

**Identifying the Impact of Truck-Lane Restriction  
Strategies  
on Traffic Flow and Safety Using Simulation**



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# **Identifying the Impact of Truck -Lane Restriction Strategies on Traffic Flow and Safety Using Simulation**

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## **ABSTRACT**

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For the safety evaluation, this research measures the impact of different truck lane restriction strategies (TLRS) using conflict as the measurement of effectiveness (MOE). Conflict has been proven to be highly related to traffic crashes on freeways (FHWA, 1990; Sayed and Zein, 1999; Kaub, 2000). The high frequency of conflicts has also made it possible to collect adequate data for statistical analysis. The MOEs used to evaluate the impact of different lane restrictions on operational performance were lane changes, average speed, speed distribution, and volume distribution. Due to the lack of existing highway locations with different lane restrictions considered in this study, the conflict data were collected using a traffic simulation tool – PARAMICS V3.0 (Quadstone Ltd., 2000), which can simulate the emergent interaction between vehicles but not random

crashes on the road network. The effectiveness of different lane restrictions in terms of the above MOEs were evaluated for 14,400 different simulation scenarios by varying lane restriction strategies, traffic conditions (volume, truck percentage) and geometric characteristics (gradient, speed limit, interchange density).

The simulation results showed that all the geometric and traffic characteristics had a significant impact on freeway safety and operation. In addition, truck percentage and volume were identified as key factors that had a significant impact on the selection of the optimal truck lane restriction strategy. The ANOVA analyses indicated that the degree of effect of truck lane restriction strategies on safety intensify with the increase in truck percentage and traffic volume. Optimal alternatives of truck lane restriction strategies under different truck percentages and volumes were identified with the objective of reducing traffic conflicts and enhancing LOS (level of service). Guidelines were then developed for the application of truck lane restrictions under alternative traffic and geometric conditions.

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## CHAPTER 1 INTRODUCTION

### 1.1 Research Background

With the development of logistics in highway transportation, the operations of commercial vehicles in the traffic mix have increased rapidly in terms of both volume and dimensions which have lead to additional and more severe truck-related traffic crashes each year. As a result, various truck-restrictive strategies have been employed to reduce the interaction between trucks and passenger cars on the highways, and consequently to diminish multi-vehicle incidents involving large trucks and passenger cars. Among these truck restrictions, lane restrictions have been widely implemented as a popular strategy across the United States. However, the effectiveness of different truck lane restriction strategies (referred as TLRS later in the thesis) for trucks differs from case to case with respect to operations and safety due to the unique factors of each site including types of restriction used, traffic characteristics, and geometric design. This project will therefore focus on evaluating the impacts of traffic and geometric characteristics on the effectiveness of TLRS with respect to safety and traffic flow, and developing guidelines for engineers to facilitate the application of lane restriction strategies on freeways.

TLRS are expected to reduce freeway crashes as well as increasing traffic mobility. Previous studies have mainly focused on identifying the operational impacts of TLRS due to the extremely limited availability of crash data on the investigated site. In measuring the operational performances of TLRS, speed, travel time, and throughput were usually employed as MOEs (measurements of effectiveness) (Gan and Jo, 2003;

Mussa, 2004; Hoel and Peek, 1999; Vidunas and Hoel, 1997; Zavoina et al, 1991). However, limited and inconsistent operational benefits have been found in such studies. In identifying the safety effects of TLRs, lane-changing frequency and speed differential were used as MOEs. However, the connection between such MOEs and crash rates on the freeway has not been established. Even though the safety benefits from applying TLRs are apparent in most cases, these benefits have not been identified at a quantitative level. This has motivated the researchers conducting this study to identify safety impacts of TLRs using conflict as the MOE. Conflict has been proven to be highly related to traffic crashes on freeways and the high frequency of conflicts have made it possible to collect enough data for a statistical analysis (FHWA, 1990; Sayed and Zein, 1999; Kaub, 2000).

Due to the limited availability of existing sites with different TLRs, this evaluation was conducted through simulation using the PARAMICS V3.0 (Quadstone Ltd., 2000) program. Its advanced Application Program Interface (API) functions can be used to simulate and collect interaction data between vehicles. The effectiveness of different lane restrictions in terms of the above MOEs was evaluated for 14,400 different simulation scenarios by varying lane restriction strategies, traffic conditions (volume, truck percentage) and geometric characteristics (gradient, speed limit, and interchange density).

Based on the data acquired from the simulation, key factors (traffic or geometric), which have significant impact on the MOEs under different TLRs, were identified through ANOVA analysis. The influence of TLRs on the safety and operational MOEs was analyzed for each category decided by the combination of number of lanes, demand

volume, and truck percentage. In addition, guidelines were developed for the selection of an appropriate TLRS for different traffic and geometric characteristics.

## **1.2 Purpose and Scope**

The purpose of this thesis was to evaluate the effectiveness of different TLRS on safety and operational characteristics for different geometric and traffic conditions.

This study used conflict as a surrogate measurement for crash in the safety evaluation and used conventional MOEs of average speed, lane changes, speed distribution, and volume distribution between restricted and unrestricted lanes for the operational evaluation. Only 3-, 4-, and 5-lane (in each direction) freeways were considered in this study as they are typical in the existing freeway systems. 2-lane highways were not considered, as it may not be wise to apply restrictions on such a limited number of lanes. The lane restriction was to restrict trucks from using certain lanes - exclusive truck lanes were not considered in this study because, in practice, assigned truck lanes also allow other vehicles to travel on them. Grade, density of interchanges, volume, truck percentage, and posted speed limits were used as independent variables. In the traffic mix, only two types of vehicles were considered - passenger cars and trucks. The simulation software PARAMICS was used as the tool to collect data for the analysis because of its advanced Application Program Interface (API) functions.

### **1.3 Study Objectives**

The specific objectives of this study were as follows:

- identify the effectiveness of different TLRS on traffic safety using surrogate measurements;
- identify the effectiveness of TLRS on traffic operation;
- identify the impacts of traffic and geometric factors on the safety and operational performance of TLRS;
- produce guidelines on the application of TLRS for traffic engineers.

### **1.4 Structure of Thesis**

The remainder of this thesis is organized as follows: Chapter 2 is a review of relevant literature including previous studies on truck lane restrictions, safety surrogate measurements, and relative functions of simulation software. Chapter 3 gives detailed algorithms of safety surrogate measurements to be collected in simulation while Chapter 4 provides the methodology describing TLRS, MOEs, and simulation designs that have been used in this study. Chapter 5 presents the analysis of safety performance of different TLRS, while Chapter 6 shows corresponding results on operational performance on the basis of simulation data. Chapter 7 gives guidelines based on analysis results from Chapters 5 and 6 for application of TLRS. In addition, a list of future research topics is presented.

## **CHAPTER 2 LITERATURE REVIEW**

### **2.1 Introduction**

This chapter consists of three components - a review of previous studies on truck lane restrictions, an introduction to the safety surrogate measurements, and an explanation of functions of PARAMICS API in collecting the data required in this research. The first part reviews the methodologies, simulation tools, conclusions from previous studies and the deficiencies which could be overcome in this study; the second part gives the concepts of the safety surrogate measurement (conflict) and its connections to the crash rate, which has been proven by previous studies; while the third part explains how the advanced API functions in PARAMICS can be used to simulate and collect data on the interaction between vehicles on the freeway.

### **2.2 Previous Studies**

There are four types of popular truck restriction methods, i.e. lane, speed, time-of-day, and route restriction. Each method may be imposed on a section of roadway separately or together with other method(s) in a combined strategy. The TLRS restricts certain types of vehicle (e.g., a truck) from using certain lanes in order to reduce slow traffic or interactions between cars and heavy vehicles when sharing the same lanes. The speed restriction usually gives trucks a lower speed limit than that for passenger cars with the premise that traveling at a lower speed makes it easier for heavy vehicles to accommodate their differences from passenger cars since trucks have limited maneuvering and braking capabilities due to their weight, length, and configuration. The

time-of-day restriction prevents trucks from using certain lanes or entire facilities during a special period when the facility is not capable of accommodating trucks well under the current LOS. The route restriction prohibits the truck from using certain routes, which have inadequate geometric design, congested traffic, or high residential density that could be harmed by hazardous materials possibly carried by trucks. All TLRS can be categorized into two major types of strategies: 1) restricting trucks from certain lanes, and 2) exclusive truck lanes. In the former strategy, trucks are prevented from using certain lanes, which actually act as passing lanes so that vehicles with higher speeds can overtake the low speed traffic, i.e. trucks. This may reduce the opportunity to form a truck leading shock wave when trucks cannot keep up with the speed of cars at grades on freeway sections. The other type of TLRS is the exclusive truck lane which confines most trucks within such lanes and prevents cars from using it at any time. Theoretically, this strategy would dramatically reduce interactions between trucks and cars unless they needed to change lanes to enter or leave the highway. However, in practice, most states allow passenger cars to travel on the exclusive truck lanes. Hence, in this study, only the former strategy is applied in the evaluation process.

Garber and Gadiraju (1990) conducted a study using simulation (SIMAN) to identify the impact of different TLRS with respect to differential speed limit (DSL) on operational and safety performance. Different simulation scenarios were produced by varying the traffic volume, truck percentage, DSL, and truck lane restriction strategies. They used volume distribution (trucks and cars in different lanes), speed distribution (in restricted lanes), time headway, and accident rates as the MOEs. The evaluation results indicate that 1) imposing the strategy of DSL alone does not impact significantly the

distribution of the volumes of trucks and cars in different lanes of the multilane highway; 2) imposing the strategy of both DSL and lane restriction will lead to an increase of interaction between trucks and cars which creates a crash potential; 3) restricting trucks to the right lane decreases the headway in the restricted lanes and the magnitude increases with the increase of AADT and truck percentage; and 4) a skewed distribution of speed and a potential crash increase will result with the imposition of such strategies. The MOE of “accident rate” was a similar concept to “conflict” and the analysis was based on simulation data. However, simulation tools, such as PARAMICS, VISSIM, and CORSIM etc are more advanced. In addition, few lane restriction strategies were applied in this study with no consideration of the geometric characteristics, and emphasis was placed on the effectiveness of differential speed limits.

Hanscom (1990) evaluated the operational effectiveness of TLRS at three highway locations by comparing the observed primary measures of effectiveness (MOEs) before and after imposition of TLRS. Two types of TLRS were applied, i.e. restricting trucks from using the leftmost lane at two 3-lane (each direction) highway segments, and restricting trucks from using the right lane at one 2-lane (each direction) highway segments. The study results indicate that 1) reduced congestions were achieved in the 3-lane segments with left-lane restrictions in terms of decreased rates of vehicles impeded by trucks and reduced queue lengths; 2) reduced speeds of vehicles impeded by trucks were found at 2-lane and right-lane restriction sections due to crowding of trucks on the left lane and fewer passing gaps remaining for the vehicles following such trucks; and 3) no speed changes were observed to indicate an adverse effect of imposing truck lane

restrictions. Few TLRS were incorporated in this study due to the limited site data and the evaluation focused only on the operational aspect and not on safety.

Zavoina et al (1991) analyzed the operational effects of left-lane truck restriction imposed on I-20 (three lanes in each direction) near Fort Worth, TX. Based on the field data collected on the investigated section on I-20, vehicle distribution with respect to classification, vehicle speed, and time gaps between vehicles were examined. The results showed significant changes in the distribution of trucks due to lane restrictions while no significant effect was observed in the distribution of cars, vehicle speeds, and time gaps attributed to lane restrictions. However, no transferable results were produced in this study since data were collected and analyzed for a very special case with respect to grade, volume, truck percentage, geometric condition, and method of lane restriction.

Hoel and Peek (1999) evaluated the impacts of TLRS by a simulation method (FRESIM) upon traffic operation characteristics of density, speed differential, and lane changes under different scenarios taking into account different volumes, truck percentages, initial volume distributions, grades, and TLRS. A total of six TLRS were applied in the simulation: restricting trucks from the left lane on a 3-lane (in each direction) freeway, restricting trucks from the right lane on a 3-lane (in each direction) freeway, restricting trucks from the far left lane on a 4-lane (in each direction) freeway, restricting trucks from the far two left lanes on a 4-lane (in each direction) freeway, restricting trucks from the far right lane on a 4-lane (in each direction) freeway, and restricting trucks from the far two right lanes on a 4-lane (in each direction) freeway. The MOEs used in this study consisted of density, speed differential, and lane changes. As a result, it was found that restricting trucks from the left lane with steep grades may cause

an increase in the speed differential while a decrease of density and the number of lane changes, and restricting trucks from the right lane leads to an increase in the number of lane changes for sites without exit and entry ramps. However, crash rates were not directly addressed in this research and merging and diverging movements around the ramp areas were also not considered.

Gan and Jo (2003) developed operational performance models using VISSIM to identify the most operationally-efficient TLRS alternative on a freeway under prevailing conditions in terms of number of lanes, interchange density, free-flow speed, volumes, truck percentages, and ramp volumes. This research revealed that 1) truck restrictions generally increase the average speed under low interchange density, low truck volume and low ramp volume condition while causing a negligible reduction in average speed under densely-spaced interchanges, high truck percentages, or high ramp volumes; 2) truck restrictions produce a higher throughput than non-restriction alternatives and such effectiveness became more apparent with the increase in the number of restricted lanes under low interchange density; 3) speed differentials between restricted and non-restricted lane groups are significant and the magnitude increases with the increase in the number of interchanges, ramp volumes, truck percentages, and free-flow speed increases; 4) lane changes are generally reduced significantly by the application of truck restrictions which indicates a potential improvement of freeway traffic safety; and 5) restricting trucks from the leftmost lane gives good performance in 3-, 4- and 5-lane freeways while restricting from the two leftmost lanes is more suitable for 4- and 5-lane freeway corridors unless the interchanges are densely distributed and high truck volume exists.

However, operational performance models developed are extremely complicated and could not be used easily to select appropriate TLRS at a site.

Mussa (2004) evaluated the operation and safety characteristics of the I-75 corridor of the 6-lane facility in north Florida where trucks are restricted from the leftmost lane throughout the day. Both field and simulation analyses were conducted. Based on the field data on geometrics and vehicle characteristics at various times of the day, the simulation study was conducted to determine the effect of travel time and speeds on the corridor with truck restrictions for different simulation scenarios taking into account traffic volume, vehicle type distribution, time of day, and other pertinent factors. Further, the study also investigated crashes in the study corridor to determine the safety experience associated with the left-lane truck restriction. The simulation results showed no significant difference in travel time and delay between restricted and non-restricted corridors but the truck restriction decreased the number of lane changes. In addition, the crash data analysis results indicate that improper lane changes contribute to traffic crash occurrence.

In summary, most of the previous studies were conducted under limited geometric and traffic conditions. In evaluating the impacts of truck lane restriction strategies on safety, only conventional MOEs such as lane changes and speed differentials were considered. Although some crash data were collected in several studies, the statistical analysis seems unreliable due to a lack of adequate site data. To overcome these shortcomings, this research used conflict as a surrogate measurement of safety as adequate conflict data could be collected from simulation that can be used for statistical analysis.

### 2.3 Safety Surrogate Measurements

Traffic safety studies have put a lot of effort in relating the crash rate to the operational independent variables such as AADT, volume to capacity ratio, and average speed, etc. These studies usually produce regression models with dependent variables of crash rates and the independent variables mentioned above. Hence, calibration of parameters is required within each model to fit a special local site. However, the crash rate is difficult to predict due to the low frequency of crashes and their random occurrence which may be caused by factors beyond the independent variables considered in the model. In other words, similar facilities may have different crash rates which may result in unstable calibrated values of parameters. This situation has diverted researchers' interests from crash rates to safety surrogate measurements which are directly related to crash rates but occur at a higher frequency. Among the safety surrogate measurements investigated over the years, *conflict* is one of the most popular and the high correlation between crash rates and conflicts has been proven by previous work (FHWA, 1990; Sayed and Zein, 1999; Kaub, 2000). In this study, the concept of conflict follows the definition first given by Amundsen and Hyden (1977) as "An observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged."

Once a conflict is defined, the occurrence and severity are decided by the value of a certain related measure. The primary occurrence measure of conflict used in previous research is *time to collision* (TTC) which is defined as *the expected time for two vehicles to collide if they remain at their present speed and on the same path* (FHWA, 2003). The

algorithm developed by FHWA (2003) computes TTC as the time it takes the encroaching vehicle to reach the current position of the other vehicle if the encroaching vehicle remains at its present speed on the same path. The shorter the TTC, the higher probability of a collision. At the same time, some researchers also use TTC as an indication of crash severity (Hyden, 1987; Hayward, 1972) which is under debate by other researchers because TTC does not directly give the absolute speed of the encroaching vehicle even though it involves speed and headway during the calculation (Kruyssen, 1991; Tiwari et al., 1995). Hence, in evaluating the severity of the collision, other values such as deceleration rate (DR) and absolute speed are highly recommended in addition to TTC (Cooper and Ferguson, 1976; Darzentas et al., 1980). In this initial study, only the frequency of conflict occurrence is used as an MOE to evaluate the safety performance of truck lane restriction strategies. Future work will be done on investigating the influence of lane restriction upon crash severity.

The research report FHWA-RD-03-050 gave detailed definitions of different conflicts in 2003 at intersections including point and line conflicts and framed out the basic process to acquire such conflict data from simulation. This study follows a similar concept and process set out in the above report but is adjusted to fit the case of freeway. Here, the conflict data collected in the simulation consist of *lane-changing*, *merging*, and *rear-end conflicts*. The lane-changing conflict is defined as that between the vehicle that makes a lane-changing maneuver and the vehicle following immediately after it in the target lane; the merging conflict is defined as that between the vehicle merging to the main road from a ramp and the vehicle following immediately after it in the target lane on the main road. The rear-end conflict is defined as that between the vehicle that suddenly

reduces its speed and the vehicle following immediately after it in the same lane and in the same direction. In the simulation, the process of tracing potential conflict is triggered by a lane-changing maneuver, a merging maneuver, or a sudden start of braking maneuver. Once a process is triggered, the position, speed, and acceleration of the vehicles involving the potential conflict will be traced for a certain period at each simulation time step. At each step, the time to conflict (TTC) is calculated and updated if the current TTC is less than all the previous ones during the tracing period. If the final TTC is less than a certain threshold set in advance, a conflict of certain type will be counted. Chapter 3 discusses detailed information regarding algorithms of safety and surrogate measurements.

Field data collection of conflicts is a cost-consuming task because each one needs to be identified at the site by observers regardless of whether this task is conducted at the site or through extraction of data from video recorded in advance. In addition, inconsistencies may exist among different observers for the same set of data and the accuracy could be ruined by the subjectivity of observers. Hence, the attention of researchers has been diverted to traffic simulation models to collect safety surrogate measurement (FHWA, 2003). To be a candidate tool for safety surrogate measurements through simulation, the software should have the capability of modeling driver/vehicle interactions (car following, gap acceptance, lane change, etc), extracting detailed data from the simulation (location, speed, acceleration/deceleration, etc), and calibrating/selecting the parameters for each model. A lot of microscopic traffic simulation software packages such as VISSIM, CORSIM, AINSUM, PARAMICS, etc are capable of performing these functions. In this study, VISSIM and PARAMICS were

available for use, but the latter was chosen because 1) PARAMICS has advanced application programming interface (API) functions which could collect and deal with conflict data during the process of simulation in real time; 2) the author has extensive experience in PARAMICS simulation modeling and API programming.

## **2.4 PARAMICS API Functions**

PARAMICS 3.0 (Parallel Microscopic Simulation), developed by Quadstone Ltd, is a suite of high performance software tools consisting of PARAMICS Modeler, Processor, Programmer, Analyzer and Monitor (Quadstone, 2002). The PARAMICS Modeler simulates lane changing, gap acceptance, and car-following behavior for each vehicle on urban and freeway networks with input geographic and traffic data in a graphic user interface (GUI). It allows the user to set a time of less than one second, at which the state (position, speed, acceleration/deceleration, etc) of each vehicle will be updated. This makes it possible to investigate the interaction between the vehicles in subtle details. The PARAMICS Processor can run the traffic simulation in a batch mode without visualization which dramatically increases the speed of simulation. The PARAMICS Analyzer is a tool that is used to read results from simulation, conduct data analysis at certain levels, and presents the analysis results in a GUI format. The PARAMICS Programmer is a Quadstone framework provided for advanced users to customize many features of the underlying simulation model through an Application Programming Interface (API). In this research, the Modeler is used to build up the simulation network, to set up the truck lane restriction strategies, and to input traffic data; the Processor is used to run the different scenarios of simulation in a batch mode by

different lane restriction strategies, geometric conditions, and traffic inputs; the Programmer is used to develop a process embedded in the Modeler to compute safety measurements in the simulation, to extract required data, and to summarize the results. This process is called Safety Surrogate Assessment Methodology (SSAM) (FHWA, 2003).

The success of developing the SSAM process here is attributed to the merits of the advanced API functions in the PARAMICS Programmer. The Programmer is able to pass additional network-wide configuration parameters into the simulation, read or write information from any of the objects used to represent the network (such as intersection, link, lane, vehicle, signal, loop detector, etc), and increase the detail of the measured data available from the simulation by vehicle tagging or tracing the process of the simulation (FHWA, 2003). The Programmer generally provides two groups of functions: control and callback. The control functions are event-driven structures which are triggered at a specific simulation stage or when special events occur; for example, when a vehicle makes a lane-changing maneuver or passes a loop detector. The callback functions return information about some of the attributes of the current vehicle (position, speed, acceleration/deceleration, etc) and its environment, e.g. the relationships between the current vehicle and other facilities in the network. The callback functions provide adequate inputs for computation in the SSAM process while the control functions assure only indispensable cases are considered and only necessary data are collected for a high efficient process.

## **2.5 Summary**

The literature review of the previous research reveals that although much effort has been placed in evaluating the effectiveness of truck lane restriction strategies, most of these studies focused on special cases and the results produced cannot necessarily be transferred to other conditions not considered in these studies. In addition, the safety performance was evaluated on the operational measures such as speed differential and lane changes. In order to effectively evaluate truck lane restriction strategies, more reliable MOEs, such as safety surrogate measures, should be used. The extensive studies that have been conducted on safety surrogate measures have proven a direct correlation between traffic crashes and traffic conflicts (FHWA, 1990; Sayed and Zein, 1999; Kaub, 2000). The merits of PARAMICS in both microscopic simulation and advanced API functions have also made it possible to collect interaction data between vehicles in the simulation. The literature review indicates the necessity for this study as its results should make a significant contribution to the safety of the art on the impact of truck lane restriction on safety and operation on freeways.

## CHAPTER 3 ALGORITHMS OF SAFETY SURROGATE MEASURES

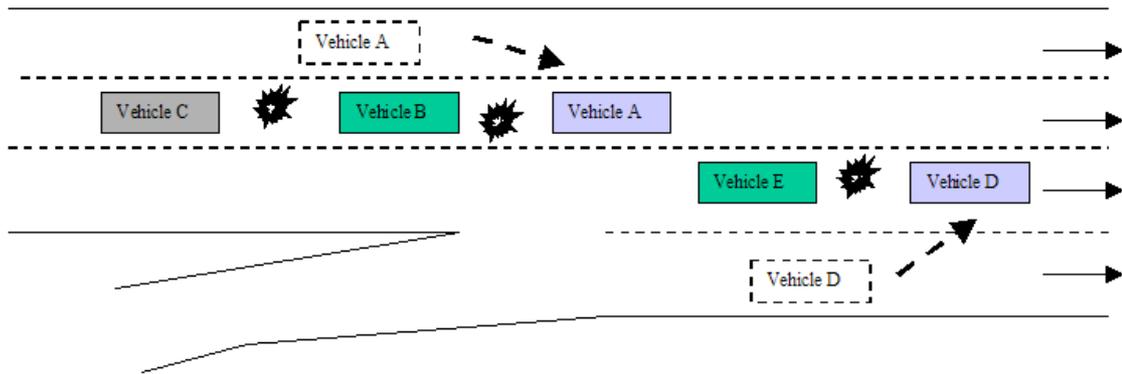
### 3.1 Introduction

The most popular measurement of safety of a highway or freeway facility is the expected number of crashes that occur at the investigated facility during a certain period. To evaluate the safety level of a newly-built or planned facility, researchers have been relating crashes that have not occurred to some operational independent variables (such as the AADT) that can be predicted at a certain reliable level. These usually result in a regression model with a dependent variable of crash and independent variable(s) of AADT and other operational variables. Most of the time, calibration is usually a prerequisite for the model. However, the rareness of crash occurrence has made such calibration less reliable, and the crash rate is still difficult to predict despite the large body of studies in this area. This has diverted the interest of researchers over time to obtain surrogate measurements that reflect the safety level of a facility, but have a much higher frequency of occurrence than that of crashes. Among all safety surrogate measurements, conflict is the most popular. Here the conflict is defined as an observable situation in which two or more road users approach each other in time and space to such an extent that there is the risk of collision if their movements remain unchanged (Amundsen and Hyden, 1977). It should be noted that the definition of conflict in this study includes only the potential collisions involving two vehicles.

Conflict is a potential collision event that does not occur due to evasive action during a collision course. It could occur either at a particular location in time and space or during a range of times and locations. The former is called a conflict point and the latter

is a conflict line (FHWA, 2003). For example, at an intersection, conflict points exist between the left-turn traffic and the through traffic in the opposite direction because they could only collide in one possible location. However, when a vehicle on a freeway makes a lane-changing maneuver, a conflict line exists between the current vehicle and the vehicle immediately behind it on the target lane of the lane-changing action because there are a series of times and locations that the two vehicles could collide on the target lane during a short time period after the lane changing maneuver begins. A conflict line exists at both intersections and freeway sections but a conflict point only exists at intersections. Since this study intends to evaluate the safety impact of truck lane restriction strategies on freeways, only conflict lines are incorporated in the conflict data collection.

The research report of FHWA-RD-03-050 gives detailed definitions of different conflicts at an intersection including point conflicts and line conflicts and frame out the basic process to acquire such conflict data from simulation. This study followed a similar concept and process set out in the above report but fitted them for freeway. Here, three kinds of conflicts are considered in the simulation: lane-changing, merging, and rear-end conflicts. As shown in Fig. 1, a *lane-changing* conflict is defined as the conflict between the vehicle that makes a lane-changing maneuver (vehicle A) and the vehicle following immediately after it in the target lane (vehicle B). *The merging conflict* is defined as the conflict between the vehicle merge to the main road from a ramp (vehicle D) and the vehicle following immediately after it in the target lane on the main road (vehicle E). *The rear-end conflict* is defined as the conflict between the vehicle that suddenly reduces its speed (vehicle B) and the vehicle following immediately after it in the same lane and in the same direction (vehicle C).



**Figure 1 Definition of Conflicts**

The typical crashes involving two vehicles on freeway segments are rear-end and sideswipe crashes assuming a physical partition exists between opposite directions. However, it is difficult to simulate the conflicts that would potentially lead to a sideswipe crash because the position of the vehicle in the simulation is given by the current lane and the distance of the vehicle from the end of the current link (freeway section between ramps). Within a lane, there is no exact transverse coordinate provided. Hence, all three types of conflicts defined above are rear-end events and are categorized into three types of conflicts by the different triggering conditions that are mainly described by the original positions by the lane of the encroaching and evasive vehicles. Such categorization of conflicts assumes the lane restrictions will encourage or discourage different vehicles (car or truck) to change lanes or stay in the current lane and the rate of these three types of conflicts will reflect the potential risks when vehicles make lane changes, merge or suddenly start to brake under such motivations. The following paragraphs will give details of the descriptions, algorithms of these conflicts, and the process to obtain them from simulation.

## 3.2 Lane-Changing Conflict and Merging Conflict

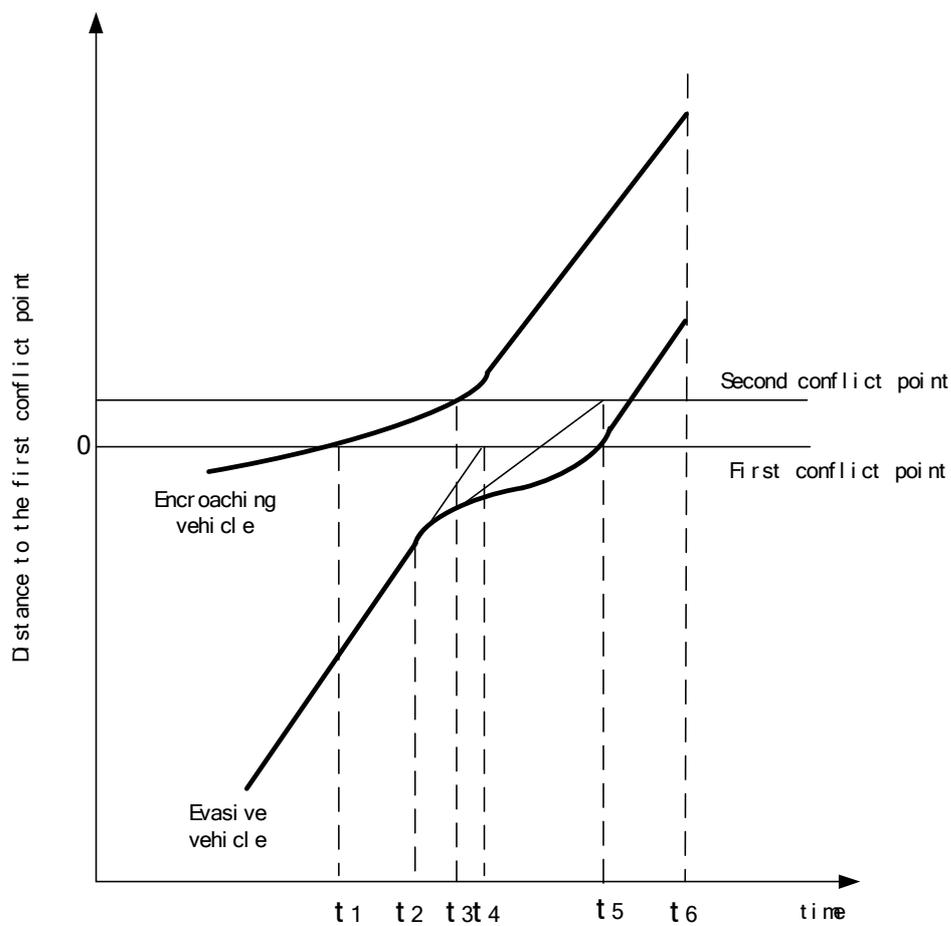
### 3.2.1 Description of Events

The lane-changing and merging conflicts are similar because encroaching vehicles in both cases make a lane-changing maneuver before the occurrence of a conflict except that the encroaching vehicle in a merging conflict changes from the acceleration lane to the rightmost lane. Since lane restrictions usually restrict trucks from using the left lane, the rightmost lane is a sensitive area, especially for traffic from entrance ramps. This is the main reason that these two types of conflicts are investigated separately. However, in the following conflict event description, only a lane-changing conflict event is introduced because the conflict event for merging conflict is almost the same.

A timeline of a conflict line event for a vehicle making a lane change in front of a vehicle progressing in the same direction on the target lane is described in Fig. 2. This timeline is adapted from the research report of FHWA-RD-03-050 (FHWA, 2003). The upper curve represents the time-space trajectory of the encroaching vehicle (which makes a lane change), while the lower curve represents the time-space trajectory of the evasive vehicle (which immediately follows the encroaching vehicle in the target lane). In the simulation, the whole timeline ends at a predefined maximum reference time. In this example, six time points from  $t_1$  to  $t_6$  are employed to describe the first two conflict points:

- At time  $t_1$ , the encroaching vehicle makes a lane-change maneuver into the same lane as the evasive vehicle;

- At time  $t_2$ , the evasive vehicle realizes that a collision might occur and begins braking to avoid the collision;
- At time  $t_3$ , the next time step of the simulation is reached and state variables for each vehicle are updated;
- At time  $t_4$ , the evasive vehicle would reach the first conflict point if it did not decelerate at  $t_2$ ;
- At time  $t_5$ , the evasive vehicle would reach the second conflict point if it did not decelerate at  $t_3$ ;
- At time  $t_6$ , the predefined maximum reference conflict time is reached.



### **Figure 2 Conflict Line of Lane-Changing Conflict**

(Adapted from FHWA-RD-03-050, FHWA final report, 2003)

Here, the difference between time  $t_4$  and  $t_1$  is the TTC for the first conflict point, e.g. for the initial states (position, speed, acceleration/deceleration) immediately after the start of encroachment, the TTC is the projected time the evasive vehicle needs to reach the position where the encroaching vehicle initiated a lane-changing maneuver if the evasive vehicle's speed stays unchanged. Similarly, the difference between time  $t_5$  and  $t_3$  is the TTC for the second conflict point, e.g. for the updated states (position, speed, acceleration /deceleration) at the beginning of the next simulation time step after the start of encroachment, the TTC is the projected time the evasive vehicle needs to reach the position of the encroaching vehicle at the start of the second time step if its speed stays unchanged. During the course of a lane-changing or merging conflict line event, there could be more than two conflict points depending on the value of time step parameter in the simulation and the predefined maximum reference conflict time. The whole course of conflict event may end before the predefined maximum reference time is reached earlier if the evasive vehicle makes a lane change to avoid collision or the encroaching vehicle makes a lane change to get off the lane or main road.

#### **3.2.2 Computational Algorithm**

The computational algorithm in simulation to calculate and collect the safety surrogate measurements of lane-changing or merging conflict is given in detail as follows:

*Triggering* A vehicle on the main road accepts a gap and makes a lane change to condition: the adjacent lane in the same direction or a vehicle on the ramp accepts a gap and makes a lane change to the rightmost lane of the main road from the acceleration lane.

## 1 Record

- 1.1 The current time step  $t_1$ ;
- 1.2 The vehicle ID of the current (encroaching) vehicle;
- 1.3 The position of the encroaching vehicle on the target lane;
- 1.4 The speed of the encroaching vehicle;
- 1.5 The acceleration/deceleration of the encroaching vehicle;
- 1.6 The vehicle ID of the vehicle immediately behind the encroaching vehicle on the target lane (evasive vehicle);
- 1.7 The position of the evasive vehicle on the target lane;
- 1.8 The speed of the evasive vehicle;
- 1.9 The acceleration/deceleration of the evasive vehicle;

## 2 Compute

- 2.1 The first conflict point (position of encroaching vehicle at time  $t_1$ );

2.2 *The project time  $t_4$  for the evasive vehicle to reach the first conflict point;*

2.3 *The first TTC as  $t_4 - t_1$ ;*

2.4 *Save  $TTC = TTC(t_1)$ .*

3 *Repeat step 1 until:*

*The predefined maximum reference time (5 sec) is reached, or*

*The encroaching vehicle makes a lane change to another lane, or*

*The evasive vehicle makes a lane change to another lane.*

3.1 *Record the updated conflict point of the encroaching vehicle at the start of the current time step  $t_c$ ;*

3.2 *Compute the projected time  $t_p$  for the evasive vehicle to reach the updated conflict point;*

3.3 *Compute the current TTC as  $t_p - t_c$ ;*

3.4 *Check:*

*If  $TTC(t) < TTC(t-1)$ , save  $TTC = TTC(t)$ .*

4 *Determine whether a conflict occurs when:*

*The predefined maximum reference time is reached, or*

*The encroaching vehicle makes a lane change to another lane, or*

*The evasive vehicle makes a lane change to another lane.*

*4.1 If  $TTC < TTC\_upper\_limit$  (predefined parameter= 0.5 sec), count  
and save this event;*

*Otherwise, do not save event data.*

*End of the process.*

### **3.3 Rear-End Conflict**

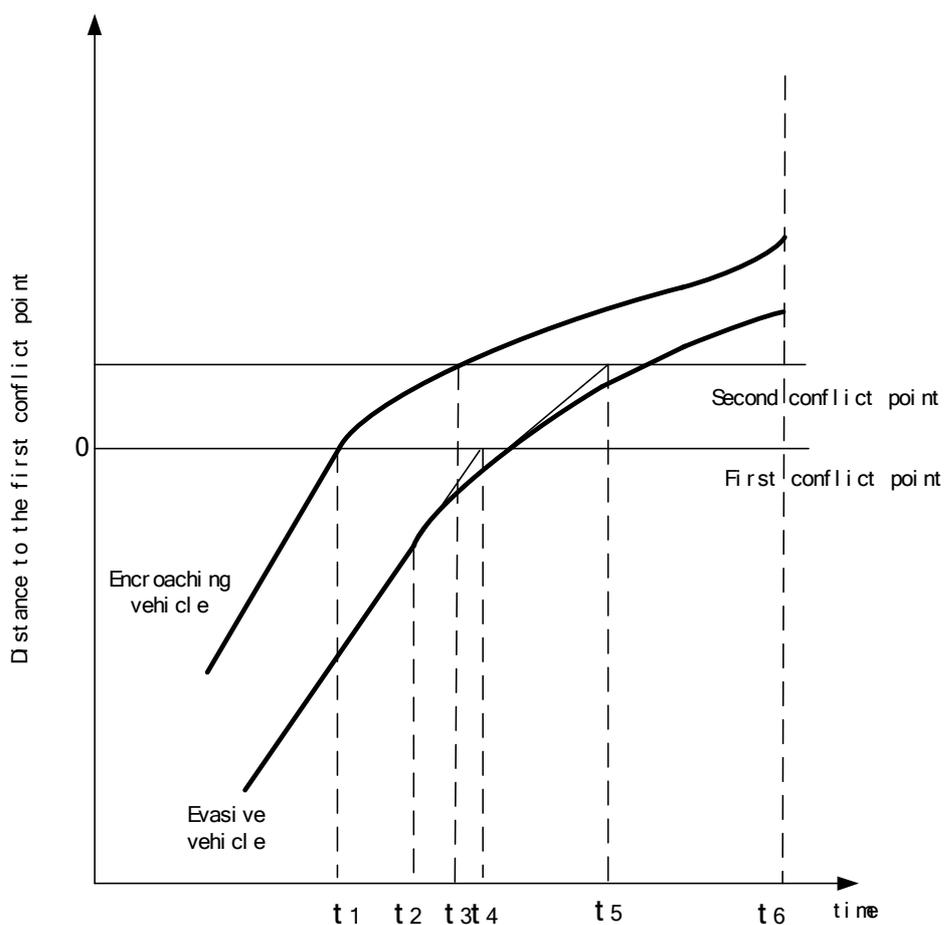
#### **3.3.1 Description of Events**

The rear-end conflict occurs when a vehicle suddenly slows down while the vehicle immediately following it is too close to react at a safe braking speed. This conflict would force the following vehicle to brake hard to avoid a rear-end collision. Such a slowdown could be caused by emergencies in front of the leading (encroaching) vehicle or the maneuver of the leading vehicle to change lanes or get off the main road. As previously discussed, the lane-changing and merging conflicts are also rear-end events while the original lane of the encroaching vehicle is different from that of the evasive vehicle. In this part, the rear-end conflicts exclude the events in 3.1.

A timeline of a rear-end conflict line event for a vehicle making a lane change in front of a vehicle progressing in the same direction on the target lane is described in Fig. 3. This timeline is adapted from the research report of FHWA-RD-03-050 (FHWA, 2003).

The upper curve represents the time-space trajectory of the encroaching vehicle (which makes a lane change) while the lower curve represents the time-space trajectory of the evasive vehicle (which immediately follows the encroaching vehicle in the target lane). In the simulation, the whole timeline ends at a predefined maximum reference time. In this example, six time points from  $t_1$  to  $t_6$  are employed to describe the first two conflict points:

- At time  $t_1$ , the leading (encroaching) vehicle suddenly slows down;
- At time  $t_2$ , the evasive vehicle realizes that a collision might occur and begins braking to avoid the collision;
- At time  $t_3$ , the next time step of the simulation is reached and state variables for each vehicle are updated;
- At time  $t_4$ , the evasive vehicle would reach the first conflict point if it did not decelerate at  $t_2$ ;
- At time  $t_5$ , the evasive vehicle would reach the second conflict point if it did not decelerate at  $t_3$ .
- At time  $t_6$ , the predefined maximum reference conflict time is reached.



**Figure 3 Conflict Line of Rear-End Conflict**

(Adapted from FHWA-RD-03-050, FHWA final report, 2003)

Here, the difference between times  $t_4$  and  $t_1$  is the TTC for the first conflict point, e.g. for the initial states (position, speed, acceleration/deceleration) immediately after the start of encroachment, the TTC is the projected time the evasive vehicle needs to reach the position where the encroaching vehicle initiated a lane-changing maneuver if the evasive vehicle's speed stays unchanged. Similarly, the difference between times  $t_5$  and  $t_3$  is the TTC for the second conflict point, e.g. for the updated states (position, speed, acceleration /deceleration) at the beginning of the next simulation time step after the start

of encroachment, the TTC is the projected time the evasive vehicle needs to reach the position of the encroaching vehicle at the start of the second time step if its speed stays unchanged. During the course of a rear-end conflict line event, there could be two more conflict points depending on the value of the time step parameter in the simulation and the predefined maximum reference conflict time. The whole course of conflict event may end before the predefined maximum reference time is reached earlier if the evasive vehicle makes a lane change to avoid the collision or the encroaching vehicle makes a lane change to get off the lane or main road.

### **3.3.2 Computational Algorithm**

The computational algorithm in the simulation to calculate and collect the safety surrogate measurements of rear-end conflict is given in detail as follows:

*Triggering* A vehicle on the main road suddenly slows down to avoid emergency condition: or to change lane or to get off the main road. This forces the vehicle immediately following it to brake hard to avoid a rear-end collision.

#### *1 Record*

*1.1 The current time step  $t_1$ ;*

*1.2 The vehicle ID of the current (encroaching) vehicle;*

*1.3 The position of the encroaching vehicle on the current lane;*

*1.4 The speed of the encroaching vehicle;*

- 1.5 *The acceleration/deceleration of the encroaching vehicle;*
- 1.6 *The vehicle ID of the vehicle immediately behind the encroaching vehicle on the target lane (evasive vehicle);*
- 1.7 *The position of the evasive vehicle on the current lane;*
- 1.8 *The speed of the evasive vehicle;*
- 1.9 *The acceleration/deceleration of the evasive vehicle;*

## 2 *Compute*

- 2.1 *The first conflict point (position of encroaching vehicle at time  $t_1$ );*
- 2.2 *The project time  $t_3$  for the evasive vehicle to reach the first conflict point;*
- 2.3 *The first TTC as  $t_4 - t_1$ ;*
- 2.4 *Save  $TTC = TTC(t_1)$ .*

## 3 *Repeat step 1 until:*

*The predefined maximum reference time is reached, or*

*The encroaching vehicle makes a lane change to another lane, or*

*The evasive vehicle makes a lane change to another lane, or*

*The evasive vehicle totally stops.*

3.1 *Record the updated conflict point of the encroaching vehicle at the start of the current time step  $t_c$ ;*

3.2 *Compute the projected time  $t_p$  for the evasive vehicle to reach the updated conflict point;*

3.3 *Compute the current TTC as  $t_p - t_c$ ;*

3.4 *Check:*

*If  $TTC(t) < TTC(t-1)$ , save  $TTC = TTC(t)$ .*

4 *Determine whether a conflict occurs when:*

*The predefined maximum reference time (5 sec) is reached, or*

*The encroaching vehicle makes a lane change to another lane, or*

*The evasive vehicle makes a lane change to another lane, or*

*The evasive vehicle totally stops.*

4.1 *If  $TTC < TTC\_upper\_limit$  (predefined parameter = 0.5 second), count and save this event;*

*Otherwise, do not save event data.*

*End of the process.*

### 3.4 Summary

Different algorithms had been developed to compute and record conflicts between vehicles triggered by lane-changing, merging, or sudden start of braking maneuvers. These algorithms were adapted from the Federal Highway Administration report of FHWA-RD-03-050 (2003) exclusively designed for application in simulation through PARAMICS. In Chapter 4 – *Simulation Design*, these algorithms will be used as the baseline of the development of API programs embedded in the PARAMICS modeler to collect conflict data.

## **CHAPTER 4 SIMULATION DESIGN**

### **4.1 Introduction**

Due to a limited availability of site data, this evaluation project is conducted using simulation data collected from PARAMICS, a microscopic simulation tool, which was calibrated using site data collected on freeways within the state of Virginia before the evaluation. Different simulation scenarios were produced by applying different truck lane restriction strategies and varying the geographic/traffic independent variables such as grade, interchange density, posted speed limit, volume, and truck percentage. These simulation scenarios cover different truck lane restriction strategies under a variety of geographic and traffic conditions. In addition, several Application Programming Interface (API) programs were developed and embedded in the simulation. The main functions of these API programs were to collect and compute the safety surrogate measurement and other operational measurements of effectiveness (MOE).

### **4.2 Calibration of PARAMICS**

#### **4.2.1 Calibration Approach**

The PARAMICS calibration in this study follows a Latin Hypercube Design (LHD) procedure proposed by a previous study conducted by Park and Qi (2004). This procedure employs the LHD algorithm to reduce the extremely large number of parameter combinations into a reasonable level while still adequately covering the entire parameter surface. The results in Park and Qi's study indicated that the LHD approach

would achieve a similar performance in obtaining optimal parameter sets as the popular Genetic Algorithm (GA) method even though it does not go through all the possible combinations of parameters. Since the focus of this study is not the calibration of the simulation tool, the LHD approach was chosen instead of the GA approach to quickly obtain the optimal parameters.

#### **4.2.2 Calibration Parameters**

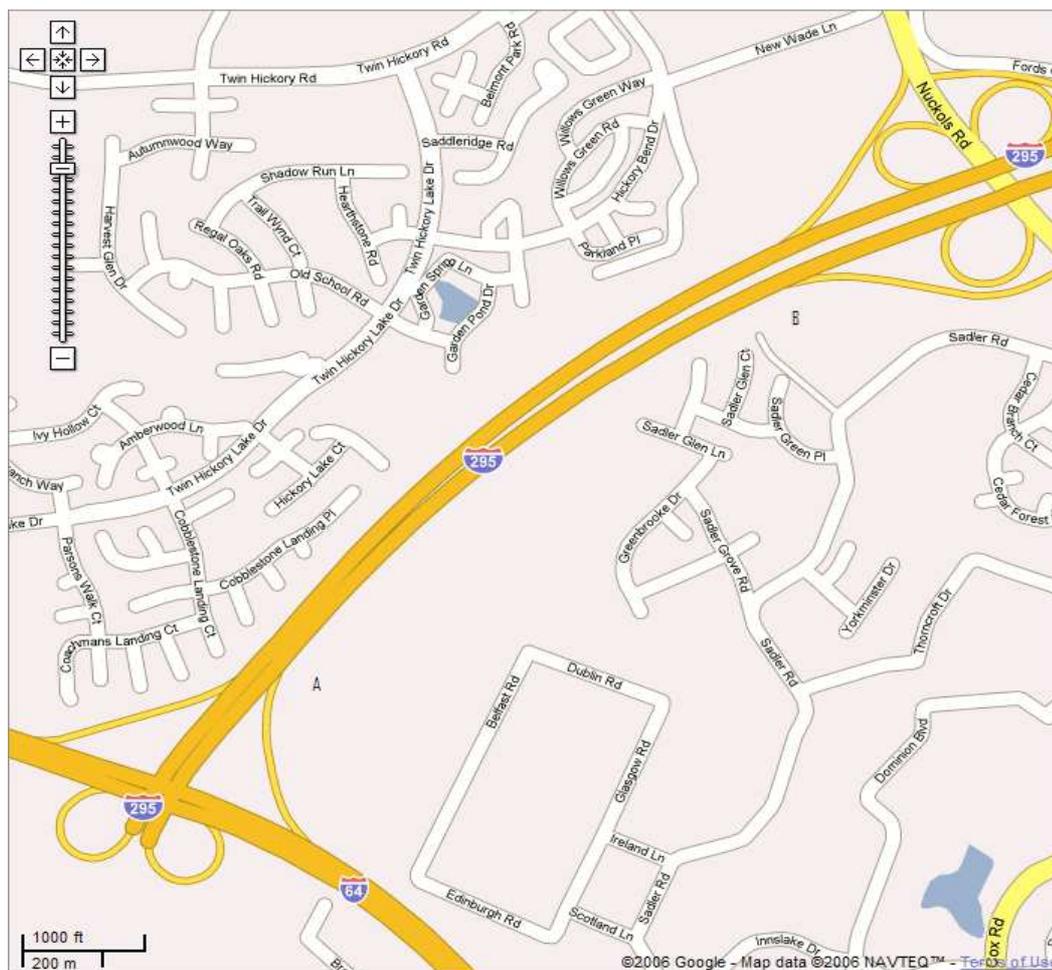
Parameters related to the car-following and lane-changing models in the simulation were selected to be calibrated because the target of this study is to evaluate the effectiveness of lane restriction strategies. These parameters were the mean time headway, mean reaction time, speed memory, curve speed factor, headway factor, and link speed. The descriptions and default values of these parameters are provided in Table 1. The acceptable range of calibrated parameters should be decided by the discretion of the research and experience from the previous study. In this study, the parameter ranges were set the same as those for the freeway section study in the work of Park and Qi (2003).

**Table 1. Calibration Parameters**

Parameter	Description	Default value	Acceptable range
Mean headway (sec)	The mean target headway, in seconds	1.0	0.6 – 2.2
Mean reaction time (sec)	The mean reaction time of each driver, in seconds	1.0	0.3 – 1.9
Speed memory	Each vehicle has the facility to remember its own speed for a number of time steps. This memory facility is used to implement driver reaction time by basing the change in speed of the following vehicle on the speed of the leading vehicle at a time in the recent past. Changing the size of the speed memory allows the modeling of larger reaction times or smaller time steps	3	1 – 9
Curve speed factor	Set a factor to control the amount to which vehicles slow down due to curvature on road	1.0	1.0 – 5.0
Headway factor	The target headway for all vehicles can be modulated using this factor. For example, in a tunnel, the user might know that drivers commonly extend their headway by 50%	1.0	0.6 – 1.4
Link speed (mph)	The desired speed when the volume is low	65	60 - 80

#### 4.2.3 Site Data Collection

The field data for calibration were collected on the I-295 freeway section at Henrico where I-295 intersects I-64 (Fig. 4 from A to B) including the volumes for every 5 mins on the ramps and main road, truck percentage, and the travel time for 2 hours from 8:00 to 9:00 am and from 12:00 am to 1:00 pm. Data set I from 8:00 to 9:00 am was used for calibration and data set II from 12:00 am to 1:00 pm was used for validation. Volume data were the input to the simulation and travel times were used as the measure of effectiveness (MOE) for the calibration.

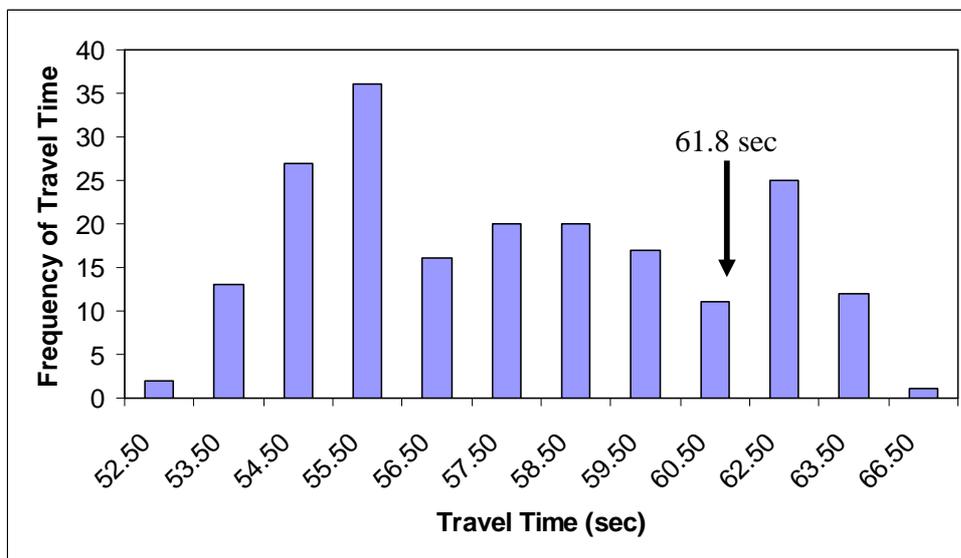


**Figure 4 Calibration Network**

#### 4.2.4 Calibration Result

Using the default value and range of the calibration parameters in Table.1 as inputs, the LHD algorithm generated 200 combinations of these parameters which are uncorrelated. Five random seeded runs were conducted in PARAMICS for each of the 200 cases resulting in a total of 1000 simulation runs. The average travel time of vehicles was recorded for each 1000 runs. The results from the five multiple runs were then averaged to represent each 200 parameter set. Fig. 5 gives the distribution of the average

travel time of vehicles from the 200 simulation scenarios. The calibration result shows that the average travel time (61.8 sec) from field data set I falls within the range of travel times produced by simulation using different scenarios of these parameters.



**Figure 5 Frequency of Travel Time**

Twenty combinations (10%) of parameters that produced similar travel times (around 61.8 sec) with the site data were chosen for the validation. The validation process is a similar simulation process with calibration except that the input volume data were those from data set II and the parameter sets were 20 combinations which produced a similar average travel time with the field average travel time (61.8 sec) in data set I. After the validation simulation runs, the average travel times produced from the 20 parameter sets were compared with the real travel time from field data set II. One parameter set (as shown in Table 2) was chosen as optimal that has reasonable parameter values as well as producing an average travel time (62.5 sec) that falls within a small range around the real travel time (59.0 sec) of data set II.

**Table 2 Optimal Parameter Set**

<b>Parameters</b>	<b>Calibrated Value</b>
Mean headway (sec)	1.35
Mean reaction time (sec)	0.53
Speed memory	4
Curve speed factor	1.5
Headway factor	1.0
Link speed (mph)	72

### 4.3 Simulation Scenarios

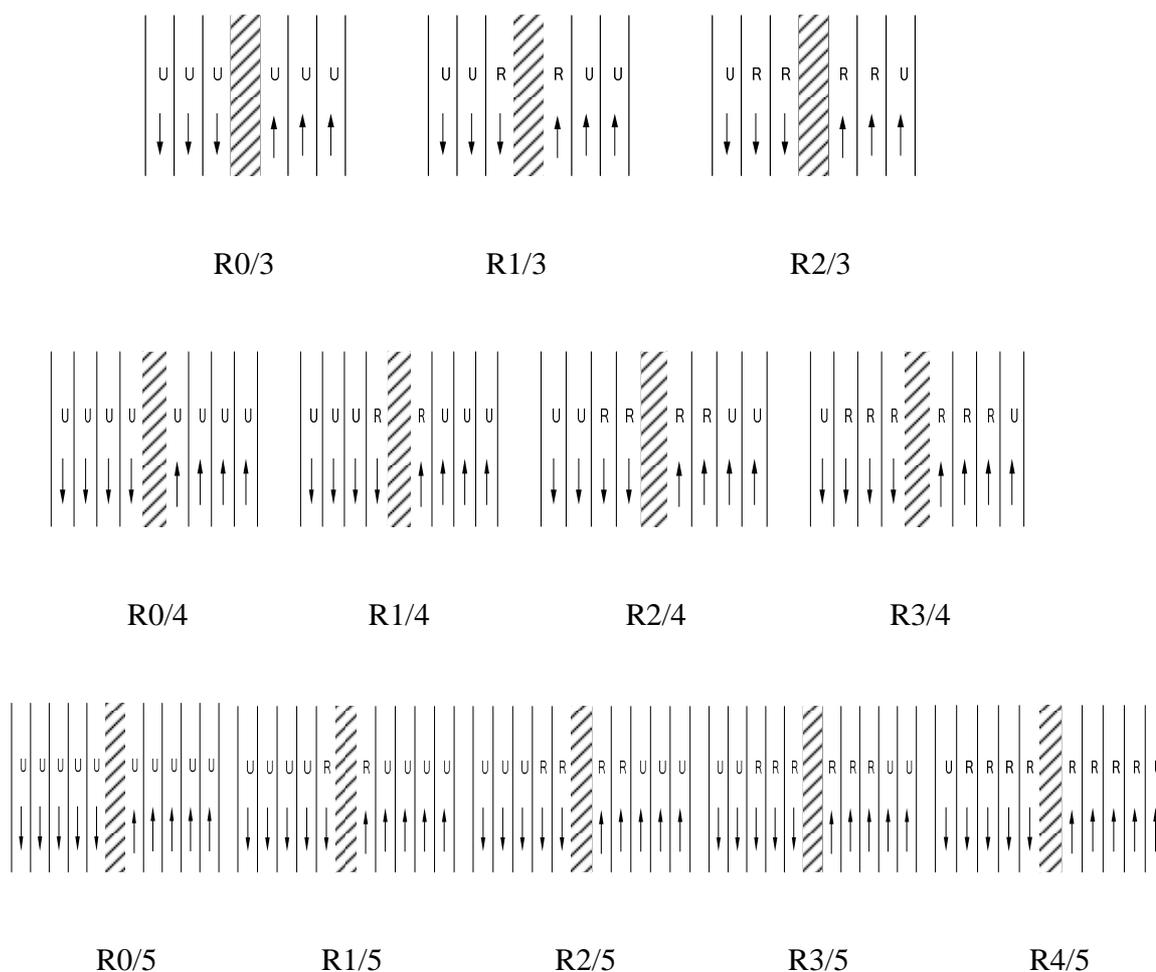
In order to identify the impact of lane restriction strategies under different situations, simulation scenarios were developed by varying lane restriction strategies, traffic conditions (volume, truck percentage) and geometric characteristics (gradient, speed limit, interchange density). The input values for each key independent variable are shown in Table 3.

**Table 3 Input Values of Independent Variables**

<b>Independent Variable</b>	<b>Input Values</b>
Truck lane restriction strategies	R0/3, R1/3, R2/3 R0/4, R1/4, R2/4, R3/4 R0/5, R1/5, R2/5, R3/5, R4/5
Grade	0%, 1%, 3%, 5%
Interchange density (no/mile)	0.25, 0.50, 0.75, 1.00
Free flow speed (mph)	55, 65, 75
Main line volume (vphpl)	100, 500, 1000, 1500, 2000
Ramp volume (vphpl)	100, 500, 1000, 1500, 2000
Truck percentage	5%, 15%, 25%, 40%, 50%

The simulation network coded in this study is a straight 5-mile freeway section with a varied number of lanes, grade, and interchange density. The lane restriction strategies applied depended on the number of lanes of the freeway in each direction. For a 3-lane freeway (each direction), three strategies were implemented: no restriction, restricting trucks from using the leftmost lane, and restricting trucks from using the two leftmost lanes. Similarly, there are four strategies for a 4-lane freeway (each direction) and five strategies for a 5-lane freeway. Fig. 6 shows different lane restriction alternatives

considered in this study. Here, “R” represents a truck-restricted lane, e.g. trucks are restricted from using such lanes, while “U” represents a non-truck-restricted lane, e.g. trucks are allowed to use such lanes.

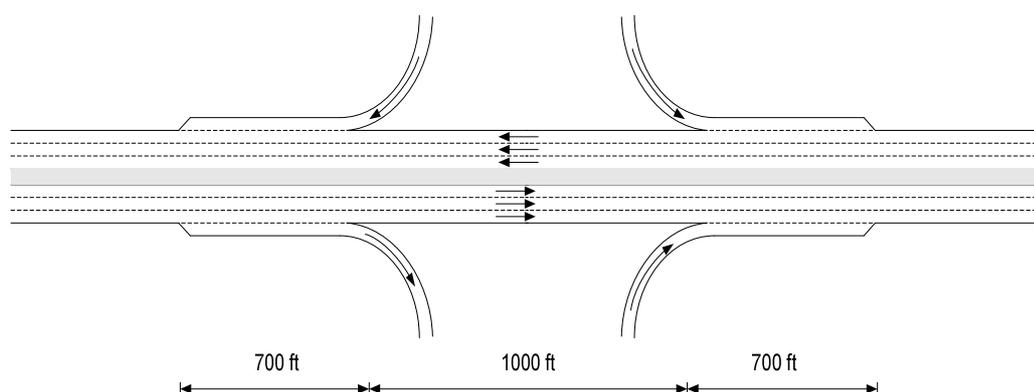


Note: R n/N means restricting trucks from using the n leftmost lanes on N-lane (in each direction) freeway.

**Figure 6 Truck Lane Restriction Strategies**

The grade of the freeway section was chosen as an independent variable in the evaluation in that the grade has a negative influence upon the acceleration ability of

trucks with a much greater mass than passenger cars. The grade of the freeway changes from 0%, 1%, 3% to 5%. The number of ramps (both entrance and exit) will impact the lane-changing maneuvers when a vehicle on the main road intends to get off the road or when a vehicle on the ramp intends to merge into the mainstream. Hence, the density of interchange (entrance ramps and exit ramps) was also incorporated into the independent variables. The interchange density varies from 0.25 to 1.00 with an incremental step of 0.25. Fig. 7 gives a typical schematic layout of an interchange in the simulation network. At each interchange, an off-ramp is followed by an on-ramp with at a distance of 800 ft. The lengths of acceleration and deceleration lanes are fixed at 1000 ft. The number of lanes on the ramp is fixed to be 1, and the width of each lane is 12 ft.



**Figure 7 Layout of Interchange in Simulation Network**

The posted speed limits were 55, 65, and 75 mph to cover a range around 65 mph which is a typical posted speed limit on interstate highways in Virginia. The traffic volumes on both main road and ramp were 100, 500, 1000, 1500 to 2000 vphpl to incorporate different LOS traffic conditions in the evaluation. For the traffic volume, it is assumed that there are only two types of vehicles in the traffic mix: passenger cars and trucks. The configurations of the two types of vehicles are given in Table 4. The truck

percentage starts from 0% and incrementally increases to 50% which is nearly the maximum recorded on I-81, which carries the highest percentage of trucks in Virginia.

**Table 4 Configurations of Cars and Trucks in Simulation**

Type	Length ft (m)	Height ft (m)	Width ft (m)	Weight (Tonne)	Top Speed mph (km/h)	Acceleration ft/s.s (m/s/s)	Deceleration ft/s/s (m/s/s)
Car	13.1 (4.0)	4.9 (1.5)	5.2 (1.6)	0.8	98.2 (158)	8.2 (2.5)	14.8 (4.5)
Truck	36.1 (11.0)	13.1 (4.0)	8.2 (2.5)	38.0	80.0 (128)	4.6 (1.4)	12.1 (3.7)

Hence the total number of simulation scenarios is computed as:

Scenarios (3-lane freeway) = 3 (strategies) \*3 (PSL) \* 5(volume levels) \*5(truck percentage) \* 4 (gradients) \*4(intersection density) = 3,600;

Scenarios (4 lanes) = 4 (strategies) \*3 (FFS) \* 5(volume levels) \*5(truck percentage) \* 4 (gradients) \*4(intersection density) = 4,800;

Scenarios (5 lanes) = 5 (strategies) \*3 (FFS) \* 5(volume levels) \*5(truck percentage) \* 4 (gradients) \*4(intersection density) = 6,000;

Hence this produces a total of  $3,600 + 4,800 + 6,000 = 14,400$  different scenarios. In addition, each scenario was applied for 5 different random seeds which would eliminate the impact of the random factors in the simulation. Therefore, the analysis of simulation results was based on 72,000 data points.

#### **4.4 API Programs**

The effectiveness of different truck restrictions in this study was evaluated through MOEs of conflict rate, lane changes, speed distribution by lane, speed

distribution by vehicle types, volume distribution by lanes, and average speed. To acquire these measurements, different API programs were developed to control or collect data from the simulation runs:

- **Control\_Program.exe:** a C++ program controlling the batch execution of PARAMICS simulation. 14,400 different simulation scenarios were run through this program in a batch simulation mode. The main function is to select an appropriate simulation network, apply certain restriction strategies, set the posted speed limit on each link, release a certain number of vehicles (trucks and cars) to the simulation network and control the rhythm of the traffic volume, and adjust the grade of the freeway section.
- **Lane\_changing\_conflict.dll:** a PARAMICS API program embedded in each simulation scenario to trace the actions of encroaching and evasive vehicles after a lane change maneuver and compute safety surrogate measurements to identify a lane-changing conflict in accordance with the algorithm given in Chapter 3. At the same time, this program collected the number of lane changes.
- **merging\_conflict.dll:** a PARAMICS API program embedded in each simulation scenario to trace the actions of encroaching and evasive vehicles after a vehicle merges into the main line from an on-ramp and compute safety surrogate measurements to identify a merging conflict in accordance with the algorithm given in Chapter 3.
- **Rear\_end\_conflict.dll:** a PARAMICS API program embedded in each simulation scenario to trace the actions of encroaching and evasive vehicles after a vehicle

suddenly brakes severely and compute safety surrogate measurements to identify a rear-end conflict in accordance with the algorithm given in Chapter 3.

- **Speed.dll**: a PARAMICS API program embedded in each simulation scenario to collect the average speed of vehicles on both restricted and unrestricted lane(s). At each simulation time step, speeds of all vehicles in the network are scanned and averaged so the average travel time produced from this program is the average travel time of vehicles existing at each time step and any places within the network during the whole simulation process.
- **Density.dll**: a PARAMICS API program embedded in each simulation scenario to collect average densities on both restricted and unrestricted lane(s). At each simulation time step, the number of all vehicles in the network were recorded and averaged along the length of the investigated lane(s) so the average density produced from this program is the average density of vehicles existing at each time step during the whole simulation process.

## 4.5 Summary

This chapter describes the process of PARAMICS calibration, simulation designs, and API (Application Program Interface) programs developed to collect both safety and operational MOEs. The calibration is a general calibration of parameters in the car-following and lane-changing models in the simulation program using data collected on Interstate Highways in Virginia although most of the cases considered in the study do not exist in practice. Another consideration for the calibration is that the author believed the calibrated parameters, which are basic driver behaviors, would not change significantly

when a new lane restriction is applied. The simulation scenarios were produced by varying different factors that would impact safety and operational performance and these factors were the number of lanes, grade, posted speed limit, volume, truck percentage, and density of interchanges. The simulations were run in a batch mode under the control of a program. During the simulations, data upon the lane-changing conflicts, merging conflicts, rear-end conflict, average speed in restricted and unrestricted lanes, and density in restricted and unrestricted lanes were collected by the API programs embedded in the simulation.

## CHAPTER 5 SAFETY PERFORMANCE ANALYSIS

### 5.1 Introduction

The effectiveness of truck lane restriction strategies (TLRS) can be evaluated through safety performance as well as operational performance because traffic safety and traffic mobility are both of importance in evaluating the effective performance of a freeway facility. This chapter focuses on the safety performance analysis of TLRS using the MOEs of lane-changing, merging, and rear-end conflicts collected from simulation experiments as designed in Chapter 4. The safety performance analysis for each type of conflict was conducted in three stages:

- Stage I: Evaluating the impacts of independent variables on conflicts and identifying the key independent variables that may influence the application of truck lane restriction strategies. The objective of this stage was to omit the independent variables that have no significant impact on the effects of the implementation of TLRS.
- Stage II: ANOVA analysis for the significance of impacts of different TLRS on conflicts within each category defined by the key independent variables. The objective of this stage was to identify situations under which the truck lane restrictions could be considered because they have significant impacts on the conflict rates. However, such significant impacts could be positive or negative.
- Stage III: Analysis of the impact of key independent variables on the application of different truck lane restrictions. The objective of this stage was to identify the impacts of truck lane restriction under each specific situation

(defined by the key independent variables) on the basis of the ANOVA analysis in stage II. This analysis result is used later in Chapter 7 for the development of guidelines for the application of different lane restriction strategies.

## **5.2 Lane-Changing Conflict Analysis**

### **5.2.1 Impacts of Independent Variables on Lane-Changing Conflicts**

#### **5.2.1.1 Aggregation of Results for Impact Analysis of Independent Variables**

The simulation results for lane-changing conflicts produced from the 14,400 simulation scenarios were aggregated for different values of independent variables - grades, posted speed limits, interchange density, demand volumes, and truck percentages vs. different truck lane restriction strategies. Table 5 gives an example of the number of lane-changing conflicts for 4-lane in each direction freeway for different lane restriction strategies and traffic and geometric characteristics. In each cell of this table, the first value gives the average number of total lane-changing conflicts (including truck-related and car-car conflicts), and the second value gives that for truck-related conflicts only. Here, the truck-related conflict is defined as one that at least one of two vehicles involved is a truck while the car-car conflict is the case where both vehicles are passenger cars. Similar concepts are also applied to the merging and rear-end conflicts. For example, the value in the first cell for a grade of 0% and restriction R0/4 is the average of lane-changing conflict rates from  $3$  (posted speed limits)  $\times 5$  (demand volumes)  $\times 5$  (truck percentages)  $\times 4$  (intersection densities) = 300 different simulation scenarios.

**Table 5 Number of Lane-Changing Conflicts for a 4-Lane in Each Direction Freeway for Different Lane Strategies and Traffic and Geometric Characteristics**

Number of Lane-Changing Conflicts (all/truck related)*					
Independent Variable		Lane Restriction Strategy			
		R0/4	R1/4	R2/4	R3/4
Grade	0%	127/35	125/37	124/34	121/27
	1%	122/32	120/33	117/29	117/25
	3%	112/29	111/30	111/27	113/23
	5%	96/23	97/25	100/22	104/20
PSL (mph)	55	102/24	101/27	100/24	104/21
	65	116/30	115/32	114/28	116/24
	75	124/34	123/35	124/32	122/25
Volume (vphpl)	2000	135/30	149/37	168/38	177/31
	1500	185/46	170/45	175/42	183/37
	1000	176/50	172/51	152/40	143/32
	500	70/19	71/21	65/18	62/15
	100	5/2	5/2	4/1	4/1
Truck Percentage	5%	170/13	168/14	171/16	178/18
	15%	141/27	136/30	132/28	148/31
	25%	114/35	111/36	111/33	117/31
	40%	81/36	82/38	83/32	73/21
	50%	65/36	69/38	67/30	54/16
Intersection density (Inter./mile)	0.25	50/13	49/13	51/12	50/10
	0.50	102/26	100/28	100/26	94/21
	0.75	133/35	133/37	131/35	134/29
	1.00	171/43	172/46	170/38	178/34

\* all: number of conflicts for all vehicles

truck-related: number of conflicts in which at least one truck is involved

R n/N means restricting truck from using the n leftmost lanes on N-lane (in each direction) freeway

In order to analyze the impact of different independent variables on the lane-changing conflicts, conflict data were further aggregated over different truck lane restriction strategies as shown in Table 6 which gives the average frequency of total lane-changing conflicts (sum of truck-related and car-car conflicts), average frequency of truck-related conflicts, lane-changing conflicts, average frequency of car-car lane-changing conflicts, and the average frequency of lane changes.

**Table 6 Number of Lane-changing Conflicts for Different Traffic and Geometric Characteristics**

(a) 3-Lane Highway (in each direction)

Three Lanes in each direction					
Independent Variables		Lane-changing Conflicts			Lane changes
		Total	Truck-related	Car-Car	
Grade (%)	0	92	21	71	1699
	1	86	18	68	1678
	3	82	17	65	1696
	5	72	13	59	1725
Posted speed limit (mph)	55	73	15	58	1760
	65	84	18	66	1692
	78	91	20	71	1646
Interchange Density (no./mile)	0.25	30	7	23	1078
	0.5	72	15	57	1486
	0.75	101	21	80	1938
	1	128	25	103	2295
Volume (vphpl)	100	2	1	1	282
	500	42	11	31	1243
	1000	113	27	86	1949
	1500	143	28	115	2404
	2000	114	20	94	2619
Truck Percentage (%)	5	129	8	121	1814
	15	103	17	86	1760
	25	83	22	61	1719
	40	56	21	35	1636
	50	44	19	25	1567

**Table 6 Number of Lane-changing Conflicts for Different Traffic and Geometric Characteristics**

(b) 4-Lane Highway (in each direction)

Four Lanes in each direction					
Independent Variables		Lane-changing Conflicts			lane changes
		Total	Truck-related	Car-Car	
Grade (%)	0	124	32	92	2163
	1	118	29	89	2136
	3	111	27	84	2159
	5	98	22	76	2217
Posted speed limit (mph)	55	101	23	78	2229
	65	115	28	87	2165
	78	123	31	92	2114
Interchange Density (no./mile)	0.25	49	28	21	1422
	0.5	98	25	73	1875
	0.75	132	34	98	2462
	1	172	40	132	2916
Volume (vphpl)	100	5	2	3	358
	500	66	18	48	1583
	1000	160	43	117	2449
	1500	178	42	136	3036
	2000	157	34	123	3421
Truck Percentage (%)	5	171	15	156	2271
	15	139	29	110	2224
	25	113	34	79	2193
	40	80	31	49	2124
	50	63	29	34	2034

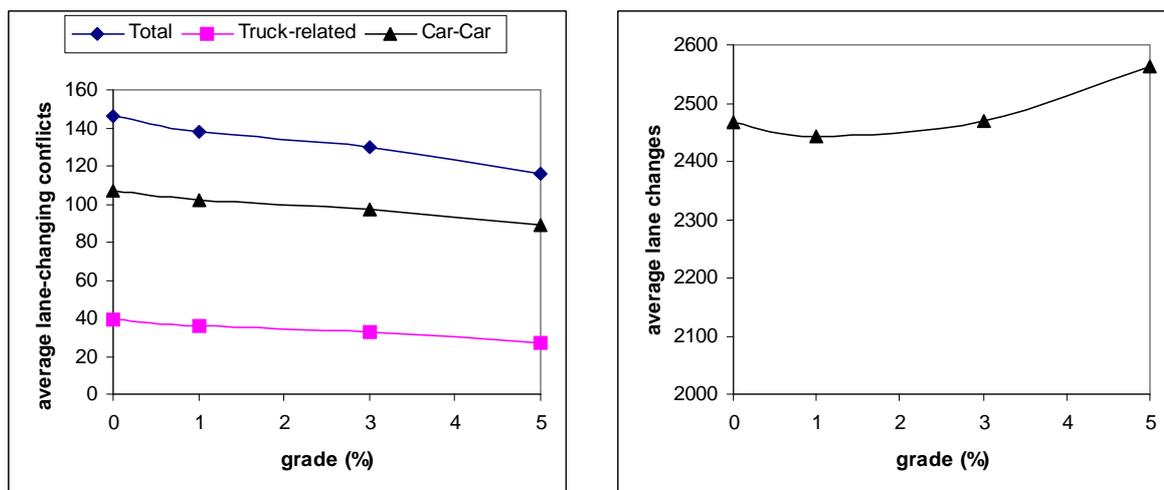
**Table 6 Number of Lane-changing Conflicts for Different Traffic and Geometric Characteristics**

(c) 5-Lane Highway (in each direction)

Five Lanes in each direction					
Independent Variables		Lane-changing Conflicts			lane changes
		Total	Truck-related	Car-Car	
Grade (%)	0	146	39	107	2466
	1	138	36	102	2444
	3	130	33	97	2469
	5	116	27	89	2564
Posted speed limit (mph)	55	118	29	89	2540
	65	134	34	100	2478
	78	145	38	107	2439
Interchange Density (no./mile)	0.25	58	14	44	1699
	0.5	116	31	85	2181
	0.75	153	40	113	2803
	1	201	49	152	3248
Volume (vphpl)	100	6	2	4	403
	500	76	23	53	1849
	1000	180	51	129	2823
	1500	200	48	152	3456
	2000	203	45	158	3934
Truck Percentage (%)	5	198	17	181	2475
	15	159	34	125	2514
	25	132	41	91	2528
	40	96	40	56	2492
	50	76	37	39	2419

### 5.2.1.2 Impact of Grade on Lane-Changing Conflicts

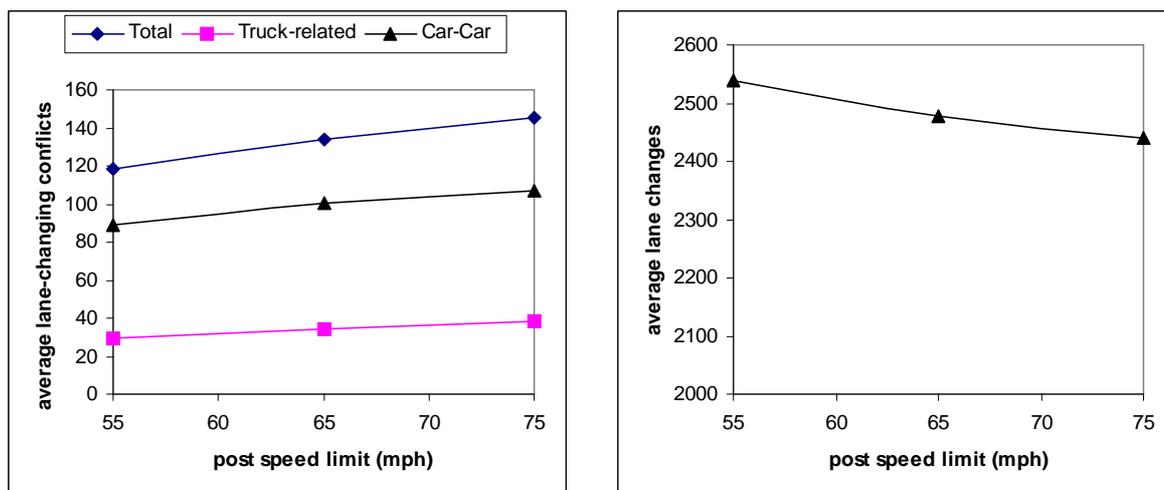
The frequencies of lane-changing conflicts for both truck-related and car-car types generally decrease with the increase of the grade of the freeway segment. However, the lane changes increase with the increase of the grade except that the lane changes at 0% grade is a little higher than that at 1% grade. Fig. 8 gives an example of this trend for 5-lane (in each direction) freeway. The reason for this may be due to 1) the slope of the freeway section decreases the speed of vehicles, and 2) the weak acceleration ability of trucks increases the gap between trucks and other vehicles.



**Figure 8 Number of Lane-Changing Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Grades**

### 5.2.1.3 Impact of Posted Speed Limit on Lane-Changing Conflicts

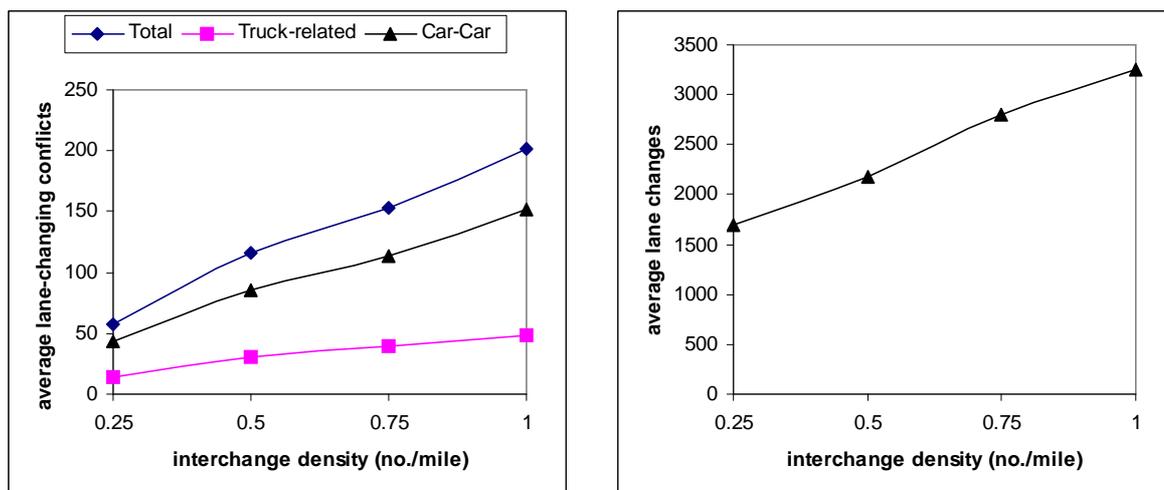
The frequencies of lane-changing conflicts for both truck-related and car-car types generally increase with the increase of the posted speed limits at an evident level. However, frequency of lane changes decrease with the increase of the posted speed limits. This phenomenon coincides with the one in the grade analysis and proves that high speed is a potential cause for lane-changing conflicts. When a vehicle accepts the same space gap, the higher the speed of the evasive vehicle on the target lane is, the higher the opportunity is for occurrence of a conflict. Fig. 9 gives an example of this trend for a 5-lane (in each direction) freeway.



**Figure 9 Number of Lane-Changing Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Posted Speed Limits**

#### 5.2.1.4 Impact of Interchange Density on Lane-Changing Conflicts

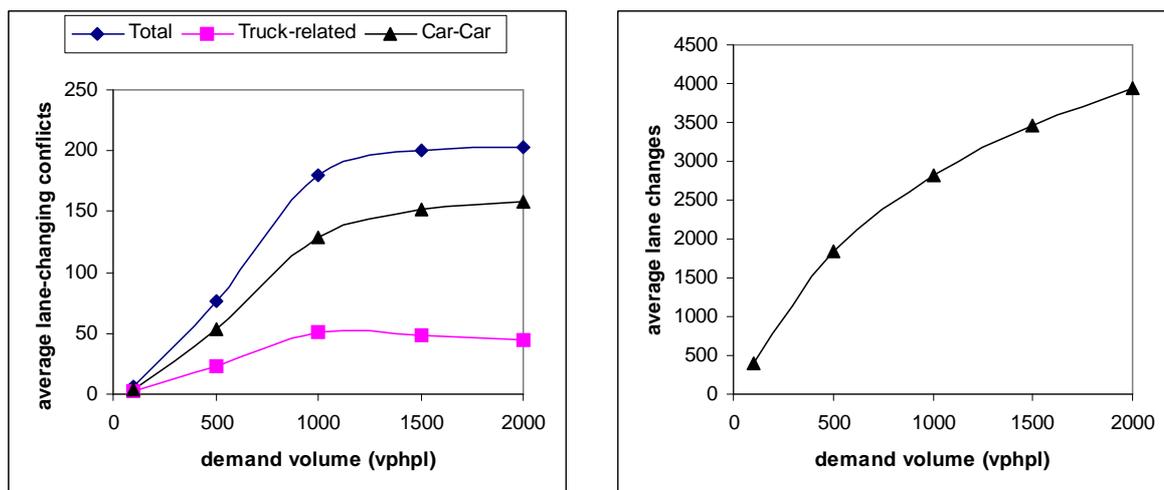
The frequencies of lane-changing conflicts for both truck-related conflicts and car-car conflicts increase with the increase in interchange density. The increase in interchange density directly leads to an increase in the number of lane changes made by the vehicles intending to get off the main road from exit ramps at the interchanges or the vehicles intending to move to the left lanes after merging into the main road from the entrance ramps. The increase of car-car lane-changing conflicts is more evident than that of truck-related lane-changing conflicts. This may be because the TLRS force the trucks to stay on the right lane(s) of the freeway section. Hence, the trucks on the main road need less lane changes to get off and the trucks on the entrance ramp usually stay on the right lane as soon as they get on the main road. On the contrary, cars would go through more lane-changing maneuvers to get from the left lane(s) or get from the ramp to the left lanes. Fig. 10 gives an example of this trend for a 5-lane (each direction) freeway section.



**Figure 10 Number of Lane-Changing Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Intersection Densities**

#### 5.2.1.5 Impact of Demand Volume on Lane-Changing Conflicts

The frequencies of lane-changing conflicts for both truck-related and car-car conflicts increase dramatically with the increase in demand volume when it is less than 1000 vphpl. However, after this point the increase reduces and the frequency of truck-related conflicts goes down even further with an increase in demand volume. However, the number of lane changes continues to increase with an increase in demand volume. Fig. 11 gives an example of this trend for a 5-lane (in each direction) freeway segment. This could be explained that a high volume, especially one on unrestricted lanes where trucks travel, results in lower speeds on the network even though lane changes continue to increase. This indicates that the number of lane changes - the conventional safety measurement - may not be able to explain the potential of crashes in some cases, for example, when the demand volume is greater than 1000 vphpl.

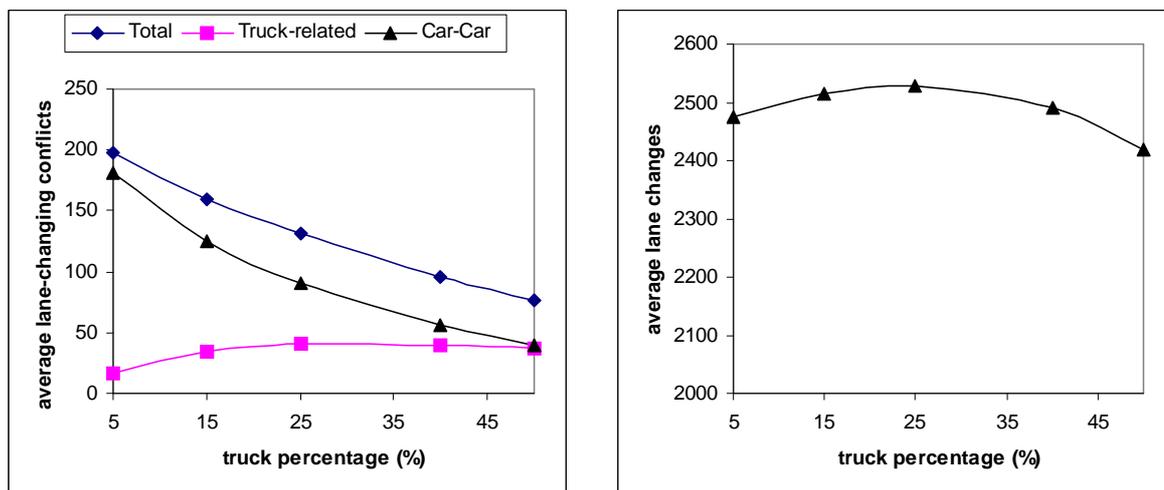


**Figure 11 Number of Lane-Changing Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Demand Volumes**

#### 5.2.1.6 Impact of Truck Percentage on Lane-Changing Conflicts

The frequency of a car-car lane-changing conflict generally decreases with the increase in truck percentage in the traffic mix. However, the truck-related lane-changing conflicts increase at the same time. The combined effect of these two phenomena resulted in an overall decrease in lane-changing conflicts with the increase of truck percentage. The reason for this may be that the increase of the truck percentage increased the truck-related conflicts but also increase the number of vehicles that have a limited lane-changing ability on the unrestricted lane(s). Hence, the total number of lane-changing conflicts decreases with the increase of the truck percentage as the total demand volume keeps stable. At the same time, the increase of truck percentage means a decrease in car percentage. The frequency of lane change increases with the increase of truck percentages when truck percentage is lower than 25%. This may be because the increase in the number of trucks on the unrestricted lanes forces more cars to stay on the left lanes which require more cars to undertake a lane-changing maneuver in order to get on or off

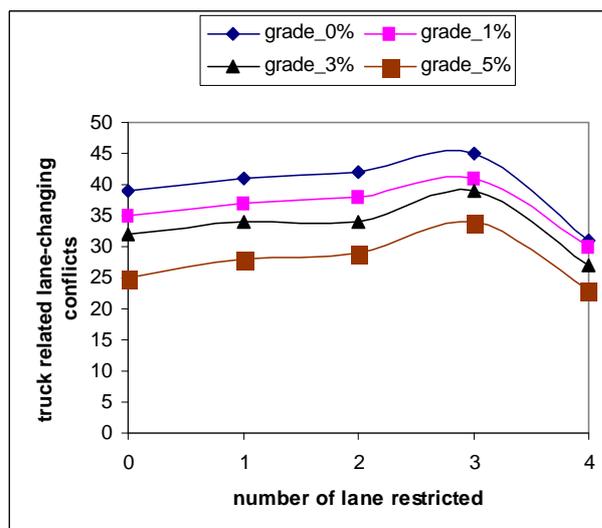
the main road. However, at a higher truck percentage, more trucks are confined on the unrestricted lanes resulting in a decrease in the number of lane changes. Fig. 12 gives an example of this trend for a 5-lane (each direction) freeway section.



**Figure 12 Number of Lane-Changing Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Truck Percentages**

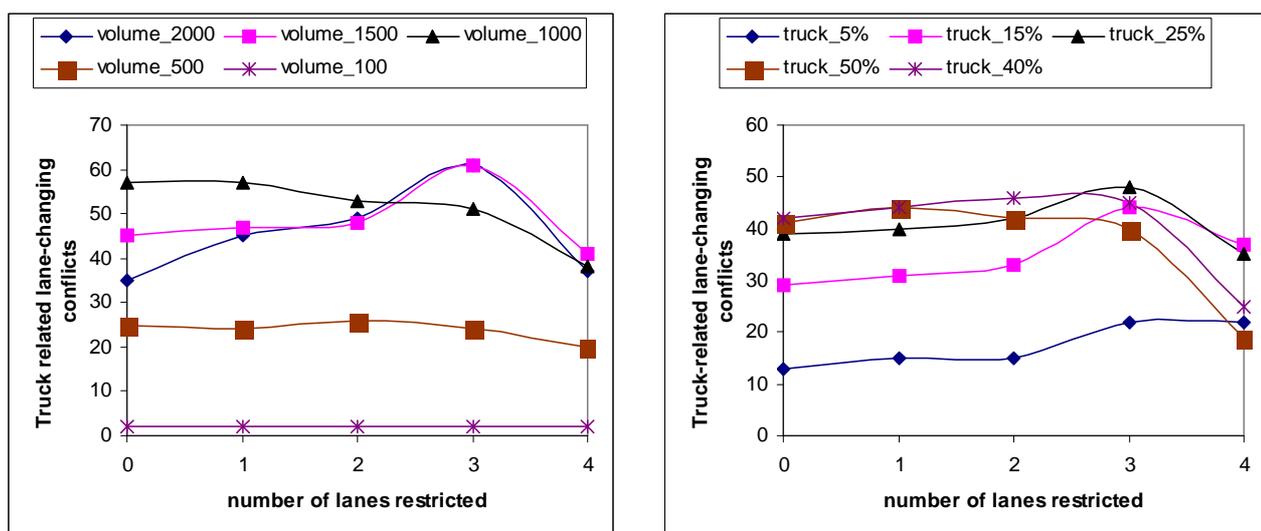
### 5.2.1.7 Identification of Key Independent Variables

From the analysis of aggregated data (see example in Table 5), it was found that the independent variables influence the effect of TLRS differently even though they all have some impact on the frequency of lane-changing conflicts and lane changes as shown above. At different values of grade of the freeway section, posted speed limit, and interchange density, the lane-changing conflicts follow a similar trend with the increase of the number of restricted lanes. Fig. 13 shows an example of the variation of truck-related lane-changing conflicts with the increase in the number of lanes restricted on a 5-lane (each direction) freeway segments with different grades. This means these variables do not impact the selection of a suitable TLRS if a lane-changing conflict is used as the MOE for evaluation.



**Figure 13 Truck-Related Lane-Changing Conflicts on 5-Lane (each direction) Freeways with Different Grades**

However, the impact of TLRS on lane-changing conflicts varies with different demand volumes or truck percentages. Fig. 14 gives examples of how the frequencies of truck-related lane-changing conflicts vary among different truck lane restriction strategies at different volumes and truck percentages.



**Figure 14 Truck-Related Lane-Changing Conflicts on 5-lane (each direction) Freeways with Different Demand Volumes and Truck Percentages**

This means that the variables that lead to a decision upon the application of TLRS are demand volume and truck percentage if the frequency of lane-changing conflict is used as a decision-making criterion. Hence, thereafter, only demand volume and truck percentage will be considered in the evaluation.

#### **5.2.1.8 Summary of Impacts of Independent Variables on Lane-changing Conflicts**

The impacts of independent variables on lane-changing conflicts were summarized and presented in Table 7.

**Table 7 Summary of Impacts of Independent Variables on Lane-Changing Conflicts**

Independent Variables	Impact Analysis	Reference Figure	Key Factors	Reference Figure
Grade	The frequencies of lane-changing conflicts for both truck-related and car-car types generally decrease with the increase of the grade of the freeway segment. However, the lane changes increase with the increase of the grade except that the lane changes at 0% grade are a little higher than that at 1% grade.	Figure 8	No	Figure 13
Posted speed limit	The frequencies of lane-changing conflicts for both truck-related and car-car types generally increase with the increase of the posted speed limits at an evident level. However, frequency of lane changes decrease with the increase of the posted speed limits.	Figure 9	No	Figure 13
Interchange Density	The frequencies of lane-changing conflicts for both truck-related and car-car conflicts increase with the increase in interchange density.	Figure 10	No	Figure 13
Volume	The frequencies of lane-changing conflicts for both truck-related and car-car conflicts increase dramatically with the increase in demand volume when it is less than 1000 vphpl. However, after this point, increase reduces, and the frequency of truck-related conflicts goes down even further with an increase of demand volume. However, the number of lane changes continues to increase with increase in demand volume.	Figure 11	Yes	Figure 14
Truck Percentage	The frequency of car-car lane-changing conflict generally decreases with the increase in truck percentage in the traffic mix. However, truck-related lane-changing conflicts increase at the same time. The combined effect of these two phenomena resulted in an overall decrease in lane-changing conflicts with an increase of truck percentage.	Figure 12	Yes	Figure 14

## 5.2.2 Effectiveness of Truck Lane Restrictions on Lane-Changing Conflicts

### 5.2.2.1 ANOVA Analysis

In order to test whether truck lane restrictions have a significant impact on lane-changing conflicts, ANOVA analyses were conducted with different restriction strategies as independent variables and the frequency of lane-changing conflicts (total, truck-related, car-car) as the dependent variable. These analyses were conducted for each category defined by three variables – number of lanes, demand volume, and truck percentage using raw data from the 14,400 simulation scenarios. The results are shown in Table 7. In each cell of this table, the first value is the p value of ANOVA analysis with a dependent variable of total lane-changing conflicts, the second value is the p value of ANOVA analysis with a dependent variable of truck-related lane-changing conflicts, and the third value is the p value of ANOVA analysis with a dependent variable of car-car conflicts. Here, the p value represents the probability of a random variable from F distribution greater than computed statistics  $F^*$ , which is calculated as:

$$F^* = \frac{\text{var}(\textit{between group})}{\text{var}(\textit{within group})} = \frac{SM \textit{ between}}{SM \textit{ error}} = \frac{SS \textit{ between} / (k - 1)}{SS \textit{ error} / (N - k)} \quad (1)$$

where:

SS between is the *sum of squares between* computed as:

$$SS \textit{ between} = \sum_{i=1}^k \sum_{j=1}^m (x_{ij} - \bar{x}_i)^2 \quad (2)$$

where:

$\bar{x}_i$  is the mean frequency of lane-changing conflicts within group  $i$  corresponding to a value level of the independent variable;  $x_{ij}$  is the  $j$ th frequency value in group  $i$ ;  $k$  is the number of group, and  $m$  is the number of values in each group.

SS within is the *sum of squares error* computed as:

$$SS \text{ error} = \sum_{i=1}^n (x_i - \bar{x})^2 \quad (3)$$

where:

$\bar{x}$  is the grand mean of frequency of lane-changing conflicts of all the samples;

$x_i$  is the  $i$ th frequency value.

Here, the statistics  $F^*$  follows a F-distribution with degree of freedom of  $(k-1)$  and  $(n-k)$ .

Hence the p value is obtained as:

$$p = \text{probability}\{F(k-1, n-k) > F^*\} \quad (4)$$

The smaller the p value, the greater probability that the means of  $x$  at different values of  $i$  are different. Assuming that  $i$  represents the truck percentage and  $x$  is the number of lane-changing conflict, a p value of less than  $(1 - 90\%) = 10\%$  means that, at a confidence level of 90%, there exist significant differences between the means of lane-changing conflicts at different levels of truck percentage.

Here, the categories where truck lane restrictions have a significant impact (at a significance level of 0.10) upon truck-related lane-changing conflicts were preliminarily identified as highlighted in Table 8.

**Table 8 p Values from ANOVA Analyses of Lane-Changing Conflicts**

(a) 3-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.906/.957/.889	.981/.737/.864	.143/.285/.064	.533/.039/.738	.193/.008/.729
500	.905/.851/.916	.950/.393/.999	.469/.662/.346	.102/.055/.295	.002/.000/.029
1000	.997/.873/.996	.891/.921/.817	.581/.508/.635	.001/.000/.032	.000/.000/.012
1500	.934/.146/.902	.256/.133/.296	.299/.015/.525	.925/.000/.138	.157/.000/.002
2000	.492/.012/.586	.003/.001/.005	.001/.089/.000	.019/.000/.001	.007/.000/.000

Table 8 p Values from ANOVA Analyses of Lane-changing Conflicts

(b) 4-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.626/.127/.723	.625/.128/.631	.602/.221/.735	.817/.213/.958	.051/.052/.230
500	.895/.889/.886	.943/.179/.967	.541/.187/.651	.062/.008/.301	.001/.000/.041
1000	.979/.181/.996	.751/.742/.594	.112/.099/.108	.000/.000/.001	.000/.000/.007
1500	.714/.000/.710	.037/.257/.012	.220/.025/.079	.257/.000/.000	.065/.000/.000
2000	.347/.000/.603	.000/.000/.000	.000/.055/.000	.000/.000/.000	.000/.000/.000

(c) 5-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.958/.306/.865	.984/.875/.990	.819/.921/.739	.603/.223/.744	.207/.149/.553
500	.977/.141/.975	.992/.104/.928	.669/.780/.509	.042/.045/.035	.000/.000/.014
1000	.999/.000/.990	.856/.083/.303	.000/.000/.000	.000/.000/.000	.000/.000/.000
1500	.621/.000/.307	.035/.000/.069	.000/.000/.000	.000/.000/.000	.003/.000/.000
2000	.183/.000/.429	.000/.000/.000	.000/.000/.000	.000/.000/.000	.000/.000/.000

Note: In each cell of this table, the first value is the p value of ANOVA analysis with a dependent variable of total lane-changing conflicts, the second value is the p value of ANOVA analysis with a dependent variable of truck-related lane-changing conflicts, and the third value is the p value of ANOVA analysis with a dependent variable of car-car lane-changing conflicts.

### 5.2.2.2 Impacts of Key Variables in Application of Truck Lane Restrictions

The ANOVA analysis above only indicates the significance of impact of TLRS upon lane-changing conflicts with no information on whether the impact is negative or positive. In order to investigate the details of the influence of TLRS, lane-changing

conflicts were analyzed for different TLRS within categories defined by demand volume and truck percentage (the same as those in the ANOVA analysis). These results were presented by column graphs in Fig. A01 to Fig. A15 in Appendix A.

Generally, the frequency of the lane-changing conflict decreases with the increase in the number of lanes restricted when the demand volume is lower than 1500 vphpl. When the demand volume is greater than 1500 vphpl, the frequency of the lane-changing conflict increases with the increase in the number of lanes restricted. However, it usually has a sharp drop when maximum lanes are restricted. The details of the influence of lanes restricted are discussed as follows for different demand volume levels:

Demand volume is less than 100 vphpl (Fig. A01, A06, A11):

- The frequencies of lane-changing conflicts are very low when the truck percentage is lower than 40%. After that, both the total and truck-related lane-changing conflicts decrease with the increase of number of lanes restricted.

Demand volume is greater than 100 and less than 500 vphpl (Fig. A02, A07, A12):

- Both the total and the truck-related lane-changing conflicts decrease with the increase in the number of lanes restricted. However, the benefit of truck lane restriction becomes apparent only when the truck percentage is over 25%.

Demand volume is greater than 500 and less than 1000 vphpl (Fig. A03, A08, A13):

- The number of car-car lane-changing conflicts decreases with the increase of number of lanes restricted. The truck-related conflicts increase with the increase of the number of lanes restricted when truck percentage is below 15%. After that, truck-related conflicts decrease with the increase in the number of lanes restricted.

The combination effects led to a similar trend of total conflict with car-car conflicts.

Demand volume is greater than 1000 and less than 1500 vphpl (Fig. A04, A09, A14):

- Truck-related conflicts increase with the increase in the number of lanes restricted when truck percentage is below 15%. After that, truck-related conflicts decrease with the increase in the number of lanes restricted. When the truck percentage is below 40%, car-car conflicts decrease first and increase later with the increase in the number of lanes restricted; When truck percentage is above 40%, car-car conflicts increase with the increase of the number of lanes restricted but there is usually a drop when the maximum number of lanes are restricted. The combined effect results in a similar trend for total conflicts.

Demand volume is greater than 1500 and less than 2000 vphpl (Fig. A05, A10, A15):

- Truck-related conflicts increase with the increase in the number of lanes restricted when truck percentage is below 25%. After that, truck-related conflicts increase first and decrease later with the increase in the number of lanes restricted. Car-car conflicts increase with the increase of the number of lanes restricted but there is usually a drop when the maximum number of lanes are restricted. The combined effect results in a similar trend of total conflicts.

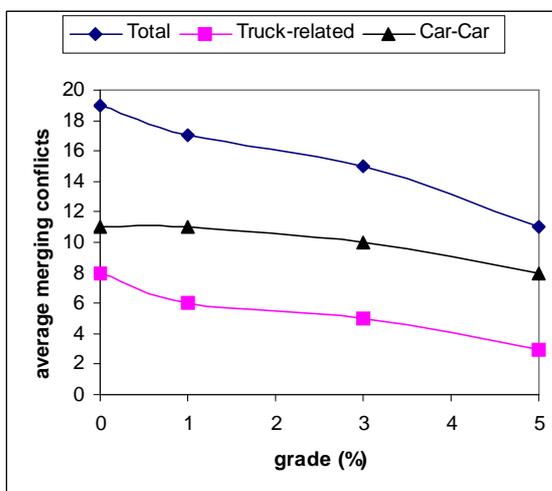
## **5.3 Merging Conflict Analysis**

### **5.3.1 Impacts of Independent Variables on Merging Conflicts**

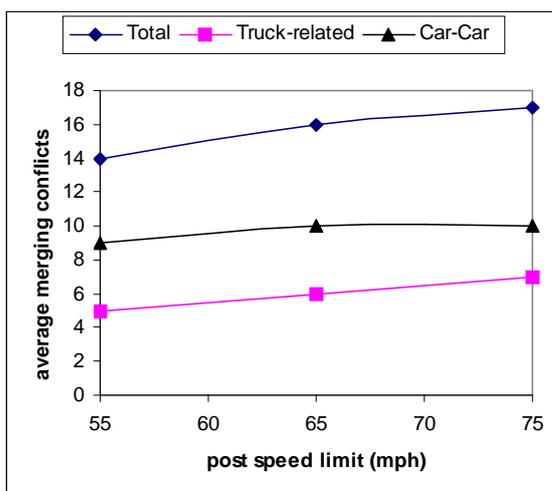
The same analyses for impacts of independent variables on merging conflicts were conducted as those on lane-changing conflicts and the results were summarized and presented in Table 9.

**Table 9 Summary of Impacts of Independent Variables on Merging Conflicts**

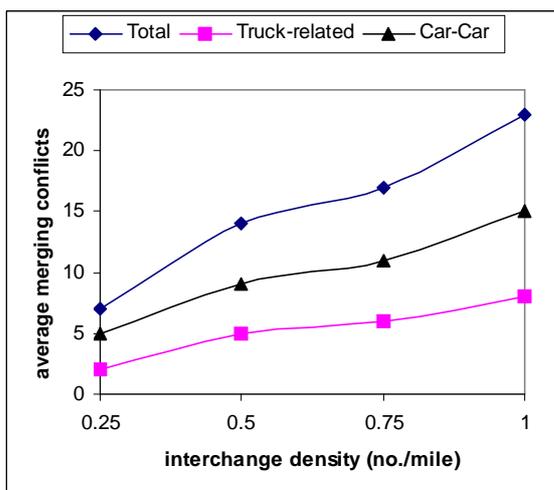
Independent Variables	Impact Analysis	Reference Figure	Key Factors	Reference Figure
Grade	The frequencies of merging conflicts for both truck-related and car-car types generally decrease with the increase in the grade of a freeway segment.	Figure 15	No	Figure 20
Posted speed limit	The frequencies of merging conflicts for both truck-related and car-car types generally increase with the increase of the posted speed limit.	Figure 16	No	Figure 20
Interchange Density	The frequencies of merging conflicts for both truck-related and car-car conflicts increase with the increase of interchange density.	Figure 17	No	Figure 20
Volume	<p>The frequencies of merging conflicts for both truck-related and car-car conflicts increase dramatically with the increase in demand volume when it is less than 1000 vphpl. However, after this point, merging conflicts tend to decrease with the increase of demand volume.</p> <p>This trend of reducing merging conflicts after about 1000 vphpl is steeper than that for lane-changing conflicts because the increase in density on the unrestricted lane(s) is much higher than the increase in volume as all the trucks are forced to the rightmost lane by lane restrictions. The high density dramatically decreases the speed of vehicles on the rightmost lane which makes vehicles easier to merge into the main road even though the gaps become smaller.</p>	Figure 18	Yes	Figure 21
Truck Percentage	The frequency of car-car merging conflicts decreases with the increase of truck percentage in the traffic mix. This may be caused by the decrease in car percentage. However, truck-related merging conflicts increase when truck percentage is lower than 40%. After that point, it decreases with the increase in truck percentage. It may be because the trucks occupy nearly half the traffic mix and more trucks are confined on unrestricted lanes which blocks some merging maneuvers when a truck barrier is formed.	Figure 19	Yes	Figure 21



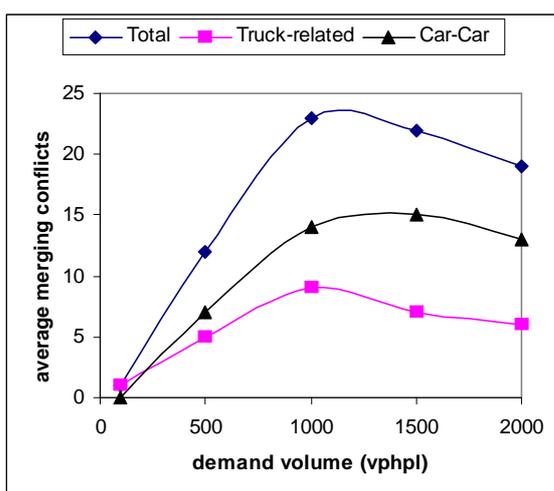
**Figure 15** Number of Merging Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Grades



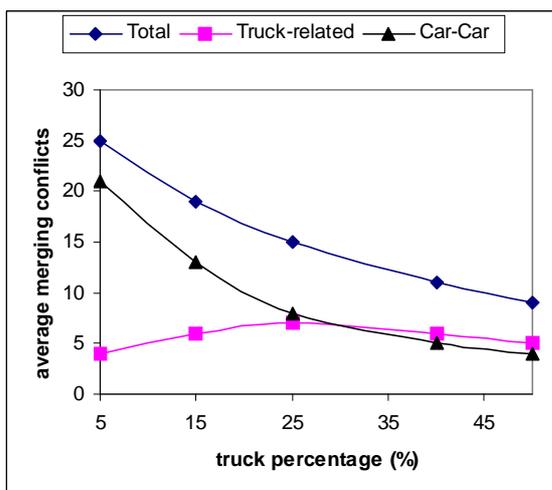
**Figure 16** Number of Merging Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Posted Speed Limits



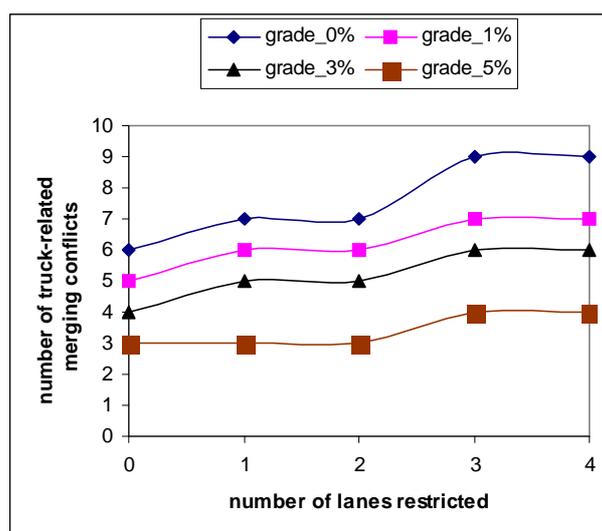
**Figure 17** Number of Merging Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Intersection Densities



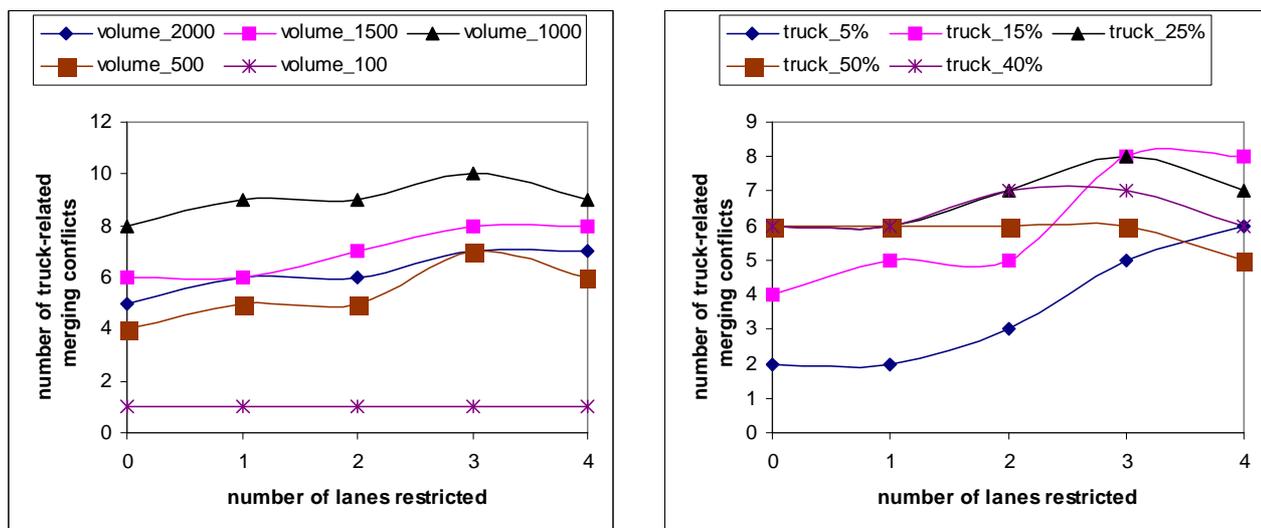
**Figure 18** Number of Merging Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Demand Volumes



**Figure 19** Number of Merging Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Truck Percentages



**Figure 20** Truck-Related Merging Conflicts on 5-Lane (each direction) Freeways with Different Grades



**Figure 21 Truck-Related Merging Conflicts at Different Demand Volume Levels and Different Truck Percentage**

### 5.3.2 Effectiveness of Truck Lane Restrictions on Merging Conflicts

#### 5.3.2.1 ANOVA Analysis

In order to test whether TLRS have significant impacts on merging conflicts, similar ANOVA analyses were conducted for merging conflicts as those for lane-changing conflicts in 5.2.2.1. The results of ANOVA are presented in Table 10:

**Table 10 p Values from ANOVA Analysis of Merging Conflicts**  
(a) 3-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.750/.216/.474	.475/.741/.544	.328/.511/.111	.924/.304/.134	.530/.231/.101
500	.846/.470/.921	.486/.078/.826	.583/.229/.783	.386/.203/.823	.111/.029/.425
1000	.544/.002/.789	.575/.001/.927	.917/.025/.199	.303/.625/.021	.002/.002/.001
1500	.778/.000/.911	.986/.006/.187	.012/.792/.000	.086/.480/.000	.010/.016/.018
2000	.875/.000/.715	.755/.000/.006	.494/.199/.002	.073/.516/.000	.739/.756/.297

**Table 10 p Values from ANOVA Analyses of Merging Conflicts**  
(b) 4-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.861/.638/.896	.671/.145/.271	.028/.127/.537	.331/.559/.066	.332/.785/.277
500	.992/.092/.908	.072/.198/.132	.212/.015/.709	.094/.270/.061	.031/.011/.001
1000	.565/.000/.899	.094/.000/.895	.875/.084/.683	.017/.002/.001	.000/.000/.000
1500	.082/.000/.692	.358/.000/.169	.740/.239/.002	.313/.129/.000	.837/.021/.000
2000	.439/.000/.998	.119/.000/.841	.909/.430/.063	.987/.249/.001	.380/.025/.001

(c) 5-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.648/.744/.206	.901/.636/.970	.221/.153/.897	.058/.532/.203	.217/.073/.391
500	.585/.000/.914	.081/.000/.541	.303/.000/.486	.006/.000/.900	.538/.133/.897
1000	.607/.000/.987	.727/.000/.021	.014/.464/.000	.000/.003/.000	.001/.043/.000
1500	.932/.000/.075	.020/.000/.000	.058/.024/.000	.083/.752/.000	.125/.519/.001
2000	.380/.000/.000	.045/.000/.000	.004/.372/.000	.074/.863/.000	.083/.319/.000

Note: In each cell of this table, the first value is the p value of ANOVA analysis with a dependent variable of total merging conflicts, the second value is the p value of ANOVA analysis with a dependent variable of truck-related merging conflicts, and the third value is the p value of ANOVA analysis with a dependent variable of car-car merging conflicts.

### 5.3.2.2 Impacts of Key Variables in Application of Truck Lane Restrictions

The ANOVA analysis above only indicates the significance of the impact of TLRS upon merging conflicts with no information on whether the impact is negative or positive. In order to investigate the details of the influence of TLRS, merging conflicts were analyzed for different TLRS within the categories defined by demand volume and truck percentage (the same as those in the ANOVA analysis). These results were presented by column graphs in Fig. B01 to Fig. B15 in Appendix B.

The details of the influence of lanes restricted are discussed as follows for different demand volumes:

The average densities are all below 11 vpmp1 (Fig. B01, B06, B11):

- The magnitudes of the frequencies of merging conflicts are very small and not significantly impacted by the lane restriction.

Demand volume is greater than 100 and less than 500 vphpl (Fig. B02, B07, B12):

- Generally, the number of merging conflicts increases with the increase in number of lanes restricted but there is usually a drop when truck percentage is high (> 40%) and the maximum number of lanes are restricted. The frequencies of the merging conflicts are all below 10 and the increase of truck-related conflict is only about 2 or 1 even though the ANOVA shows significant influence.

Demand volume is greater than 500 and less than 1000 vphpl (Fig. B03, B08, B13):

- Generally, the frequency of car-car merging conflicts decreases with the increase in the number of lanes. The frequency of truck-related merging conflict increases with the increase in the number of lanes restricted when the truck percentage is lower than 40%. When the truck percentage is higher than 40%, it decreases with the increase in the number of lanes restricted. This combined effect has led to a similar trend for the total merging conflicts. However, total merging conflicts start to decrease with the increase in the number of lanes restricted - around 25% truck percentage.

Demand volume is greater than 1000 and less than 1500 vphpl (Fig. B04, B09, B14):

- Generally, the frequency of the truck-related merging conflict increases with the increase in the number of lanes restricted when the truck percentage is lower than 40%. When the truck percentage is greater than 40%, this trend first becomes flat and then decreases with the increase of the number of lanes restricted. The car-car

merging conflicts decrease with the increase of the number of lanes. This combined effect resulted in a similar trend for the total merging conflict as that for car-car conflicts except that the total merging conflicts do not change much with the increase in the number of lanes restricted at a truck percentage of 5%.

Demand volume is greater than 1500 and less than 2000 vphpl (Fig. B05, B10, B15):

- Generally, the frequency of the truck-related merging conflict increases with the increase in the number of lanes restricted when the truck percentage is lower than 25%. When the truck percentage is greater than 25%, this trend first becomes flat and then decreases with the increase in the number of lanes restricted. The car-car merging conflicts decrease with the increase in the number of lanes. This combined effect resulted in a similar trend for the total merging conflicts as that for car-car conflicts.

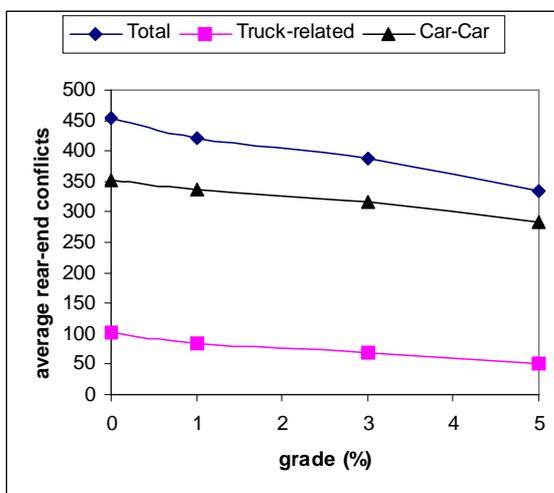
## **5.4 Rear-End Conflict Analysis**

### **5.4.1 Impacts of Independent Variables**

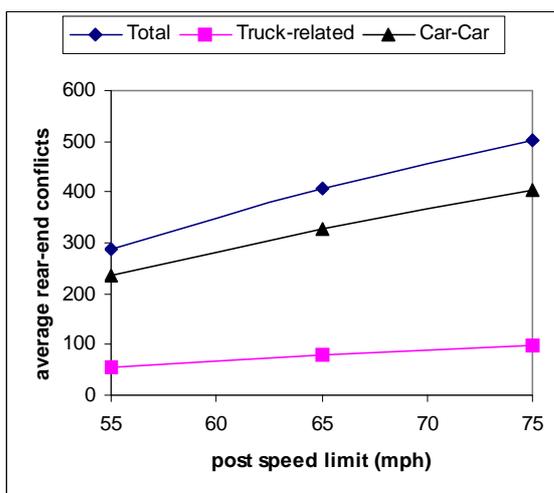
The same analyses for the impacts of independent variables on rear-end conflicts were conducted as those on lane-changing conflicts and the results were summarized and presented in Table 11.

**Table 11 Summary of Impacts of Independent Variables on Rear-end Conflicts**

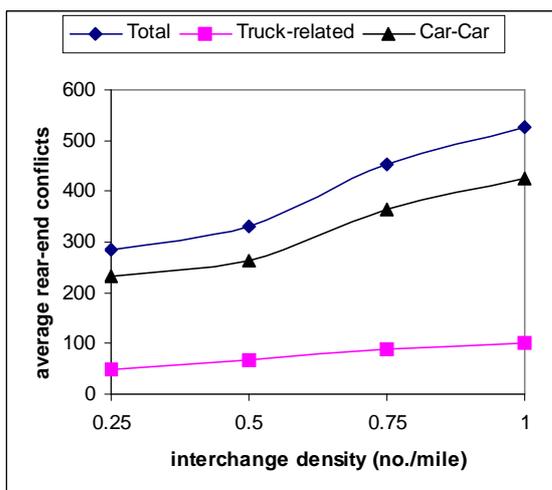
<b>Independent Variables</b>	<b>Impact Analysis</b>	<b>Reference Figure</b>	<b>Key Factors</b>	<b>Reference Figure</b>
Grade	The frequencies of truck-related and car-car rear-end conflicts decrease with the increase in the grade of freeway section.	Figure 22	No	Figure 27
Posted speed limit	The frequencies of truck-related and car-car rear-end conflicts increase with the increase of the posted speed limits.	Figure 23	No	Figure 27
Interchange Density	The frequencies of truck-related and car-car merging conflicts increase with the increase in interchange density. This may be because the increase in interchange density results in the increase in the number of lane-changing and merging maneuvers which disturb the traffic stream and produce more rear-end conflicts.	Figure 24	No	Figure 27
Volume	The frequencies of truck-related and car-car rear-end conflicts increase dramatically with the increase in the demand volume when it is less than 1500 vphpl. However, after this point, rear-end conflicts tend to decrease with the increase of demand volume. This may be because the increase in volume certainly increases the chance of rear-end interaction between vehicles. However, these interactions become less dangerous when the density is extremely high and the vehicles just follow each other at low speed.	Figure 25	Yes	Figure 28
Truck Percentage	The frequency of car-car rear-end conflict decreases with the increase in the truck percentage in the traffic mix. This may be caused by the decrease in the number of cars. However, truck related rear-end conflicts increase with the increase in truck percentage, but this increase curve is very flat. This may be due to the increase in the number of trucks on unrestricted lanes which certainly increase the chances of truck-related rear-end interactions but these chances are also diminished by slow speeds with the increase of truck density on unrestricted lane(s).	Figure 26	Yes	Figure 28



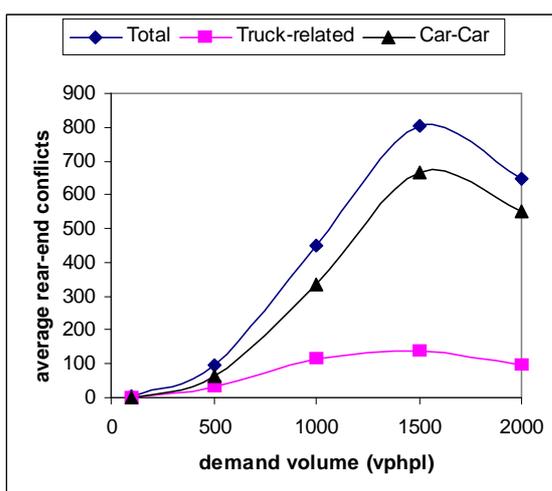
**Figure 22 Number of Rear-End Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Grades**



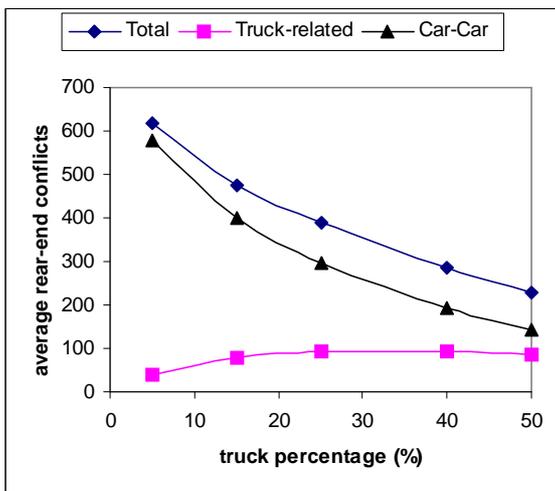
**Figure 23 Number of Rear-End Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Posted Speed Limits**



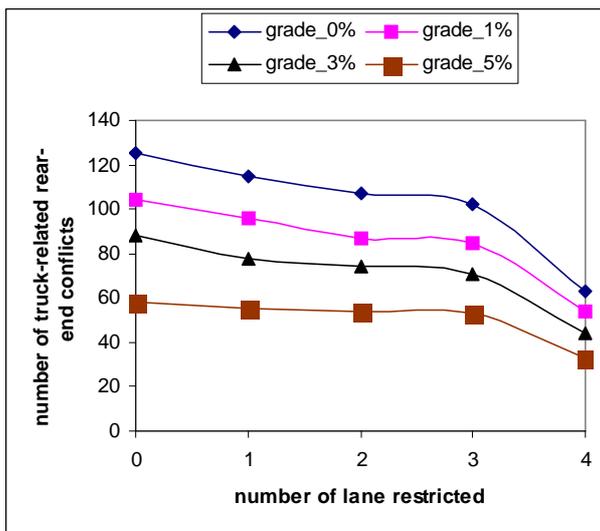
**Figure 24** Number of Rear-End Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Intersection Densities



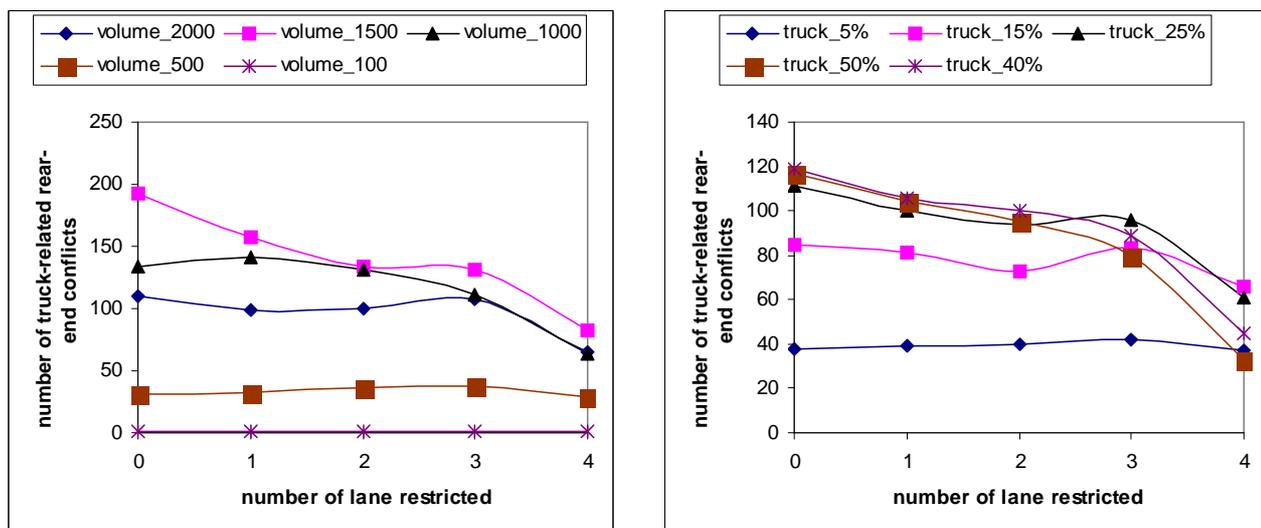
**Figure 25** Number of Rear-End Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Demand Volumes



**Figure 26 Number of Rear-End Conflicts and Lane Changes on 5-Lane (each direction) Freeways with Different Truck Percentages**



**Figure 27 Truck-Related Rear-End Conflicts on 5-Lane (each direction) Freeways with Different Grades**



**Figure 28 Truck-Related Rear-End Conflicts on 5-Lane (each direction) Freeways with Different Demand Volumes and Truck Percentages**

## 5.4.2 Effectiveness of Truck Lane Restrictions on Rear-End Conflicts

### 5.4.2.1 ANOVA Analysis

In order to test whether TLRs have significant impacts on rear-end conflicts, the similar ANOVA analyses were conducted for rear-end conflicts as those for lane-changing conflicts in 5.2.2.1. The results of ANOVA are presented in Table 12.

**Table 12 p Values from ANOVA Analyses of Rear-End Conflicts**  
(a) 3-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.775/.124/.530	.418/.202/.498	.991/.571/.702	.111/.318/.215	.309/.120/.013
500	.888/.487/.906	.926/.617/.982	.412/.913/.239	.856/.972/.673	.494/.144/.972
1000	.952/.829/.960	.913/.655/.943	.936/.327/.692	.170/.000/.626	.000/.000/.265
1500	.825/.849/.785	542/.006/.321	.174/.000/.352	.015/.000/.000	.047/.000/.000
2000	.172/.022/.127	.000/.039/.000	.000/.002/.000	.001/.000/.000	.000/.000/.000

**Table 12 p Values from ANOVA Analyses of Rear-End Conflicts**  
(b) 4-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.279/.611/.225	.946/.133/.604	.615/.734/.618	.057/.105/.060	.405/.297/.756
500	.945/.449/.942	.891/.915/.822	.687/.845/.595	.663/.831/.490	.168/.039/.063
1000	.936/.993/.926	.838/.652/.880	.666/.033/.110	.004/.000/.550	.000/.000/.069
1500	.512/.842/.469	.163/.025/.038	.019/.000/.000	.000/.000/.000	.002/.000/.000
2000	.002/.178/.001	.000/.094/.000	.000/.398/.000	.000/.000/.000	.000/.000/.000

(c) 5-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.510/.175/.241	.695/.241/.933	.491/.837/.383	.080/.331/.128	.377/.521/.483
500	.901/.212/.925	.493/.045/.775	.776/.647/.756	.313/.092/.009	.031/.000/.008
1000	.958/.156/.984	.253/.071/.214	.597/.000/.194	.001/.000/.226	.000/.000/.002
1500	.700/.372/.603	.425/.000/.128	.000/.000/.000	.000/.000/.000	.000/.000/.000
2000	.065/.356/.030	.000/.044/.000	.000/.000/.000	.000/.000/.000	.000/.000/.000

Note: In each cell of this table, the first value is the p value of ANOVA analysis with a dependent variable of total rear-end conflicts, the second value is the p value of ANOVA analysis with a dependent variable of truck-related rear-end conflicts, and the third value is the p value of ANOVA analysis with a dependent variable of car-car rear-end conflicts.

#### 5.4.2.2 Impacts of Key Variables in Application of Truck Lane Restrictions

The ANOVA analysis above only indicates the significance of impact of TLRS upon rear-end conflicts with no information on whether the impact is negative or positive. In order to investigate the details of the influence of TLRS, rear-end conflicts were analyzed for different TLRS within the categories defined by demand volume and truck percentage (the same as those in the ANOVA analysis). These results were presented by column graphs in Fig. C01 to Fig. C15 in Appendix C.

Generally, the frequency of the car-car rear-end conflict has a much higher value than that of the truck-related rear-end conflict and the former increases with the increase of the number of lanes restricted while the latter decreases at the same time. The details

of the influence of lanes restricted are discussed as follows for different demand volume levels:

Demand volume is less than 100 vphpl (Fig. C01, C06, C11):

- The frequencies of rear-end conflicts are very low and not significantly influenced by TLRS.

Demand volume is 500 vphpl (Fig. C02, C07, C12):

- The frequencies of rear-end conflicts are very low and are significantly influenced only when truck percentage is as high as 50% for 4-lane (in each direction) highways and 40-50% for 5-lane (in each direction) highways.

Demand volume is greater than 100 and less than 500 vphpl (Fig. C03, C08, C13):

- Generally, the frequencies of truck-related and car-car rear-end conflicts increase with the increase in the number of lanes restricted when the truck percentage is below 40%. However, when truck percentage is above 40%, the increase in the car-car rear-end conflicts becomes flat and the truck-related conflicts decrease with the increase in the number of lanes restricted. The combined effect results in a similar trend for total rear-end conflicts as that for truck-related conflicts.

Demand volume is greater than 1000 and less than 1500 vphpl (Fig. C04, C09, C14):

- Generally, the frequency of the car-car rear-end conflict increases with the increase of the number of lanes restricted while that of the truck-related conflict decreases at the same time. The combined effect results in a similar trend for the total rear-end conflicts as that for the car-car rear-end conflicts.

Demand volume is greater than 1500 and less than 2000 vphpl (Fig. C05, C10, C15):

- Generally, the frequency of the car-car rear-end conflict increases with the increase of the number of lanes restricted while that of the truck-related conflict does not show a significant variation except for a drop when the maximum number of lanes are restricted. The combined effect results in a similar trend for total rear-end conflicts as that for the car-car rear-end conflicts.

## 5.5 Summary

This chapter evaluates the safety performance of different TLRS using safety surrogate measurements, i.e. lane-changing, merging, and rear-end conflicts. Generally, the independent variables (grade, posted speed limit, interchange density, volume, truck percentage, lane restrictions) show significant impacts upon different safety surrogate measurements in different categories (truck-related and car/car conflicts). Demand volume and truck percentage are identified as the key independent variables that may lead to a decision on an appropriate TRLS. The influence of the TLRS depends on which category (defined by demand volume levels and truck percentage) the evaluation is conducted. Generally, the truck lane restriction has a positive influence on the lane-changing and merging conflicts while it has a negative impact on rear-end conflicts. These impacts are greater for trucks than for cars and are greater for lane-related conflicts (such as lane-changing and merging conflicts) than for other conflicts (such as rear-end conflicts).

## CHAPTER 6 OPERATIONAL PERFORMANCE ANALYSIS

### 6.1 Introduction

The objectives of application of truck lane restrictions are twofold - providing fast lane(s) by removing slow traffic (truck) from such lane(s) and reducing truck-related crashes by constraining trucks to certain lane(s). This chapter focuses on the operational performance analysis of truck lane restriction strategies (TLRS) using operational MOEs of *average speed* and *density* collected from the simulation experiments as designed in Chapter 4. The operational performance analysis for each type of conflict was conducted in three stages:

- Stage I: Evaluating the impacts of independent variables on average speed or density;
- Stage II: ANOVA analysis for the significance of impacts of different TLRS on average speed or density within each category defined by demand volume and truck percentage
- Stage III: Analysis of the impacts of demand volume and truck percentage on the application of different TLRS.

### 6.2 Average Speed Analysis

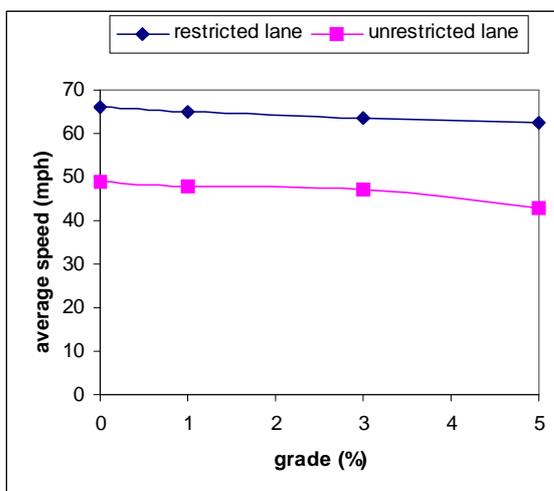
#### 6.2.1 Impacts of Independent Variables on Average Speed

The same analyses for the impacts of independent variables on average speeds were conducted as those on safety surrogate measurements and the results were summarized and presented in Table 13. The only difference is that the dependent variable

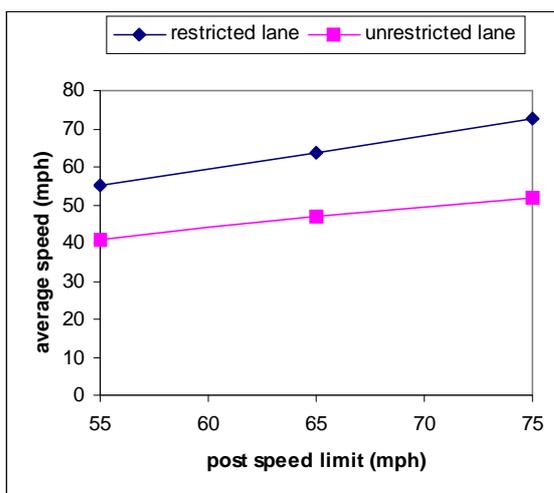
discussed here is the average speed on the restricted lanes or on the unrestricted lanes instead of truck-related or car-car conflicts. In addition, the key independent variables were chosen to be the same as those in the conflict analysis in order to keep consistency with the safety performance analysis in developing application guidelines for TLRS later in Chapter 7.

**Table 13 Summary of Impacts of Independent Variables on Average Speed**

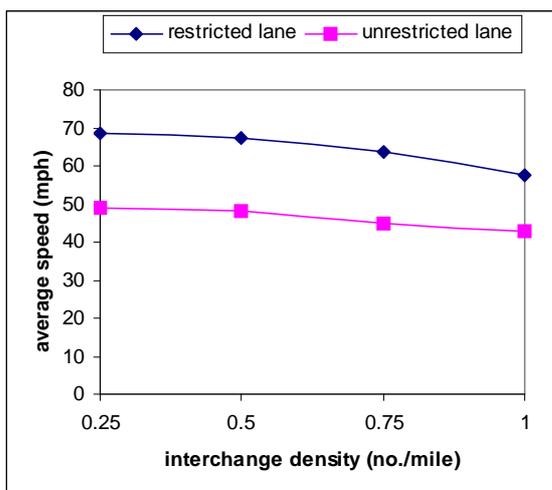
<b>Independent Variables</b>	<b>Impact Analysis</b>	<b>Reference Figure</b>	<b>Key Factors</b>
Grade	The average speeds decrease with the increase in the grade on both restricted and unrestricted lanes. However, this trend is steeper for those on unrestricted lanes because the grade has a less negative influence on the acceleration ability of cars on restricted lanes than that of trucks on unrestricted lanes. Besides, the average speed on restricted lanes is much higher than that on unrestricted lanes.	Figure 29	No
Posted speed limit	The average speeds increase with the increase in the posted speed limit on both restricted and unrestricted lanes.	Figure 30	No
Interchange Density	The average speeds decrease at a small magnitude with the increase in the interchange density on both restricted and unrestricted lanes.	Figure 31	No
Volume	The average speeds decrease dramatically with the increase in the demand volume on both restricted and unrestricted lanes. However, this trend is steeper for the average speed on unrestricted lanes. This may be because all the trucks within the increased demand volume will be forced to the unrestricted lanes by the truck lane restriction strategies.	Figure 32	Yes
Truck Percentage	The average speeds decrease with the increase in the truck percentage on both restricted and unrestricted lanes. However, this trend is steeper for the average speed on unrestricted lanes. The increase in the truck percentage increases the truck density on the unrestricted lanes. The reason for the decrease of average speed of cars on the restricted lane may be the increased waiting time for getting off the main road caused by more trucks on the rightmost lane.	Figure 33	Yes



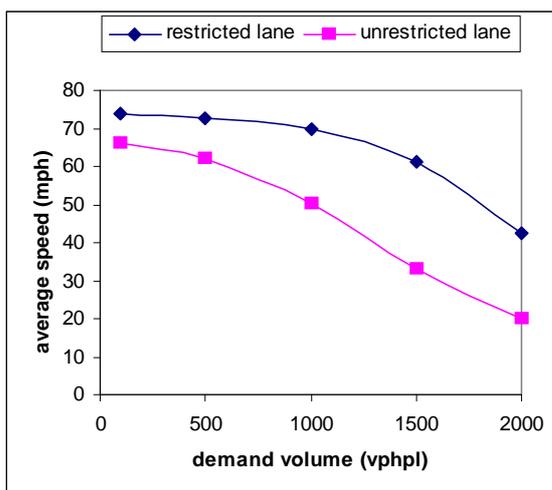
**Figure 29 Average Speed on 5-Lane (each direction) Freeways with Different Grades**



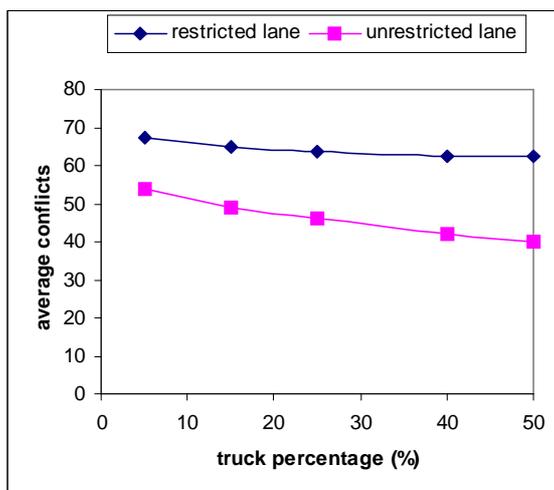
**Figure 30 Average Speed on 5-Lane (each direction) Freeways with Different Posted Speed Limits**



**Figure 31 Average Speed on 5-Lane (each direction) Freeways with Different Intersection Densities**



**Figure 32 Average Speed on 5-Lane (each direction) Freeways with Different Demand Volumes**



**Figure 33 Average Speed on 5-Lane (each direction) Freeways with Different Truck Percentages**

## 6.2.2 Effectiveness of Truck Lane Restrictions on Average Speeds

### 6.2.2.1 ANOVA Analysis

In order to test whether TLRS has a significant impact on average speed, similar ANOVA analyses were conducted for average speed as those for safety surrogate measurements in 5.2.2.1. The only difference is that the dependent variables in this ANOVA analyses are average speed on restricted lanes and unrestricted lanes instead of truck-related or car-car conflicts. The results of ANOVA are presented in Table 14.

**Table 14 p Values from ANOVA Analyses of Average Speed**  
(a) 3-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.000/.232	.000/.162	.000/.169	.000/.186	.000/.175
500	.000/.042	.000/.011	.000/.003	.000/000.	.000/000.
1000	.000/.001	.000/000.	.000/000.	.000/000.	.000/000.
1500	.000/000.	.000/000.	.001/000.	.001/000.	.000/000.
2000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.

**Table 14 p Values from ANOVA Analysis of Average Speed**  
(b) 4-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.001/.041	.000/.029	.000/.068	.000/.122	.000/.079
500	.000/.007	.000/.001	.000/000.	.000/000.	.000/000.
1000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
2000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.

(c) 5-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.000/.641	.000/.519	.000/.229	.000/.138	.000/.168
500	.000/.013	.000/000.	.000/000.	.000/000.	.000/000.
1000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
2000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.

Note: In each cell of this table, the first value is the p value of ANOVA analysis with a dependent variable of average speed on restricted lanes and the second value is the p value of ANOVA analysis with a dependent variable of average speed in unrestricted lanes.

### 6.2.2.2 Impacts of Key Variables in Application of Truck Lane Restrictions

The ANOVA analysis above only indicates the significance of the impact of TLRS upon average speed with no information on whether the impact is negative or positive. In order to investigate the details of the influence of TLRS, average speeds were analyzed for different TLRS within the categories defined by demand volume and truck percentage (the same as those in the ANOVA analysis). These results were presented by column graphs in Fig. D01 to Fig. D15 in Appendix D.

Generally, the average speed on both restricted and unrestricted lanes decreases with the increase in truck percentages. The average speed has a sudden increase in the restricted lane when the restriction strategy changes from R0 to R1. Thereafter, the average speeds on both restricted and unrestricted lanes decrease with the increase in the

number of lanes restricted. However, such a decreasing trend for speeds on unrestricted lanes is much steeper than those on restricted lanes. The details of the influence of lanes restricted are discussed as follows for different demand volumes:

Demand volume is less than 100 vphpl (Fig. D01, D06, D11):

- The average speed (around 65 mph) on unrestricted lanes does not change significantly with the increase in the number of lanes restricted and that on the restricted lane reaches its peak (above 75 mph) when only the leftmost lane is restricted.

Demand volume is greater than 100 and less than 500 vphpl (Fig. D02, D07, D12):

- The average speed on restricted lanes reaches its peak (75 mph) when only the leftmost lane is restricted and it decreases slowly to 70 mph with the increase in the number of lanes restricted. The average speed on unrestricted lanes does not change significantly with the increase in the number of lanes restricted when the truck percentage is below 25% and after that it decreases from 60 to 40 mph with the increase in the number of lanes restricted.

Demand volume is greater than 500 and less than 1000 vphpl (Fig. D03, D08, D13):

- The average speed on restricted lanes reaches its peak (75 mph) when only the leftmost lane is restricted and its value decreases slowly to 65 mph with the increase in the number of lanes restricted. The average speed on unrestricted lanes does not change much with the increase in the number of lanes restricted when the truck percentage is below 5% and after that it decreases from 60 to 20 mph with the increase in the number of lanes restricted.

Demand volume is greater than 1000 and less than 1500 vphpl (Fig. D04, D09, D14):

- The average speed on restricted lanes reaches its peak (70 mph) when only the leftmost lane is restricted and it decreases to 50 mph with an increase in the number of lanes restricted when truck percentage is below 40%. However, when the truck percentage is greater than 40%, the average speed on restricted lanes tends to increase with the increase in the number of lanes restricted. The average speed on unrestricted lanes decreases with the increase in the number of lanes restricted.

Demand volume is greater than 1500 and less than 2000 vphpl (Fig. D05, D10, D15):

- The average speed on restricted lanes reaches its peak (40 mph) when only the leftmost lane is restricted and it decreases to 35 mph with the increase of the number of lanes restricted when truck percentage is below 25%. However, when the truck percentage is greater than 25%, the average speed on restricted lanes tends to increase with the increase in the number of lanes restricted. The average speed on unrestricted lanes decreases with the increase in the number of lanes restricted from 30 to 15 mph.

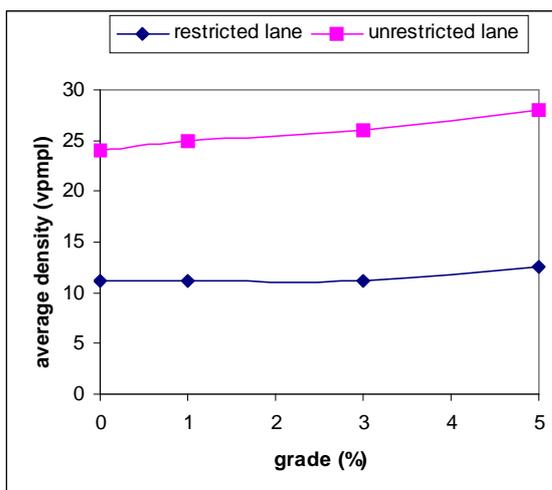
## **6.3 Density Analysis**

### **6.3.1 Impacts of Independent Variables on Density**

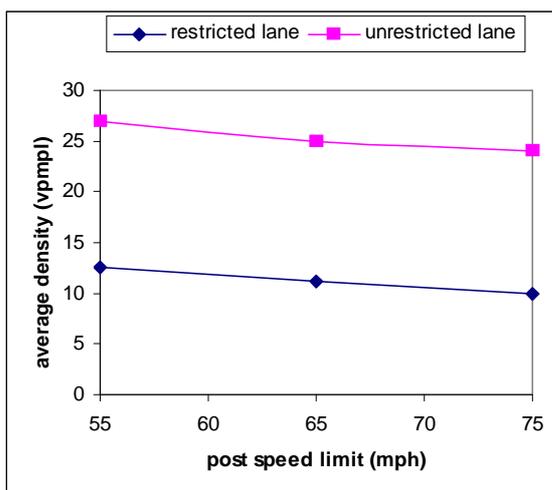
The same analyses for the impacts of independent variables on density were conducted as those on average speed and the results were summarized and presented in Table 13. The only difference is that the dependent variable discussed here is the traffic density on restricted lanes or on unrestricted lanes instead of average speed.

**Table 15 Summary of Impacts of Independent Variables on Average Speed**

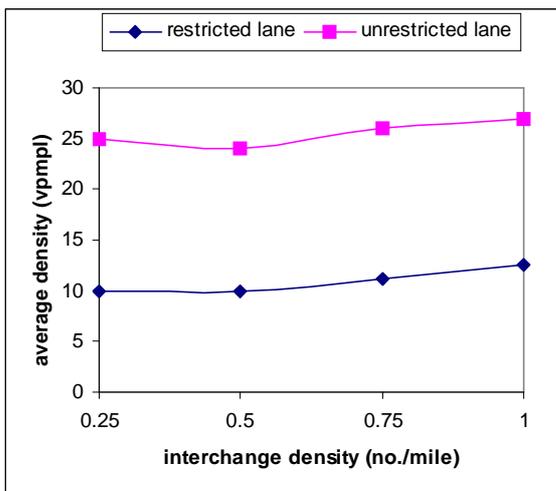
<b>Independent Variables</b>	<b>Impact Analysis</b>	<b>Reference Figure</b>	<b>Key Factors</b>
Grade	The average density increases at a small magnitude with the increase in the grade on both restricted and unrestricted lanes. However, this trend is steeper for that on unrestricted lanes than that on the restricted lane.	Figure 34	No
Posted speed limit	The average density decreases with the increase in the posted speed limit on both restricted and unrestricted lanes.	Figure 35	No
Interchange Density	The average density increases at a small magnitude with the increase in the interchange density on both restricted and unrestricted lanes. It could be concluded that the interchange density has much less influence on operational MOEs than on safety MOEs.	Figure 36	No
Volume	The average density increases dramatically with the increase in the demand volume on both restricted and unrestricted lanes. However, this trend is steeper for those on unrestricted lanes.	Figure 37	Yes
Truck Percentage	The average density increases with the increase in the truck percentage on unrestricted lanes while that on restricted lanes goes in the opposite direction. This may be because the increase of truck percentage increases the number of trucks on unrestricted lanes. However, it also decreases the number of cars on restricted lanes when the total volume keeps stable.	Figure 38	Yes



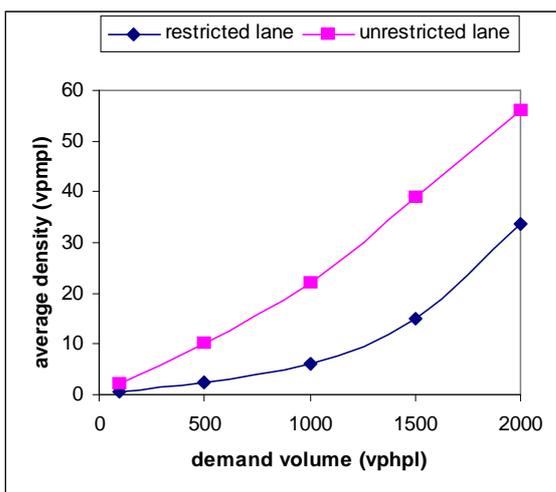
**Figure 34 Density on 5Lane (each direction)  
Freeways with Different Grades**



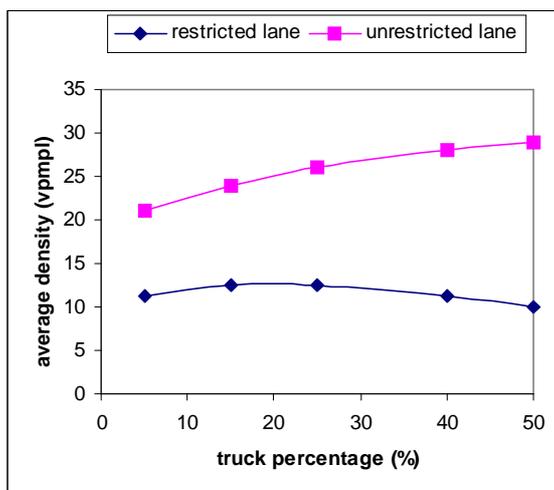
**Figure 35 Density on 5-Lane (each direction)  
Freeways with Different Posted Speed Limits**



**Figure 36 Density on 5-Lane (each direction) Freeways with Different Intersection Densities**



**Figure 37 Density on 5-Lane (each direction) Freeways with Different Demand Volumes**



**Figure 38 Density on 5-Lane (each direction) Freeways with Different Truck Percentages**

### 6.3.2 Effectiveness of Truck Lane Restrictions on Density

#### 6.3.2.1 ANOVA Analysis

In order to test whether TLRS has significant impacts on traffic density, similar ANOVA analyses were conducted for density as those for safety surrogate measurements in 5.2.2.1. The only different is that the dependent variables in the ANOVA analyses are density on restricted lane and unrestricted lane instead of truck-related or car-car conflicts. The results of ANOVA are presented in Table 16.

**Table 16 p Values from ANOVA Analysis of Average Density**  
(a) 3-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.000/.000	.000/.000	.000/.000	.000/000.	.000/000.
500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
2000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.

**Table.16 p Values from ANOVA Analyses of Average Density**  
(b) 4-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
2000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.

(c) 5-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
100	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
1500	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.
2000	.000/000.	.000/000.	.000/000.	.000/000.	.000/000.

### 6.3.2.2 Impacts of Key Variables in Application of Truck Lane Restrictions

The ANOVA analysis above only indicates the significance of impact of TLRS upon traffic density with no information on whether the impact is negative or positive. In order to investigate the details of the influence of TLRS, traffic density was analyzed for different TLRS within the categories defined by demand volume and truck percentage (the same as those in the ANOVA analysis). These results were presented by column graphs in Fig. E01 to Fig. E15 in Appendix E.

Generally, the average densities on restricted lanes and unrestricted lanes decrease with the increase in truck percentages. The average density has a sudden decrease in the restricted lane when the restriction strategy changes from R0 to R1. The details of the influence of lanes restricted are discussed as follows for different demand volume levels:

Demand volume is less than 100 vphpl (Fig. E01, E06, E11):

- The average densities are all below 11 vpmp (LOS A).

Demand volume is greater than 100 and less than 500 vphpl (Fig.E02, E07, E12):

- Most of the average densities are below 18 vpmpl (LOS B) while some of those fall above 18 but below 26 vpmpl (LOS B).

Demand volume is greater than 500 and less than 1000 vphpl (Fig.E03, E08, E13):

- All the average densities in restricted lanes below 18 vpmpl (LOS B). For a 3-lane freeway, the density in restricted lanes is above 35 vpmpl (LOS E) when truck percentage is 50% and R2/3 is applied; for a 4-lane freeway, the density in restricted lanes is above 35 vpmpl (LOS E) when truck percentage is over 40% and R3/4 is applied; for a 5-lane freeway, the density in restricted lanes is above 35 vpmpl (LOS E) when truck percentage is over 25% and R3/5 or R4/5 is applied.

Demand volume is greater than 1000 and less than 1500 vphpl (Fig. E04, E09, E14):

- All the average densities in restricted lanes below 26 vpmpl (LOS C). For a 3-lane freeway, the density in restricted lanes is above 35 vpmpl (LOS E) when truck percentage is 25% and R2/3 or R1/3 is applied; for a 4-lane freeway, the density in restricted lanes is usually above 35 vpmpl (LOS E) when truck percentage is over 15%; for a 5-lane freeway, the density in restricted lanes is above 35 vpmpl (LOS E) when truck percentage is over 5%.

Demand volume is greater than 1500 and less than 2000 vphpl (Fig.D05, D10, D15):

- The average density in the unrestricted lane is usually greater than 35 vpmpl (LOS E). The density in the restricted lane decreases with the increase of the number of lanes restricted when truck percentage is over 25%.

## **6.4 Summary**

This chapter evaluates the operational performance of different truck lane restriction strategies on the basis of operational MOEs – average speed and traffic density. Generally, the independent variables (grade, posted speed limit, interchange density, volume, truck percentage, lane restrictions) show significant impacts upon different operational MOEs in different categories (on restricted and on unrestricted lanes). The influence of the truck lane restriction strategies depends on which category (defined by demand volume level and truck percentage) the evaluation is conducted. Generally, the truck lane restriction has a positive influence upon the LOS within restricted lanes while it has a negative impact on those within unrestricted lanes.

## **CHAPTER 7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

### **7.1 Introduction**

This study evaluated the effectiveness of truck lane restriction strategies (TLRS) under different traffic and geometric conditions using conflict as the safety MOE. This chapter summarizes the evaluation results produced in Chapters 5 and 6. These results were used in combination to develop comprehensive guidelines for the application of TLRS with the objectives of increasing LOS on restricted lanes and decreasing the probability of truck-related crashes. In addition, future research needs are identified.

### **7.2 Summary of Analysis**

This study examined the safety performance of TLRS on a freeway through simulation. A safety surrogate measurement – conflict – was used as the MOE for the evaluation. Three types of conflict events that represent critical situations that have a strong potential for crashes on freeways were analyzed for different TLRS under various geometric and traffic conditions. The geometric conditions consisted of the number of lanes in each direction (3, 4, and 5), uphill grade of the freeway section (0%, 1%, 3%, and 5%), and the interchange density (0.25/mile, 0.5/mile, 0.75/mile, and 1.00/mile). The traffic conditions include the posted speed limit (55 mph, 65 mph, and 75 mph), the traffic volume (100, 500, 1000, 1500, and 2000 veh/hr/lane), and truck percentage in the traffic mix (5%, 15%, 25%, 40%, and 50%). These geometric and traffic characteristics produced 14,400 different simulation scenarios on a 5-mile freeway section.

In order to capture and compute the safety surrogate measurements, three PARAMICS API programs were developed including *lane\_changing\_conflict.dll*, *merging\_conflict.dll*, and *rear-end\_conflict.dll*. These programs were embedded in the simulation procedure and run in parallel mode with the simulation modeler. Their functions were scanning the simulation objects to identify potential events that may lead to a conflict, tracing vehicles involving such potential events, and computing safety surrogate measurements to decide whether a conflict occurred. In addition, two other PARAMICS API programs *speed.dll* and *density.dll* were developed to collect the operational MOEs – average speed and density on both restricted and unrestricted lanes.

From the simulation results produced by the above simulation design and PARAMICS API programs, the safety and operational MOEs were separately analyzed after aggregating the simulation data for different truck lane restriction strategies on freeway sections with different grades, interchange densities, posted speed limits, volume levels, and truck percentages. These analyzes were conducted in stages: first, the impact of each individual independent variable was analyzed, and as a result, the key variables that had a significant impact on the effect of the TLRS were identified; second, ANOVA analysis was conducted to examine the significance of the impacts of the key independent variables on MOEs for different conditions; third, the details of the variation of MOEs with the increase of the number of lanes restricted were discussed for different categories defined by the key independent variables.

## 7.3 Conclusions

Based on the results of the analyses conducted in Chapters 5 and 6, the following conclusions were made:

### 7.3.1 Impact of Truck Lane Restrictions

Generally, the frequency of lane-changing conflicts decreases with the increase in the number of lanes restricted when the demand volume is lower than 1500 vphpl. When the demand volume is greater than 1500 vphpl, the frequency of the lane-changing conflicts increases with the increase in the number of lanes restricted. However, it usually has a sharp drop when the possible maximum lanes are restricted. The frequency of the truck-related merging conflicts increases with the increase in the number of lanes restricted while the frequency of car-car merging conflicts decreases at the same time. However, this trend for truck-related merging conflicts tends to go in the opposite direction when the demand volume is over 1500 vphpl. The frequency of rear-end conflicts increases with the increase in the number of lanes restricted except for cases when the demand volume is below 1000 vphpl and the truck percentage is over 40%. For these cases, frequency of rear-end conflicts decreases with the increase in the number of lanes restricted. Significant influences of truck lane restrictions usually exist when demand volume is over 1000 vphpl.

The truck lane restriction strategies have a significant impact on the average speed and density on both restricted and unrestricted lanes for all combinations of different demand volumes and truck percentages. Generally, average speeds on both restricted and unrestricted lanes decrease with the increase in truck percentages. The average speed

suddenly increases in restricted lanes when the TLRS changes from R0 to R1. Thereafter, average speeds on both restricted and unrestricted lanes decrease with the increase in the number of lanes restricted. However, the decreasing trend for speeds on unrestricted lanes is much steeper than that on restricted lanes. The analysis on average densities produces similar results as those for average speeds analysis as these variables are related to each other.

### **7.3.2 Impact of Grade of the Freeway Section**

The frequencies of lane-changing, merging, and rear-end conflicts generally decrease with the increase in the grade of freeway section. This phenomenon is more evident for trucks than cars which may be caused by the weak acceleration ability of trucks on the uphill freeway sections resulting in an increase in the gaps between trucks and other vehicles. On the other hand, the average speeds on both restricted and unrestricted lanes decrease with the increase in the grade while the densities increase at the same time.

### **7.3.3 Impact of Posted Speed Limit on the Freeway Section**

The frequencies of lane-changing, merging, and rear-end conflicts increase with the increase in the posted speed limit. This indicates high speed is a potential cause for all kinds of conflicts. On the other hand, the average speeds on both restricted and unrestricted lanes increase with the increase of the posted speed limit while the densities decrease at the same time.

#### **7.3.4 Impact of Traffic Volume on the Freeway Section**

The frequencies of lane-changing conflicts increase dramatically with the increase in the demand volume when it is below 1000 vphpl. However, the rate of increase decreases when the demand volume is over 1000 vphpl with the truck-related lane-changing conflicts reducing slightly. The merging conflicts first increase with the increase in the demand volume when it is below 1000 vphpl and reduces sharply when the demand volume is over 1000 vphpl. A similar trend occurred for rear-end conflicts except that the changing point is around the demand volume level of 1500 vphpl and the truck-related curve is much flatter than those of total and car-car conflicts. On the other hand, average speeds on both restricted and unrestricted lanes decrease with the increase of volume while the densities increase at the same time.

#### **7.3.5 Impact of Interchange Density on the Freeway Section**

The frequencies of lane-changing, merging, and rear-end conflicts increase with the increase in the interchange density. Apparently, more interchanges will increase the number of lane changes made by the vehicles that intend to get off the main road from exit ramps at the interchanges and increase the number of merging maneuvers for vehicles that intend to merge onto the main road from the entrance ramps. The frequent lane-changing or merging maneuvers also give rise to more sudden braking actions by the vehicle immediately following on the target lane. This is one of the main reasons for the increase in rear-end conflicts. However, the increase in car-car lane-changing conflicts is much more evident than that in truck-related lane-changing conflicts because truck lane restrictions force the trucks to stay on right lane(s) of the freeway section. Hence, the

trucks on the main road need less lane changes to get off and the trucks on the entrance ramp usually stay on the right lane as soon as they get on the main road.

### **7.3.6 Impact of the Truck Percentage in the Traffic Mix**

The frequency of car-car conflicts decreases with the increase in the truck percentage in the traffic mix. However, truck-related conflicts increase first with the increase of the truck percentage and decrease later when the truck percentage is over 25%. The combined effect of these two phenomena resulted in a trend of total conflicts that is similar to that of car-car conflicts. The reason for this may be that the increase in the truck percentage increased truck-related conflicts but the increase in the truck percentage also means a decrease in the car percentage in the traffic mix on both the main road and ramp. This resulted in a decrease in car-car conflicts. However, when the truck percentage is higher than 25%, the large volume of trucks forms a barrier on unrestricted lane(s) with extremely slow traffic and blocks some vehicles from entering freely.

### **7.3.7 Significant Impact of Independent Variables**

The ANOVA analysis results indicate that, for a significance level of 0.1, the independent variables – truck lane restrictions, grade, interchange density, posted speed limit, volume, and truck percentage have a significant impact on all types of conflicts (lane-changing, merging, and rear-end) for all categories (total conflict events, truck-related conflict events, and car-car conflict events). These independent variables also have a significant impact on operational measures of average speed and density except

that the influence of grade for car-car conflicts is not as significant as that for truck-related conflicts.

The influence of TLRS on conflicts and operational performances depends on investigated categories defined by the demand volume and truck percentage. Generally, more significant impact is found when demand volume is greater and trucks occupy a larger portion in the traffic mix.

#### **7.4 Proposed Guidelines**

Comprehensive guidelines (Table 17) for the application of truck lane restrictions were developed after combining the results from both the safety and operational analyses using the following criteria:

- The truck lane restriction should provide a traffic situation of LOS C or better on a restricted lane, and LOS D or better on an unrestricted lane, and
- If the LOS has been as low as E, no restriction should be applied, and
- There should be no significant increase in frequency of merging conflict, and
- There should be a significant decrease in lane-changing conflict or rear-end conflict, and
- Reducing lane-changing conflicts has a higher priority than reducing rear-end conflicts in deciding the application of lane restrictions when there is a conflict between the influences of the lane restriction on them.

- Reducing truck-related conflicts has a higher priority than reducing car-car conflicts in deciding the application of lane restrictions when there is a conflict between the influences of the lane restriction on them.

**Table 17 Comprehensive Truck Lane Restriction Recommendation**

(a) 3-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
<100	NA	NA	NA	NA	NA
100 - 500	NA	NA	NA	R2/3	R2/3
500 - 1000	R2/3	R2/3	R1/3	R1/3	R0/3
1000 - 1500	R2/3	R1/3	R0/3	R0/3	R0/3
1500 - 2000	R0/3	R0/3	R0/3	R0/3	R0/3

(b) 4-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
<100	NA	NA	NA	NA	NA
100 - 500	NA	NA	NA	R3/4	R3/4
500 - 1000	R3/4	R3/4	R2/4	R1/4	R1/4
1000 - 1500	R1/4	R1/4	R0/4	R0/4	R0/4
1500 - 2000	R0/4	R0/4	R0/4	R0/4	R0/4

(c) 5-lane freeway section

Volume (vphpl)	Truck Percentage (%)				
	5	15	25	40	50
<100	NA	NA	NA	NA	NA
100 - 500	NA	NA	NA	R3/5	R3/5
500 - 1000	R4/5	R3/5	R2/5	R2/5	R1/5
1000 - 1500	R1/5	R0/5	R0/5	R0/5	R0/5
1500 - 2000	R0/5	R0/5	R0/5	R0/5	R0/5

Different guidelines can be produced for different priorities and concerns of the decision-maker. For example, should the reduction of lane-changing conflicts take priority over reducing merging conflicts? In order to assist a decision-maker, studies should be conducted on the severity and crash types that are associated with different conflicts on freeways.

## 7.5 Future Research

This study has not covered all factors that could have been considered in the simulation due to limited time and availability of data. Future research should attempt to incorporate these factors. These future research needs include:

- Develop conflict and average speed regression models using simulation data;
- Enlarge the range or include more values within the current range of demand volume level and truck percentage to produce more detailed guidelines for application of truck lane restriction in practice;
- Incorporate the severity of crashes occurring from different types of conflicts into the analysis in addition to the occurrence of conflicts;
- Consider more types of truck lane restriction strategies, such as restricting trucks from using certain rightmost lane(s);
- Evaluate truck lane restriction strategies using site data, e.g. conflict data observed from a real freeway section when time and budget are sufficient;
- Correlate conflicts in simulation to crashes on site to investigate or prove a relationship between the surrogate safety measurements and crashes;
- Incorporate differential speed limits for trucks and passenger cars;
- Incorporate the effect of weather conditions;

- Incorporate some human factor characteristics, such as aggressive drivers.

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## APPENDIX A

### Graphs of Lane-Changing Conflicts Analysis

Please note in the following graphs:

- In each category, the first bar represents the frequency of total lane-changing conflicts, the second the frequency of car-car lane-changing conflicts, and the third represents the frequency of truck-related lane-changing conflicts.
- Categories in the horizontal axis are defined by truck percentage and truck lane restriction strategy. For example, T25%\_R2 means the truck percentage is 25% and trucks are restricted from the two leftmost lanes.

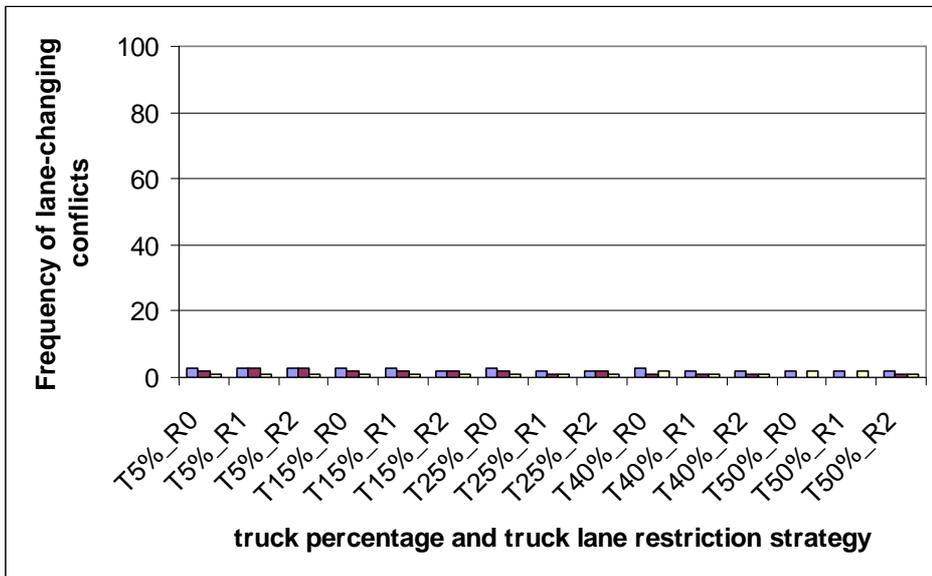


Figure A01 lane-changing conflicts on 3-lane freeway with demand volume of 100 vphpl

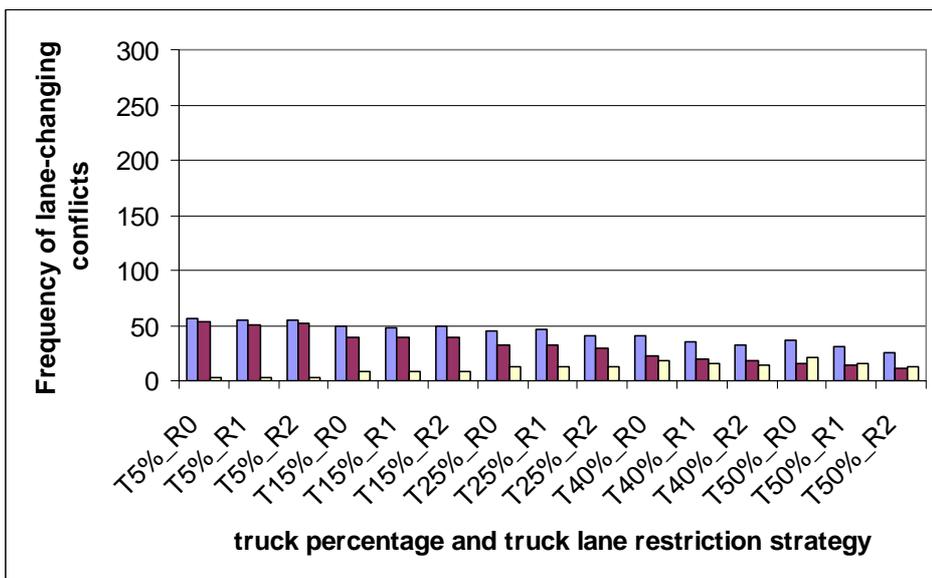


Figure A02 lane-changing conflicts on 3-lane freeway with demand volume of 500 vphpl

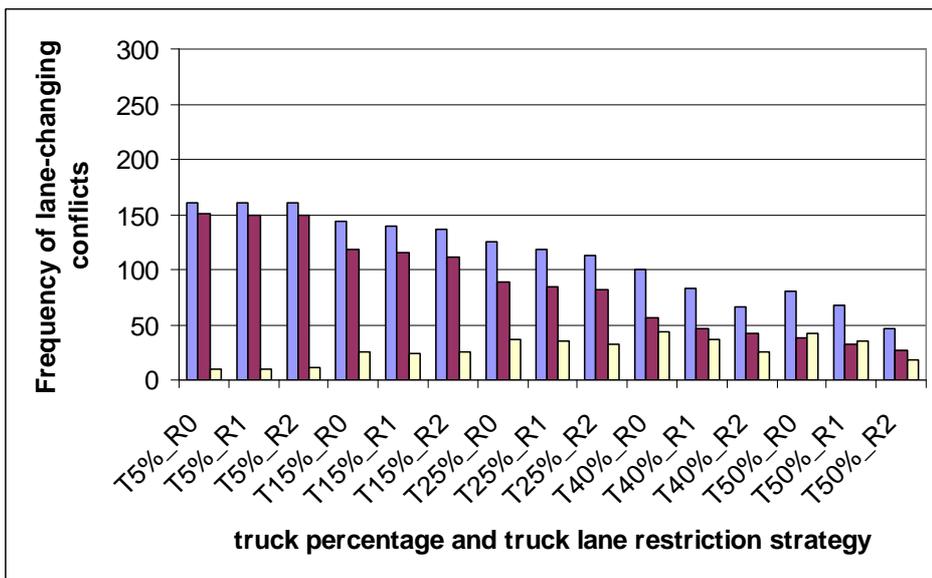


Figure A03 lane-changing conflicts on 3-lane freeway with demand volume of 1000 vphpl

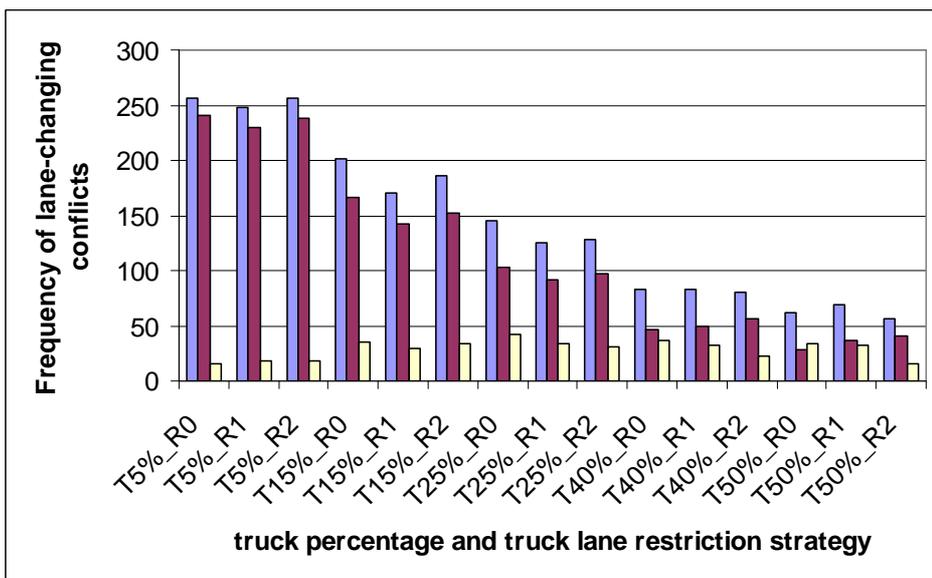


Figure A04 lane-changing conflicts on 3-lane freeway with demand volume of 1500 vphpl

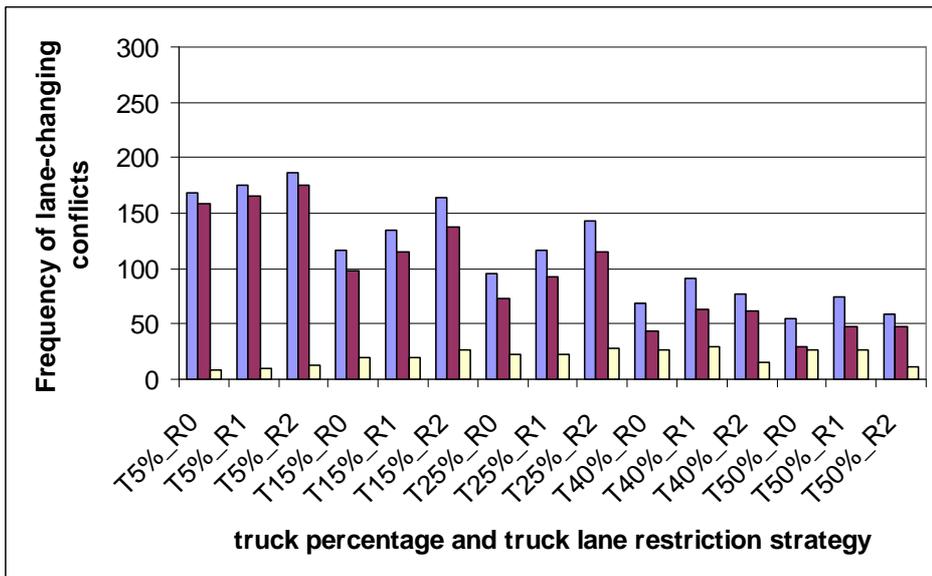


Figure A05 lane-changing conflicts on 3-lane freeway with demand volume of 2000 vphpl

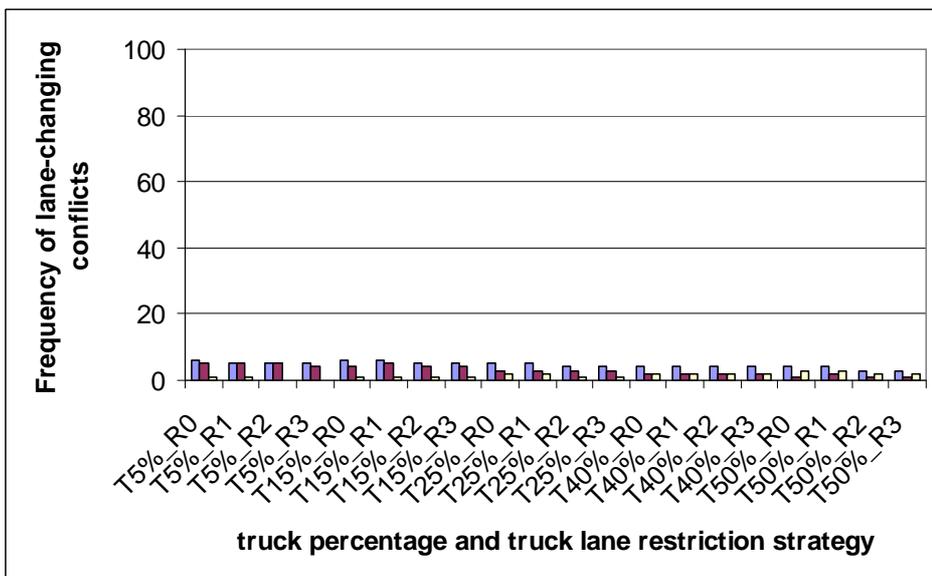


Figure A06 lane-changing conflicts on 4-lane freeway with demand volume of 100 vphpl

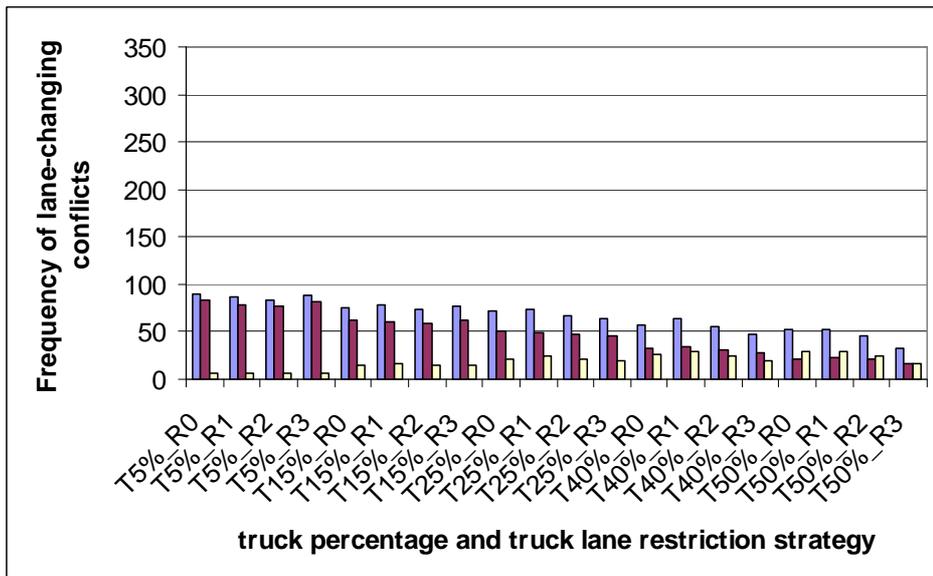


Figure A07 lane-changing conflicts on 4-lane freeway with demand volume of 500 vphpl

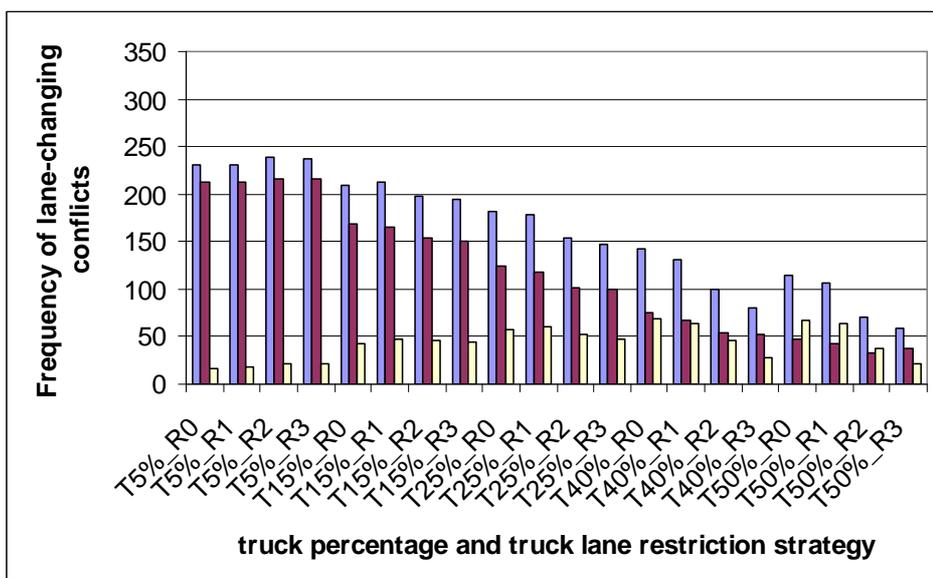


Figure A08 lane-changing conflicts on 4-lane freeway with demand volume of 1000 vphpl

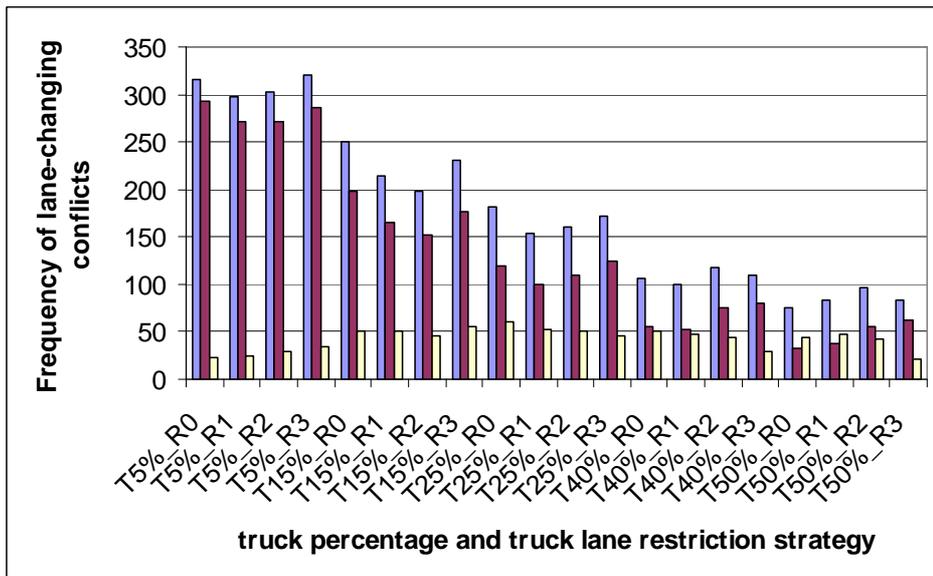


Figure A09 lane-changing conflicts on 4-lane freeway with demand volume of 1500 vphpl

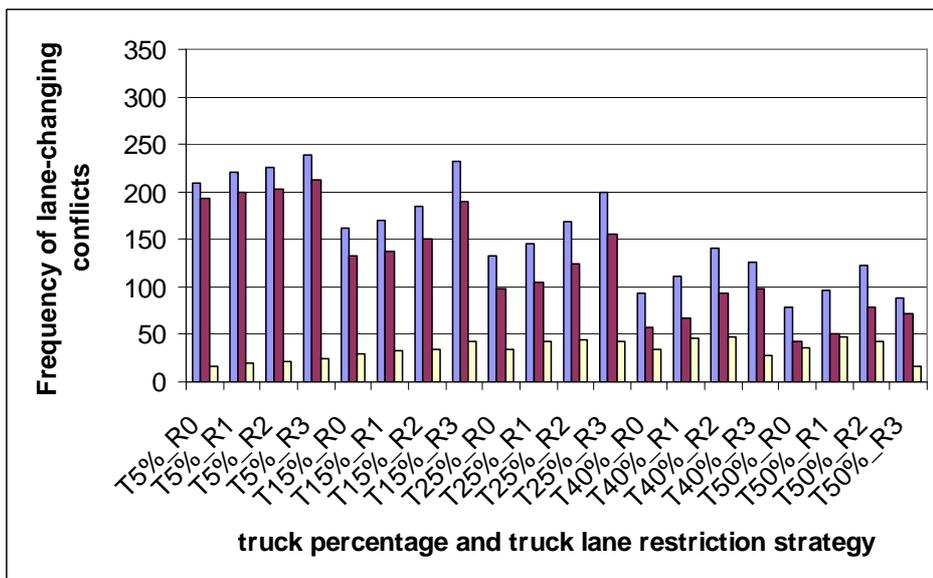


Figure A10 lane-changing conflicts on 4-lane freeway with demand volume of 2000 vphpl

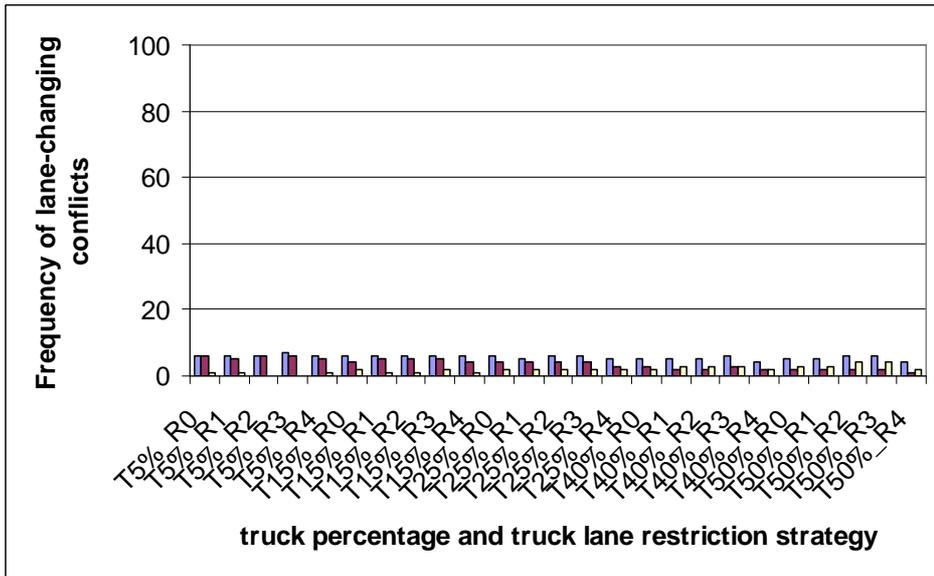


Figure A11 lane-changing conflicts on 5-lane freeway with demand volume of 100 vphpl

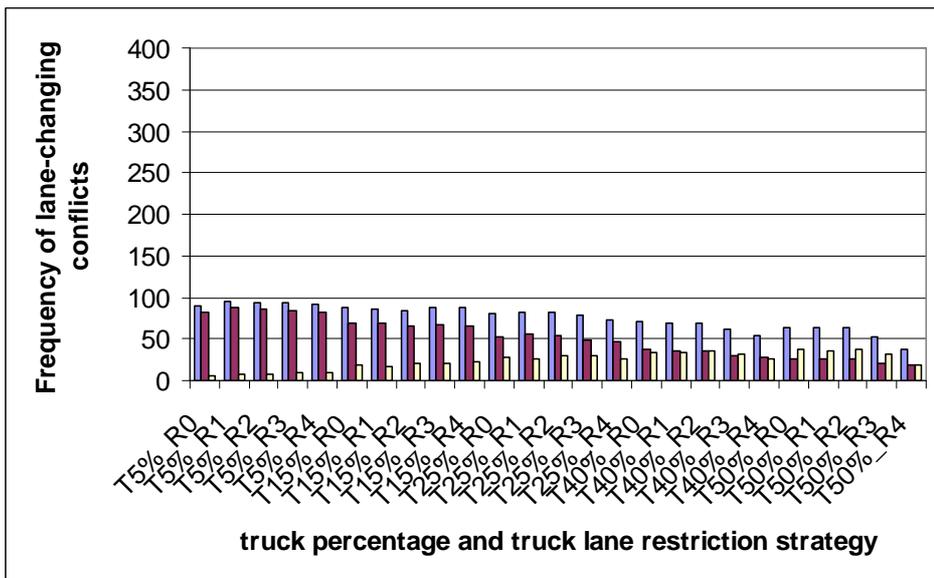


Figure A12 lane-changing conflicts on 5-lane freeway with demand volume of 500 vphpl

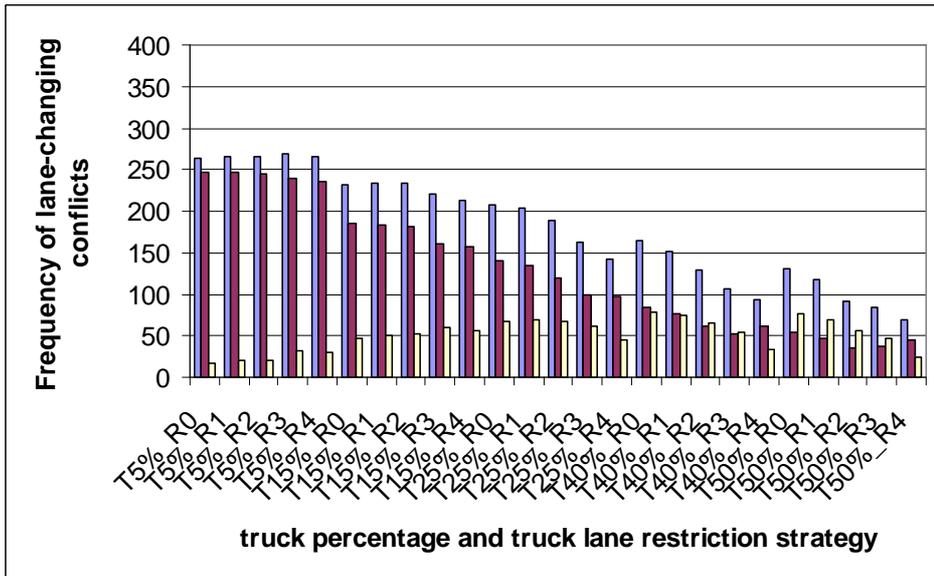


Figure A13 lane-changing conflicts on 5-lane freeway with demand volume of 1000 vphpl

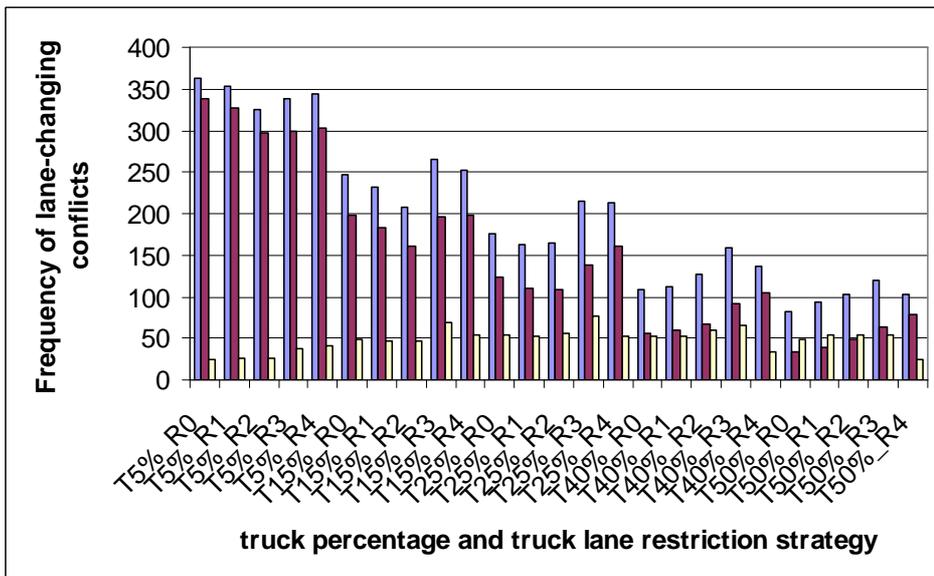


Figure A14 lane-changing conflicts on 5-lane freeway with demand volume of 1500 vphpl

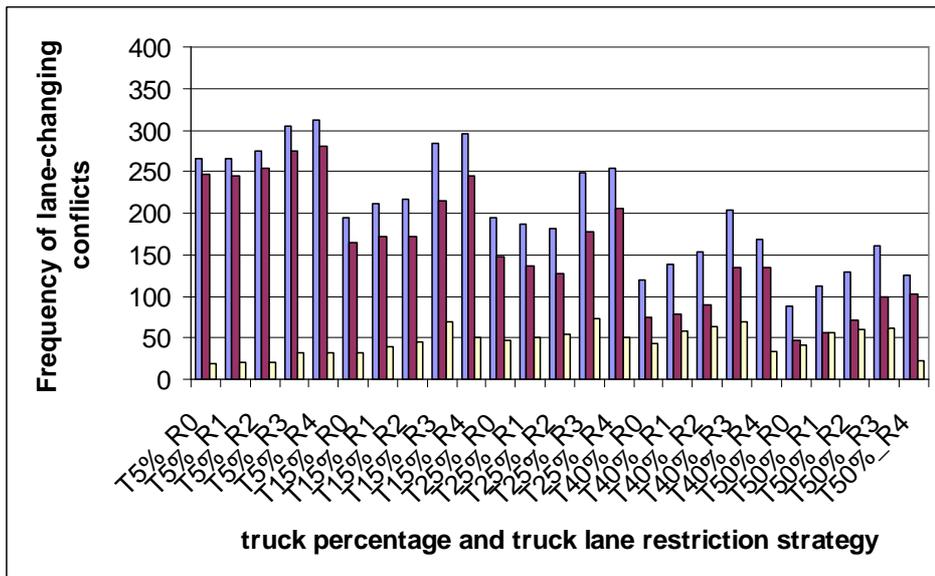


Figure A15 lane-changing conflicts on 5-lane freeway with demand volume of 2000 vphpl

## **APPENDIX B**

### **Graphs of Merging Conflicts Analysis**

Please note in the following graphs:

- In each category, the first bar represents the frequency of total merging conflicts, the second the frequency of car-car merging conflicts, and the third bar represents the frequency of truck-related merging conflicts.
- Categories in the horizontal axis are defined by truck percentage and truck lane restriction strategy. For example, T25%\_R2 means the truck percentage is 25% and trucks are restricted from the two leftmost lanes.

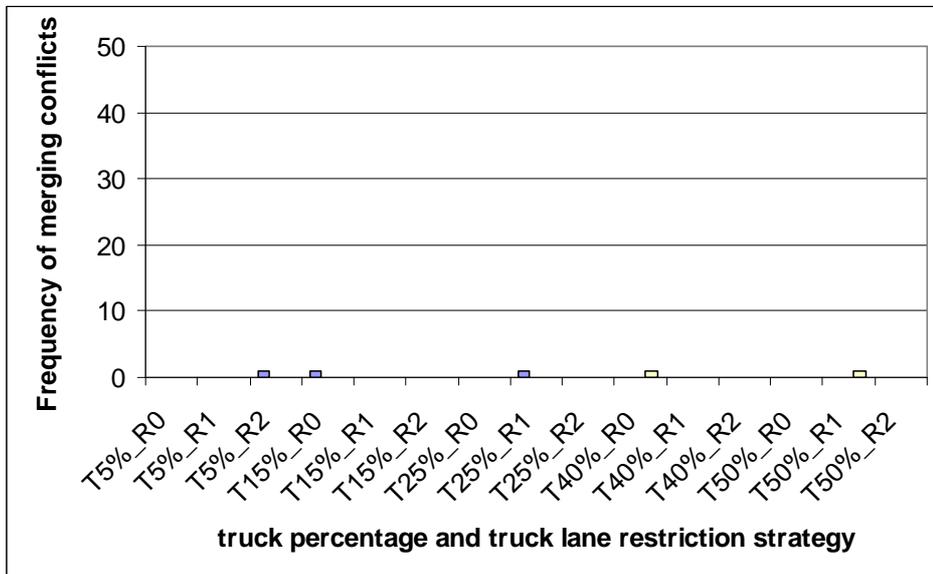


Figure B01 merging conflicts on 3-lane freeway with demand volume of 100 vphpl

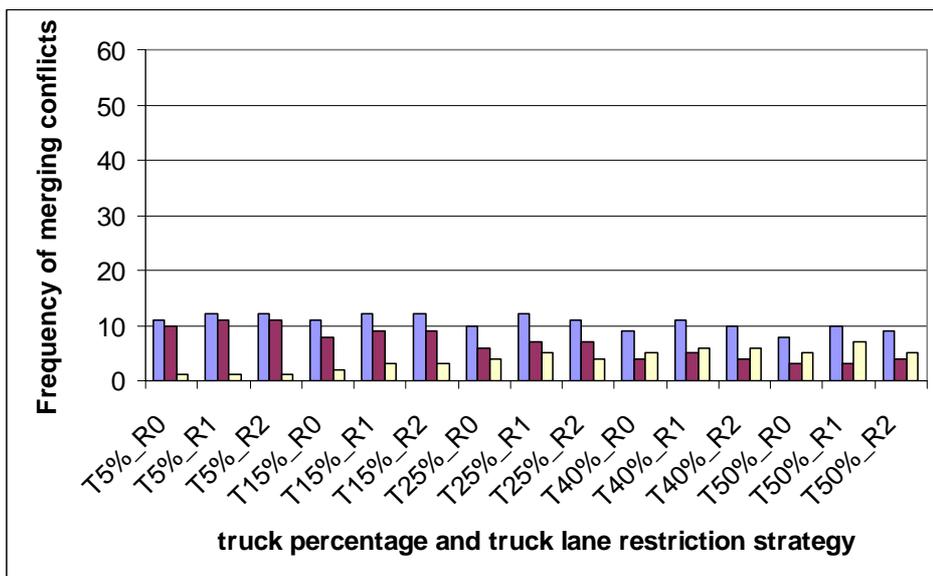


Figure B02 merging conflicts on 3-lane freeway with demand volume of 500 vphpl

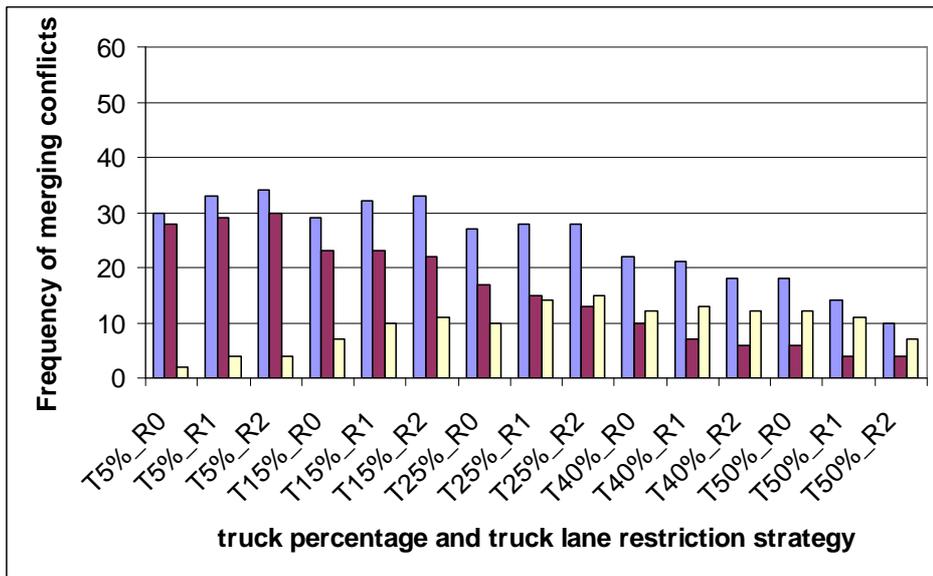


Figure B03 merging conflicts on 3-lane freeway with demand volume of 1000 vphpl

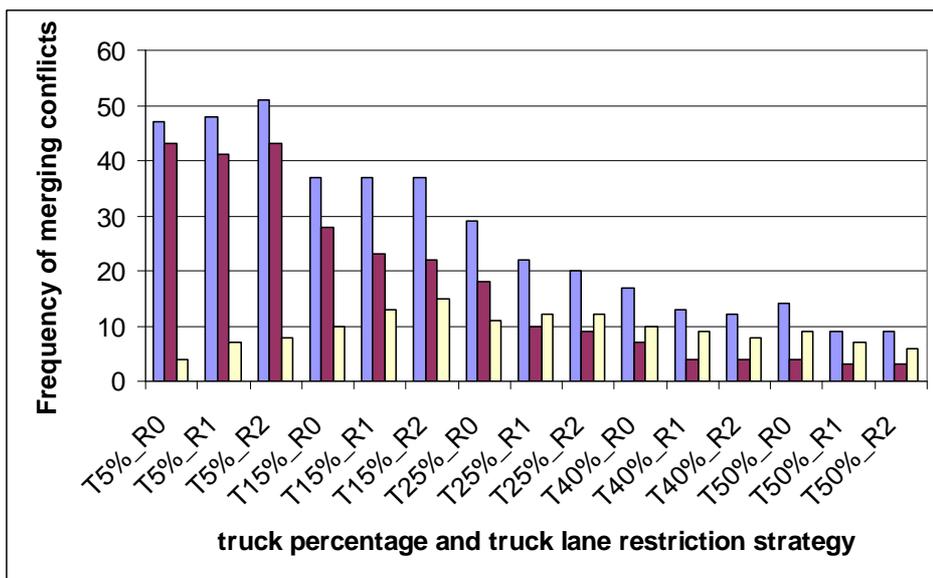


Figure B04 merging conflicts on 3-lane freeway with demand volume of 1500 vphpl

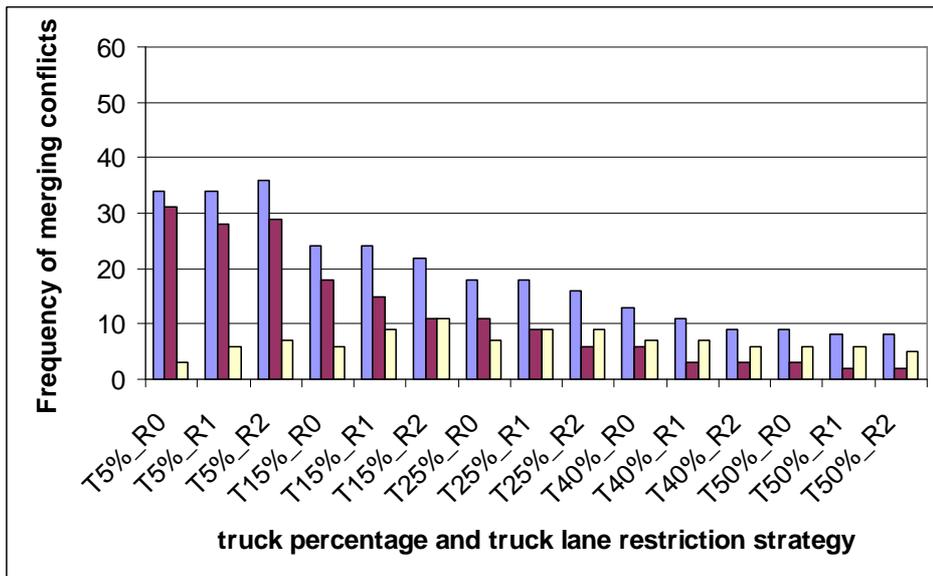


Figure B05 merging conflicts on 3-lane freeway with demand volume of 2000 vphpl

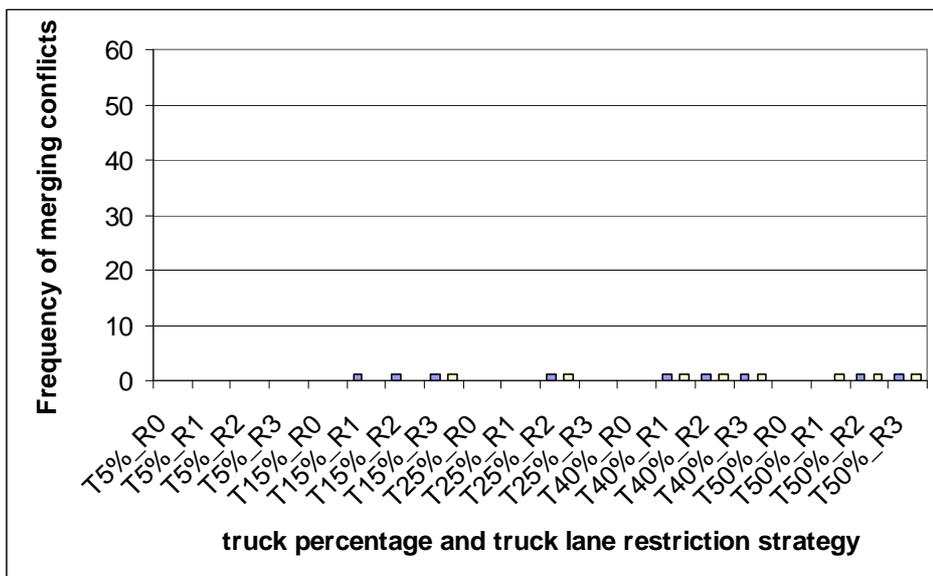


Figure B06 merging conflicts on 4-lane freeway with demand volume of 100 vphpl

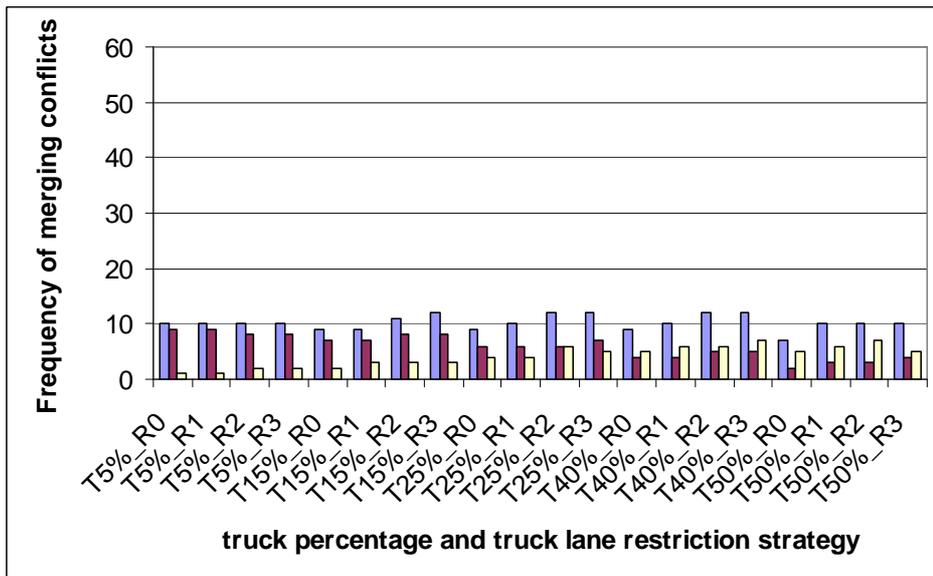


Figure B07 merging conflicts on 4-lane freeway with demand volume of 500 vphpl

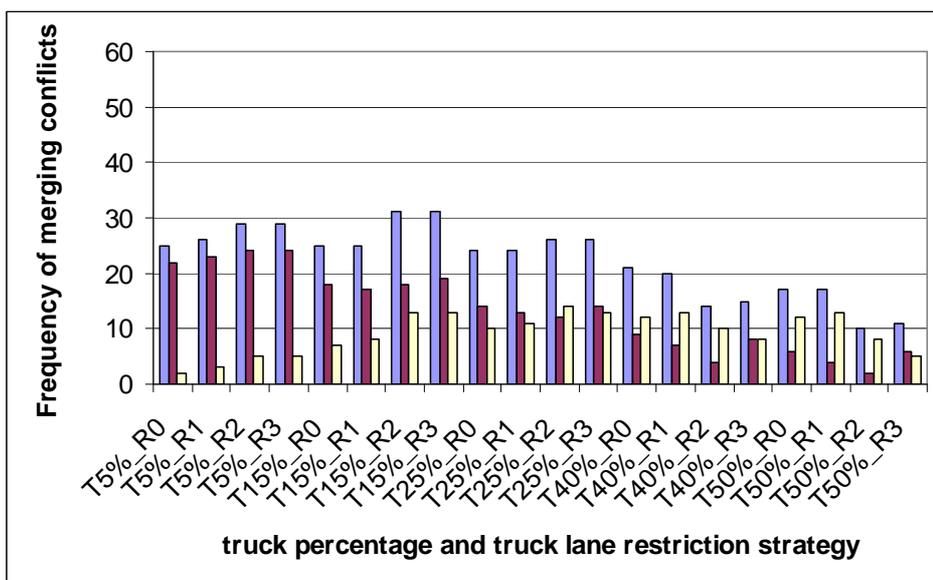


Figure B08 merging conflicts on 4-lane freeway with demand volume of 1000 vphpl

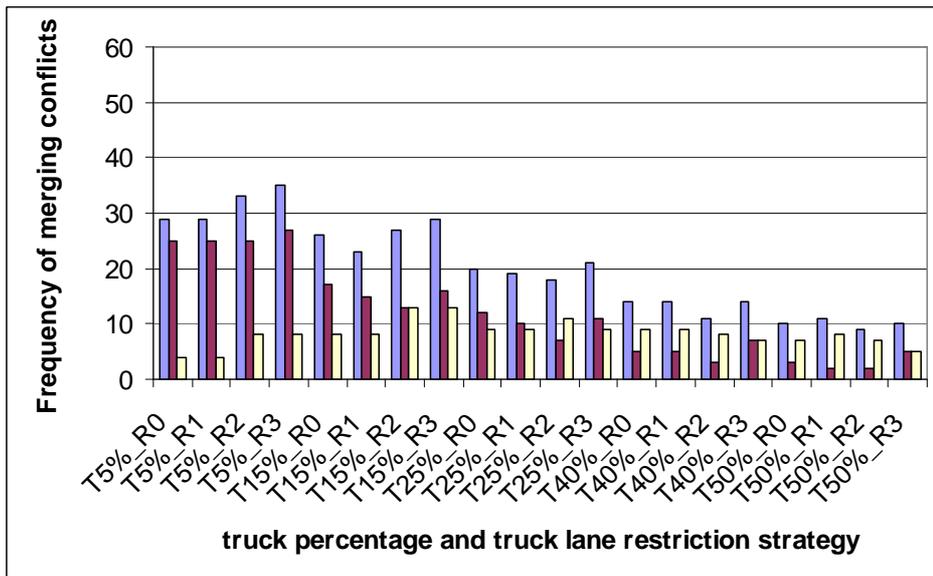


Figure B09 merging conflicts on 4-lane freeway with demand volume of 1500 vphpl

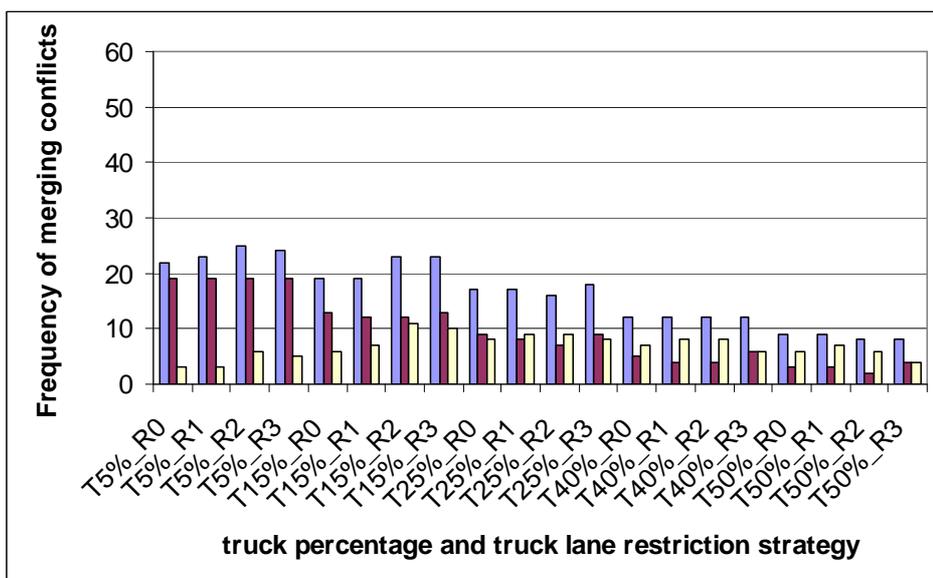


Figure B10 merging conflicts on 4-lane freeway with demand volume of 2000 vphpl

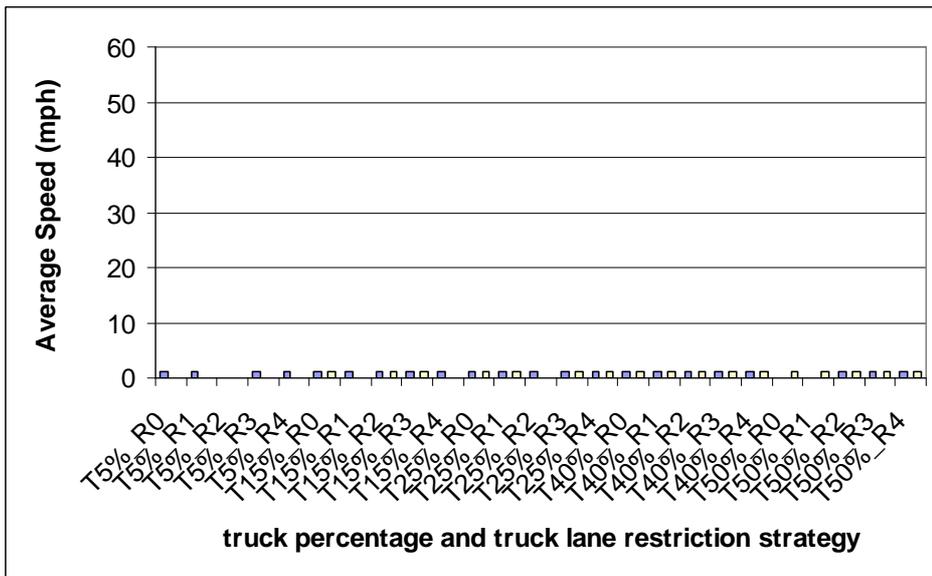


Figure B11 merging conflicts on 5-lane freeway with demand volume of 100 vphpl

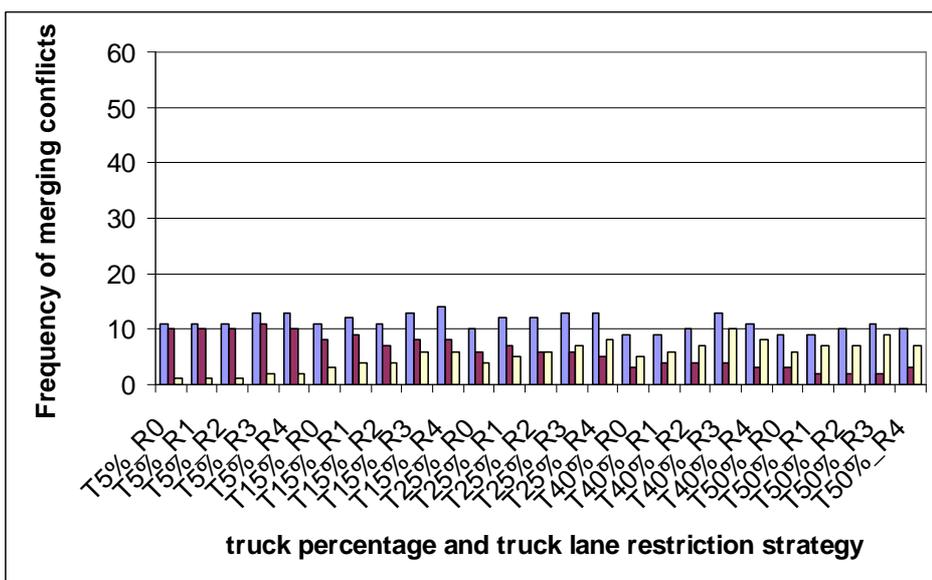


Figure B12 merging conflicts on 5-lane freeway with demand volume of 500 vphpl

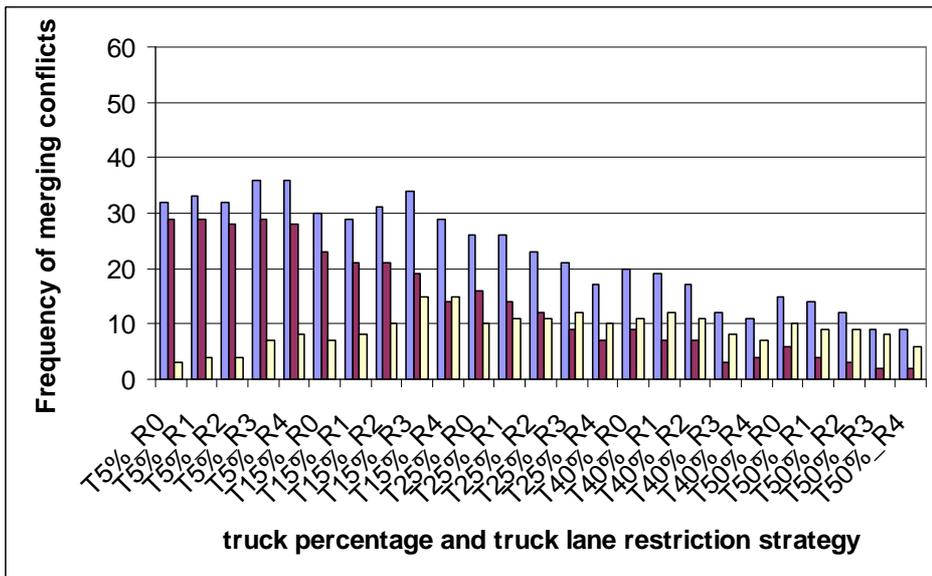


Figure B13 merging conflicts on 5-lane freeway with demand volume of 1000 vphpl

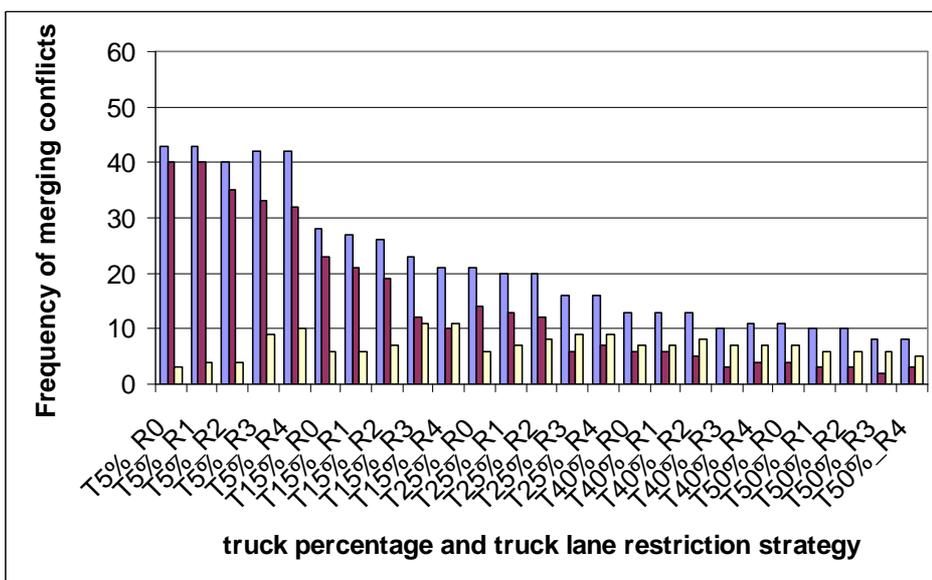


Figure B14 merging conflicts on 5-lane freeway with demand volume of 1500 vphpl



## APPENDIX C

### Graphs of Rear-End Conflicts Analysis

Please note in the following graphs:

- In each category, the first bar represents the frequency of total rear-end conflicts, the second the frequency of car-car rear-end conflicts, and the third bar represents the frequency of truck-related rear-end conflicts.
- Categories in the horizontal axis are defined by truck percentage and truck lane restriction strategy. For example, T25%\_R2 means the truck percentage is 25% and trucks are restricted from the two leftmost lanes.

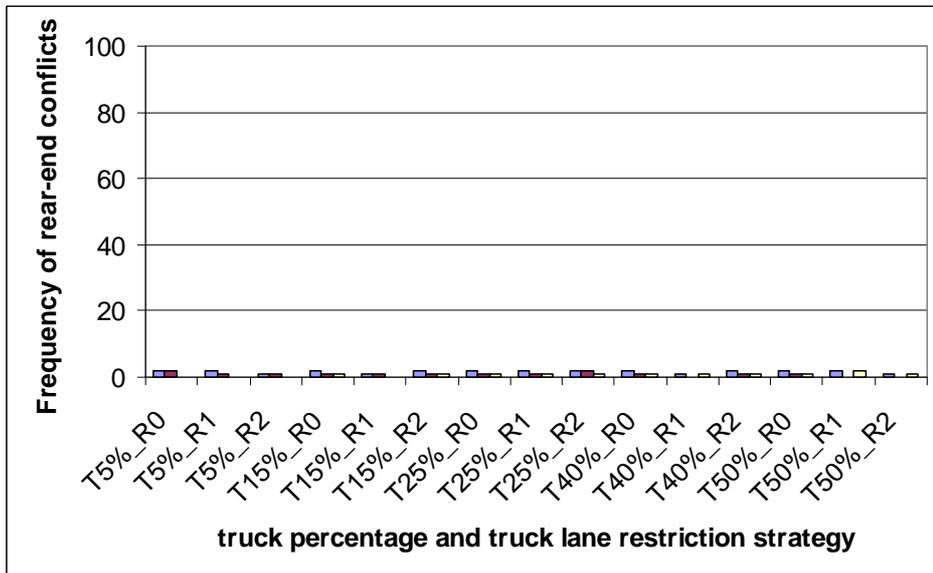


Figure C01 rear-end conflicts on 3-lane freeway with demand volume of 100 vphpl

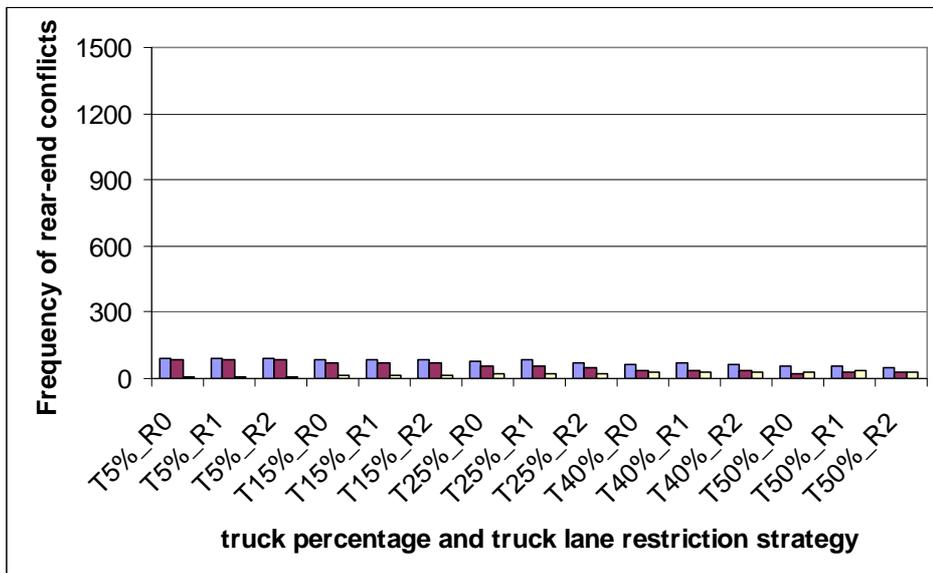


Figure C02 rear-end conflicts on 3-lane freeway with demand volume of 500 vphpl

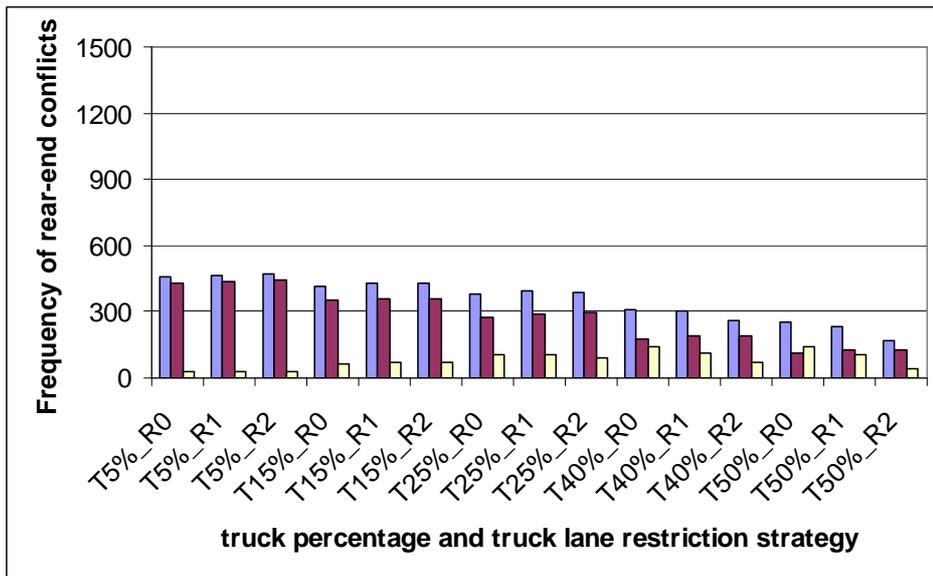


Figure C03 rear-end conflicts on 3-lane freeway with demand volume of 1000 vphpl

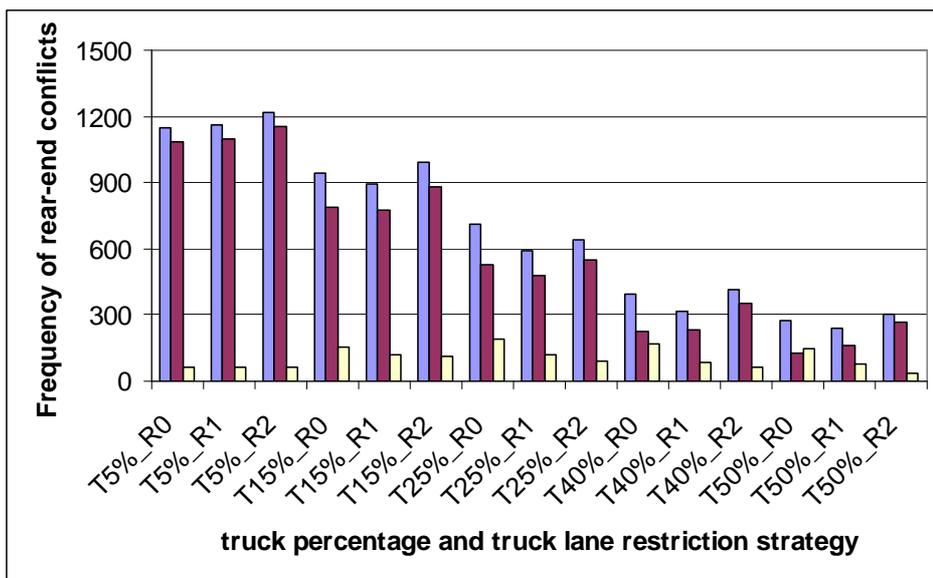


Figure C04 rear-end conflicts on 3-lane freeway with demand volume of 1500 vphpl

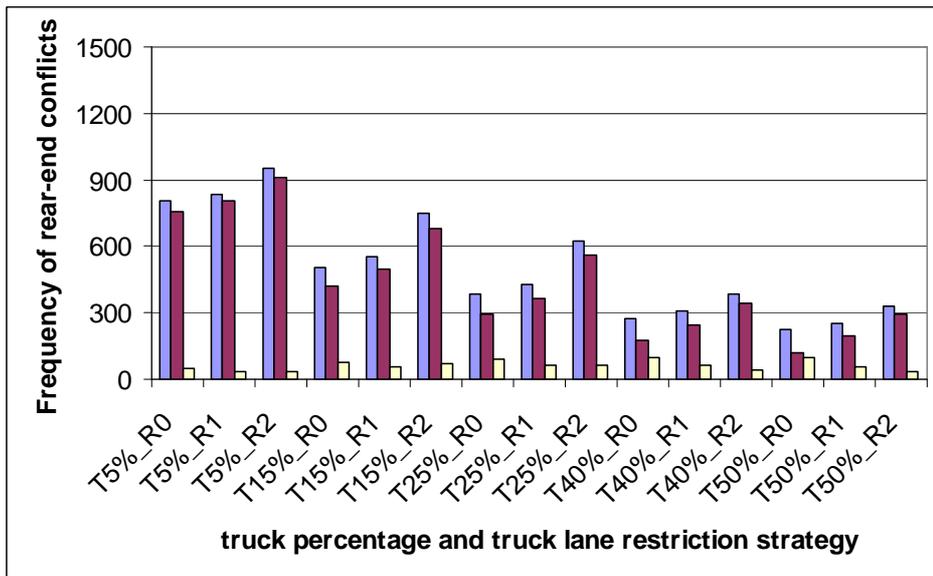


Figure C05 rear-end conflicts on 3-lane freeway with demand volume of 2000 vphpl

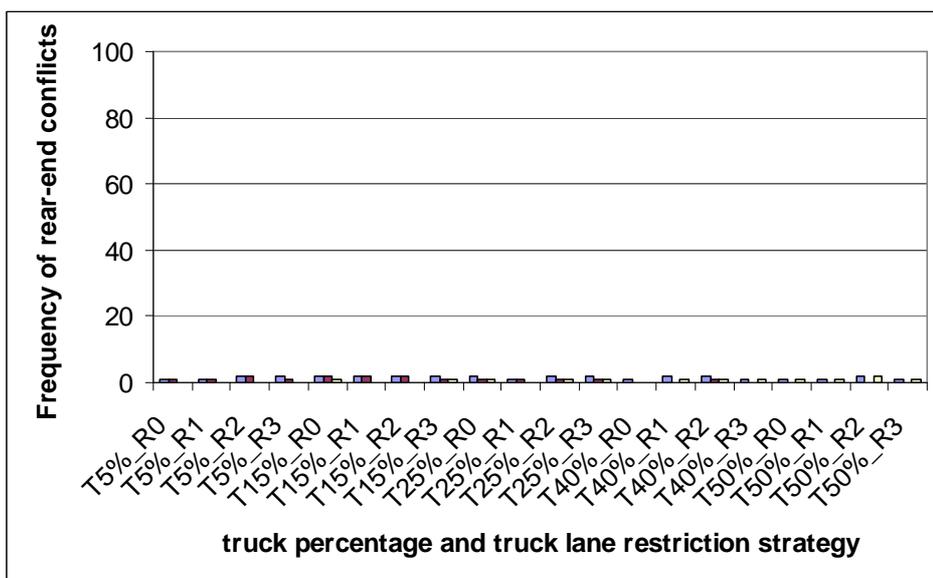


Figure C06 rear-end conflicts on 4-lane freeway with demand volume of 100 vphpl

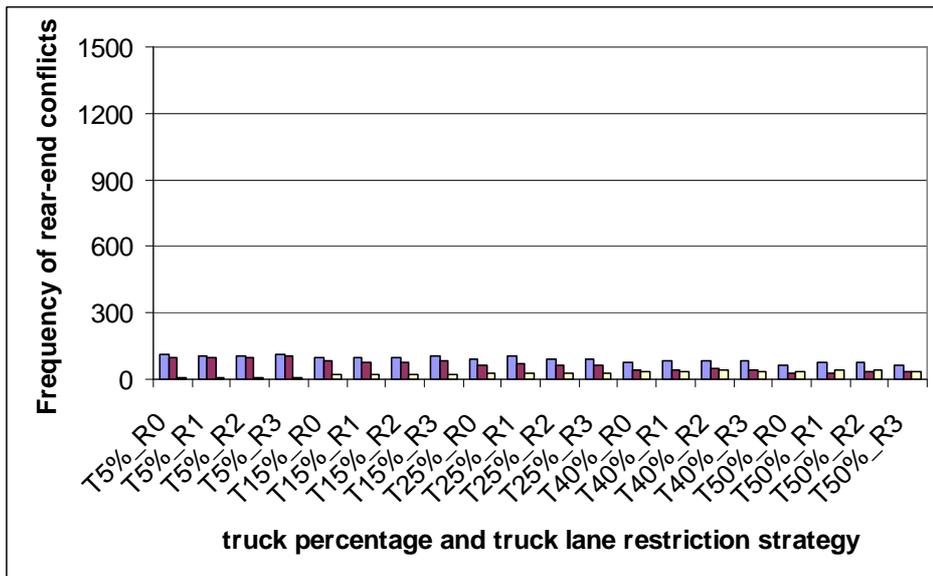


Figure C07 rear-end conflicts on 4-lane freeway with demand volume of 500 vphpl

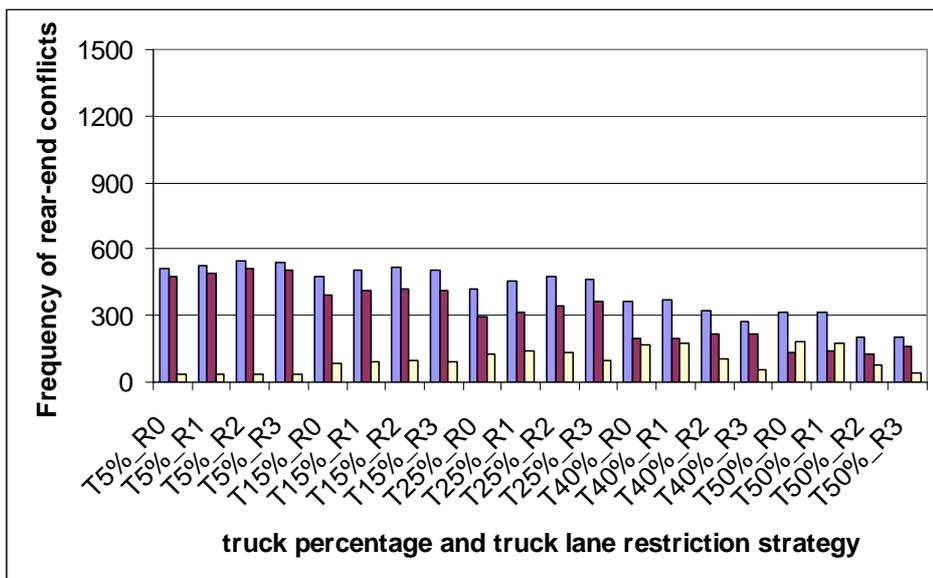


Figure C08 rear-end conflicts on 4-lane freeway with demand volume of 1000 vphpl

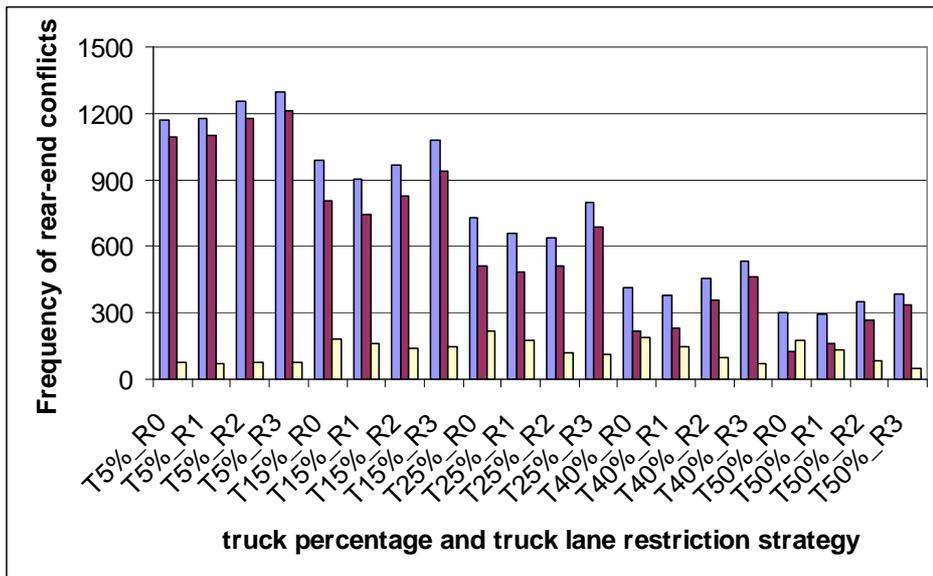


Figure C09 rear-end conflicts on 4-lane freeway with demand volume of 1500 vphpl

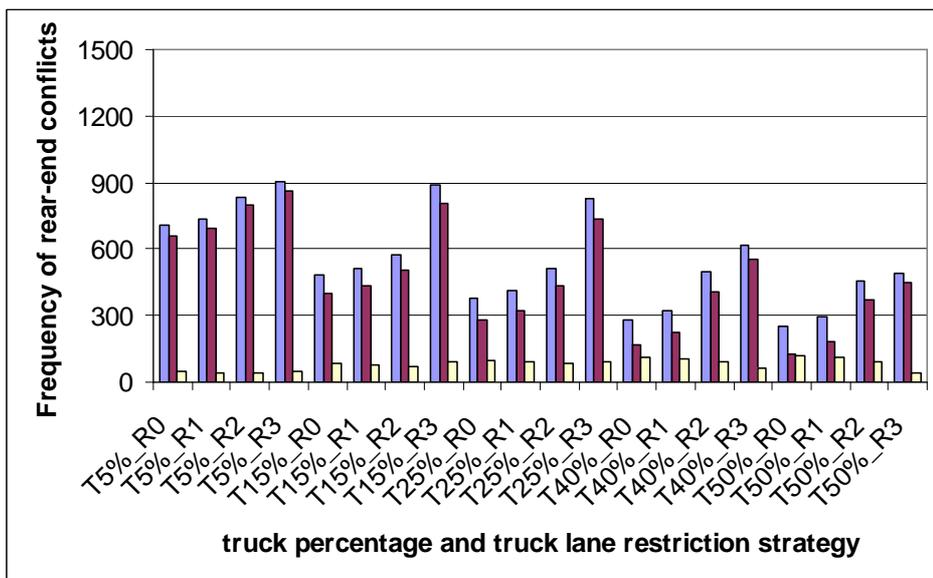


Figure C10 rear-end conflicts on 4-lane freeway with demand volume of 2000 vphpl

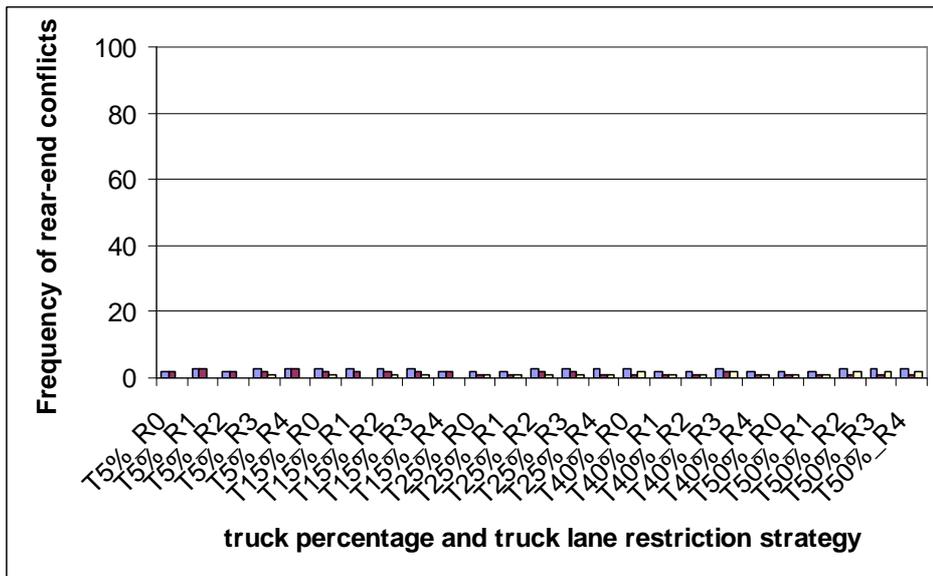


Figure C11 rear-end conflicts on 5-lane freeway with demand volume of 100 vphpl

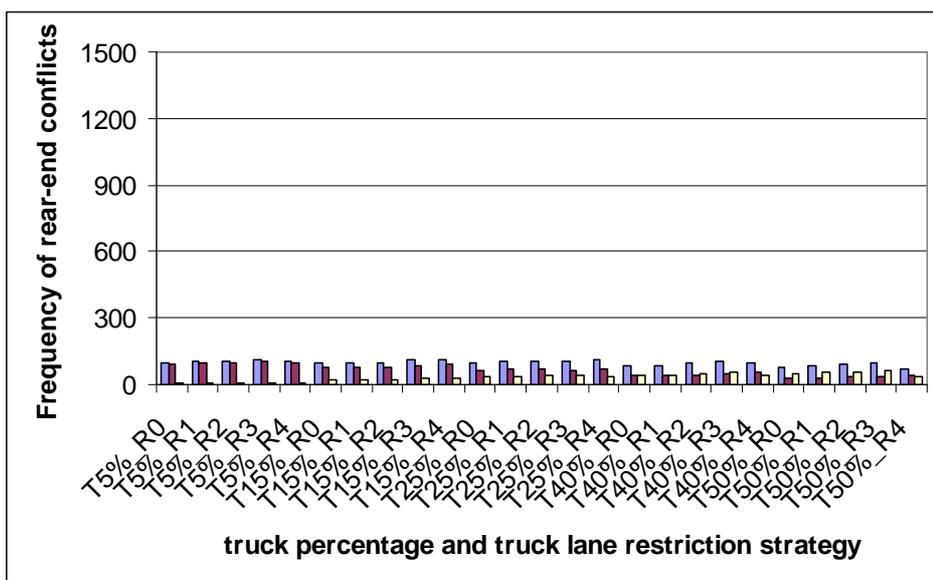


Figure C12 rear-end conflicts on 5-lane freeway with demand volume of 500 vphpl

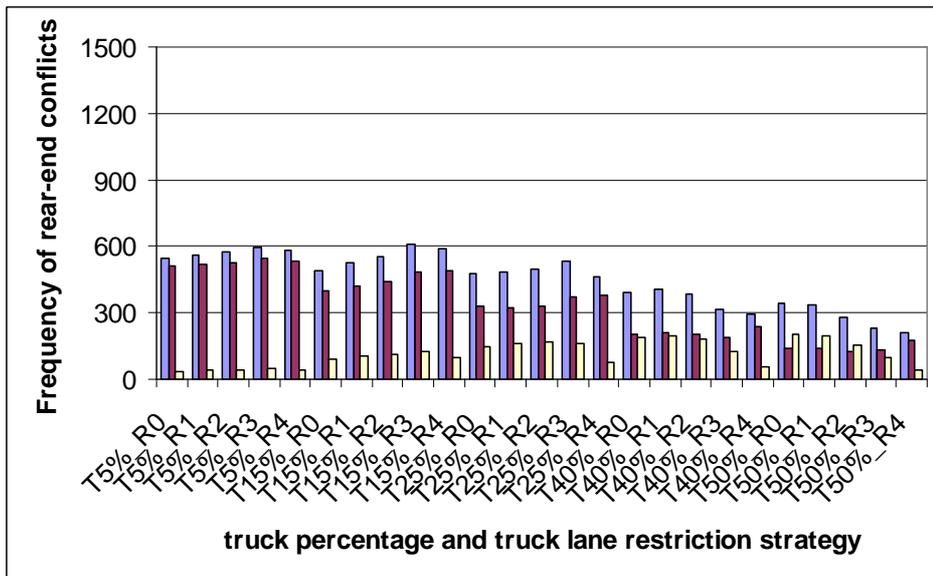


Figure C13 rear-end conflicts on 5-lane freeway with demand volume of 1000 vphpl

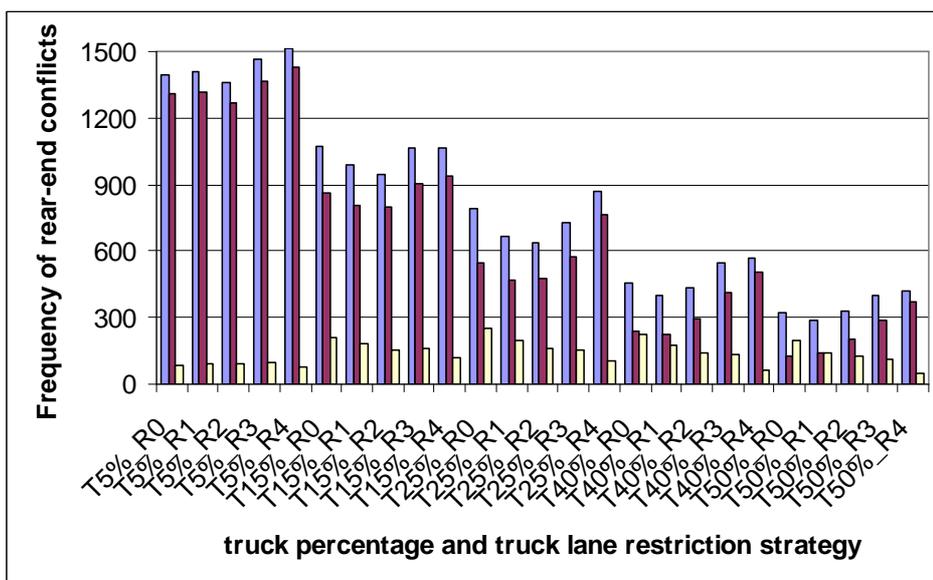


Figure C14 rear-end conflicts on 5-lane freeway with demand volume of 1500 vphpl

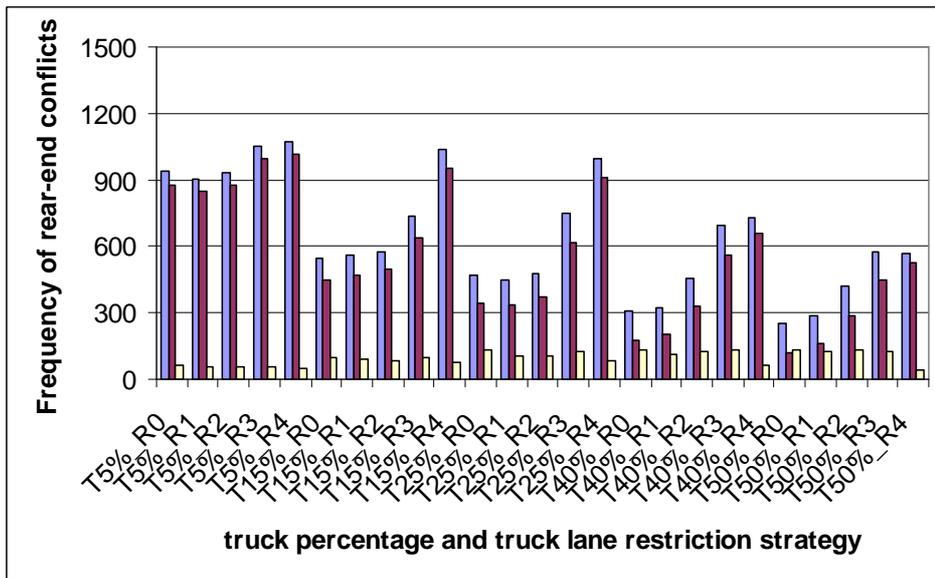


Figure C15 rear-end conflicts on 5-lane freeway with demand volume of 2000 vphpl

## **APPENDIX D**

### **Graphs of Average Speed Analysis**

Please note in the following graphs:

- In each category, the first bar represents the average speed in restricted lanes, the second the average speed in unrestricted lanes, and the third bar represents average speed of trucks.
- Categories in the horizontal axis are defined by truck percentage and truck lane restriction strategy. For example, T25%\_R2 means the truck percentage is 25% and trucks are restricted from the two leftmost lanes.

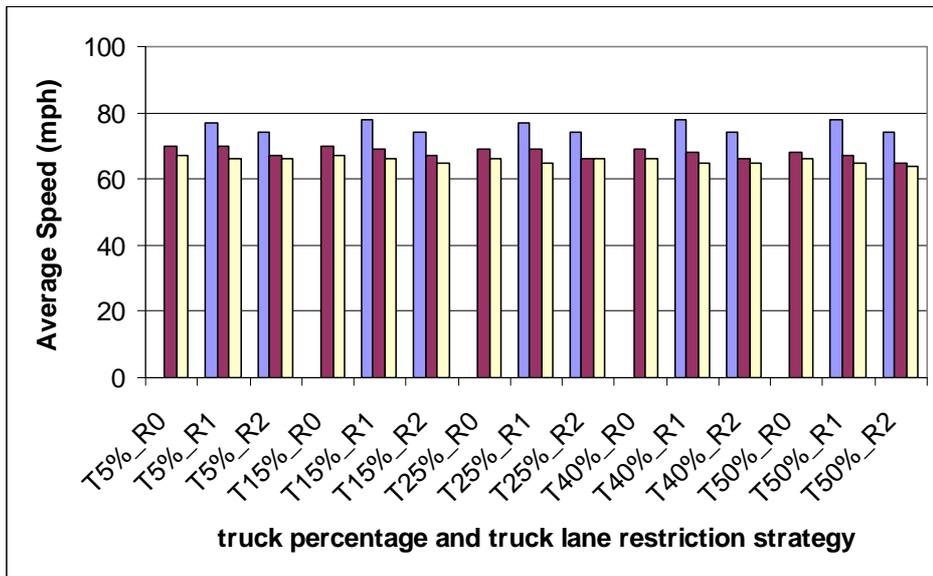


Figure D01 Average speed on 3-lane freeway with demand volume level of 100 vphpl

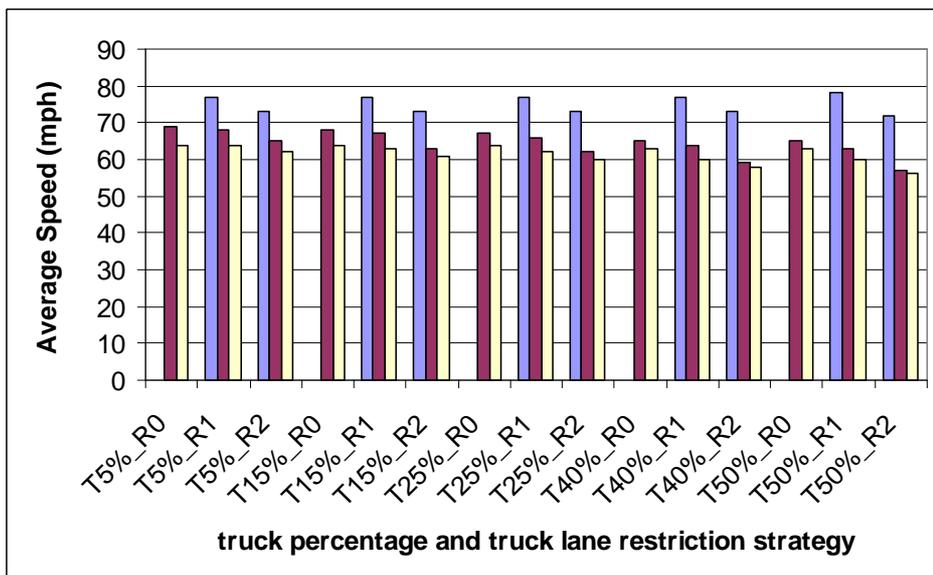


Figure D02 Average speed on 3-lane freeway with demand volume level of 500 vphpl

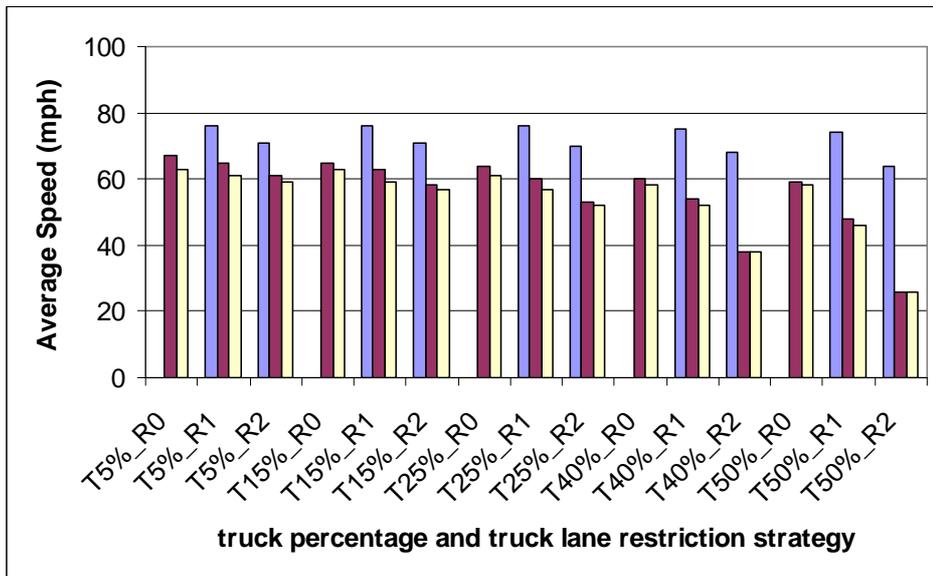


Figure D03 Average speed on 3-lane freeway with demand volume level of 1000 vphpl

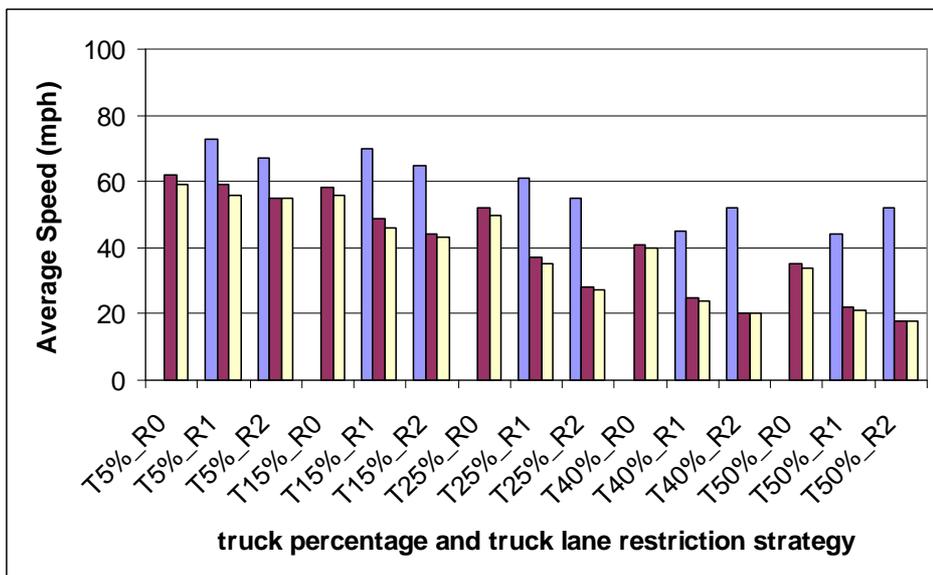


Figure D04 Average speed on 3-lane freeway with demand volume level of 1500 vphpl

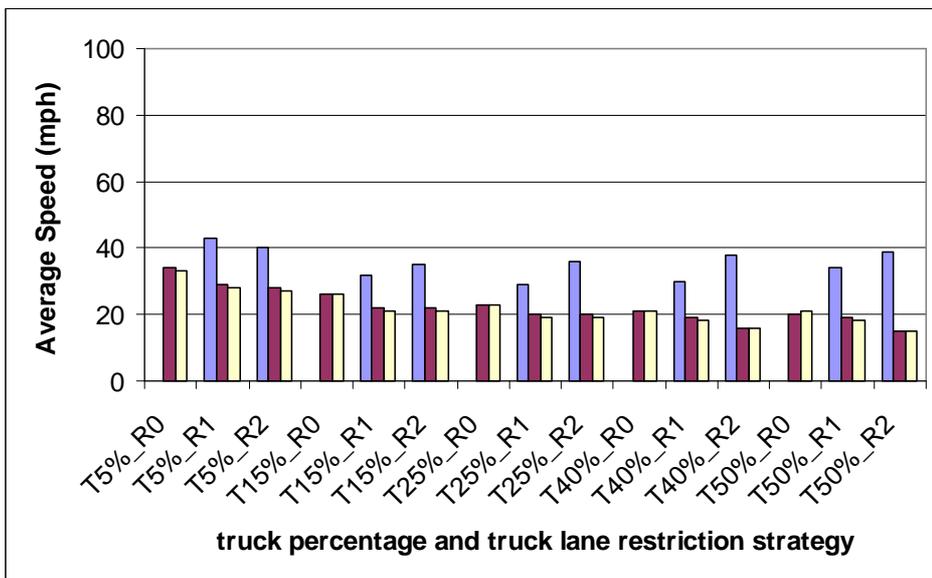


Figure D05 Average speed on 3-lane freeway with demand volume level of 2000 vphpl

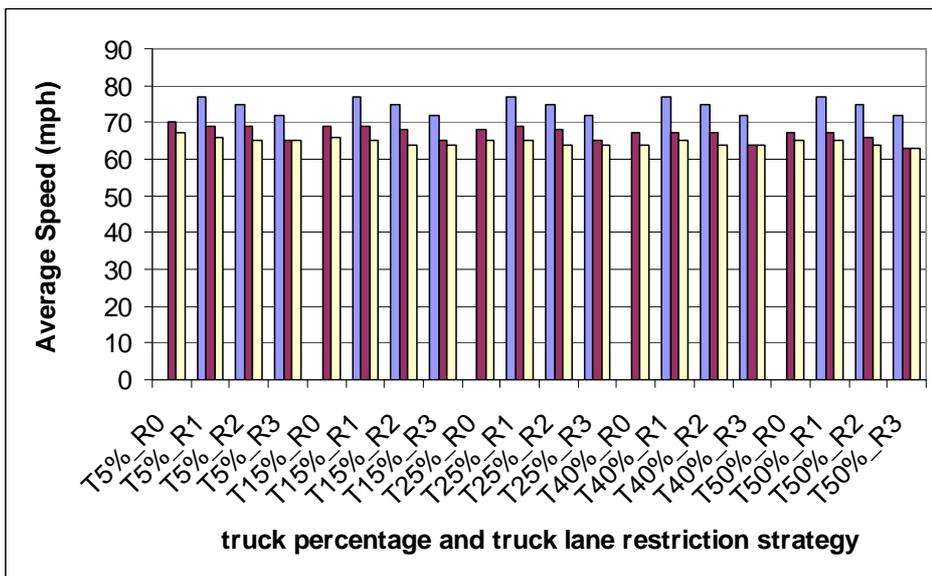


Figure D06 Average speed on 4-lane freeway with demand volume level of 100 vphpl

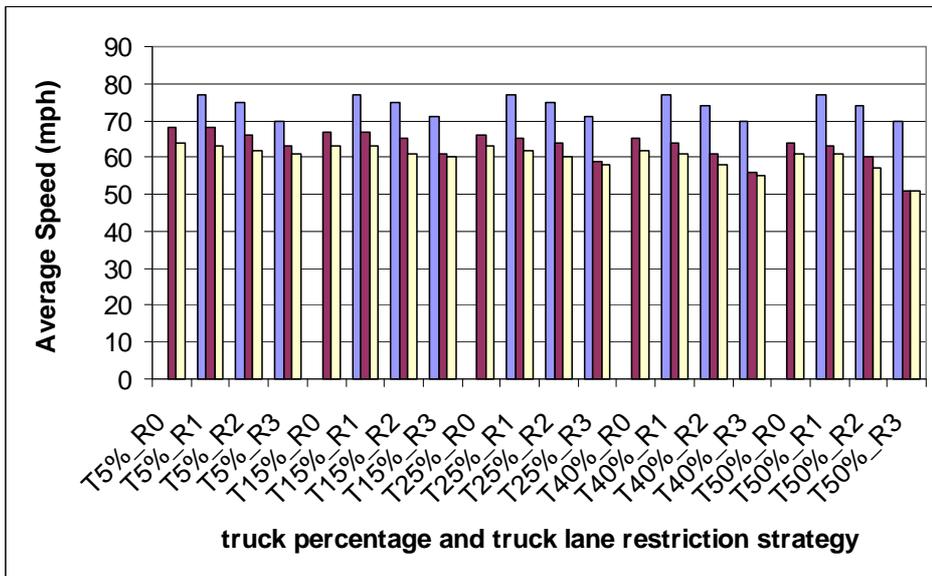


Figure D07 Average speed on 4-lane freeway with demand volume level of 500 vphpl

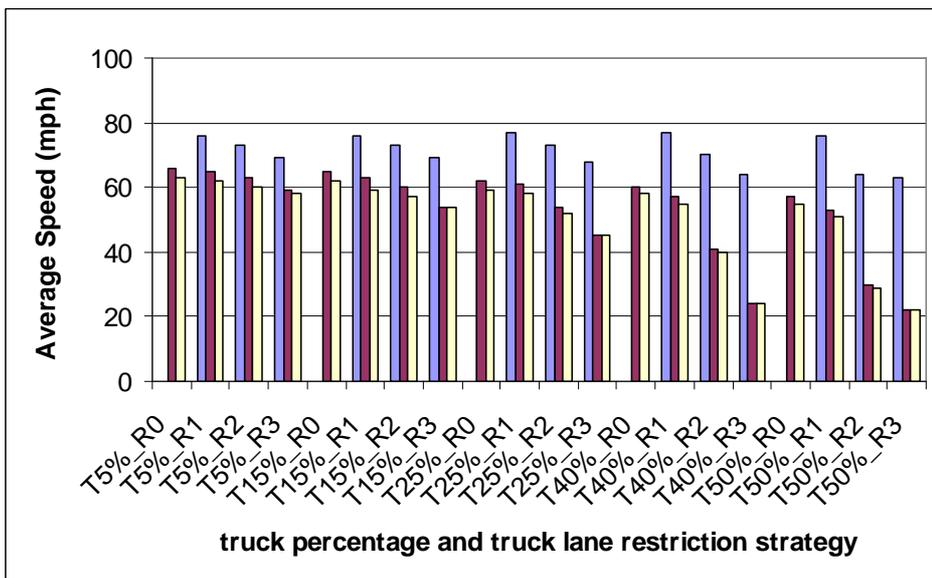


Figure D08 Average speed on 4-lane freeway with demand volume level of 1000 vphpl

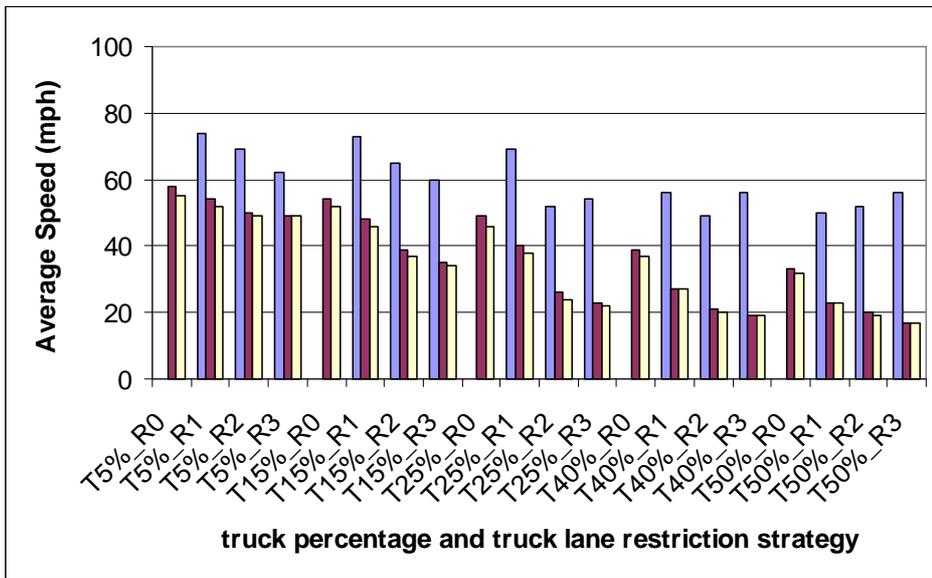


Figure D09 Average speed on 4-lane freeway with demand volume level of 1500 vphpl

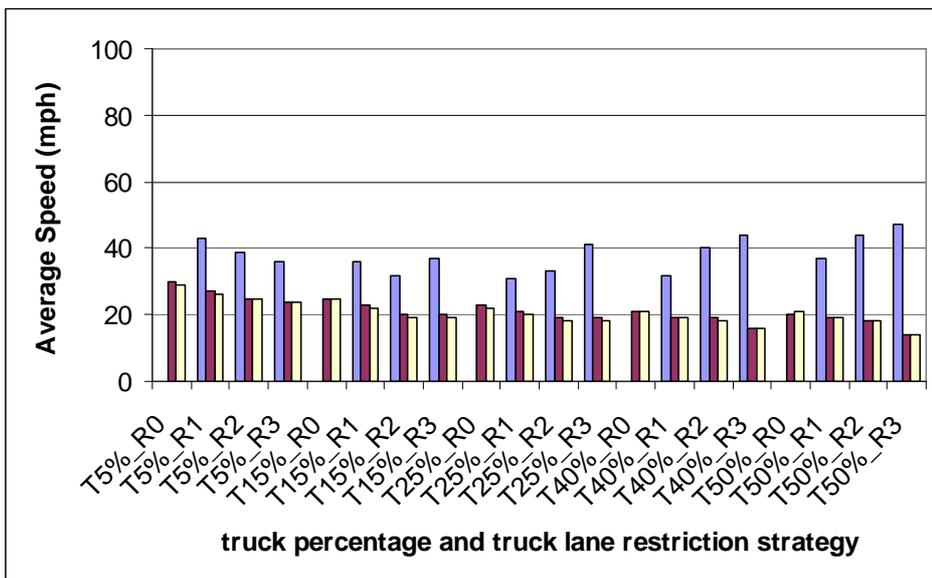


Figure D10 Average speed on 4-lane freeway with demand volume level of 2000 vphpl

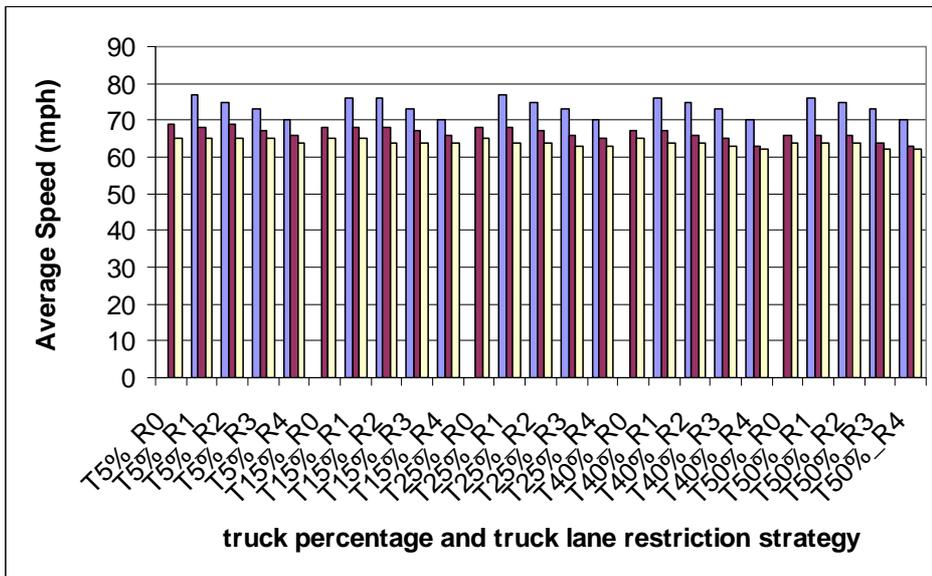


Figure D11 Average speed on 5-lane freeway with demand volume level of 100 vphpl

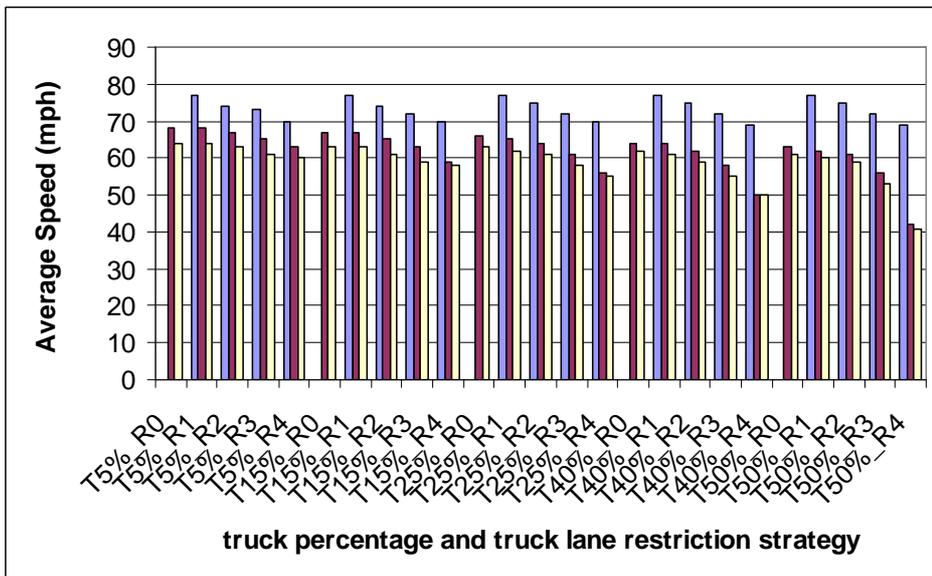


Figure D12 Average speed on 5-lane freeway with demand volume level of 500 vphpl

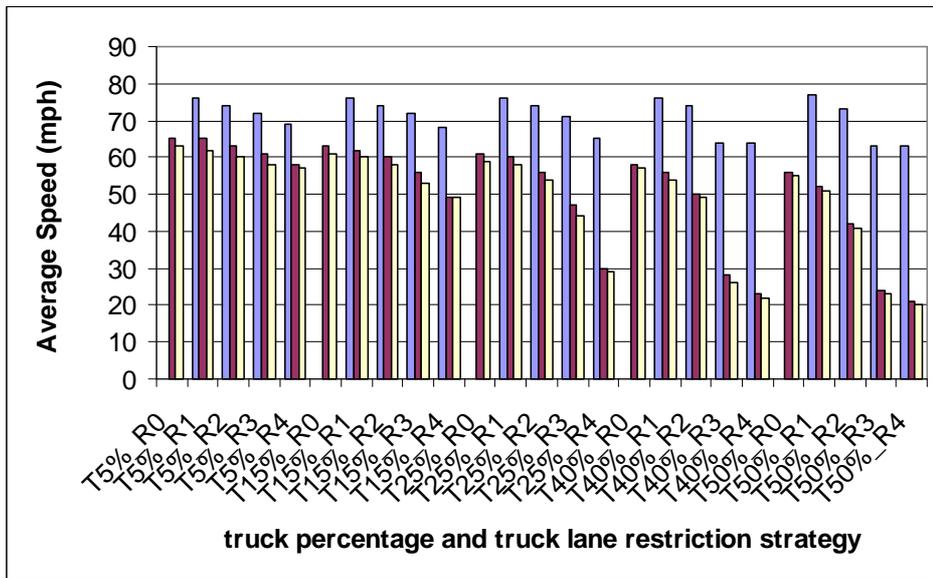


Figure D13 Average speed on 5-lane freeway with demand volume level of 1000 vphpl

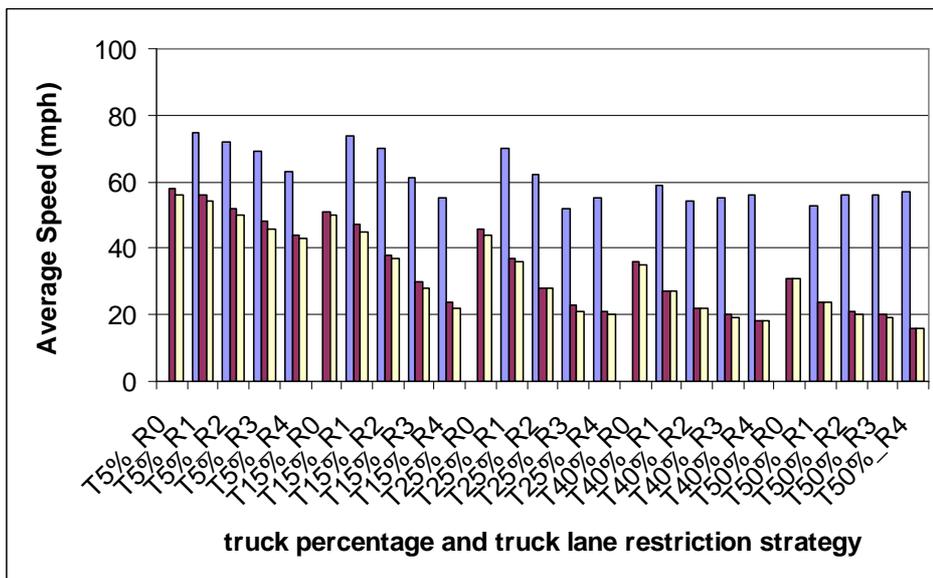


Figure D14 Average speed on 5-lane freeway with demand volume level of 1500 vphpl

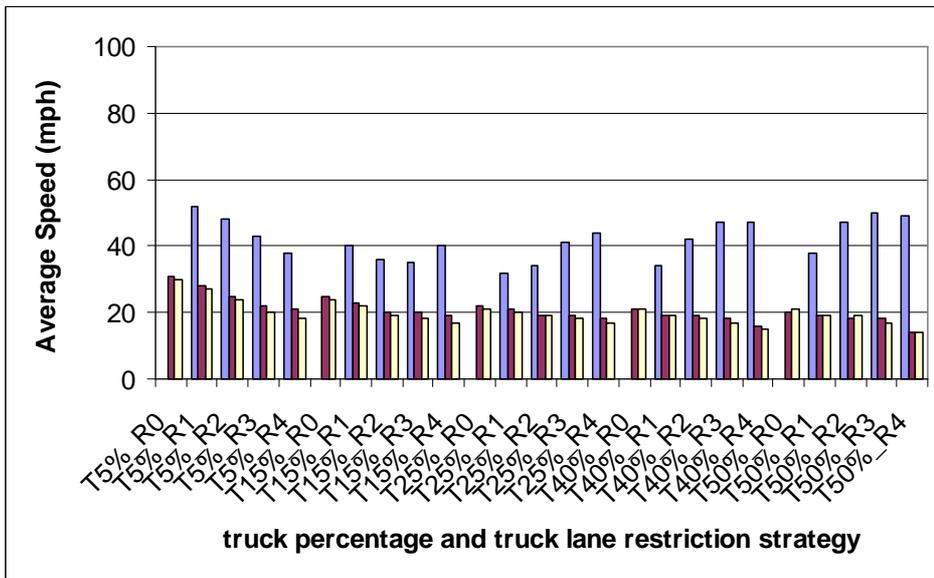


Figure D15 Average speed on 5-lane freeway with demand volume level of 2000 vphpl

## **APPENDIX E**

### **Graphs of Average Density Analysis**

Please note in the following graphs:

- In each category, the first bar represents the density in restricted lanes, and the second represents the density in unrestricted lanes.
- Categories in the horizontal axis are defined by truck percentage and truck lane restriction strategy. For example, T25%\_R2 means the truck percentage is 25% and trucks are restricted from the two leftmost lanes.

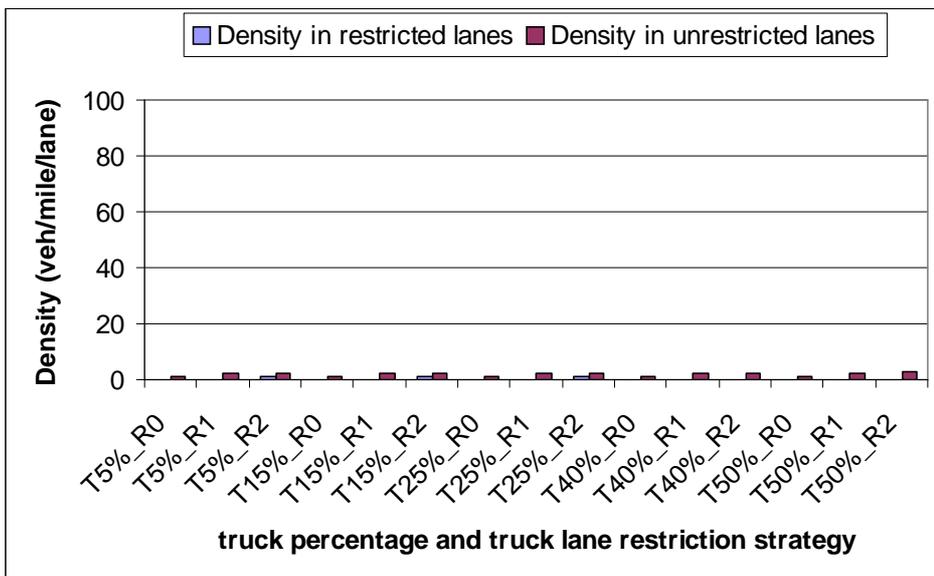


Figure E01 Average density on 3-lane freeway with demand volume level of 100 vphpl

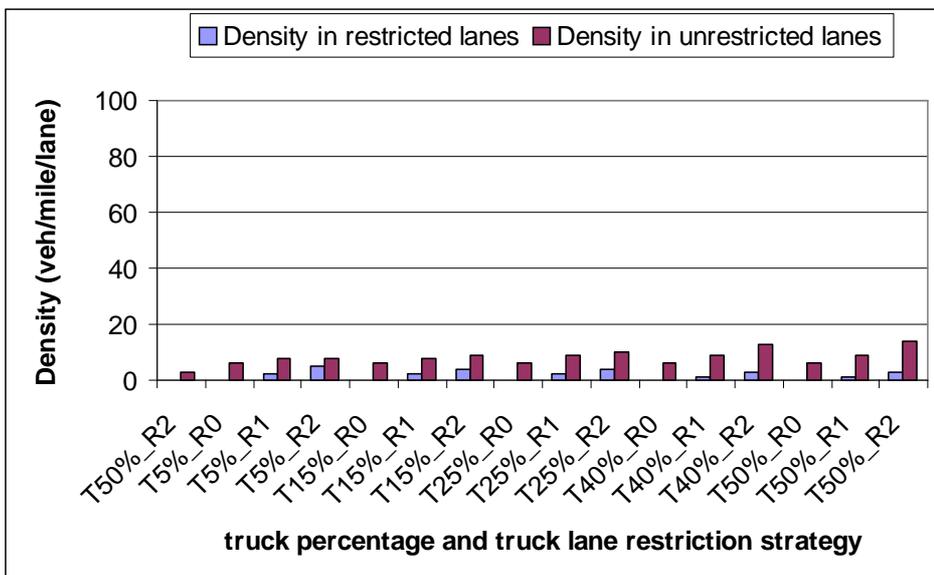


Figure E02 Average density on 3-lane freeway with demand volume level of 500 vphpl

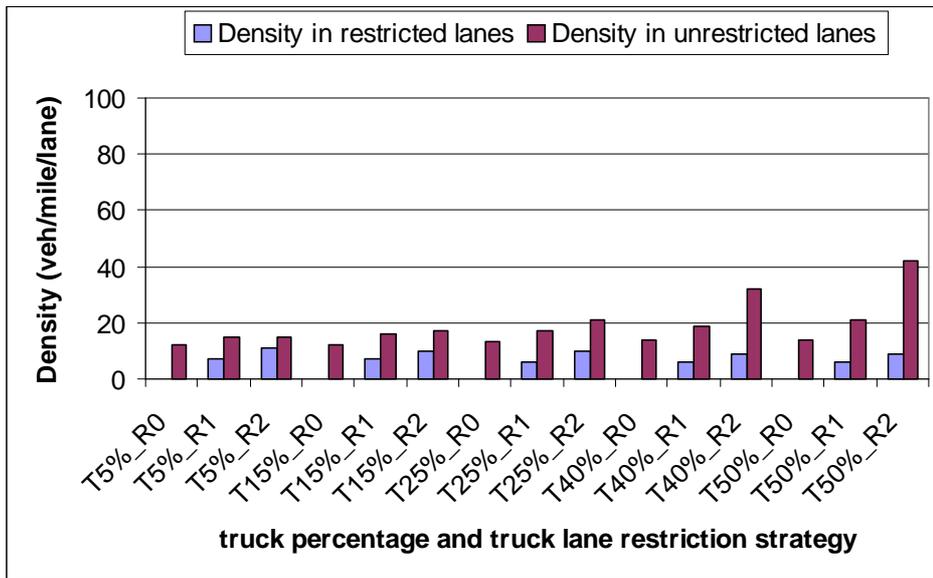


Figure E03 Average density on 3-lane freeway with demand volume level of 1000 vphpl

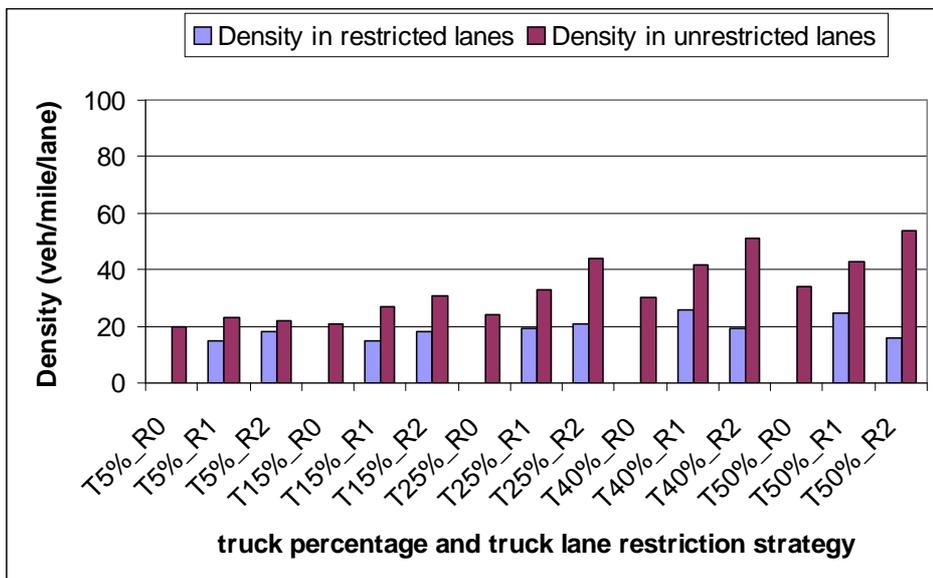


Figure E04 Average density on 3-lane freeway with demand volume level of 1500 vphpl

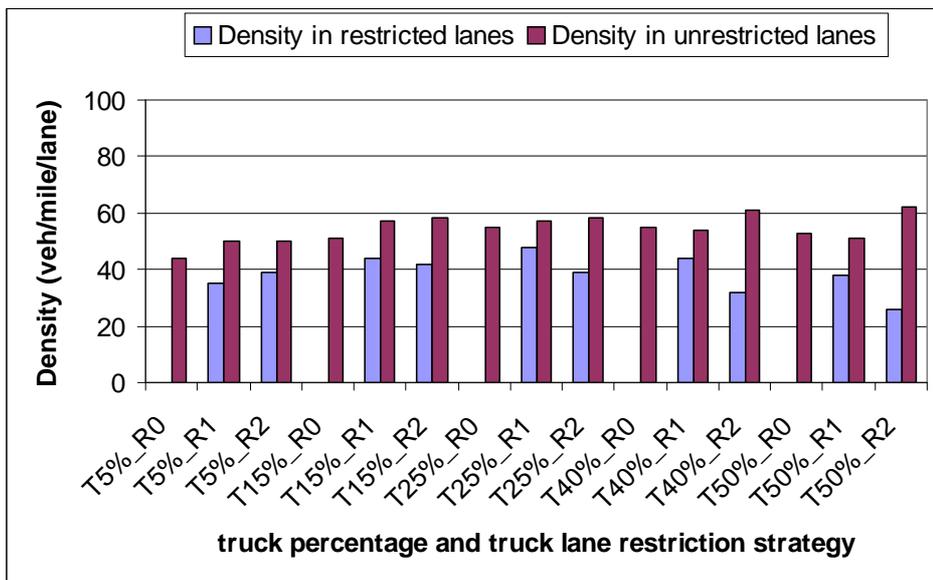


Figure E05 Average density on 3-lane freeway with demand volume level of 2000 vphpl

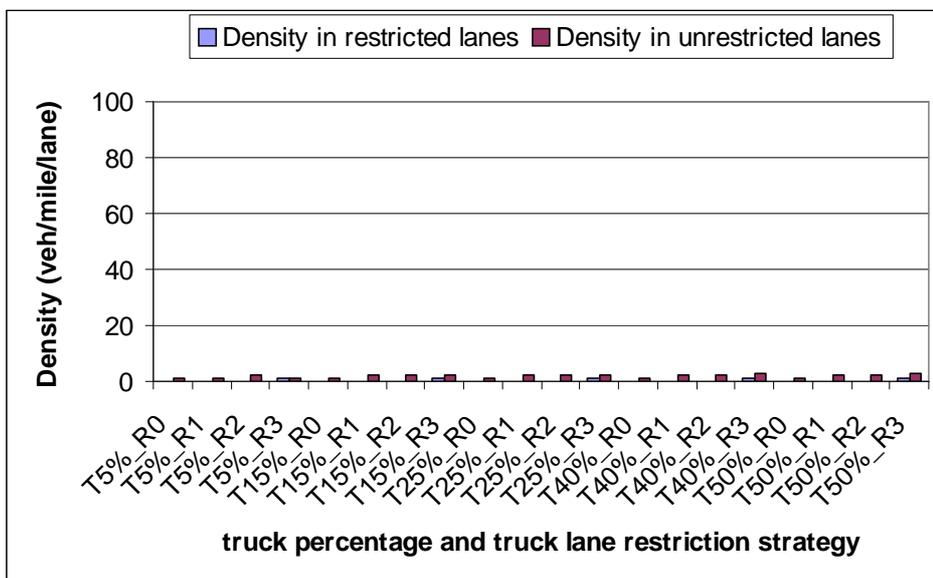


Figure E06 Average density on 4-lane freeway with demand volume level of 100 vphpl

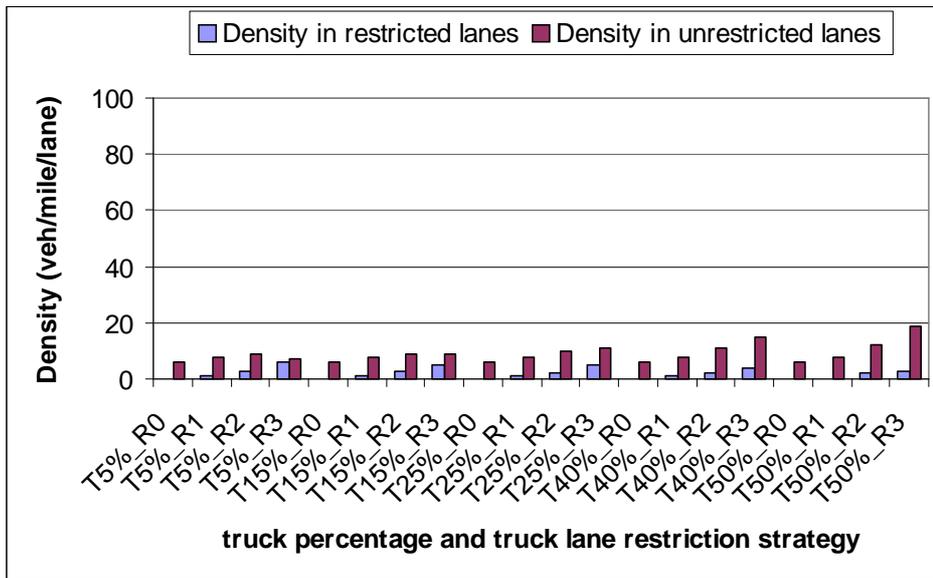


Figure E07 Average density on 4-lane freeway with demand volume level of 500 vphpl

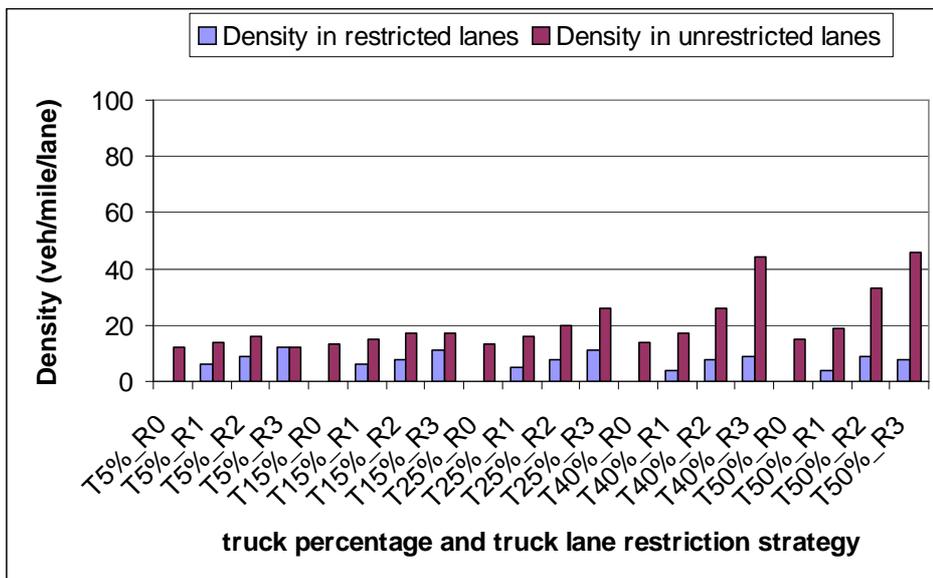


Figure E08 Average density on 4-lane freeway with demand volume level of 1000 vphpl

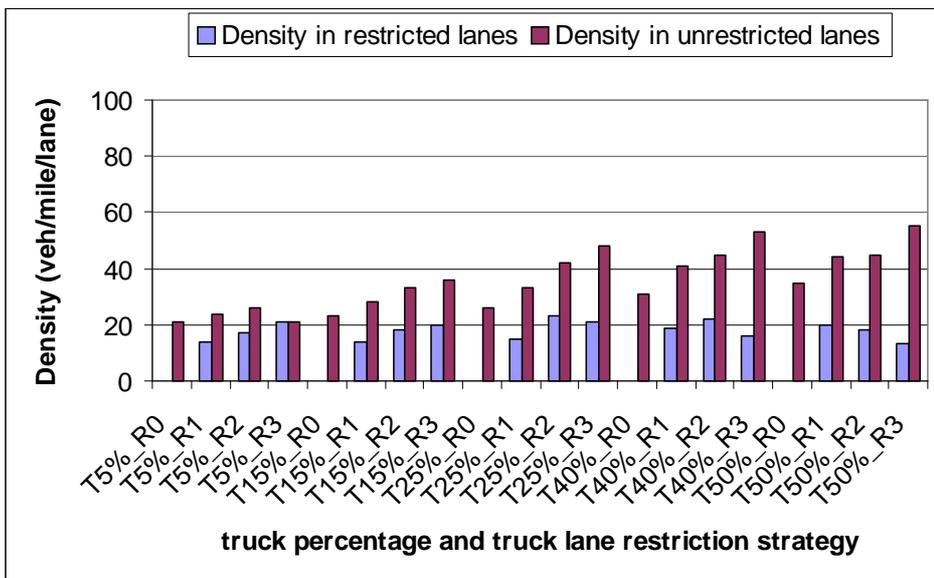


Figure E09 Average density on 4-lane freeway with demand volume level of 1500 vphpl

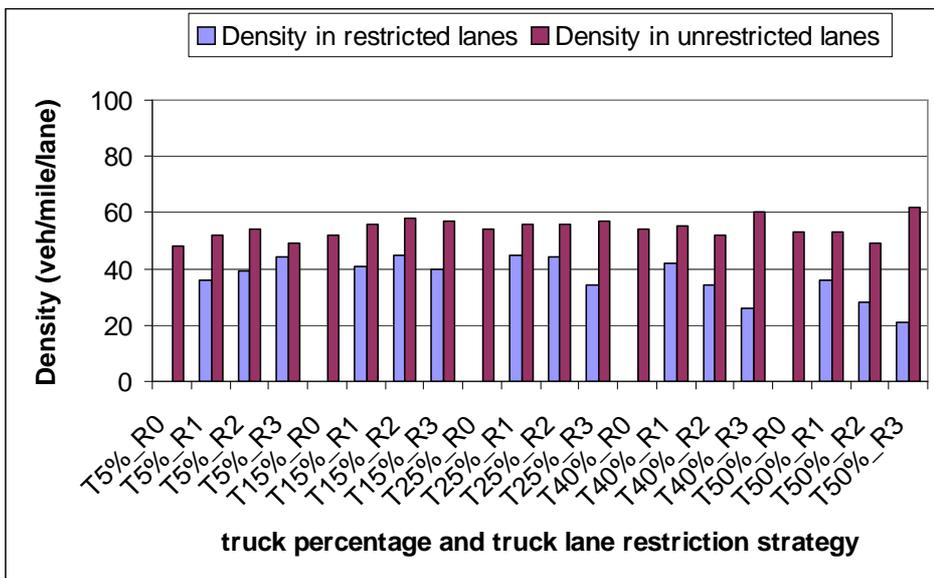


Figure E10 Average density on 4-lane freeway with demand volume level of 2000 vphpl

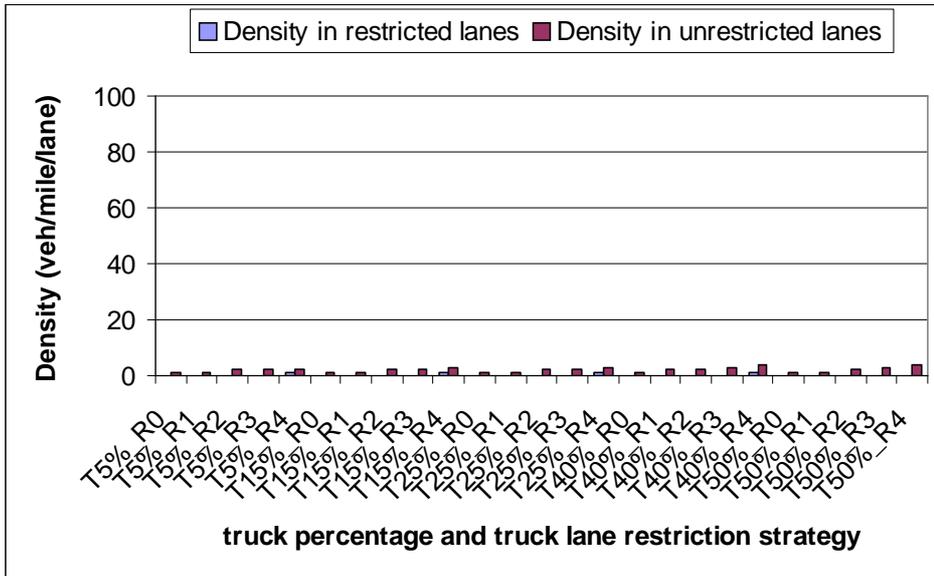


Figure E11 Average density on 5-lane freeway with demand volume level of 100 vphpl

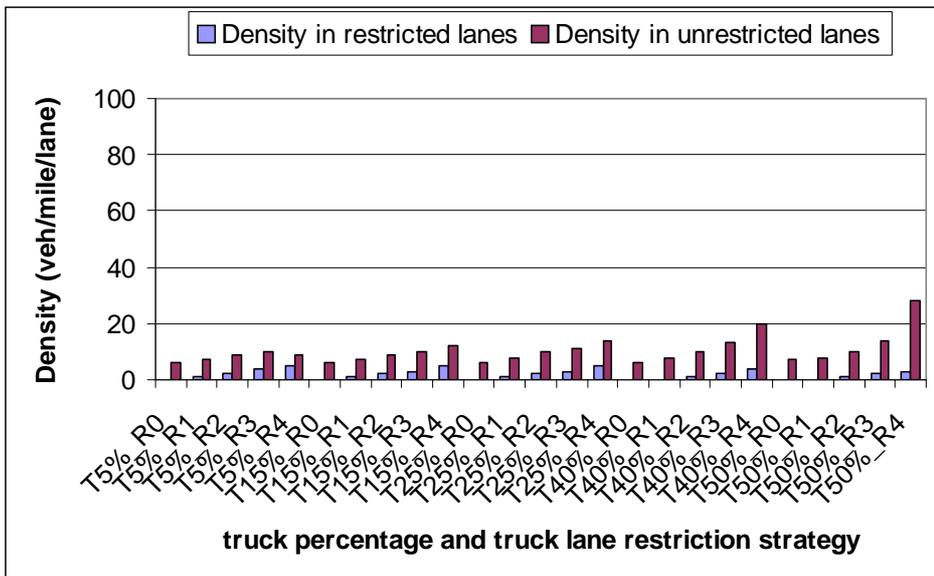


Figure E12 Average density on 5-lane freeway with demand volume level of 500 vphpl

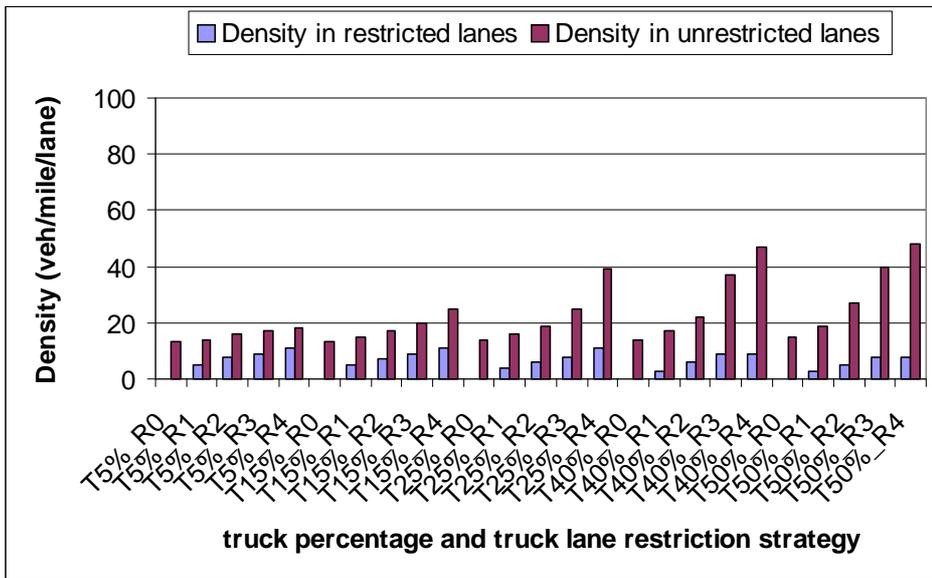


Figure E13 Average density on 5-lane freeway with demand volume level of 1000 vphpl

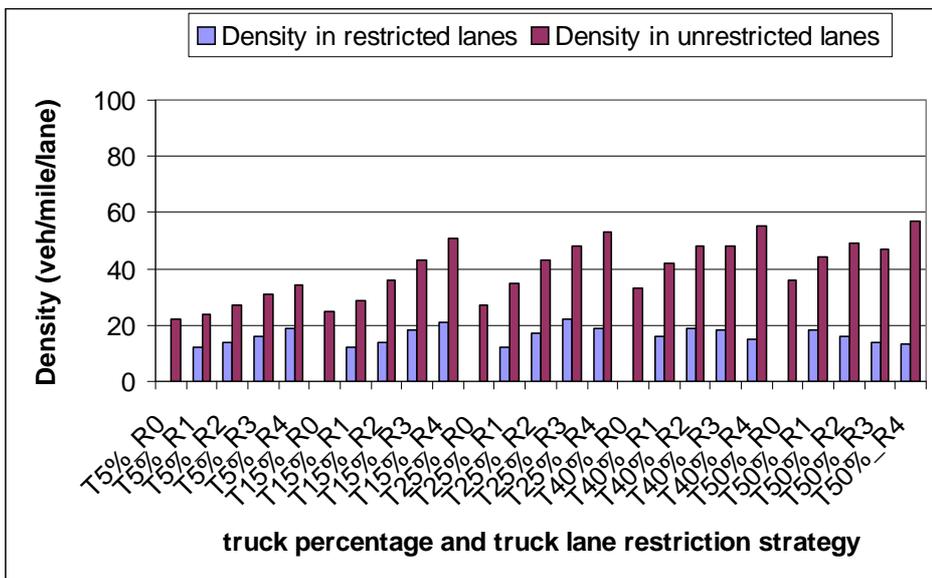


Figure E14 Average density on 5-lane freeway with demand volume level of 1500 vphpl

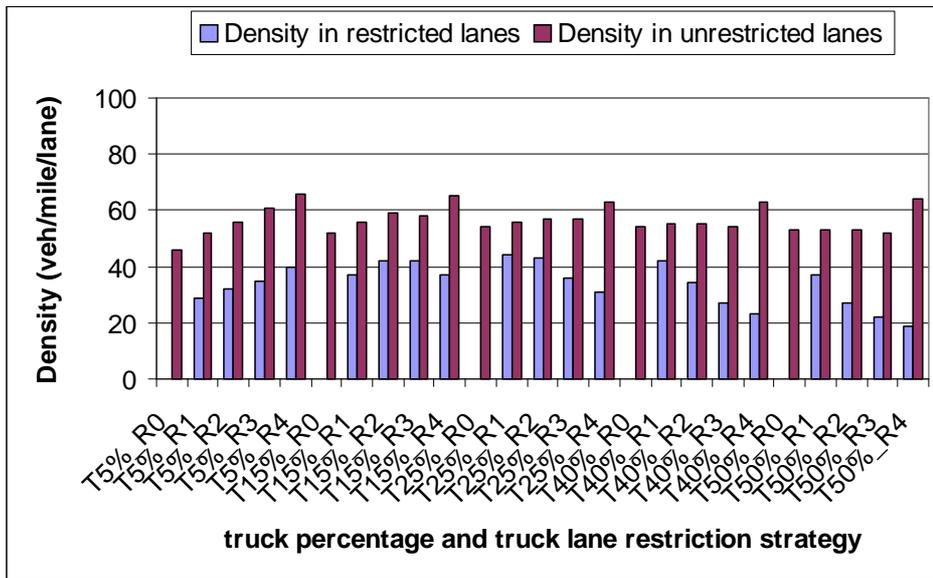


Figure E15 Average density on 5-lane freeway with demand volume level of 2000 vphpl