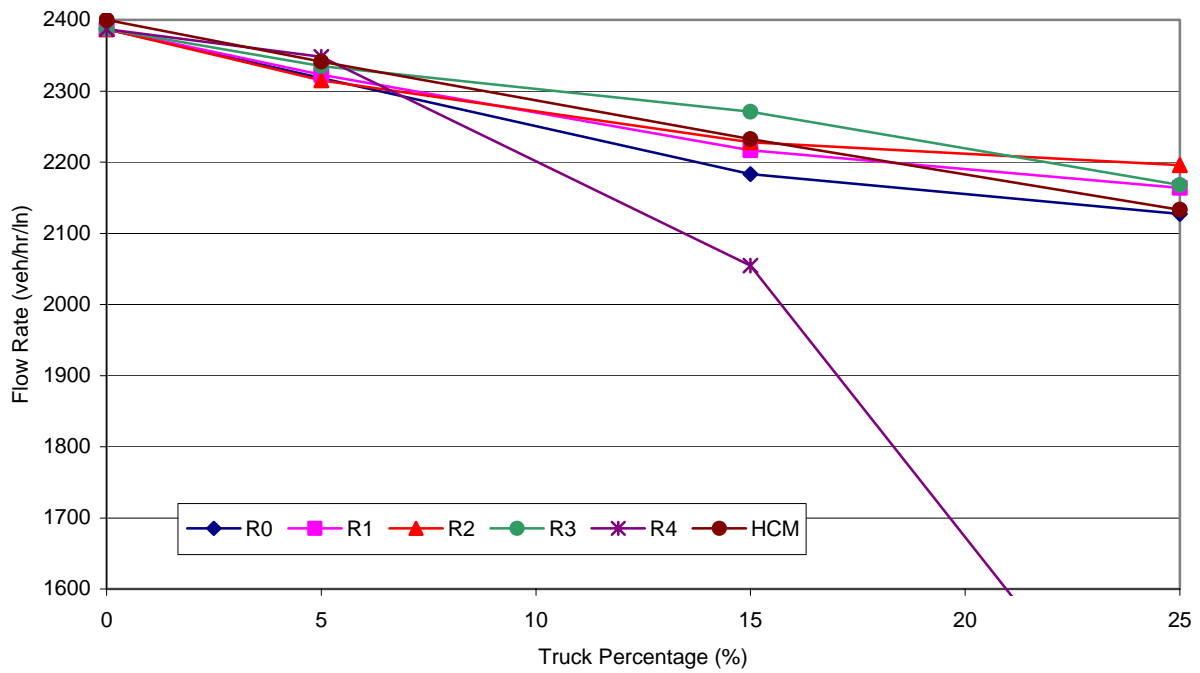
(b) Five-Lane Freeway

Figure 4-14. Throughput and Truck Percentage for Basic Segment (75 mph FFS)

4.5.2. Ramp Volume

Figures 4-15 (a) and (b) show the relationships between throughput and truck percentages for 0.5/mile interchange density under different ramp volumes. It was found that throughput decreased as ramp volume increased. Truck-lane restriction alternatives provide improved throughput compared to the non-restriction alternative under low truck percentage (up to 15%) and low and moderate ramp volumes (up to 500 veh/hr), except for the R3 case. However, the advantage of the truck-lane restriction on throughput disappears when ramp volume increased to over 1000 veh/hr, as shown in Figure 4-15 (b).
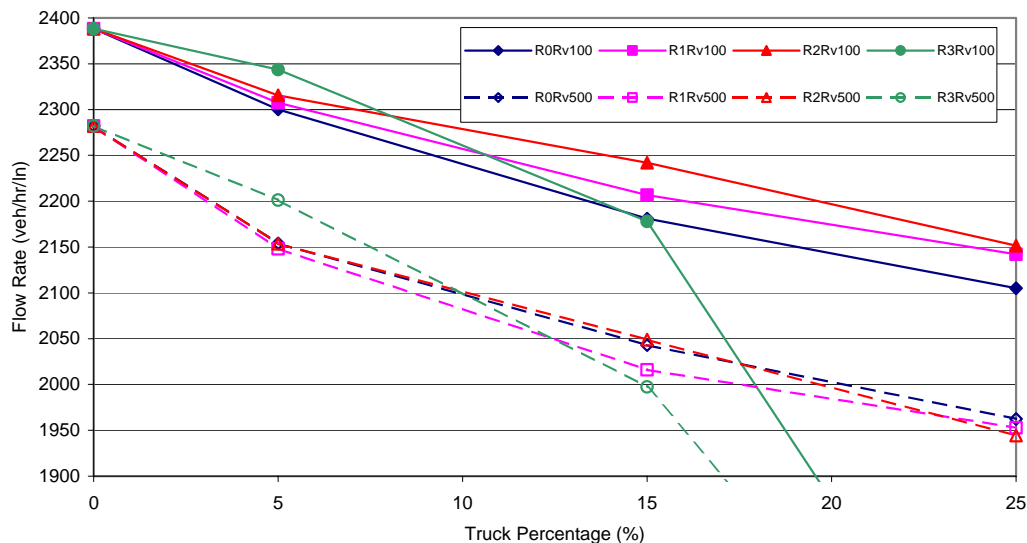
(a) 0.5/mile Density, 75 mph FFS, and Low Ramp Volumes (100 and 500 veh/hr)
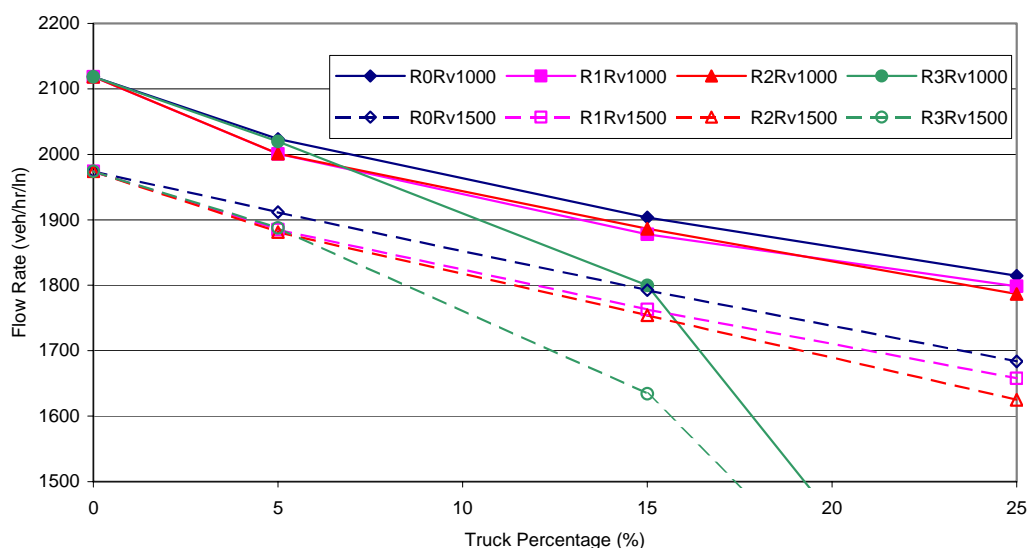
(b) 0.5/mile Density, 75 mph FFS, and High Ramp Volumes (1000 and 1500 veh/hr)

Figure 4-15. Throughput and Ramp Volumes for Four-Lane Corridors

Similar phenomena were found for three-and five-lane corridors, as shown in Figures 4-16 (a) and (b). Although the difference is very small, the non-restriction alternative provides improved throughput when ramp volume is greater than 500 veh/hr and truck percentage is greater than 15% for both the three- and five-lane cases.
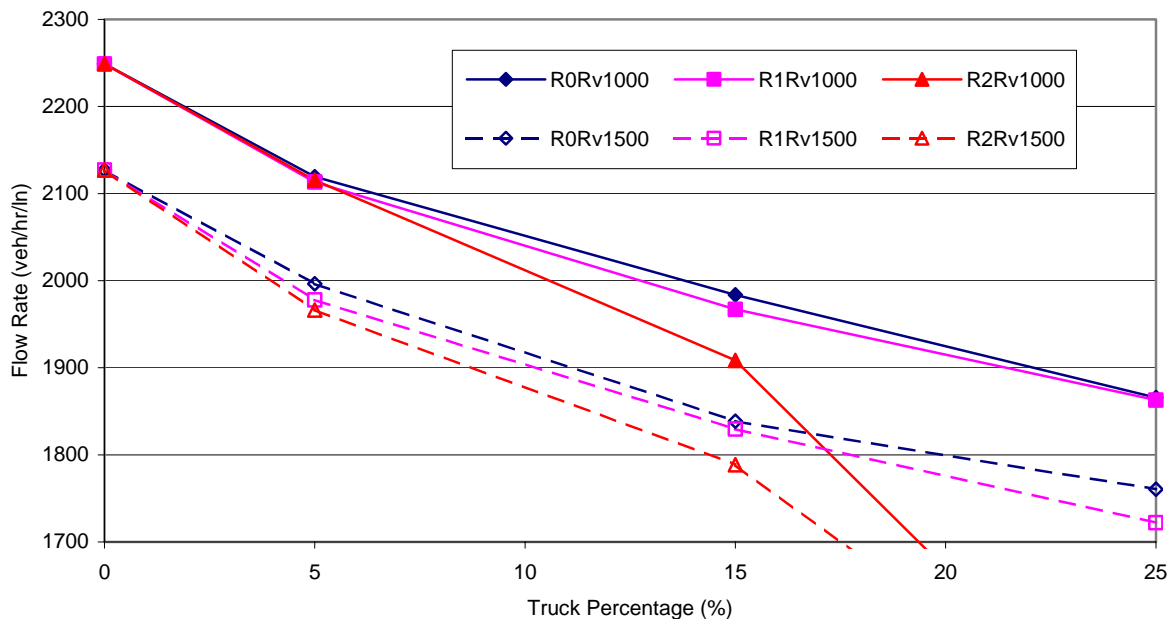
(a) Three-Lane Corridors (1000 and 1500 veh/hr Ramp Volumes)
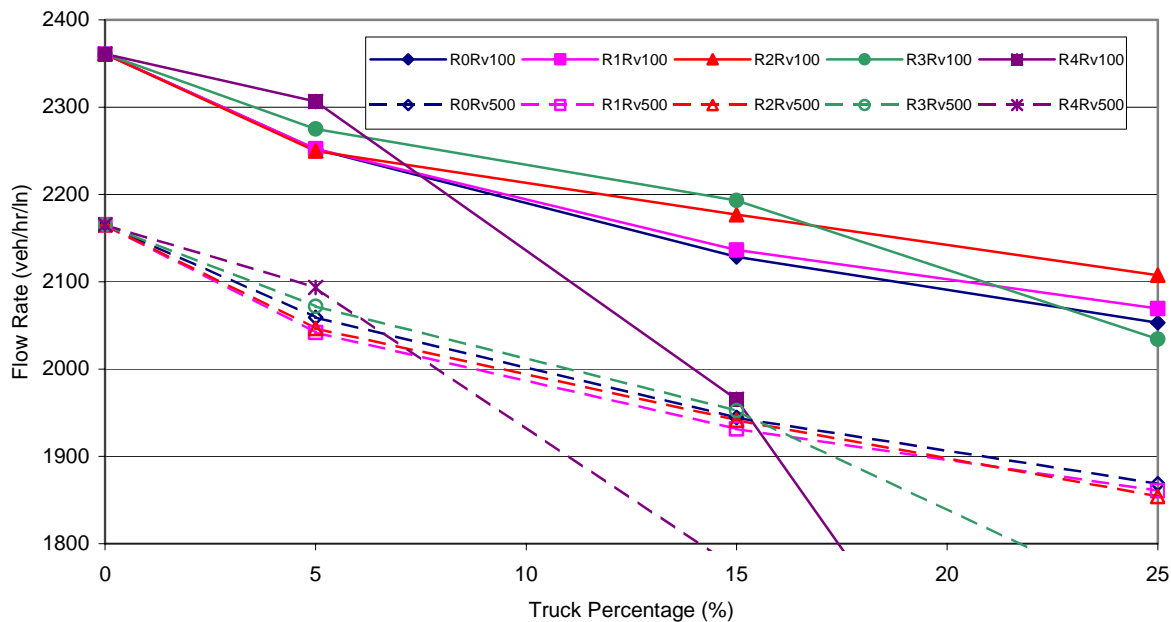
(b) Five-Lane Corridors (100 and 500 veh/hr Ramp Volumes)

Figure 4-16. Throughput and Ramp Volumes for Three-and Five-Lane Corridors (15% Trucks, 75 mph FFS and 0.5/mile interchange density)

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4.5.3. Interchange Density

Figures 4-17 (a) and (b) illustrate the relationships between throughput and interchange densities. Throughput decreased as interchange density increased. Differences in throughput among the various restriction alternatives were indistinguishable for all cases with the 0.5/mi and 1/mile densities except for that of a high number of restricted lanes (R3). However, Figure 4-17 (b) shows that significant throughput reductions after restriction were found for the 2/mile density cases when truck percentages were greater than 15% and ramp volumes were larger than 1000 veh/hr.
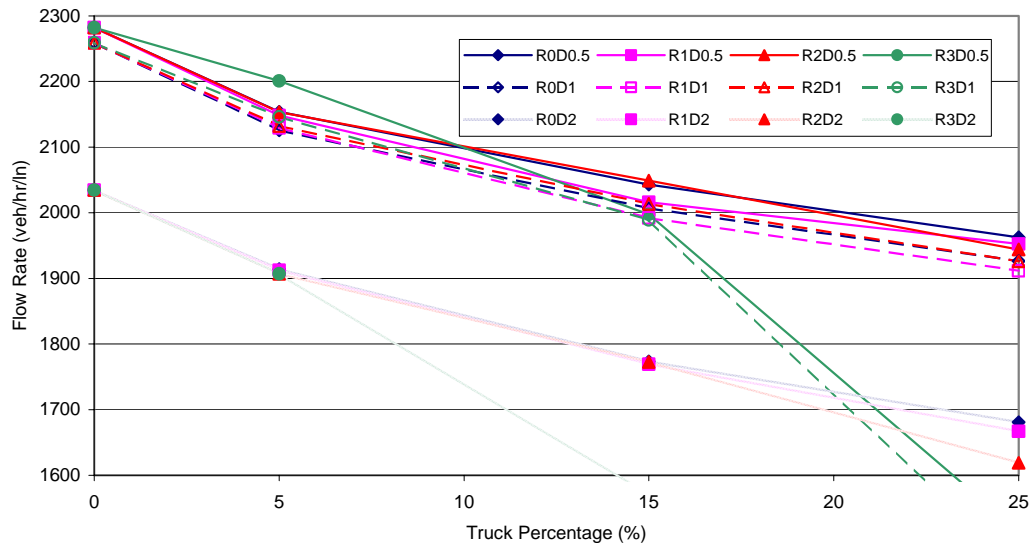
(a) 500 veh/hr Ramp Volume and 75 mph FFS
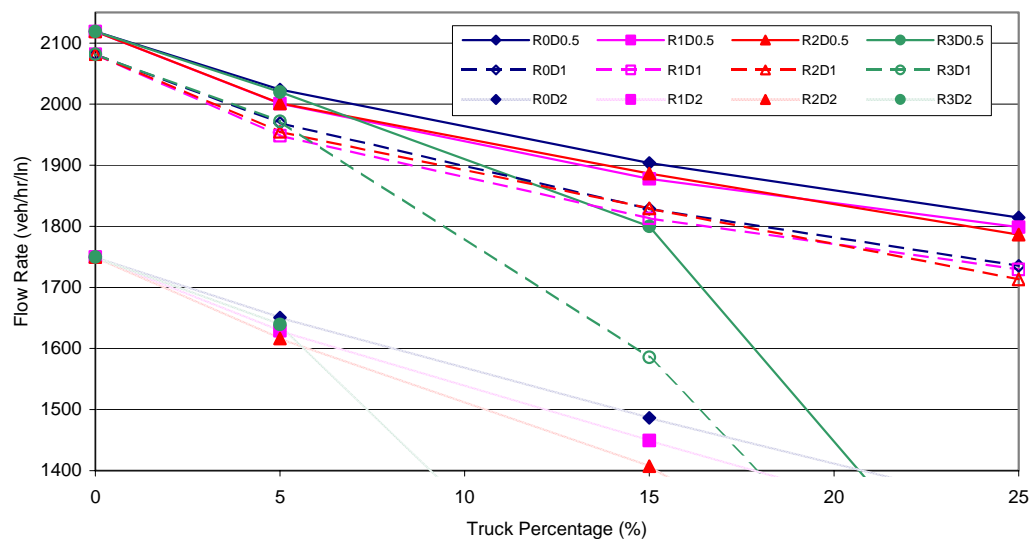
(b) 1000 veh/hr Ramp Volume and 75 mph FFS

Figure 4-17. Throughput and Interchange Density for Four-Lane Corridors

Figures 4-18 (a) and (b) show the relationship between throughput and interchange density for three- and five-lane freeway corridors. Truck restriction alternatives provide larger or equal throughput when truck percentages are under 15% and interchange density is lower than 2/mile. For 0.5/mile or 1/mile interchange density cases (D0.5 and D1), throughput differences among the restriction alternatives are practically negligible even under heavy truck influence, except in the case of a large number of restricted lanes.
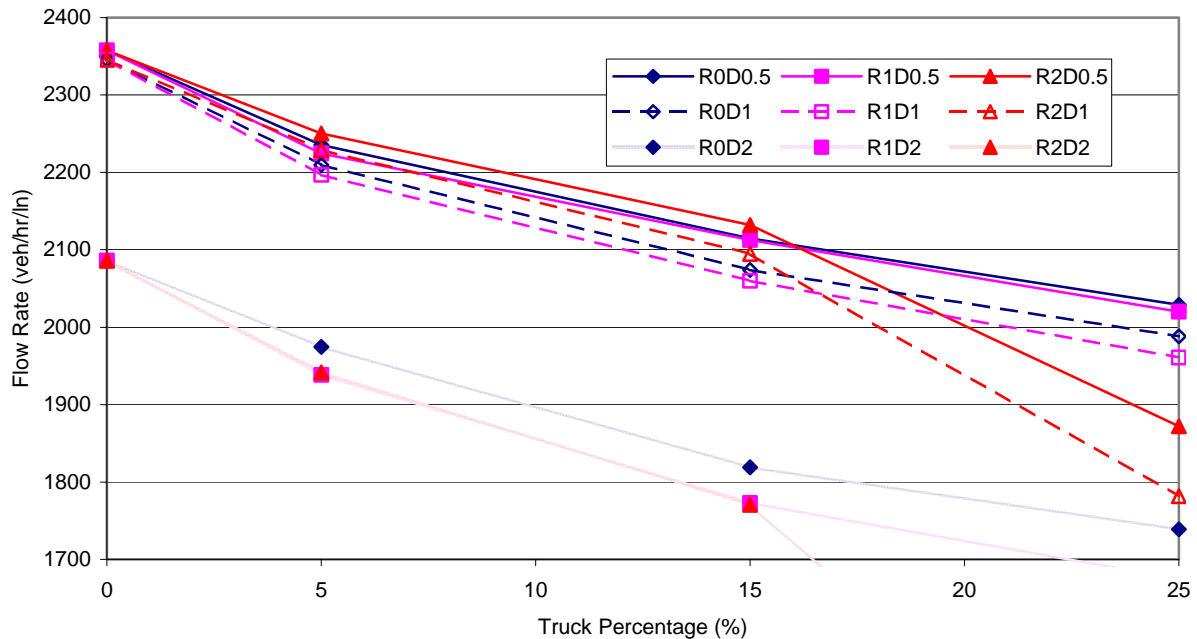
(a) Three-Lane Corridor (500 veh/hr Ramp Volume and 75 mph FFS)
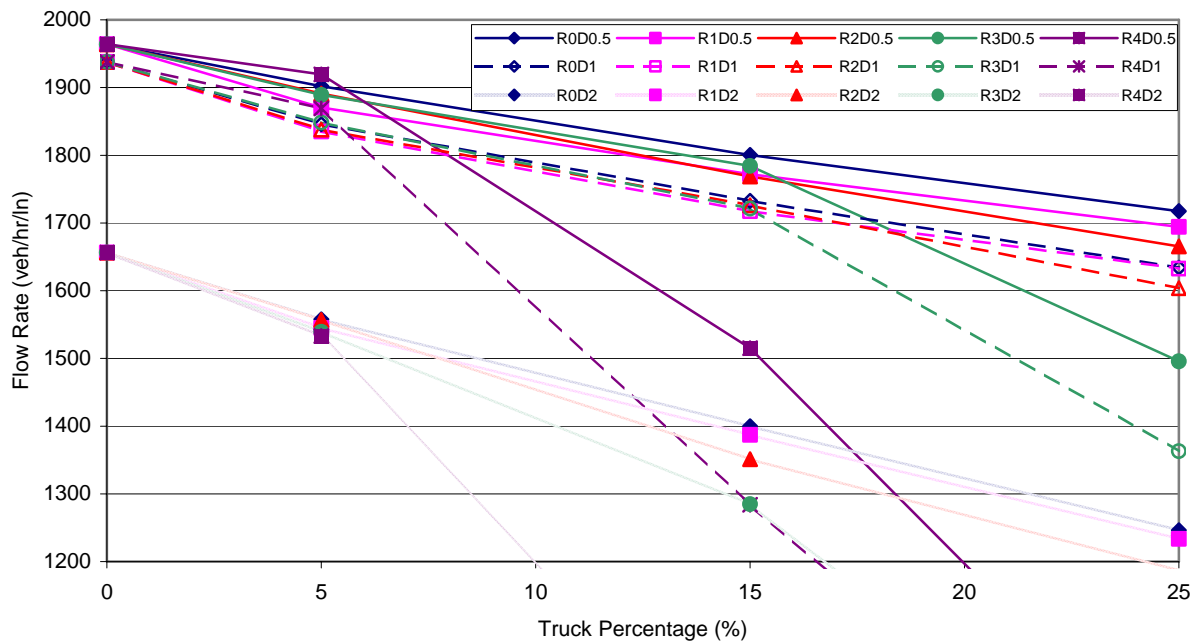
(b) Five-Lane Corridor (1000 veh/hr Ramp Volume and 75 mph FFS)

Figure 4-18. Throughput and Interchange Density for Three- and Five-Lane Corridors

4.6. Lane Changes

The number of lane changes is defined as the total lane changes divided by the total traffic volume (including ramp volumes). The number of lane changes per vehicle is used to determine the uniformity of traffic flow. A low number of lane changes indicates that there is less of a need to pass slower moving vehicles encountered by the subject vehicle. The paired sample t-test procedure was used to investigate the statistical significance of the number of lane changes. Since the basic case was set as the "before" case, the difference indicates that an increase (or decrease) of lane changes occurs after the implementation of the truck-lane restriction.

4.6.1. Basic Segment

Figure 4-19 (a) shows that lane changes per vehicle were significantly reduced with restriction. The number of lane changes increases until the average flow rate per lane reaches approximately 1,200 veh/hr/ln, and decreases slightly as the link reaches near-capacity conditions. The number of lane changes fluctuates slightly when the link is oversaturated. Similar trends also occur for three- and five-lane freeway conditions as shown in Figures 4-19 (b) and (c), respectively. The larger the number of restricted lanes, such as R4 for the five-lane case, tends to cause significant reductions in lane changes.
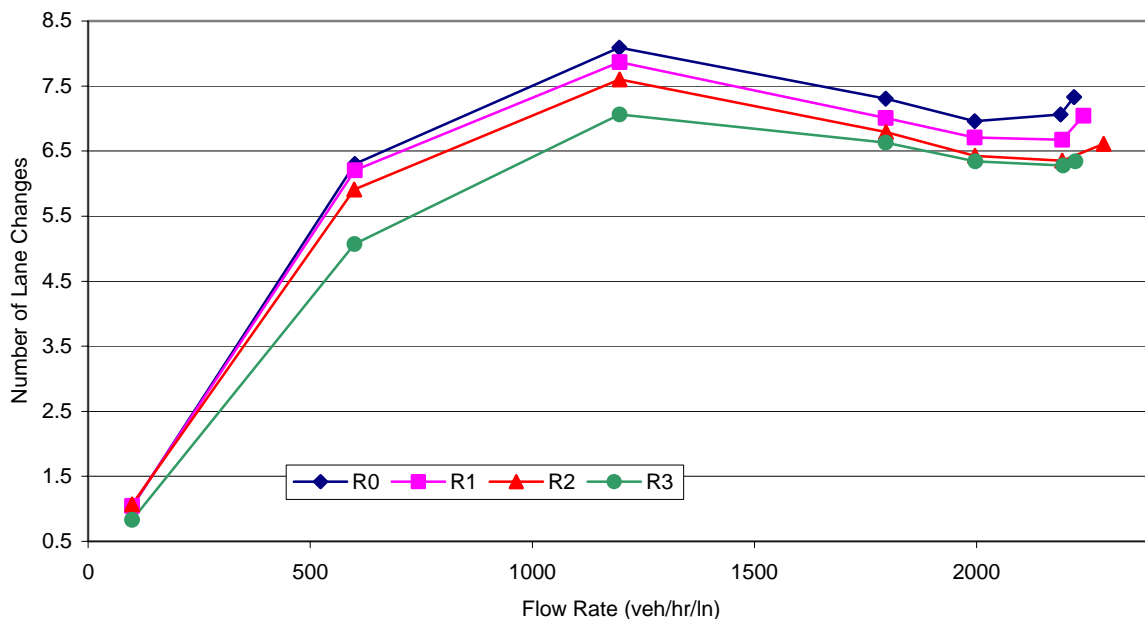
(a) Number of Lane Changes for Four-Lane Corridor (15% Trucks)
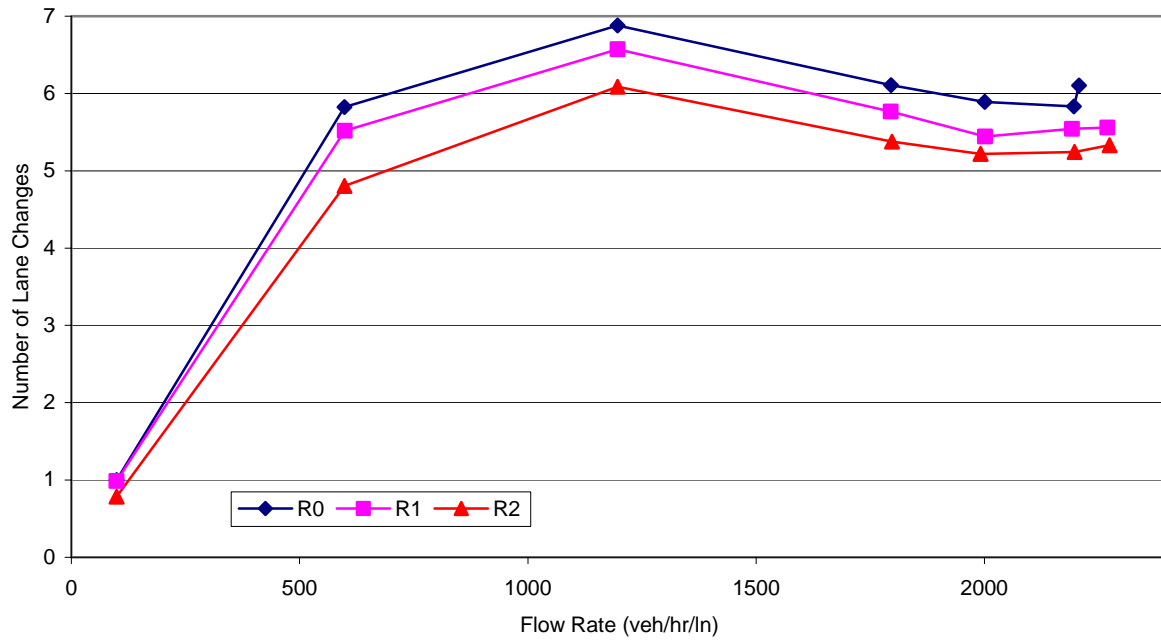
(b) Number of Lane Changes for Three-Lane Corridor (15% Trucks)
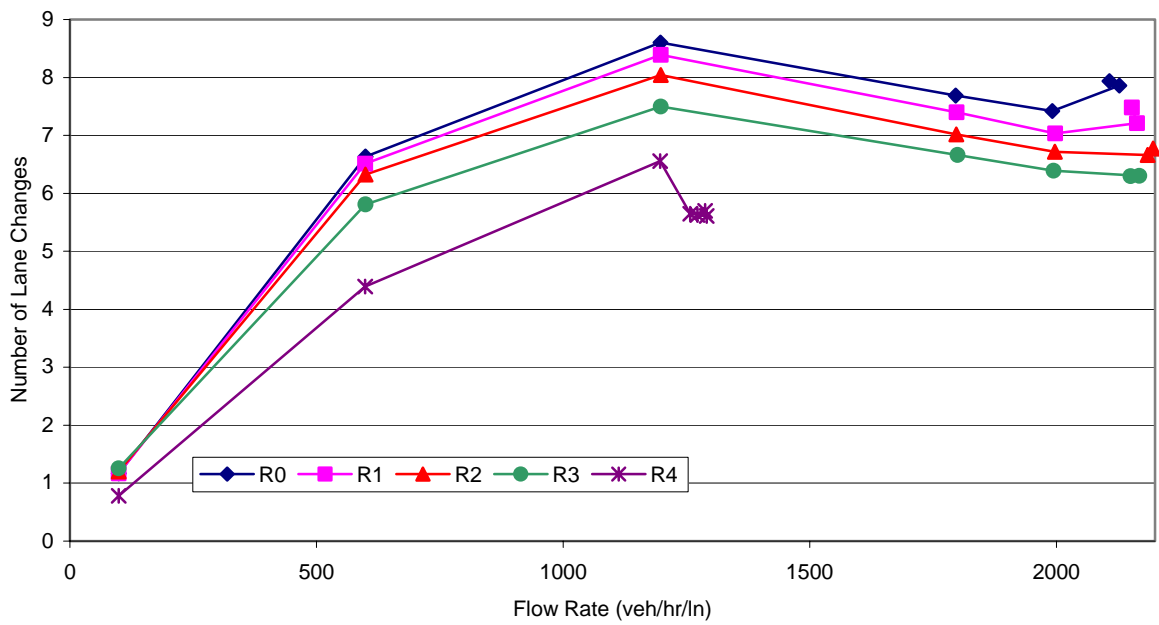
(c) Number of Lane Changes for Five-Lane Corridor (25% Trucks)

Figure 4-19. Number of Lane Changes and Flow Rates
(70 mph FFS)

4.6.2. Ramp Volume

Figure 4-20 (a) shows the relationships between the number of lane changes and the flow rate under different ramp volumes for four-lane freeways. Since slow-moving trucks do not hinder passenger car movements under this condition, the number of lane changes decreases after the truck restriction is implemented. Truck restriction alternatives reduce the number of lane changes for the entire range of the traffic flow rate. Since the number of lane changes is sensitive to high volumes of traffic, the ramp volume does not significantly affect the number of lane changes. Similar phenomena are found for three- and five-lane freeway in Figures 4-20 (b) and (c), respectively.
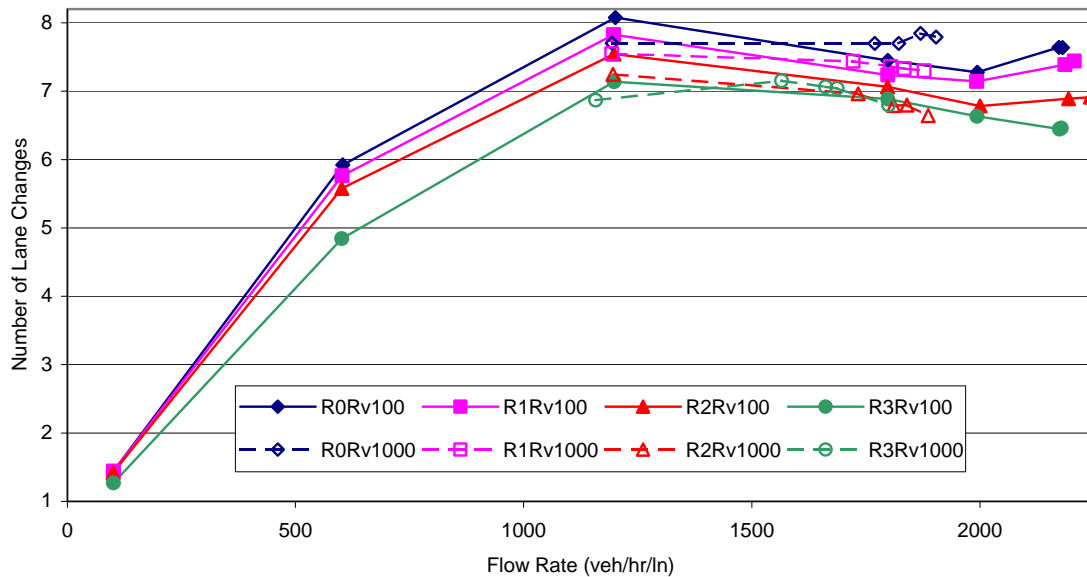
(a) Four-Lane Corridor (0.5/mile density and 75 mph FFS)
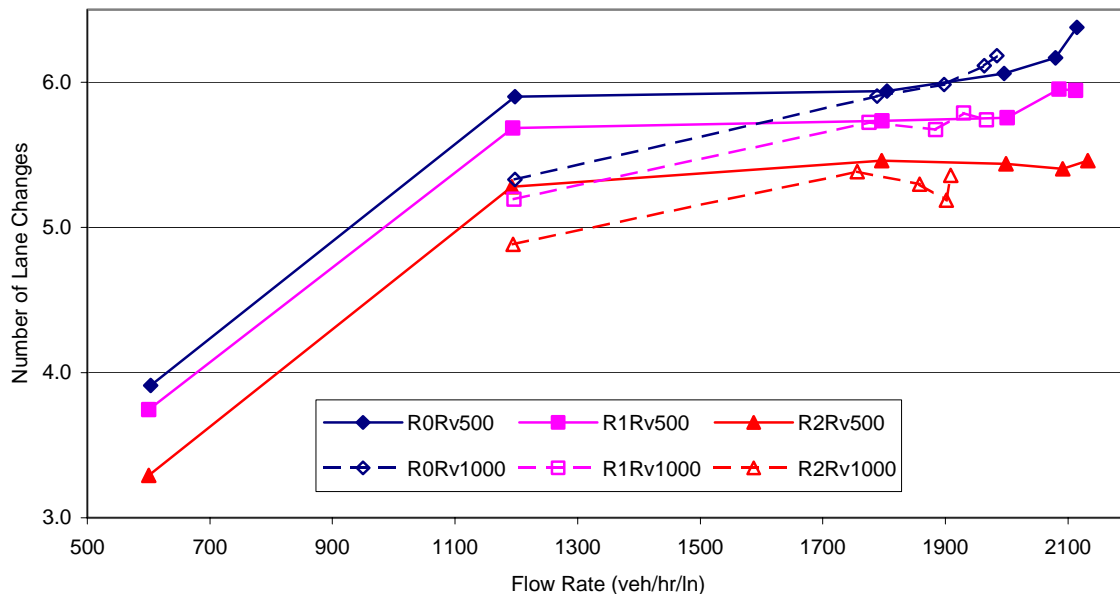
(b) Three-Lane Corridor (0.5/mile density and 75 mph FFS)

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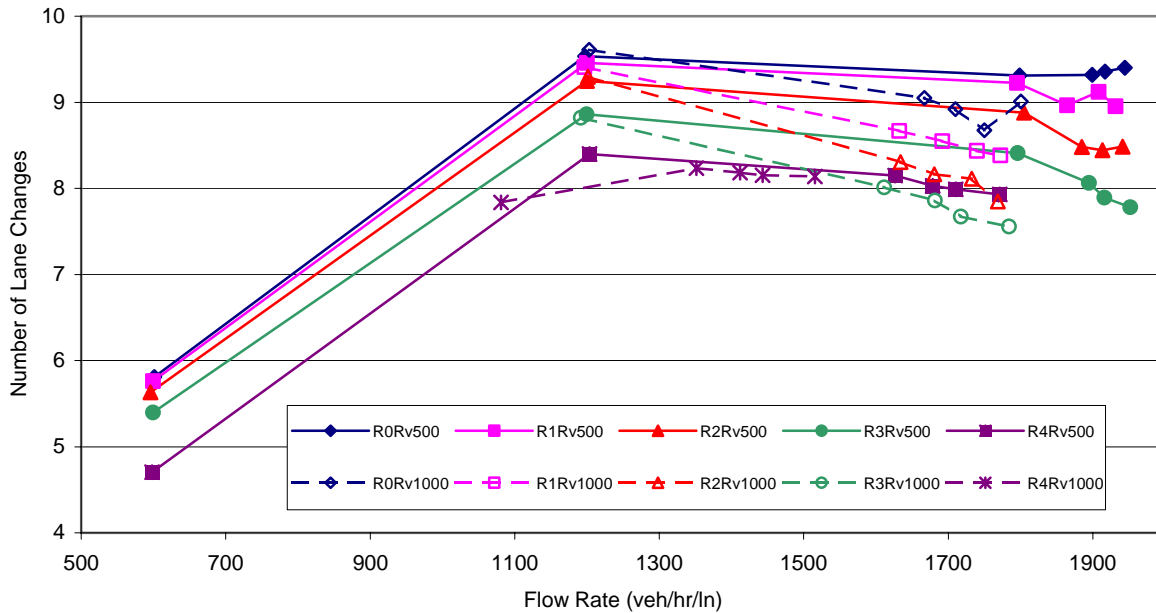
(c) Five-Lane Corridor (0.5/mile density and 75 mph FFS)

Figure 4-20. Number of Lane Changes and Ramp Volumes

4.6.3. Interchange Density

Figures 4-21 (a) and (b) show the relationships between the number of lane changes and flow rate under different interchange densities for four-lane corridors. The number of lane changes under the various truck restriction alternatives is always less than under non-restriction alternatives regardless of density. In addition, the number of lane changes for the 0.5/mile and 1/mile density cases behave in nearly the identical trajectory under moderate truck percentage and ramp volume conditions. However, more lane changes are found for the 2/mile density case due to close interchange spacing. The average number of lane change decreases due to the increased influence of merging and diverging traffic when the main line flow rates are greater than 1600 veh/hr/ln. Figures 4-22 (a) and (b) show that similar phenomena are found for three- and five-lane freeways, respectively.
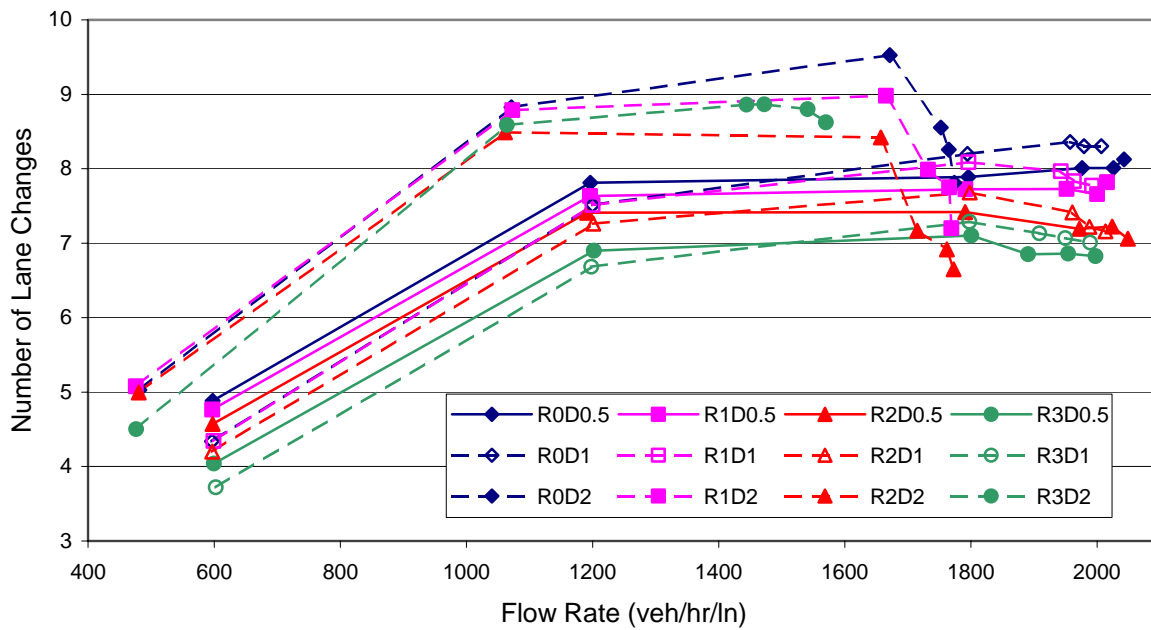
(a) Truck 15%, Ramp Volume 500 veh/hr and 75 mph FFS
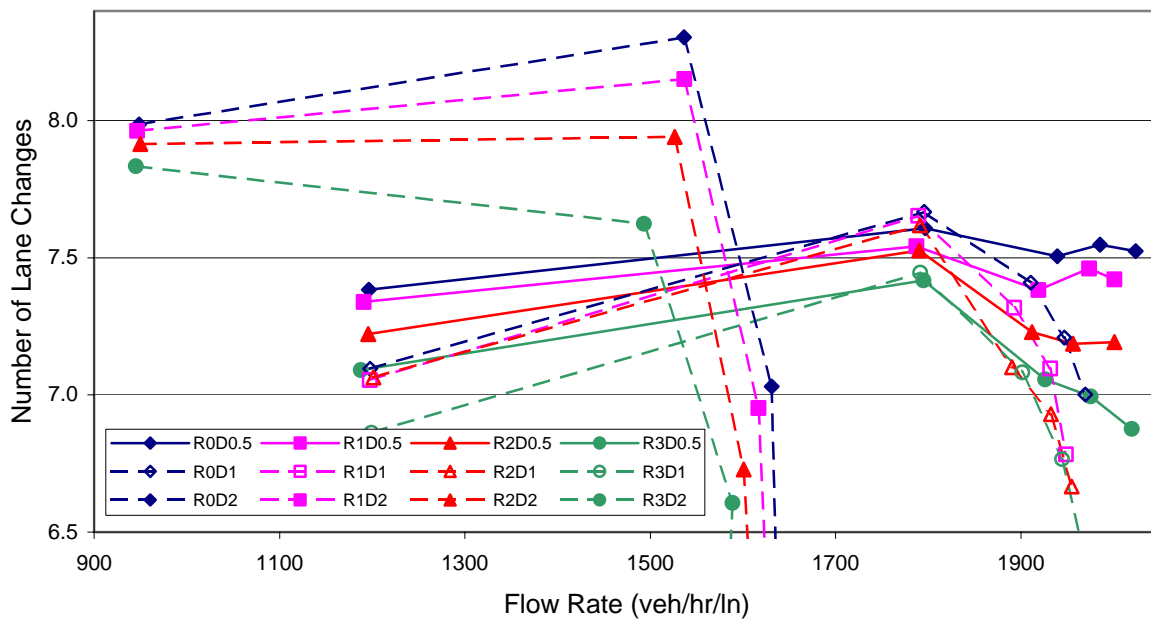
(b) Truck 5%, Ramp Volume 1000 veh/hr and 75 mph FFS

Figure 4-21. Number of Lane Changes and Interchange Density for Four-Lane Corridor
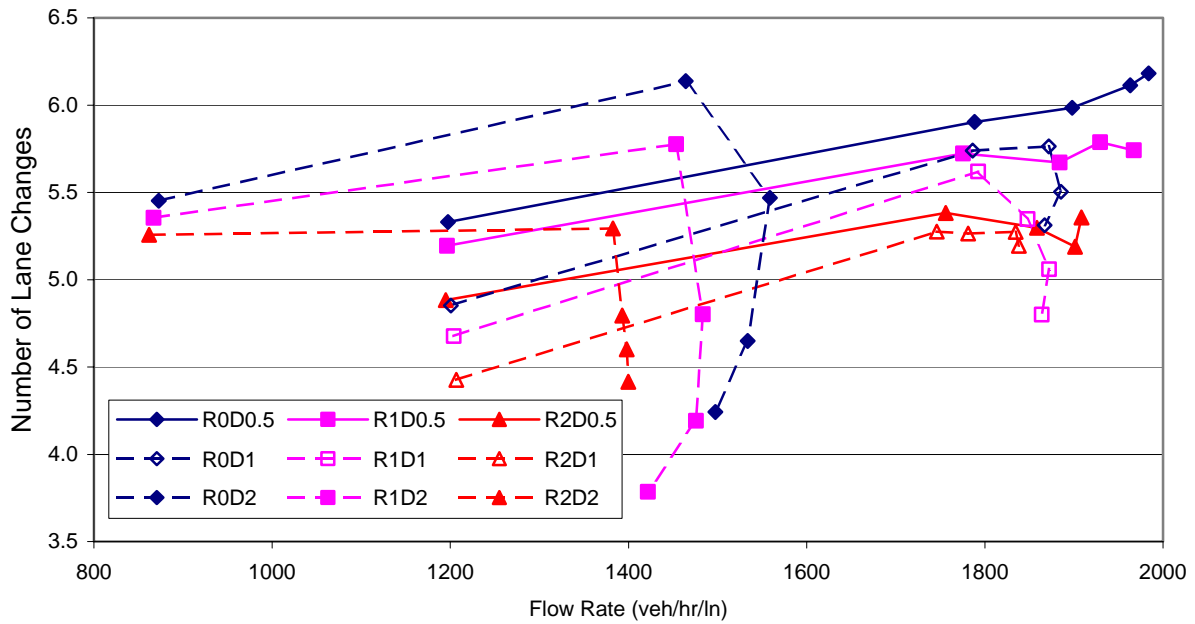
(a) Three-Lane Freeway (Truck 15% and Ramp Volume 1000 veh/hr/ln)
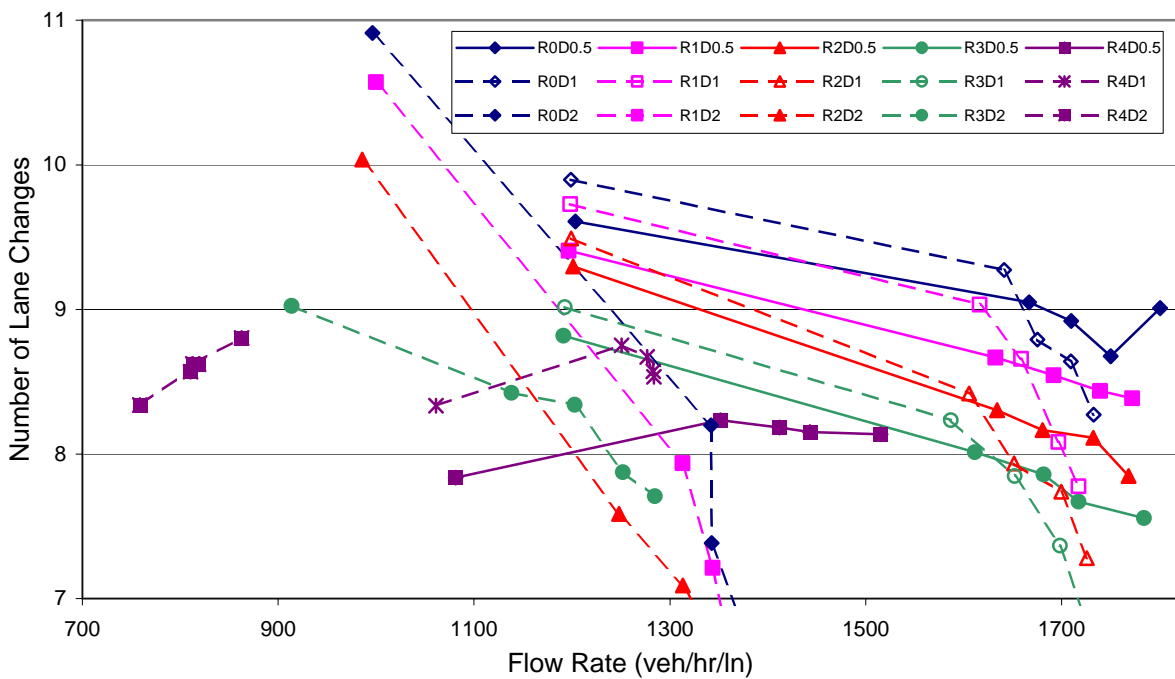
(b) Five-Lane Freeway (Truck 15% and Ramp Volume 1000 veh/hr/ln)

Figure 4-22. Number of Lane Changes and Interchange Density for Three- and Five-Lane Corridors
(75 mph FFS)

4.6.4. Statistical Comparison of Number of Lane Changes

The paired sample t-test procedure was used to determine if there is a reduction in the number of lane changes due to truck-lane restriction. The following hypotheses were assumed and tested for significance:

$$H_0 : \mu_1 = \mu_2 \qquad\qquad H_1 : \mu_1 > \mu_2$$

where μ_1 = number of lane changes before restriction and
μ_2 = number of lane changes after restriction.

Tables 4-4, 4-5, and 4-6 show the effects of the truck restriction condition on the number of lane changes for three-, four-, and five-lane corridors, respectively. The results show that the average number of lane changes decreases significantly after the truck restrictions are put in place. In general, the difference in the number of lane changes increases as the number of restricted lanes increases.

Table 4-5. Average Number of Lane Changes for Three-Lane Corridors

Interchange Density	Rest	μ_1	μ_2	$\mu_1-\mu_2$	t	Significance	Result	Sample Size
0	R1	5.17	4.87	0.302	9.830	0.000	Decreased	63
	R2	5.17	4.45	0.721	11.423	0.000	Decreased	63
0.5	R1	5.31	4.98	0.337	17.367	0.000	Decreased	198
	R2	5.31	4.66	0.654	22.209	0.000	Decreased	198
1	R1	5.00	4.71	0.291	17.800	0.000	Decreased	198
	R2	5.00	4.53	0.471	15.153	0.000	Decreased	198
2	R1	5.08	4.81	0.272	14.812	0.000	Decreased	198
	R2	5.08	4.78	0.306	8.988	0.000	Decreased	198

Table 4-6. Average Number of Lane Changes for Four-Lane Corridors

Interchange Density	Rest	μ_1	μ_2	$\mu_1-\mu_2$	t	Significance	Result	Sample Size
0	R1	5.70	5.50	0.192	7.878	0.000	Decreased	63
	R2	5.70	5.22	0.475	8.564	0.000	Decreased	63
	R3	5.70	4.81	0.884	10.502	0.000	Decreased	63
0.5	R1	6.55	6.24	0.308	14.894	0.000	Decreased	198
	R2	6.55	5.89	0.662	18.799	0.000	Decreased	198
	R3	6.55	5.59	0.965	19.761	0.000	Decreased	198
1	R1	6.41	6.14	0.277	14.240	0.000	Decreased	198
	R2	6.41	5.84	0.578	16.231	0.000	Decreased	198
	R3	6.41	5.63	0.785	13.838	0.000	Decreased	198
2	R1	6.57	6.29	0.283	12.916	0.000	Decreased	198
	R2	6.57	6.08	0.490	11.477	0.000	Decreased	198
	R3	6.57	6.13	0.445	7.363	0.000	Decreased	198

Table 4-7. Average Number of Lane Changes for Five-Lane Corridors

Interchange Density	Rest	μ_1	μ_2	μ_1-μ_2	t	Significance	Result	Sample Size
0	R1	5.49	5.37	0.127	6.590	0.000	Decreased	63
	R2	5.49	5.16	0.331	7.376	0.000	Decreased	63
	R3	5.49	4.91	0.582	8.464	0.000	Decreased	63
	R4	5.49	4.45	1.040	9.671	0.000	Decreased	63
0.5	R1	7.11	6.83	0.283	14.675	0.000	Decreased	198
	R2	7.11	6.52	0.600	16.601	0.000	Decreased	198
	R3	7.11	6.27	0.848	19.733	0.000	Decreased	198
	R4	7.11	5.68	1.429	18.794	0.000	Decreased	198
1	R1	7.33	7.08	0.252	12.521	0.000	Decreased	198
	R2	7.33	6.76	0.576	14.982	0.000	Decreased	198
	R3	7.33	6.51	0.822	16.476	0.000	Decreased	198
	R4	7.33	5.97	1.360	14.852	0.000	Decreased	198
2	R1	7.64	7.35	0.285	12.386	0.000	Decreased	198
	R2	7.64	7.09	0.551	12.441	0.000	Decreased	198
	R3	7.64	7.07	0.571	8.510	0.000	Decreased	198
	R4	7.64	6.84	0.803	8.561	0.000	Decreased	198

CHAPTER 5
OPERATIONAL PERFORMANCE MODELS

This chapter describes the process of developing the operational models for the various truck-lane restrictions examined in previous chapters. These models can be used to estimate the performance of various truck-lane restriction alternatives under given prevailing conditions.

5.1. Performance Estimation Models

In the following subsections, the development of operational performance models for average speed, throughput, number of lane changes, and speed differentials are presented. The SPSS statistical package was used to develop non-linear regression models based on the simulation data described in the previous chapter.

5.1.1. Average Speed

A monotonic decreasing relationship was found between the average link speed and the independent variables including flow rate, truck percentage, ramp volume, and interchange density. An exponential function, defined as follows, was used to describe the relationship between the average speed and the independent variables:

$$Speed = FFS(\alpha + \beta \times \exp(\gamma \times IDen \times \frac{RVol}{2000} + \delta \times \frac{MVol}{MF_i} + \varepsilon \times Tp)) \qquad (5\text{-}1)$$

where Speed = average speed,
   FFS   = free-flow speed,
   IDen   = interchange density (interchanges/mi),
   RVol   = ramp volume (veh/hr),
   MVol   = mainline volume per lane (veh/hr/ln),
   MF_i = maximum flow rate (pc/hr/ln) under FFS i as defined in HCM 2000,
   Tp   = truck proportion, and
 $\alpha, \beta, \gamma, \delta, \varepsilon$ = parameters associated with the independent variables.

Table 5-1 gives the coefficients for the average speed model for different restriction alternatives and number of lanes. The positive coefficients for all variables except β provide evidence that the monotonic decreasing relationship between the average speed and all independent variables is significant. In other words, average speed decreases as interchange density, ramp volume, average lane volume, or truck percentage increases. Since most of the R^2 values are relatively high, it can be concluded that the models sufficiently predict the average speed under given conditions.

Table 5-1. Average Link Speed Models

No. of Lanes	Restriction	α	β	γ	δ	ε	R^2
3	R0	1.2754	-0.2652	0.1631	0.7034	0.5308	0.9215
	R1	1.3229	-0.3071	0.1741	0.6530	0.4708	0.9206
	R2	1.2774	-0.2657	0.2076	0.6913	0.7333	0.9159
4	R0	1.1007	-0.0979	0.4735	1.1914	1.0539	0.8152
	R1	1.1256	-0.1210	0.4503	1.0805	0.7767	0.8177
	R2	1.2256	-0.2185	0.2864	0.7296	0.4663	0.8113
	R3	1.1942	-0.1814	0.4470	0.7612	1.0946	0.7453
5	R0	1.0574	-0.0609	0.6374	1.4931	1.1812	0.7693
	R1	1.0673	-0.0686	0.5359	1.4092	1.2445	0.7636
	R2	1.1227	-0.1181	0.4211	1.0275	0.8661	0.7493
	R3	1.1540	-0.1479	0.3599	0.8594	0.8253	0.7692
	R4	1.1087	-0.1002	0.8176	0.9557	1.9247	0.6948

5.1.2. Throughput

The following non-linear regression model, adapted from the general formula for heavy vehicle factors (f_{hv}), is used to estimate the throughput for various truck-lane restriction alternatives under prevailing conditions:

$$Throughput = \frac{\alpha \times MF_i \times \exp(\gamma \times IDen \times \frac{RVol}{2000})}{1 + \beta \times Tp} \qquad (5\text{-}2)$$

where MF_i = maximum flow rate (pc/hr/ln) under FFS i as defined in HCM 2000,
   Tp = truck proportion,
   $IDen$ = interchange density (interchanges/mile),
   $RVol$ = ramp volume (veh/hr), and
   α, β, γ = parameters associated with the independent variables.

HCM specifies the capacity for the basic freeway segments as 2400, 2350, and 2250 pc/hr/ln for FFS 75 mph, 65 mph, and 55 mph, respectively. The initial value of α is thus set at 1.0. Similarly, β is set at 0.5 initially to emulate the passenger car equivalent (PCE) for trucks (E_T). The parameter β directly denotes the change in throughput. When β is greater than 0.5, it indicates that a truck-lane restriction results in a reduction to throughput.

Table 5-2 gives the coefficients for the throughput model for different restriction alternatives and number of lanes. When a small number of lanes are restricted (for example, R1 for three-lane freeways and R1 and R2 for five-lane freeways), the parameter β is always lower than that of R0. However, when a large number of lanes are restricted, the regression equation results in a very high value of β, implying severe reduction of throughput. In addition, the parameter γ decreases as the number of restricted lanes increases, indicating that ramp volume and interchange density affect the throughput more severely under a large number of lane restriction alternatives. Except

for the cases in which a high number of lanes are restricted, all the regression models explain 90% or more of the total variations.

Table 5-2. Throughput Models

Number of Lanes	Restriction	α	β	γ	R^2
3	R0	1.0280	0.7052	-0.3056	0.9470
	R1	1.0326	0.7002	-0.3286	0.9337
	R2	1.0783	1.2902	-0.4004	0.8545
4	R0	1.0087	0.6881	-0.3463	0.9477
	R1	1.0114	0.6919	-0.3614	0.9377
	R2	1.0273	0.7271	-0.4008	0.9110
	R3	1.0910	2.2122	-0.4727	0.8456
	R0	0.9722	0.6741	-0.3820	0.9446
	R1	0.9725	0.6657	-0.3898	0.9345
	R2	0.9803	0.6664	-0.4116	0.9259
	R3	1.0159	1.0236	-0.4847	0.8713
	R4	1.0623	3.0982	-0.5054	0.8626

5.1.3. Number of Lane Changes

While monotonic decreasing relationships were found between average speed or throughput and some independent variables, this simple trend was not found in the case of number of lane changes. Number of lane changes increases when the flow rates were low and decreases when flow rates are above a certain range. To model this behavior, a convex parabolic function with respect to flow rate was considered in the regression model. The model for number of lane changes is given as follows:

$$NLC = \alpha + \beta \times \left(\frac{MVol}{MF_i}\right)^2 + \gamma \times \frac{MVol}{MF_i} + \delta \times IDen + \varepsilon \times Tp + \rho \times \frac{RVol}{2000} \qquad (5\text{-}3)$$

where NLC = number of lane changes,
      MVol = mainline volume per lane (veh/hr/ln),
      MF_i = maximum flow rate (pc/hr/ln) under FFS i as defined in HCM 2000,
      IDen = interchange density (interchanges/mile),
      Tp = truck proportion,
      RVol = ramp volume (veh/hr), and
  α, β, γ, δ, ε, ρ = parameters associated with the independent variables.

Table 5-3 shows the relationships between the dependent variable and the independent variables. Note that all γ parameters are positive, indicating that the number of lane changes increase as interchange density increases.

The parameters associated with truck percentages have two different signs: positive under the non-restriction alternative and negative under the restriction alternatives. A positive sign of δ indicates that a high percentage of trucks may increase the number of lane changes under the

non-restriction alternative; since trucks travel slower than passenger cars, cars tend to maneuver to overtake them more often. The number of lane changes, however, decreases as truck percentage increases under the truck-lane restriction alternatives. The change of sign from positive to negative on this variable is consistent with the findings of the previous chapter.

Table 5-3. Number of Lane Changes

No. of Lanes	Rest.	α	β	γ	δ	ε	ρ	R^2
3	R0	1.2010	-11.2492	15.2746	0.0253	0.2020	-1.8589	0.8326
	R1	1.6732	-10.9765	14.6451	0.0668	-2.9598	-1.9850	0.8181
	R2	1.5684	-9.9898	13.3766	0.2001	-3.9841	-1.1816	0.8177
4	R0	0.5745	-12.5391	18.2292	0.3459	1.2560	-1.6413	0.7766
	R1	1.1487	-12.4099	17.8209	0.3383	-2.2853	-1.8566	0.7696
	R2	1.4254	-11.8814	16.5770	0.3551	-3.3915	-1.4045	0.7464
	R3	0.9688	-9.6189	14.2601	0.6928	-2.7713	0.1625	0.7639
5	R0	-0.1438	-14.0604	20.4267	0.7281	2.1040	-1.0502	0.6557
	R1	0.4359	-14.0936	20.2191	0.6877	-1.4980	-1.1866	0.6531
	R2	0.8535	-13.6588	19.1395	0.6634	-3.1432	-0.9813	0.6371
	R3	0.7249	-13.0919	17.9222	0.8446	-2.8094	0.0152	0.6480
	R4	0.7211	-10.3578	15.1374	1.1053	-4.6957	1.2169	0.6677

5.1.4. Speed Differentials between Lane Groups

Unlike average speed, the speed differentials between the restricted lane(s) and non-restricted lane(s) decrease as the flow rate increases. However, when the flow rates approach the saturation point, the speed differentials increase. Accordingly, a concave parabolic function with respect to flow rate was used to fit the model, as follows:

$$SpdDiff = \alpha + \beta \times \left(\frac{MVol}{MF_i} \right)^2 + \gamma \times \frac{MVol}{MF_i} + \delta \times IDen \times RVol + \varepsilon \times Tp + \rho \times FFS \tag{5-4}$$

where SpdDiff = speed differentials between lane groups,
       MVol   = mainline volume per lane (veh/hr/ln),
       MF_i = maximum flow rate (pc/hr/ln) under FFS i as defined in HCM 2000,
       IDen   = interchange density (interchanges/mi),
       RVol   = ramp volume (veh/hr),
       Tp   = truck proportion,
       FFS   = free-flow speed, and
  α, β, γ, δ, ε, ρ = parameters associated with the independent variables.

Table 5-4 shows the results of non-linear regression model to predict the speed differentials after the truck-lane restriction. All the parameters except for intercept (ρ) and α, β associated with the average lane volume, are positive, indicating monotonic increasing relationship between speed differentials and independent variables. Note that these models are applicable after truck-lane restriction alternatives are implemented. The R^2 values for the models are approximately 0.7.

Table 5-4. Speed Differential Models

No. of Lanes	Rest.	α	β	γ	δ	ε	ρ	R^2
	R1	-0.4583	27.6562	-32.1132	0.0040	20.9891	0.1042	0.6931
	R2	-5.3623	17.2386	-21.5982	0.0058	53.4256	0.1284	0.7628
	R1	-1.2843	29.0772	-32.2658	0.0048	20.5506	0.0958	0.6909
	R2	-3.9869	24.5351	-27.7951	0.0058	34.7781	0.1150	0.7648
	R3	-10.0203	16.3033	-19.9696	0.0086	77.2897	0.1619	0.8216
	R1	-1.3658	30.9186	-32.0092	0.0054	20.2341	0.0791	0.6385
	R2	-2.6605	28.9434	-30.4135	0.0058	28.5793	0.0954	0.7299
	R3	-10.2913	17.7649	-19.6961	0.0074	59.2769	0.1508	0.6891
	R4	-15.1330	11.5729	-12.6345	0.0093	92.6378	0.2017	0.7959

5.2. Model Comparisons

This section provides a somewhat limited assessment of the accuracy of the performance models developed. Due to lack of field data, average speed and throughput models were compared only to those of HCM 2000. Since HCM does not consider truck-lane restriction, only the basic section without truck restrictions can be compared.

5.2.1. Average Speed Model

Figure 5-1 compares the speed-flow curves of simulated data for three-, four-, and five-lane basic freeway segments to that of the HCM and the Bureau of Public Roads (BPR) formula with 75 mph FFS. Since the calibration procedures were mainly focused on capacity, some discrepancies were found between the VISSIM results and the HCM. The results show that the modeled average speed drops more rapidly than that of the HCM or BPR. While speed drops occur when flow rate reaches 1150 pc/hr/ln in HCM, the modeled speeds begin to decrease at low flow rates.
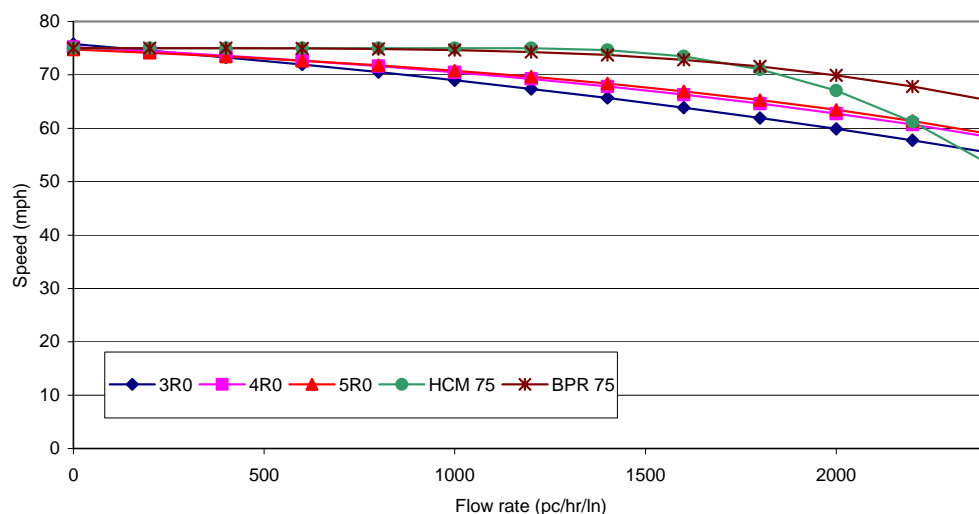

Figure 5-1 Validation of Speed-Flow Curve

5.2.2. Throughput Model

Figure 5-2 shows the relationship between capacity and truck percentage as simulated for three-, four-, and five lane basic freeway segments and HCM under 75 mph FFS. Since the models were based on data of the entire length of these corridors, including ramp and interchange effects, the regression models do not follow the exact trajectory of the HCM model. When the truck percentage is low (below 15%), simulation data from four-lane corridors were close to the HCM model. When the truck percentage exceeds 15%, three-lane freeway data were found to be close to the HCM. However, the model for five-lane freeway provides lower capacity than that of HCM.
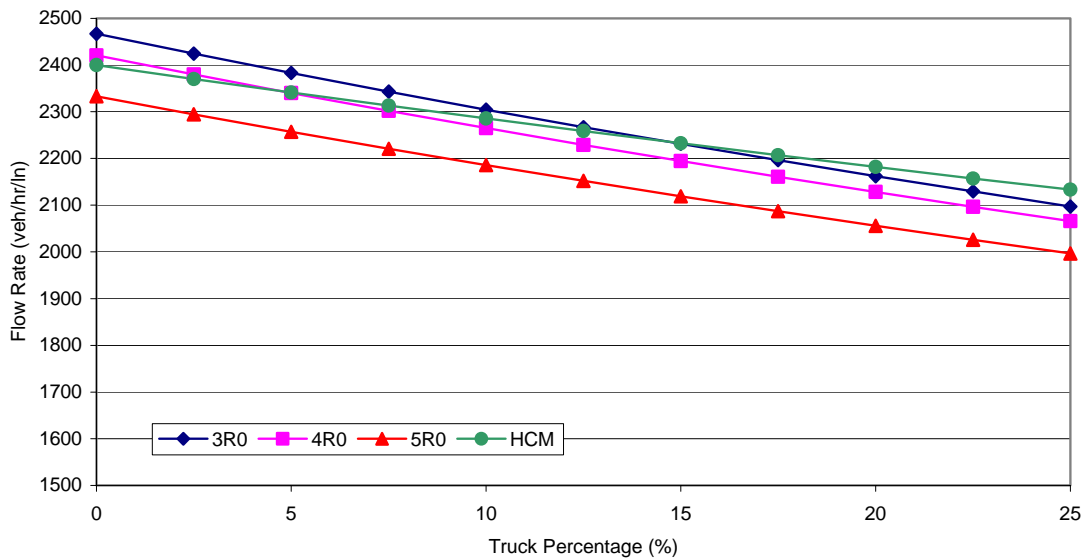
Figure 5-2 Validation of Throughput

5.3. Model Application

By utilizing a variety of measures (i.e., the average speed or throughput rate of freeway corridors), the main application of these performance models is to help determine which truck-lane restriction alternative will perform best on the highway system. The basic decision rule is that a truck-lane restriction alternative is recommended when its overall performance, considering various measures, is better than that of the other restriction alternatives, including non-restriction (for example, greater throughput or higher average speed).

All the regression models provide relatively high R^2 value and consistent signs, indicating that they can be used to enhance the decision-making process in all cases but one. Since the speed differential data can be captured only after the implementation of truck-lane restriction, the data cannot be used for in the decision-making model. However, this study and others confirm that speed differentials and number of lane changes are significantly different between the restricted and non-restricted alternatives, indicating that restriction alternatives always outperform the non-restriction alternative. In addition, they may be used as a surrogate for crash experience.

The following steps are suggested for applying the performance models for various measures to determine the desired restriction alternative under prevailing conditions:

1. Calculate and compare the average speeds and throughputs of various alternatives.
2. Select the alternative that gives the best overall average speed and throughput.
3. Calculate the number of lane changes and speed differentials of various alternatives to make sure that the selected alternative also performs acceptably in terms of these measures. If not, choose another alternative that provides lower number of lane changes and speed differentials while providing a reasonable average speed and throughput.

For demonstration purposes, Table 5-5 provides a set of prevailing conditions as input for an application example, to be described below.

Table 5-5. Application Example

Independent Variables	Input Value
Number of Lanes	4
Interchange Density	1 per mile
Free-flow Speed	75 mph
Truck Percentage	12%
Ramp Volume	500 veh/hr
Average Lane Volume	1800 veh/hr/ln (7200 veh/hr)

Based on Equation 5-1, the average speeds for various truck-lane restrictions, including no restriction, are calculated as follows:

$$Spd(R0) = 75 \times \left(1.1007 - 0.0979 \times \exp\left(0.4735 \times 1 \times \frac{500}{2000} \right) + 1.1914 \times \frac{1800}{2400} + 1.0539 \times 0.12 \right) = 59.6$$

$$Spd(R1) = 75 \times \left(1.1256 - 0.1240 \times \exp\left(0.4503 \times 1 \times \frac{500}{2000} \right) + 1.10805 \times \frac{1800}{2400} + 0.7767 \times 0.12 \right) = 59.4$$

$$Spd(R2) = 75 \times \left(1.2256 - 0.2185 \times \exp\left(0.2864 \times 1 \times \frac{500}{2000} \right) + 0.7296 \times \frac{1800}{2400} + 0.4663 \times 0.12 \right) = 59.8$$

$$Spd(R3) = 75 \times \left(1.1942 - 0.1814 \times \exp\left(0.4470 \times 1 \times \frac{500}{2000} \right) + 0.7612 \times \frac{1800}{2400} + 1.0946 \times 0.12 \right) = 58.9$$

Although the average speed under the R2 alternative is the highest, the difference in average speed among the four alternatives is not significantly different.

The throughputs based on Equation 5-2 are calculated as follows:

$$Throughput(R0) = \frac{1.0087 \times 2400}{1 + 0.6881 \times 0.12} \times \exp\left(-0.3463 \times 1 \times \frac{500}{2000} \right) = 2051$$

$$Throughput\,(R1) = \frac{1.0114 \times 2400}{1 + 0.6919 \times 0.12} \times \exp\left(-0.3614 \times 1 \times \frac{500}{2000}\right) = 2048$$

$$Throughput\,(R2) = \frac{1.0273 \times 2400}{1 + 0.7271 \times 0.12} \times \exp\left(-0.4008 \times 1 \times \frac{500}{2000}\right) = 2052$$

$$Throughput\,(R3) = \frac{1.0910 \times 2400}{1 + 2.2122 \times 0.12} \times \exp\left(-0.4727 \times 1 \times \frac{500}{2000}\right) = 1838$$

Again, the R2 alternative out performs the others in terms of capacity, although the difference is only significant compared to the R3 alternative, which has a much lower throughput.

Based on Equation 5-3, the number of lane changes for various alternatives are calculated as follows:

$$NLC\,(R0) = -12.5391 \times \left(\frac{1800}{2400}\right)^2 + 18.2292 \times \frac{1800}{2400} + 0.3459 \times 1 + 1.2560 \times 0.12 - 1.6413 \times \frac{500}{2000} + 0.5745 = 7.3$$

$$NLC\,(R1) = -12.4089 \times \left(\frac{1800}{2400}\right)^2 + 17.8209 \times \frac{1800}{2400} + 0.3383 \times 1 - 2.2853 \times 0.12 - 1.8566 \times \frac{500}{2000} + 1.1487 = 7.1$$

$$NLC\,(R2) = -11.8814 \times \left(\frac{1800}{2400}\right)^2 + 16.5770 \times \frac{1800}{2400} + 0.3551 \times 1 - 3.3915 \times 0.12 - 1.4045 \times \frac{500}{2000} + 1.4254 = 6.8$$

$$NLC\,(R3) = -9.6189 \times \left(\frac{1800}{2400}\right)^2 + 14.2601 \times \frac{1800}{2400} + 0.6928 \times 1 - 2.7713 \times 0.12 - 0.1625 \times \frac{500}{2000} + 0.9688 = 6.7$$

The results indicate that the by going to the R2 alternative from no restriction, safety is likely to improve due to the reduced number of lane changes.

The results of Equation 5-4 for speed differentials between restricted and non-restricted lane groups, below, provide further analysis:

$$SDiff\,(R1) = 29.0772 \times \left(\frac{1800}{2400}\right)^2 - 32.2658 \times \frac{1800}{2400} + 0.0048 \times 1 \times 500 + 20.5506 \times 0.12 + 0.0958 \times 75 - 1.2843 = 2.9$$

$$SDiff\,(R2) = 24.5351 \times \left(\frac{1800}{2400}\right)^2 - 27.7951 \times \frac{1800}{2400} + 0.0058 \times 1 \times 500 + 34.7781 \times 0.12 + 0.1150 \times 75 - 3.9869 = 4.7$$

$$SDiff\,(R3) = 16.3033 \times \left(\frac{1800}{2400}\right)^2 - 19.9696 \times \frac{1800}{2400} + 0.0086 \times 1 \times 500 + 77.2897 \times 0.12 + 0.1619 \times 75 - 10.0283 = 9.9$$

The results show that, while the R2 alternative is superior to the R3 alternative, it has a higher speed differential than the R1 alternative, which provides the lowest speed differential. When the performance of the R1 alternative in terms of the other measures are considered, it appears that R1 is also an acceptable alternative since its average speed and throughput are comparable to those of the R2 alternative while having only a slightly higher number of lane changes. It can also be concluded that R3 is clearly not desirable for the given conditions because its throughput is significantly lower while the speed differential is higher.

CHAPTER 6
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Highways are designed to facilitate the movement of all modes of traffic including passenger cars, trucks, buses, recreational vehicles, and so on. The impacts of these different vehicle types are not uniform, however, creating problems in highway operations and safety. As passenger cars traffic has increased, both the volume and dimension of truck operations has also increased; decision-makers must take into account the variety of issues that must be addressed. A common approach to reducing the impacts of truck traffic on freeways has been to restrict trucks to certain lane(s) as a means of minimizing the interaction between trucks and other vehicles and compensating for their differences in operational characteristics. While the potential benefits of truck-lane restriction are safety and operations, only a limited number of related studies exist in the literature.

Many possible design alternatives for truck-lane restrictions exist. Some use one restricted lane while others use two or more; some restrict trucks to the rightmost lane(s) while others to the leftmost lane(s). The performance of these different truck-lane restriction alternatives differs under different traffic and geometric conditions. Thus, a good estimate of the operational performance of different truck-lane restriction alternatives under prevailing conditions is needed to help make informed decisions on truck-lane restriction alternatives. The operational performance measures examined in this study include average speed, throughput, speed differentials, and lane changes. Prevailing conditions include number of lanes, interchange density, free-flow speeds, volumes, truck percentages, and ramp volumes. This study has developed operational performance models that can be applied to help identify the most operationally efficient truck-lane restriction alternative on a freeway under prevailing conditions.

Recognizing the difficulty of collecting sufficient data on the wide variety of variables required for empirical modeling, the simulation approach was used to estimate the performance values for various truck-lane restriction alternatives under various traffic and geometric scenarios. Simulation models were developed to replicate the complex interactions among the many variables of interest involved. Both the CORSIM and VISSIM simulation models were examined for their ability to model truck-lane restrictions. Due to a major problem found in the CORSIM model for truck-lane modeling, the VISSIM model was adopted as the simulator for this study.

The VISSIM model was calibrated mainly to replicate the capacity provided by the 2000 Highway Capacity Manual (HCM) for various free-flow speeds under ideal basic freeway section conditions. A program was developed to automate the process of running multiple VISSIM runs and extracting the corresponding output for various input scenarios. Non-linear regression models were then developed to relate the average speed, throughput, number of lane changes, and speed differentials under prevailing conditions. Although the coefficients of the regression models show consistent and logical relationships between dependent variable and independent variables, the model validation based on comparison with the HCM was somewhat limited. Further studies may attempt to validate the simulation results with field data, when they become available. Based on these performance models, a simple decision procedure was recommended to select the desired truck-lane restriction alternative for prevailing conditions.

As part of the analysis of simulated data in this study, it was found that:

1. In general, truck restriction alternatives increase the average speed under low interchange density, low truck volume, and low ramp volume condition. When a freeway corridor is congested due to densely spaced interchanges, high truck percentages, or high ramp volumes, truck-lane restrictions reduce the average speed. However, the speed reduction is negligibly small, except where a large number of restricted lanes is implemented, for example, restricting three out of four total number of lanes. This suggests that restricting an appropriate number of lanes to truck traffic is generally beneficial since it may improve traffic safety without worsening the efficiency of moving traffic.

2. A high number of the restricted lanes results in a higher throughput under low truck percentages with sparsely spaced interchanges. A relatively low number of restricted lanes (such as one out of three lanes, or one or two out of four and five lanes, respectively) generally provide a higher capacity than the non-restriction alternative for truck percentages up to 25%.

3. Statistical analysis shows that the speed differentials between restricted and non-restricted lane groups are significant, and that the magnitude increases as the number of interchanges, ramp volumes, truck percentages, and free-flow speed increases.

4. Truck-lane restrictions significantly reduce the number of lane changes by separating slower vehicles from faster vehicles, thus reducing maneuvers to overtake one another. Since lane changes are a major cause of crashes, a reduction in lane changes through truck-lane restrictions can potentially improve freeway traffic safety.

5. One-lane truck restriction is suitable for three-, four- and five-lane freeways while two-lane truck restriction is more suitable for four- and five-lane freeway corridors except when there is a high interchange density and a larger than average truck percentage.

Due to time constraints, software limitations, and lack of field data, this study has been somewhat limited in scope. It is recommended that further studies focus on the following areas to refine and generalize the models developed in this study:

1. Includes right-lane restrictions, i.e., trucks are not allowed to use the rightmost lane(s). Only left-lane restrictions are modeled in this study.

2. Models exclusive truck lane(s), i.e., passenger cars are not allowed to use the lanes designated for trucks.

3. Models trucks of various dimensions and operating characteristics. The models developed in this study are based on only one average truck type.

4. Incorporates the impact of restriction-compliance with various truck violation rates (i.e., percentage of trucks that use the truck-restricted lane(s)). The models developed in this

study assume 100% compliance. It is noted, however, that the current versions of CORSIM and VISSIM do not explicitly model violation rates.

5. Models speed differentials within a traffic stream in the same lane group, in addition to the current model for speed differentials between restricted and non-restricted lane groups.

6. Uses different on- and of-ramp volumes. The models developed in this study assume that the on- and off-ramp volumes are the same. Consequently, the models are not suitable for evaluating corridors with significantly different on- and off-ramp volumes.

7. Considers other configurations of ramps, such as two successive on-ramps, two successive off-ramps, and ramps that form weaving sections.

It is noted that in the latest version of CORSIM that comes with TSIS Version 5.1, the problem described in section 3.1 appears to have been corrected. Accordingly, CORSIM should be reconsidered as a simulator for further studies. The use of CORSIM offers the advantage of applying a simulator that has been calibrated based on the U.S. traffic conditions and driver behaviors. In addition, CORSIM also includes four different types of trucks with calibrated default values for truck dimensions and operating characteristics.

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