MODELING THE INTERACTION BETWEEN PASSENGER CARS AND TRUCKS

A Dissertation

by

JACQUELINE MARIE JENKINS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2004

Major Subject: Civil Engineering

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Approved as to style and content by:

Laurence R. Rilett (Chair of Committee)	Rodger J. Koppa (Member)
Mark W. Burris (Member)	Cliff H. Spiegelman (Member)
Paul Roschke (Head of Department)	

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ABSTRACT

Modeling the Interaction Between Passenger Cars and Trucks. (August 2004)

Jacqueline Marie Jenkins, Ba.Sc., University of Waterloo;

M.E., Texas A&M University

Chair of Advisory Committee: Dr. Laurence R. Rilett

The topic of this dissertation was the use of distributed computing to improve the modeling of the interaction between passenger cars and trucks. The two main focus areas were the development of a methodology to combine microscopic traffic simulation programs with driving simulator programs, and the application of a prototype distributed traffic simulation to study the impact of the length of an impeding vehicle on passing behavior.

The methodology was motivated by the need to provide an easier way to create calibrated traffic flows in driving simulations and to capture vehicle behavior within microscopic traffic simulations. The original design for the prototype was to establish a two-way, real time exchange of vehicle data, however problems were encountered that imposed limitations on its development and use.

The passing study was motivated by the possible changes in federal truck size and weight regulations and the current inconsistency between the passing sight distance criteria for the design of two lane highways and the marking of no-passing zones. Test drivers made passing maneuvers around impeding vehicles that differed in length and speed. The main effects of the impeding vehicle length were found to be significant for the time and distance in the left lane, and the start and end gap distances.

Passing equations were formulated based on the mechanics of the passing maneuver and included behavior variables for calibration. Through a sensitivity analysis, it was shown that increases in vehicle speeds, vehicle length, and gap distance increased the distance traveled in the left lane, while increases in the speed difference and speed gain decreased the distance traveled in the left lane. The passing equations were calibrated using the current AASHTO values and used to predict the impact of increased vehicle lengths on the time and distance in the left lane. The passing equations are valuable for evaluating passing sight distance criteria and observed passing behavior.

DEDICATION

This is dedicated to Derek

Together
We ride out the trials and tribulations
And celebrate the accomplishments
With love

ACKNOWLEDGEMENTS

I have spent over five years in College Station, attending Texas A&M University, and there are many friends, colleagues, and mentors that I have to thank for my success. Their guidance, encouragement, and support are truly appreciated.

First of all, I thank Dave Richardson for introducing me to the late Daniel Fambro and for encouraging me to attend Texas A&M University. His continued support over the years is truly appreciated and I value our friendship.

The next person to thank is Dr. Laurence Rilett for his guidance, tutelage, and general advise. As my graduate chair, he made an investment in my studies and I surely hope that he is as pleased with the outcome as I am. I also owe thanks to Dr. Rodger Koppa for introducing me to the area of human factors, granting me the opportunity to gain some practical experience, and providing input on this research. In addition, I thank Drs. Cliff Spiegelman and Mark Burris for their effort and comments. Several other people who I thank for their contributions to this research are Michael Manser, Ashwin Kekre, Roelof Engelbrecht, Sangita Sunkari, Gary Gandy, and of course all those test drivers who participated in the passing study.

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I also thank the AAA Foundation for Traffic Safety, the Texas Transportation Institute, and the Southwest Region Transportation University Center for the financial support that I received.

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1 INTRODUCTION

The topic of this dissertation was the use of distributed computing to improve the modeling of the interaction between passenger cars and trucks. There were two main areas of focus for this research. The first focus area was the development of a methodology to combine microscopic traffic simulation programs with driving simulator programs. This was motivated by the current capabilities of such programs and the potential to increase their usefulness through the development and application of distributed simulations. A distributed traffic simulation, combining a traffic simulation and a driving simulation, would provide a way to create specific traffic flows in the driving simulation and capture both driver and traffic data simultaneously, thus allowing the interactions between vehicles, the roadway, and the environment to be investigated. The results could be utilized to improve how vehicle movements are modeled in simulations.

The second focus area was the application of a distributed traffic simulation. The specific application was the problem of predicting how the length of an impeding vehicle impacts the passing behavior of drivers and was taken into account during the creation of a prototype distributed traffic simulation. Investigation into this problem was motivated by the existing inadequacies of the passing sight distance design criteria and the current no-passing zone marking practices which may be exacerbated by a future increase in the federal regulations on truck weights and sizes. The results were used to develop a passing distance equation that was based on the mechanics of the maneuver and included behavior variables. This equation could be used to evaluate passing sight distance criteria and passing behavior observed in the field.

1.1 Background

To understand the motivations behind the first area of focus, the capabilities of microscopic traffic simulation programs and driving simulator programs were reviewed along with the current High Level Architecture (HLA) standards used to guide the creation of distributed simulations. To understand the motivations behind the second area of focus, the current passing sight distance criteria were reviewed along with the history of passing studies. These literature

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This dissertation follows the style and format of the *Transportation Research Record*.

reviews are summarized in the following sections and comprehensively detailed in Sections 2 and 3.

1.1.1 Microscopic Traffic Simulation Programs

A microscopic traffic simulation model is a simplified description of a traffic system that includes details about the traffic network, traffic controls, and the movement of individual vehicles. Theories of car following and lane changing that explain the fundamental relationships between vehicles and the interaction with traffic controls under specific roadway environments are derived from facts, conjecture, reasoning, speculation, and supposition. These theories are the basis of the program logic controlling the movement of vehicles. Dynamic, stochastic models are capable of mimicking complex traffic systems and are studied through simulation.

The general acceptance and popularity of traffic simulation programs is evident by the inclusion of a chapter on simulation and other models in the 2000 version of the Highway Capacity Manual (*1*). In a review conducted in 1997 (*2*), fifty-seven existing microscopic traffic simulation programs were identified that were used to simulate the operation of intersections, urban street networks, freeways, integrated networks, et cetera.

Microscopic traffic simulation programs are used to evaluate and optimize traffic systems, predict the impact of changes, evaluate alternatives, and conduct sensitivity analyses. They model individual vehicles and have the ability to simulate sophisticated vehicle movements, however their ability to model complex behavioral aspects are limited.

Many programs output statistics on the operation of the traffic system being simulated, such as delays, travel times, level of service, etc., but provide little information about driver behavior. In fact, parameters used to calibrate the simulation reflect the behavior of drivers in the system but rarely have a direct interpretation.

It is becoming common for microscopic traffic simulation programs to include some sort of visualization capability to view the traffic simulation. This capability provides the means to visually verify that the simulation is behaving as expected and to identify where operational problems are occurring in the simulated network.

1.1.2 Driving Simulator Programs

Driving simulators have developed as a visualization tool and have been used for driver training and driving research including perceptual, cognitive, and behavioral studies. Test drivers control a vehicle in a computer generated driving environment and details about the test drivers' control of the vehicle are captured. The use of driving simulators has grown as illustrated by the variety of commercial systems available as well as the variety of driving simulators that continue to develop through independent research efforts. INRETS maintains a listing of driving simulators that currently includes over fifty research simulators and twenty training simulators from around the world (*3*).

Driving simulators are an attractive alternative to field and course testing as the test drivers are in a safe and highly controlled driving environment. The human-in-the-loop nature of the apparatus allows the stochastic and dynamic nature of driver behavior to be captured. In addition, personal contact with the test drivers provides the opportunity to administer detailed questionnaires about the test drivers' driving habits, experience, health, et cetera.

One of the issues in developing driving simulators is how to create traffic that can behave autonomously and at the same time have traffic that can be specifically controlled to create a highly orchestrated traffic environment. So far, a combination of scripted vehicles, which are programmed to behave in a predetermined fashion, and ambient traffic, which is made up of randomly generated vehicles that act as background traffic to add a sense of realism to the driving environment have been used. Generally, vehicles move according to some vehicle attributes such as the acceleration, speed, headway, tailway, et cetera. While these techniques are suitable for creating a driving scenario with relatively few vehicles, problems arise when specific, or calibrated traffic flows are desired or when the movement of vehicles needs to mimic real car following and lane changing behavior.

The output from driving simulator programs is largely focused on measures of driver behavior and vehicle control. Little information is available about the traffic environment being modeled. This limitation can be problematic when details about the traffic or the movement of a group of vehicles are required. For instance, to conduct a gap acceptance study the spacing between consecutive vehicles is needed.

1.1.3 Distributed Traffic Simulations

The main advantage of distributed computing is the flexibility of combining a variety of disparate simulations while maintaining the integrity of the individual simulations. In a distributed traffic simulation, a number of traffic simulations are combined to run together taking advantage of the strengths of the individual simulations. Information about vehicle movements, traffic controls and other dynamic entities can be communicated between the individual simulations.

A distributed traffic simulation that combines a microscopic traffic simulation with a driving simulator could be used to investigate the interaction between passenger cars and trucks for a variety of driving behaviors such as car following, lane changing, and passing under a variety of traffic environments since both driver and traffic data could be recorded simultaneously. Driver behavior studies could be conducted using a traffic simulation that is calibrated to existing or predicted future traffic conditions. The results of these studies could be used to improve understanding of driver behavior and used to enhance the traffic models used in the simulation. The distributed traffic simulation also allows researchers to view traffic simulations from anywhere in the network from the driver's point of view and, if desired, the driver could interact with the simulated traffic and vice versa.

Distributed traffic simulation is also beneficial for both traffic simulation program developers and driving simulator developers. Each could focus on developing the strengths of their programs and by meeting certain design considerations, could contribute to a distributed traffic simulation. Programs could be specific to a type of transportation investigation, type of facility, type of vehicle, or method of visualization and would not have to provide all capabilities for all uses. Developers could then direct future research and development of their programs to meet the specific needs of particular user groups and to provide the capabilities needed for distributed traffic simulation. Intuitively, the ability to model background traffic using a previously calibrated and validated microscopic traffic simulation model would allow driving simulator developers to concentrate on developing advanced visualization software and vehicle dynamics models. Likewise, having access to powerful visualization tools would allow microscopic traffic simulation program developers to concentrate on improving how the traffic network, traffic controls, and the movement of individual vehicles are modeled.

1.1.4 Passing Maneuver

One of the more complicated and inherently dangerous driving tasks is the passing maneuver. A driver uses the opposing lane to accelerate around an impeding vehicle while providing enough space to prevent colliding with the impeding or opposing vehicles. Driver behavior is a function of the atmospheric, roadway and traffic conditions, the performance capabilities of the vehicle, and the skills and attitudes of the driver.

1.1.5 Current Passing Sight Distance Design Practices

In the 1930's a significant effort was made to collect passing data in the field (*4*, *5*, *6*, *7*). Observations were made from fixed points or test vehicles and speedometers, stopwatches, cameras, and markings and/or detectors on the road were used to measure and/or record the observations with varying success. The Holmes method (*8*) was used to collect data for over 20,000 passes and Prisk (*9*) extracted 3,521 simple passes with a delayed start and a hurried return for analysis. This analysis set the foundation for the passing sight distance values given in the American Association of State Highway and Transportation Officials (ASSHTO) publication *A Policy on Geometric Design of Highways and Streets* (*10*, *11*).

1.1.6 Current No-Passing Zone Marking Practices

The ASSHTO passing sight distance values are much larger than those found in the *Manual on Uniform Traffic Control Devices* (*12*) used for marking no-passing zones. These latter values were developed as a compromise between the sight distances needed for a flying pass and a delayed pass. They were also a compromise between safety and making excessive restrictions on passing, such that safety would require good driver judgment. Although it is not clear where these numbers originated, they can be traced as far back as the 1940 AASHTO publication *A Policy on Criteria for Marking and Signing No-Passing Zones on Two and Three Lane Roads* (*13*).

1.1.7 Passing Models

Over the years, a number of models have been developed to describe the passing maneuver. In 1972, Herman and Lam (*14*) developed an analytical model of the passing maneuver and proposed the idea that there exists a point of no return where the driver is better to complete rather than abort the maneuver. A decade later, Lieberman (*15*) developed an analytic model based on the kinematics of the passing maneuver and described the critical position as the moment that completing or aborting the passing maneuver would offer the driver the same clearance with oncoming vehicles. The idea of a critical point or a point of no return was adopted by numerous authors (*16*, *17*, *18*, *19*) and their passing models were used to evaluate the AASHTO passing sight distance design values and the MUTCD no-passing zone marking values, both of which consider a passenger car passing another passenger car. Assumptions were made about the values of the head-on clearance, gap size, deceleration rate, and speed differential. Some of the passing models were also used to predict the impact of trucks on the needed passing sight distance.

1.1.8 Truck Impact

By varying the vehicle length used in the passing models, it was predicted that when a truck was being passed, the needed passing sight distance was greater (*15*, *16*, *18*, *20*, *21*). This result was a consequence of how the vehicle length was taken into account in the models. For instance, in the Lieberman (*15*) and Saito (*16*) models, the increase in passing sight distance reflected the increased distance the passing vehicle needed to travel along the length of the impeding vehicle. However, in the Glennon model, the result was amplified by the speed of the impeding vehicle (*20*).

In 2000, Polus, Livneh and Frischer (*22*) aimed to quantify the major components of the passing maneuver by examining approximately 1,500 passing maneuvers videotaped from vantage points and from a hovering helicopter. The speed differential, headway between the passing and impeding vehicles at the beginning of the maneuver, distance the opposing lane was occupied, tailway between the passing and impeding vehicles at the end of the maneuver, and clearance to the opposing vehicle were observed to be greater when the impeding vehicle was a tractor semi trailer. This result suggested that the impact of an increase in the impeding vehicle length was not limited to the added distance traveled along the length of the impeding vehicle, and that the passing behavior of the driver differed depending on the type of impeding vehicle.

Understanding what impact trucks have on passing sight distance is important because there are currently pressures on the United States to increase the allowable federal truck length limits to compare with those of Canada and Mexico. To permit the use of longer trucks, it is imperative that the current design practices and no-passing zone marking practices will be adequate.

1.2 Statement of Problem

1.2.1 Need a Method to Capture Behavior in Microscopic Traffic Simulation Programs

Microscopic traffic simulation programs are developed for engineering analyses. These models are very good at modeling traffic flows and produce measures of effectiveness describing the operation of the traffic system. Traffic conditions are calibrated by adjusting the values of behavioral parameters. Unfortunately, these values generally have no direct interpretation. To gain driver behavior data, studies in the field, on a test track, or using a driving simulator are conducted. These types of studies have their own limitations including cost, risk, and the type and quality of data that can be collected. What is needed is a method to introduce a test driver into the microscopic traffic simulation that has calibrated traffic conditions so that driver behavior data can be captured in a safe and efficient manner.

1.2.2 Need a Method to Create Calibrated Vehicle Flows in Driving Simulators

Driving simulators are developed for driver training and behavior research. Test drivers control a vehicle in a computer generated driving environment and measures of their control of the vehicle are recorded. To create the traffic conditions, individual vehicles are specifically programmed and ambient traffic is included to provide a sense of realism. Calibrating the traffic conditions may require each vehicle in the simulation to be specifically programmed, which would be a time consuming and laborious task. An easier method to create a specific or calibrated traffic flow is needed.

1.2.3 Need to Identify What Impact Trucks Have on Passing Sight Distance

A number of models have been developed and applied to determine whether longer impeding vehicles require greater passing sight distances. The models were used to predict that greater passing sight distance is required when longer impeding vehicles are passed. However, the predictions reflected how the vehicle length was taken into account in the development of the models. A recent field study was conducted and the results suggested that the impact of longer vehicles was not limited to the length of the vehicle. What is needed is to identify what impact trucks have on the needed passing sight distance.

The limitations of traditional data collection methods for field studies, test track studies, and driving simulator studies include cost, risks, and the type and quality of data. What is needed is an alternate method that allows both traffic and driver data to be collected in a safe and controlled driving environment at a reasonable cost to determine whether longer impeding vehicles influence the mechanics of the passing maneuver and/or the passing behavior of drivers.

1.2.4 Need to Classify the Factors that Potentially Impact Passing Sight Distance

Passing behavior is highly variable, resulting from the influences of the environment and the capabilities of the vehicles and drivers. It is not realistic or practical to include every factor when building a model to describe the needed passing sight distance. What is needed is a classification of factors to identify which factors have the potential to impact the mechanics of the passing maneuver and/or the passing behavior of drivers.

1.2.5 Need to Develop a Passing Sight Distance Equation

Numerous models have been developed describing the mechanics of the passing maneuver but most are based on the concept of a point of no return or a critical point, which has not been validated. What is needed is an equation for the passing distance that is based on the mechanics of the passing maneuver and also has behavior parameters for calibration.

1.3 Research Objectives

It was hypothesized that the traffic modeling capabilities of microscopic traffic simulation programs and the visualization capabilities of driving simulation programs could be exploited by combining the disparate programs into a distributed traffic simulation. The combined simulation could then be used to capture driver behavior and traffic data simultaneously for a variety of driver behaviors in a variety of traffic environments and the results applied to improve the current traffic models. The objectives of this research were to:

1. Develop a general methodology to combine microscopic traffic simulation programs with driving simulator programs, providing an easier way to create calibrated traffic flows in driving simulators and to capture vehicle behavior in microscopic traffic simulation programs;
2. Evaluate the benefits and drawbacks of this methodology;
3. Apply the distributed traffic simulation to study the passing maneuver, as an alternative study method to the costly and dangerous field study;
4. Classify the factors that have the potential to impact passing sight distance; and
5. Formulate a passing equation that describes the mechanics of the maneuver and includes behavior parameters. This equation could be used to improve the logic used by both microscopic traffic simulation programs and driving simulator programs.

The methodology was intended to be developed in a generalized manner such that it could be applied to a variety of driver behaviors and traffic environments. Pedestrian movements and the operation of traffic control devices were outside the scope of this research.

1.4 Research Framework and Methodology

This research was divided into eight tasks. The purpose and description of each task is presented in the following sections.

1.4.1 Literature Review

The first task was to perform a comprehensive literature review on the aspects of combining traffic simulation programs. Passing literature was also reviewed, including the data collection methods used to capture passing maneuver data, models that have been developed, and behavioral studies that have been conducted. This review reflected the multidisciplinary nature of this research, drawing from simulation, distributed computing, transportation, human factors, and psychology publication sources. The purpose of the literature review was to ensure that no research, which might contribute to this study, was overlooked or unnecessarily duplicated.

1.4.2 Framework for Distributed Traffic Simulations

The second task was to develop a general framework that outlined the methodology for creating and applying a distributed traffic simulation and the avenues for feedback to improve the individual simulations, the distributed traffic simulation, and understanding of the particular application.

1.4.3 Combine the Simulation Programs

The third task was to use the general framework to guide the design and development of a distributed traffic simulation. High Level Architecture was adopted to combine a microscopic traffic simulation with a driving simulation. Issues concerning the exchange of data, consistency in the meaning of data, and synchronization were expected (*23*). Each of these issues was addressed in this research.

A cursory look at the capabilities of the microscopic traffic simulation program VISSIM (*24*) and the DriveSafety (*25*) driving simulator located at the Texas Transportation Institute, which were both proprietary programs, suggested that combining them was feasible. VISSIM had an External Driver Application Programming Interface (API) that could be used to control vehicles in the traffic simulation from an external source. DriveSafety used Transmission Control Protocol/Internet Protocol (TCP/IP) to transfer information through sockets.

1.4.4 Evaluate the Distributed Traffic Simulation

The fourth task was to evaluate the distributed traffic simulation. A review of some recent simulation publications revealed that distributed traffic simulations have previously been developed based on HLA (*26*, *27*), including one for simple urban traffic. The developers noted that there was no noticeable slowdown in the animation but slowdown could occur if larger traffic networks were modeled. For this research, the distributed traffic simulation was evaluated to verify that it was working as expected and that performance levels were acceptable, including the data transfer processes and the quality of the animation. The evaluation results were used to construct recommendations for improvements.

1.4.5 Conduct a Simulation Study

The fifth task was to conduct a simulation study, thereby demonstrating the potential benefits and drawbacks of the distributed traffic simulation. The chosen application was the impact of the length of the impeding vehicle on passing. The impeding and opposing vehicles in DriveSafety were generated by VISSIM and their speeds were updated based on the VISSIM simulation. The test drivers controlled the test vehicle and passed the slower, impeding vehicles. Data about the movement of vehicles and the test drivers' control of the test vehicle were captured.

1.4.6 Reduce and Analyze Simulation Data

The sixth task was to analyze the simulation study data and compare the results to the recent field data. An analysis of variance was run for each dependent factor to examine the effects of the speed and type of the impeding vehicle on the passing behavior of these test drivers. The results were compared to field data collected by Polus et al. (*22*).

1.4.7 Evaluate the Use of the Distributed Traffic Simulation

In addition to the evaluation of the distributed traffic simulation carried out as Task 4, further recommendations were constructed based on the experience gained and lessons learned conducting the simulation study. The seventh task was to evaluate the overall suitability of the distributed traffic simulation for studying driver behavior and recommend future developments.

1.4.8 Formulate a Passing Sight Distance Equation

The eighth task was to formulate a passing model that is structured on the mechanics of the passing maneuver and includes behavior parameters. Atmospheric, roadway and traffic conditions, vehicle operating characteristics, and driver characteristics that have the potential to impact passing sight distance were grouped by their expected impact on the mechanics of the passing maneuver and passing behavior. The equation was calibrated using the AASHTO passing distance values (*10*) and predictions about the impact of the length of the impeding vehicle on the passing distance were made. The passing equation could be used to evaluate passing sight distance criteria, and passing behavior observed in the field. The equation could also be used in microscopic traffic simulations and driving simulations to control passing vehicles on rural two-way, two-lane rural highways.

1.5 Organization of the Dissertation

This dissertation was divided into 9 sections. Section 1 is an introduction to the research and includes the background, statement of the problem, research objectives, methodology, contribution of the research, and organization of the dissertation. Sections 2 and 3 contain a comprehensive literature review of the state of the art of the main topics of this research, drawing from simulation, computing, transportation, human factors, and psychology sources. Part 1 of the literature review is focused on the capabilities of microscopic traffic simulation programs and driving simulation programs, and includes a review of the HLA for distributed simulation. Part 2 of the literature review is focus on aspects of the passing maneuver and passing behavior. In section 4, the methodology for using distributed simulations to address behavior and traffic problems is presented as a framework and discussed in detail. In section 5, the framework is used as a guide to create a prototype combining VISSIM with DriveSafety. In section 6, the prototype is used to conduct a passing behavior study in an attempt to find a solution to the passing behavior problem. The suitability of using the distributed traffic simulation as an alternate data collection method for such applications is discussed. This is followed by section 7, which contains a further examination of the passing study data. Driver, vehicle and environment factors are classified by their potential to impact the mechanics of the passing maneuver and passing behavior. In section 8, the insights gained about passing behavior are used to develop an equation for the passing sight distance. This equation is adjusted to fit the AASHTO passing sight distance values and predictions about the impact of the impeding vehicle length are made. Section 9 contains a summary, a discussion about the contributions of this research, and suggestions for future research.

2 LITERATURE REVIEW – PART 1

Simulation is a technique used to emulate system operations. Computer simulation has grown in popularity with the advances in computer processing and the availability of powerful software to create and run simulations. For this review, the existing capabilities of microscopic traffic simulation programs and driving simulator programs were reviewed in terms of how driver behavior is simulated and calibrated to demonstrate the need to improve these technologies and the potential to do so through distributed computing. The intent of this review was to provide a picture of the general capabilities of these programs and not the capabilities specific to individual programs, since there are a wide variety of such programs available (*2*, *3*). However, the examples were drawn from specific programs when adequate documentation was secured.

2.1 Need a Method to Capture Behavior in Microscopic Traffic Simulation Programs

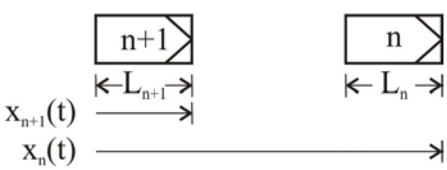
A microscopic traffic simulation program is a piece of computer software that is used to create a model of a traffic system that is dynamically changed with respect to the progression of time. The model itself is a simplified description of a traffic network inclusive of the roadway, traffic controls, and the individual vehicles. Each time the state of the model is changed, the dynamic features such as traffic control signals and the movement of individual vehicles are updated thus simulating the operation of the traffic system being modeled. The manner in which the vehicles are updated is prescribed by car following, lane changing, and passing algorithms. The simulation may be animated, allowing the behavior of individual vehicles to be observed and the output may include details about the movement of individual vehicles, and/or groups of vehicles.

The behavior exhibited by the vehicles is a consequence of how the model is described and simulated. This includes the model input, the logic that prescribes how vehicles move, the stochastic mechanisms, the values of the calibration parameters, and the time advance approach. Therefore, two programs that differ in how the model is described and simulated are likely to produce different behaviors, animations, and output. The car following, lane changing, and passing algorithms used in microscopic traffic simulation programs were reviewed to demonstrate the variety in the approaches.

Traffic simulation programs are used to mimic traffic behavior, not capture it, thus there is a reliance on obtaining data to adequately describe and simulate the traffic system. As the model description or simulation becomes more complex, the data needs increase. Collecting the needed data in the field may be arduous, time intensive, expensive, and even dangerous. An alternative would be to have test drivers drive within the microscopic traffic simulation and collect behavior data specific to the model description and simulation.

2.1.1 Car Following Algorithms

The basic car following situation is depicted in Figure 2.1. The lead vehicle, n, has a length of L_n and travels in front of the following vehicle, n+1, which has a length of L_{n+1}. At time t, the position, speed, and acceleration of each vehicle is denoted by $x_i(t)$, $s_i(t)$, and $a_i(t)$, respectively, where the subscript i denotes the specific vehicle. The acceleration rate of the following vehicle $a_{n+1}(t+\Delta t)$ is specified at Δt time after time t, where Δt is referred to as the perception/reaction time of the following driver. The distance headway is calculated by $x_n(t)-x_{n+1}(t)$ and the relative velocity is calculated by $s_n(t)-s_{n+1}(t)$.



n = lead vehicle
n+1 = following vehicle
t = at time t (seconds)
$t+\Delta t$ = Δt time after time t (seconds)
L_i = length of vehicle i (feet)
x_i = position of vehicle i (feet)
s_i = speed of vehicle i (feet/second)
a_i = acceleration rate (or deceleration rate) of vehicle i (feet/second^2)

FIGURE 2.1. A notation for the car following theories.

Car following algorithms are used in all microscopic traffic simulation programs. These algorithms were predated by the models developed based on theories of how drivers followed lead vehicles. Pipes' theory (*28*) was based on the heuristic that the following driver leaves one car length for every 10 mph of speed that is being traveled. Assuming a vehicle length of 20 feet, the minimum safe distance headway, d_{min} is expressed as Equation 2.1 and the minimum safe time headway, h_{min} is expressed as Equation 2.2.

$$d_{min} = 1.36\left[s_{n+1}(t)\right] + 20 \tag{2.1}$$

$$h_{min} = 1.36 + \frac{20}{s_{n+1}(t)} \tag{2.2}$$

Forbes (*29*, *30*, *31*) derived minimum time headway as the time taken for the following driver to react plus the time required for the lead vehicle to travel a distance equal to its length. Assuming a reaction time of 1.5 seconds and a vehicle length of 20 feet, the minimum time headway, h_{min} and the minimum safe distance headway, d_{min} are expressed by Equations 2.3 and 2.4 respectively.

$$h_{min} = 1.50 + \frac{20}{s_n(t)} \tag{2.3}$$

$$d_{min} = 1.50 s_n(t) + 20 \tag{2.4}$$

Both the Pipes' theory and the Forbes' theory were rather simplistic in nature (*32*). Under both theories, the minimum safe distance headway increases with speed. The stopped headway is 20 ft, or the assumed length of a single vehicle, therefore when stopped the vehicles would be bumper to bumper. The minimum time headway continuously decreases with speed. According to Pipes' theory, as the speed of the following vehicle becomes infinitely large, the minimum safe time headway reaches an absolute minimum of 1.36 seconds. This is referred to as the jam headway. Since the flow is the reciprocal of the time headway, under this theory the maximum flow would be 2647 vehicles/hour/lane, which exceeds the accepted lane capacity of 2400 passenger cars/hour/lane for a free flow speed of 120 km/h (75 mph) (*1*). The jam headway is better represented by Forbes' theory.

General Motors' (GM) researchers (*33*, *34*, *35*, *36*), along with some associates, developed five GM mathematical models of car following, each of which had the general form

response = stimuli x sensitivity (2.5)

The models described the acceleration (i.e. response) of the following vehicle in terms of the relative speed between the lead and following vehicles (i.e. stimuli), and the sensitivity of the following driver. These models are well known and have been reviewed at great length (*32*, *37*, *38*, *39*, *40*, *41*)

In the first GM model, the sensitivity was represented as a constant, α.

$$a_{n+1}(t + \Delta t) = \alpha\left[s_n(t) - s_{n+1}(t)\right] \tag{2.6}$$

If the relative velocity is positive, the response is acceleration. Conversely, if the relative velocity is negative, the response is deceleration. The amount of acceleration/deceleration is the product of the sensitivity parameter and the relative velocity. If the lead vehicle and following vehicle are traveling at the same speed, the response is to maintain a constant speed. The GM researchers obtained values for the reaction time (△t) and the sensitivity (α) parameters through field experiments. The reaction time ranged from 1.0 to 2.2 seconds and the sensitivity ranged from 0.17 to 0.74 second^{-1}.

Following the idea that the sensitivity of the driver has two states: one for close following and one for distant following, a second sensitivity parameter was introduced resulting in the second model. Equation 2.7 describes the response of the following vehicle.

$$a_{n+1}(t + \Delta t) = \overset{\alpha_1}{\underset{\alpha_2}{\text{or}}}\left[s_n(t) - s_{n+1}(t)\right] \tag{2.7}$$

The difficulty with this approach was to identify the values of the two sensitivity parameters and distinguish between the two discontinuous sensitivity states. This led to further field experiments and the discovery that the relationship between the sensitivity parameter and the distance headway was inversely proportional. This significant finding was incorporated into the third model. Equation 2.8 describes the response of the following vehicle, where the sensitivity is a function of a constant α_0 and the distance headway.

$$a_{n+1}(t + \Delta t) = \frac{\alpha_0}{x_n(t) - x_{n+1}(t)}\left[s_n(t) - s_{n+1}(t)\right] \tag{2.8}$$

The values of the reaction time (Δt) and the sensitivity (α_0) parameters were obtained through field experiments. At the General Motors test track, the reaction time was 1.5 seconds and the sensitivity parameter was 40.3 feet/second.

To improve upon the third model, the speed of the following vehicle was included. As the speed of the traffic stream increased, it was believed that the following driver would be more sensitive to the relative speed with the lead vehicle. For the fourth model, the response of the following vehicle is described by

$$a_{n+1}(t+\Delta t) = \frac{\alpha'[s_{n+1}(t+\Delta t)]}{x_n(t) - x_{n+1}(t)}[s_n(t) - s_{n+1}(t)] \tag{2.9}$$

The sensitivity is a function of a constant α', the speed of the following vehicle, and the distance headway.

In an effort to generalize the sensitivity term, the speed of the following vehicle was raised to the power *m*, and the distance headway term was raised to the power *l*, thus producing the fifth and final model. The response of the following vehicle is described by

$$a_{n+1}(t+\Delta t) = \frac{\alpha_{l,m}[s_{n+1}(t+\Delta t)]^m}{[x_n(t) - x_{n+1}(t)]^l}[s_n(t) - s_{n+1}(t)] \tag{2.10}$$

The fifth model can be reduced to any of the previous GM car following models by specifying the values of *l* and *m*. The first and second models are obtained when $l = m = 0$, with consideration of the sensitivity states defined in those models. When $l = 1$ and $m = 0$, the third model is obtained, whereas the fourth model is obtained when $l = m = 1$.

The experiments that were conducted and the theories developed by the GM researchers and associates advanced the understanding of car following. Their work was of significant importance because these theories were related to the theories of macroscopic traffic flow that were being developed separately and concurrently. In fact, it has been demonstrated that most macroscopic traffic flow models, including the Greenberg (*42*), Drew (*43*), Greenshields (*44*), Edie (*45*), and Underwood (*46*) models can be derived from the fifth GM model with specified values for *l* and *m* (*35*, *36*, *47*).

2.1.1.1 INTRAS/FRESIM - Pitt Model. The program INTRAS (INtegrated TRaffic Simulator) was developed in 1970 by KLD Associates, Inc. for the Federal Highway Administration (FHWA). INTRAS simulated the operation of freeways by using the Pitt car following algorithm (*48*, *49*, *50*) developed at the University of Pittsburgh. In 1994, INTRAS was enhanced but the car following algorithm remained unchanged. The resulting program was FRESIM (FREeway SIMulation) and was included in the Traffic Software Integrated Systems (TSIS).

The Pitt model was based on maintaining constant space headway between the leading and following vehicles. Using a driver sensitivity factor k (seconds), and a calibration constant b (seconds/ft), the space headway is calculated as follows:

$$d = L_n + 10 + ks_{n+1} + bk\left(s_n - s_{n+1}\right)^2 \tag{2.11}$$

$$b = \begin{cases} 0.1 & s_n < s_{n+1} \\ 0 & \text{Otherwise} \end{cases} \tag{2.12}$$

In FRESIM, the default values of the driver sensitivity factor range from 0.6 to 1.5. At low values, the behavior is more aggressive and the following vehicles maintain smaller space headways.

It has been previously shown that under steady-state conditions, the Pitt model compares to Pipes theory of car following (*51*, *52*). Under steady state conditions, the lead vehicle and the following vehicle travel at an equal constant speed. The final term in Equation 2.11 tends to zero and the resulting equation compares to Pipes' theory described by Equation 2.1.

For the scanning interval of duration T (seconds), equivalent to the size of the time step used to advance the simulation, the position of the leader is updated and the acceleration needed to achieve the desired space headway is calculated for the follower as follows:

$$a = \frac{2\left(x_n - x_{n+1} - L_n - 10 - s_{n+1}(k+T) - bk(s_n - s_{n+1})^2\right)}{T^2 + 2kT} \tag{2.13}$$

The acceleration change is applied to the following vehicle after the response lag time, R (seconds). This requires that T>>R. The current default for the driver response lag time is 0.3 seconds. The calculated acceleration for the following vehicle must also satisfy the emergency and the performance requirements such that the following vehicle must be able to stop safely behind the lead vehicle should the lead vehicle start to decelerate at the maximum allowable emergency deceleration. The lower bound for non-emergency acceleration is –8 ft/sec^2 (2.4 m/sec^2) and the maximum change in acceleration, or jerk is limited to 7 ft/sec^2 (2.1 m/sec^2). The following vehicle must also satisfy the performance capabilities such as maximum acceleration, maximum deceleration, maximum jerk, and response lag time that were assigned to its vehicle type.

2.1.1.2 NETSIM Car Following Model. The program NETSIM (NETwork SIMulation) (*48*, *49*, *50*) was originally developed by KLD Associates, Inc. for the Federal Highway Administration (FHWA). NETSIM simulates the operation of urban traffic on surface streets by calculating vehicle accelerations based upon vehicle performance characteristics and response to traffic control devices, traffic routing plans, and other factors. NETSIM is also part of the Traffic Software Integrated Systems (TSIS).

In NETSIM, the simulation time step, T is fixed at one second. For each time step, every vehicle is classified as a leader, follower, or independent of any other vehicle. In the car following situation, the position of the lead vehicle is first updated and after a response time, R the following vehicle is moved. The acceleration of the following vehicle is given by:

$$a_{n+1} = \frac{2\left[x_n - x_{n+1} - L_n - s_{n+1}(1+R)\right] + \frac{s_n^2}{e_n} - \frac{s_{n+1}^2}{e_{n+1}}}{(2R+1) + 2\frac{s_{n+1}}{e_{n+1}}} \tag{2.14}$$

The emergency deceleration rates e_n and e_{n+1} are used to ensure that if the lead vehicle suddenly stops, the following vehicle can also stop, thereby avoiding a collision. The distance traveled during the response time is also included. The default value of the response time, R is 0.3 seconds and the default maximum emergency deceleration rate is 12 ft/sec^2 (3.6 m/s^2).

Under steady-state conditions, the NETSIM model compares to Pipes theory of car following (*51*). The lead vehicle and the following vehicle travel at an equal constant speed and have equal stopping distances. The time step is 1 second and the driver response time is zero. Therefore, space headway maintained by the following vehicle as shown in equation 2.15

reduces to equation 2.16, which is comparable to Pipes' theory with a driver sensitivity factor of one.

$$d = L_n + s_{n+1}T + s_{n+1}R + \frac{s_n^2}{2e_n} - \frac{s_{n+1}^2}{2e_{n+1}} \qquad (2.15)$$

$$d = L_n + s_{n+1} \qquad (2.16)$$

2.1.1.2 MULTSIM – Gipps Model. Gipps (*53*, *54*, *55*) argued that the equations produced by Pipes, Forbes, and the GM researchers were essentially continuous and therefore not suitable for simulation. The reaction times could be greater than the simulation time step and therefore would require large amounts of data to be stored between simulation time steps. Gipps claimed that ideally, a car following algorithm for simulation should 1) mimic real traffic behavior 2) be computationally fast and avoid large data storage, and 3) have parameters that describe obvious driver and vehicle characteristics.

Gipps theory was to set limits on the performance of the driver and vehicle and use these limits to calculate safe speed with respect to the preceding vehicle. He specified constraints on the desired speed of the driver, S and the maximum acceleration rate accepted by the driver, A to arrive at the inequality

$$s_{n+1}(t+T) \le s_{n+1}(t) + 2.5A_{n+1}T\left(1 - \frac{s_{n+1}(t)}{S_{n+1}}\right)\sqrt{\left(0.025 + \frac{s_{n+1}(t)}{S_{n+1}}\right)} \qquad (2.16)$$

He also specified a constraint on the maximum braking rate, e that the driver would accept. A response time was introduced, along with a safety reaction time that was assumed to be equal to half the response time. The maximum braking rate of the lead vehicle was replaced by an estimated braking rate, $\hat{e}$. The resulting inequality was

$$s_{n+1}(t+T) \le e_{n+1}T + \sqrt{e_{n+1}^2T^2 - e_{n+1}\left[2\left(x_n(t) - s_n - x_{n+1}(t)\right) - s_{n+1}(t)T - \frac{s_n(t)^2}{\hat{e}_n}\right]} \qquad (2.17)$$

In a car following situation, the speed of the following vehicle was chosen as the minimum of the speeds calculated using equations 2.16 and 2.17. In congested flow, the speed is limited for almost all vehicles by equation 2.16, whereas in free flow conditions, equation 2.17 is the limiting condition for a substantial proportion of vehicles. This algorithm was implemented in the microscopic traffic simulation program MULTSIM.

2.1.1.4 Action Point Models. The action point models are based on theories that perception thresholds control car following behavior, which were proposed by Michaels (*56*) and Todosiev (*57*, *58*). The thresholds are based on changes in the distance and relative speed between vehicles, and/or the rate of divergence of the visual angle subtended by the lead vehicle, as perceived by the following driver. According to Weber's Law, the changes must be large enough to be perceived (*59*). The four action points are the:

1. Minimum desired following distance, which is the spacing when stopped plus the minimum spacing to account for the travel speed;
2. Maximum desired following distance, which is the spacing when stopped plus the maximum spacing to account for the travel speed;
3. Recognition of small negative (closing) speeds, which corresponds to the threshold for perception of the divergence of the visual angle; and
4. Recognition of small positive (opening) speeds, which also corresponds to the threshold for perception of the divergence of the visual angle.

When a threshold is crossed, a driver may perceive an unacceptable change in either the distance or relative speed and respond by adjusting the vehicle acceleration. The oscillation between thresholds produces the distance-relative speed spiral plots characteristic of real car following behavior (*60*, *61*) however the validity of this approach remains unclear.

In the sixties, the perceptual thresholds were measured through empirical studies conducted in the field (*62*) and the results were found to be statistically consistent (*63*). Measurements were later made on German Autobahns and apart from the thresholds there were significant differences in behavior (*64*). German drivers were observed to be more aggressive, accepting greater deceleration rates when approaching lead vehicles. More recent field studies have shown

(*61*, *65*) differences in the functional form for the perception thresholds for the closing speeds and opening speeds, and differences in minimum desired following distances.

Using the action points, researchers at IfV Karlsruhe in Germany developed a psychophysical model of car following for simulation (*64*). This model and derivations of it have been implemented in the simulation programs MISSION (*66*), which is used within the ICARUS project (*67*), VISSIM (*24*), PELOPS (*68*), and PARAMICS (*69*). Similar models have also been developed Lee and Jones (*70*).

2.1.2 Lane Changing Algorithms

The situation at the beginning of a lane change maneuver for vehicle n+1 is depicted in Figure 2.2. The lead vehicle, n, has a length of L_n and travels in front of the following vehicle, n+1, which has a length of L_{n+1}. In the adjacent lane, the putative lead vehicle, $^*n$ has a length of L^*_n and travels in front of the putative tailing vehicle $^*n+2$, which has a length of L^*_{n+2}. At time t, the position, speed, and acceleration of each vehicle is denoted by $x_i(t)$, $s_i(t)$, and $a_i(t)$, respectively, where the subscript i denotes the specific vehicle. A lane change occurs when the following vehicle, n+1 moves into the adjacent lane behind the putative lead vehicle, $^*n$ and in front of the putative tailing vehicle $^*n+2$.

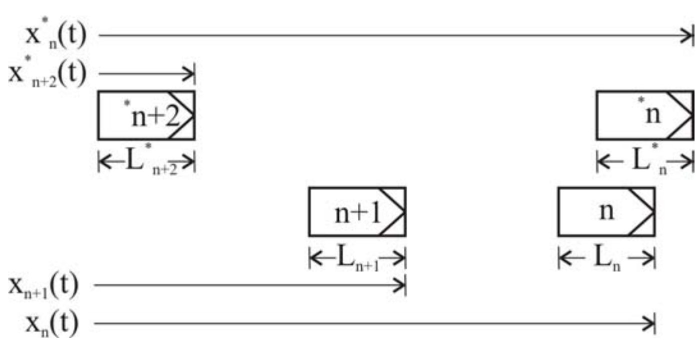


FIGURE 2.2. A schematic of the situation at the beginning of a lane change maneuver.

Not all microscopic traffic simulation programs contain lane changing logic. However, the more advanced programs that simulate multilane traffic flows, including freeways, urban arterials and urban networks contain lane changing logic to simulate the relationships between parallel lanes of traffic. In the following sections, the algorithms that have been implemented in some well known programs are presented.

2.1.2.1 FRESIM Algorithm. In FRESIM, the feasibility of the following vehicle performing a lane change is evaluated in terms of the gaps with respect to the putative leading and trailing vehicles (*49*). The required deceleration for the following vehicle is calculated to ensure that a safe headway distance is maintained in the event that the putative leading vehicle stops using the maximum deceleration rate. The required deceleration for the putative trailing vehicle is also calculated to ensure that a safe headway distance is maintained with the lane changer. The acceptability of the gaps is determined through a comparison of the level of risk (i.e. acceptable deceleration) to the required deceleration. The level of risk depends on whether the lane change is 1) mandatory, 2) discretionary, or 3) anticipatory.

Mandatory lane changes include merging onto the freeway from an on-ramp, getting into the appropriate lane to exit the freeway, moving out of a lane that is obstructed by an incident, and moving out of a lane that ends. To enter and exit the freeway, the level of risk is calculated using the minimum acceptable deceleration, a_{min}, the emergency deceleration rate, e, the distance to the end of the opportunity, O_E and the length of the opportunity, O_L as shown in Equation 2.18.

$$a_{accept} = a_{min} + \left(e - a_{min}\right)\sqrt{\frac{O_E}{O_L}} \tag{2.18}$$

The end of the opportunity is the distance to the end of the auxiliary lane of the on-ramp or the end of the gore of the off-ramp. The length of the opportunity is the length of the auxiliary lane or the distance between the warning sign and the off-ramp gore. To move out of a lane that ends or is obstructed by an incident, the risk increases linearly as the distance to the end or obstruction decreases.

Discretionary lane changes are made to move ahead of slower vehicles and are evaluated by the motivation, advantage, and urgency of making the maneuver. The motivation increases as the speed of the follower decreases. Each vehicle is assigned a tolerable speed and if the current speed is less than the tolerable speed, the motivation to change lanes is high. The advantage is the benefits gained by changing lanes as compared to the disadvantages of not changing lanes.

The urgency is the strength of the desire to change lanes and is calculated using the minimum acceptable deceleration for discretionary lane changes, a_{min}, maximum acceptable deceleration for discretionary lane changes, a_{max}, an urgency factor, U, and the driver response time, R.

$$a = \begin{cases} a_{min} & U < 1 - 0.05R \\ a_{min} + \left(a_{max} - a_{min}\right)\dfrac{U + 0.05R - 1}{0.05R} & U \geq 1 - 0.05R \end{cases} \qquad (2.19)$$

Anticipatory lane changes are made in anticipation of a mandatory lane change, such as moving into the appropriate lane to exit the freeway. They are evaluated similar to discretionary lane changes except that the advantage is described in terms of the volume and prevailing speed in the vicinity of the on-ramp gore and are given a high urgency.

2.1.2.2 NETSIM Algorithm. The NETSIM algorithm is very similar to the FRESIM algorithm in that the putative gaps are evaluated by comparing the required deceleration with the acceptable risk. In NETSIM, there are only mandatory and discretionary lane changes (*49*). Mandatory lane changes include those made because of lane channelization, lane drop, lane closure, or to move into the appropriate lane for an upcoming turning movement. The acceptable risk by the lane changer is equal to the maximum emergency deceleration rate and the acceptable risk by the putative tailing vehicle is 2/3 the maximum emergency deceleration rate.

Discretionary lane changes are motivated by speeds less than half of the assigned tolerable speed or intolerable headways. The acceptable risk is calculated using the minimum acceptable deceleration for discretionary lane changes, a_{min}, maximum acceptable deceleration for discretionary lane changes, a_{max}, an urgency factor, U, and an urgency factor threshold, $U_{threshold}$.

$$a = \begin{cases} a_{min} & U \leq U_{threshold} \\ a_{min} + \left(a_{max} - a_{min}\right)\sqrt{\dfrac{U - U_{threshold}}{1 - U_{threshold}}} & U \geq U_{threshold} \end{cases} \qquad (2.20)$$

The acceptable risk of the putative trailing vehicle is also calculated using Equation 2.20, however a safety factor is applied to represent the alertness of the driver to the lane change.

2.1.2.3 Gipps Algorithm. Gipps (*54*, *71*) developed a model of the lane changing process in urban settings to be used in conjunction with the Gipps car following model. It is actually a series of questions that guide the lane change process and has been represented as a flow chart. The process is outlined as follows:

- Select the target lane;
- Assess the feasibility of changing lanes, which is simply a check that the target lane is available to traffic and devoid of obstructions;
- Determine the proximity of the intended turn, which upon an affirmative answer, the lane change is performed so long as it is safe to do so;
- Determine the urgency of changing lanes increases, which adjusts the drivers willingness to brake harder;
- Evaluate the situation in terms of the types of vehicles and lanes (transit versus nontransit);
- Access the acceptability of the target lane with respect to the intended turn;
- Access the relative advantages of the target lane over the current lane;
- Consider the effect of heavy vehicles in the current and target lanes;
- Consider the speed advantage given the lead and putative lead vehicles;
- Assess the safety of changing lanes, which is an evaluation of the gaps; and finally
- Move into the target lane.

The model includes objective and subjective questions that are written in mathematical terms for a specific implementation. This model was implemented in MULTSIM (*72*) and used as the basis for the lane changing algorithms in MITSIM (*73*).

2.1.2.4 Sparmann Algorithm. The Sparmann algorithm is based on an action point or psychophysical model of lane changing. The underlying theoretical model was developed by Willmann (*74*) and was based on human decision processes about lane changing. By means of various investigations and extensive field measurements (*75*), Sparmann refined and calibrated the theoretical model thereby producing the algorithm (*76*) that was implemented in programs such as MISSION (*66*), and VISSIM (*24*). Many of the original works by Willmann and Sparmann are published in German; therefore this review reflects what others (*66*) have written about the Sparmann algorithm.

The lane changing decision processes has a hierarchical structure whereby the driver addresses the following questions in order:

1. Is there a desire to change lanes? There may be an obstruction that creates the desire to move to a faster lane. The severity of the obstruction is a function of the difference between the speed of the obstruction and the desired speed. The lane changes to faster lanes were categorized as:
   - Free, influenced by the current lead vehicle
   - Lead, influenced by the current lead vehicle and a closer putative lead vehicle
   - Lag, influenced by the current lead vehicle and putative tailing vehicle
   - Gap, influenced by the current lead vehicle, closer putative lead vehicle, and putative tailing vehicle

   There may also be a desire to move to a slower lane to keep right or to move out of the way of a faster approaching vehicle. The lane changes to slower lanes were categorized as:
   - Free, there is no current tailing vehicle
   - Accel, influenced by current tailing vehicle
2. Is the present driving situation in the adjacent lane favorable? A change to a faster lane is favorable if the putative lead vehicle is traveling faster than the current lead vehicle. A change to a slower lane is only favorable if there is no foreseeable obstruction within a given time frame.
3. Is the movement to the adjacent lane possible? Movement is possible if no dangerous situation results from the lane change, as valued by the estimation of distances and speed differences.

Perceptual thresholds were introduced to describe the actual influences on lane changing, specifically the distances and relative speeds between vehicles of the current situation, and the potential influences or estimates of future potential situations. The thresholds for potential influences are given as multiples of the thresholds of the actual influences. The results of Sparmann's field measurements were used to calibrate the lane changing model and define the perception thresholds to fit the measured values.

Fritzsche developed a similar action point model to consider the following two lane changing situations. The desire to move into the fast lane is caused by a slower lead vehicle and the actual movement is enabled or prevented by the putative leading and tailing vehicles. The desire to move into the slow lane is caused by a faster approaching vehicle and the position of the putative tailing vehicle while the actual movement is possible if the lane changer can follow the putative leader without changing acceleration for some time. This approach was implemented in PARAMICS (*69*)

2.1.3 Passing Algorithms

The situation at the beginning of a passing maneuver for vehicle n+1 is depicted in Figure 2.3. The lead vehicle, n, has a length of L_n and travels in front of the following vehicle, n+1, which has a length of L_{n+1}. In the opposing lane, the opposing lead vehicle, $^*n$ has a length of L^*_n and travels in front of the next opposing vehicle $^*n+1$, which has a length of L^*_{n+1}. At time t, the position, speed, and acceleration of each vehicle is denoted by $x_i(t)$, $s_i(t)$, and $a_i(t)$, respectively, where the subscript i denotes the specific vehicle. A pass occurs when the following vehicle, n+1 moves into the opposing lanes, overtakes the current lead vehicle, n by traveling at a higher speed ($s_{n+1}>s_n$), and moves back into the current lane. The maneuver must be carried out while maintaining a safe distance from the opposing vehicle $^*n+1$.

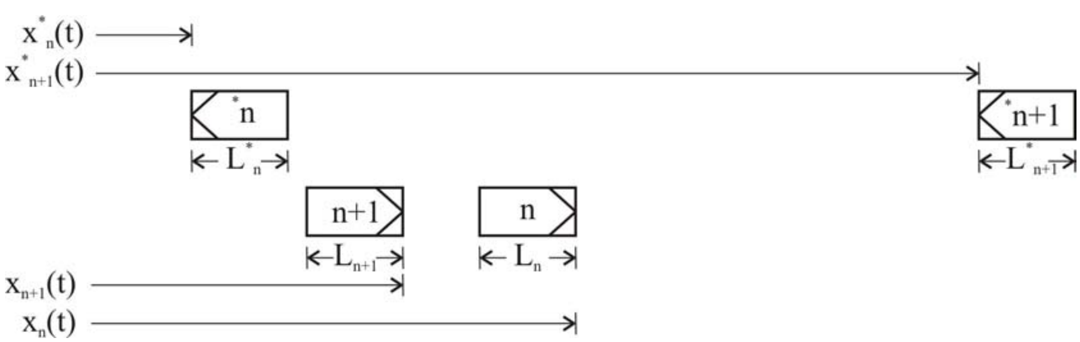


FIGURE 2.3. A schematic of the situation at the beginning of a passing maneuver.

The passing maneuver is typically performed on two-lane, two-way rural roads. Only a small number of programs have been developed to simulate passing maneuvers. In 1982, in a review of the state-of-the-art of rural traffic simulation five programs were identified (*77*) including:

- North Carolina State University's program (SOVT) (*78*) that was based on the Franklin Institute Research Laboratories (FIRL) program SIMMOD (*79*) developed by Cassel and Janoff using the results of extensive field studies (*80*, *81*, *82*, *83*);
- Midwest Research Institute's (MRI) program (*84*, *85*) was originally known as TWOWAF. It was modified to include the car following logic of INTRAS and the Schuhl distribution for vehicle generation (*86*, *87*) used in SOVT, and renamed ROADSIM. ROADSIM was used in the development of the 1985 and 1994 versions of the Highway Capacity Manual (*88*, *89*) and included in TRAF (*90*). Apart from the development of ROADSIM, TWOWAF was also further developed by MRI (*91*, *92*) to produce TWOPAS (*93*). An input interface UCBRURAL (*94*), and an output analysis program TWOSUM (*95*) were developed independently. TWOPAS was further developed as TWOPAS98 and has been used in the writing of the 2000 (*96*) Highway Capacity Manual, and implemented in the Federal Highway Administration program Interactive Highway Safety Design Model (IHSDM) (*97*);
- Swedish National Road and Traffic Research Institute's program VTI;
- Brazilian Agency for Transportation Planning's (GEIPOT) program SOFOT; and
- Australian Road Research Board's (ARRB) program TRARR (*98*), which was based on field data (*99*). In TRARR, 35 different maneuvers are recognized, classified as free travel, following, following in a passing lane, overtaking using the passing lane, aborting an overtaking maneuver, thinking about the merge at the end of the passing lane. TRARR has 60 parameters to describe the driver and vehicle characteristics associated with 18 vehicle classes. The TRARR program has undergone enhancements (*100*) and the user interface UCBRURAL has been enhanced to support TRARR (*101*, *102*, *103*).

The passing algorithms used in these programs are based on different methodologies and assumptions about passing behavior and produce wide variations in the performance of the two-way traffic flows. According to the 1982 review (*77*), SOFOT and TRARR incorporate deterministic rules for passing whereas SOVT, TWOWAF/TWOPAS, and VTI use gap acceptance probabilities derived from extensive field studies. TWOWAF/TWOPAS, VTI, SOFOT, and TRARR can model a range of passing situations but SOVT only describes accelerative passes where overtaking is limited by the gaps in the opposing traffic.

The passing algorithm in TWOPAS98 is supposedly detailed in the working paper entitled "Upgrade of TWOPAS code" prepared for Task 6 of the NCHRP Project 3-55(3) however this working paper is not readily available from any known publication source. The algorithms used in the original TWOWAF are detailed in NCHRP Report 185 (*84*) but with all the revisions to the program over the last 25 years, it is difficult to say what has remained intact. In TWOWAF, vehicles were processed depending on what state they were in: unimpeded, overtaking an impeder, following an impeder, and closely following an impeder. The motivation to pass was assessed and if motivated, tests and calculations were conducted to reach decisions about initiating a pass, the feasibility of the pass based on performance capabilities, and finally to carry out the pass. During a pass, decisions about aborting or continuing the pass were made.

In the IHSDM engineer's manual (*97*) the following features of the TWOPAS program are identified:

- Vehicle positions are updated every second;
- Variations in driver performance based on field data;
- Unimpeded vehicle speeds are assigned given the user-specified, desired speed distribution; impeded vehicle speeds determined by the incorporated car following model, the preferred following distance, relative speeds, and desire to pass;
- Decisions such as starting a pass, aborting a pass, and returning to the original lane are based on field data; and
- Behavior in passing/climbing/multi-lane sections based on field data.

It is clear, even from the general program descriptions and the general description of the passing algorithm used TWOPAS98, that these programs rely heavily on field data to simulate passing maneuvers and the operation of two-lane two-way rural roads.

2.1.4 Stochastic Mechanisms

In order for a microscopic traffic simulation to mimic the variability in driver behavior, mechanisms to introduce stochastic responses are needed. The common approach is to use a psuedo-random number generator and specified random number seeds. Alternate approaches that have received attention recently are the use of fuzzy logic (*104*, *105*, *106*) and neural networks that derive from Artificial Intelligence (AI) technology.

Many random number generators use the linear-congruent method for producing a sequence of integers (*107*). For example, $z_1, z_2, z_3, \ldots$ are defined by the recursive formula

$$z_i = (bz_{i-1} + c)(\text{mod } m) \tag{2.21}$$

The multiplier b, the increment c, the modulus m, and the seed or starting value z_0 are nonnegative integers. In addition, the inequalities $0<m$, $b<m$, $c<m$, and $z_0<m$ are satisfied. To produce a uniform distribution U_i for i= 1, 2, 3,… on [0,1], $0 \le z_i \le m-1$, and $U_i = z_i / m$. The uniform distribution can then converted into the specified distribution. Some random number generators use multiplicative congruent method (*108*), whereby $z_1, z_2, z_3, \ldots$ are defined by

$$z_i = bz_{i-1}(\text{mod } m) \tag{2.22}$$

NETSIM uses a multiplicative congruent method to generate random numbers to simulate the randomness of traffic flow. It uses one random number seed to start the stochastic processes of the traffic stream and another to start the responses to traffic choices (*109*). The latter is also used in FRESIM. VISSIM uses only one random number seed (*24*). TWOWAF used four random number seeds; one to start the generation of vehicles for each traffic flow, one to assign desired speeds, and one to make passing decisions (*84*).

2.1.5 Calibration

The car following, lane changing and passing algorithms used to update the movement of the vehicles in microscopic traffic simulations do not necessarily reflect the traffic behavior of the system being simulated. To fit the simulation to the observed conditions, the simulation is calibrated or fine-tuned. This process is separate from the verification and validation processes that are performed to ensure that the logic is correct and that it is programmed without errors.

In CORSIM, there are car following sensitivity parameters (record type 68), and lane change parameters (record types 70, 81, and 152) in addition to input requirements to define the traffic network, traffic conditions, vehicle performance, and driver types. The car following sensitivity factor can be adjusted for any of 10 defined driver types. The default values range from 0.6 to

1.5 where low values represent more aggressive behavior and vehicles maintain smaller space headways. The lane change parameters effect how mandatory, discretionary and anticipatory lane changes are performed. Changing these parameters not only impacts the interaction between vehicles but also impacts the performance of the simulated traffic system. Similarly, the parameters used in the Wiedemann and Sparmann algorithms in VISSIM can be adjusted thereby changing the values of the perception thresholds that are considered during the simulation.

Calibration is a very powerful technique for fitting a microscopic traffic simulation, which is essentially a “black box”, to specific traffic conditions. The algorithms contained within the programs are based on field data that describe certain conditions that were prevalent during the observations. Therefore changes in the conditions have to be accounted for by adjusting parameters used in the algorithms. The more complex the simulation and the underlying models, the calibration process becomes more involved and requires more field data for comparison.

The purpose of microscopic traffic simulation programs is to mimic the operation of a real traffic system. Therefore, one of the inherent shortcomings is the inability to accurately simulate unobserved traffic conditions. The approach that is often used to combat this shortcoming is to calibrate the simulation for an existing condition, manipulate the traffic conditions, and evaluate the change in the performance of the system. This approach neglects the potential changes in behavior that may occur given the change in traffic conditions. A method is needed to capture the behavior of driver under the unobserved traffic conditions.

2.2 Need a Method to Create Calibrated Vehicle Flows in Driving Simulators

A driving simulator is an apparatus used to present an imitation of a driving setting or situation to a test driver. Modern driving simulators are computer based and contain software to create models of driving settings (i.e. driving scenes) and add dynamic features such as traffic control signals and vehicles to produce driving situations (i.e. driving scenarios). The driving scene or driving scenario is a driving simulation and when it is run the animation is presented to the test driver. The output may include details about the movement of the test vehicle and its relationship to other vehicles in the simulation. Peripheral equipment may be included such as eye trackers, heart monitors, and skin sensors to record measures about the test driver. Driving simulation applications include driver training exercises and driver experiments, such as studies pertaining to aspects of driver physiology, psychology, cognition, and motor skills.

One of the challenges in using driving simulation is to control what the test driver observes, by controlling how the vehicles in the simulation behave yet ensure that the vehicles behave in a realistic manner. These are sometimes contradictory demands. Most modern driving simulators have the capability to generate vehicles that behave autonomously and through the use of control mechanisms such as beacons and triggers, scripting commands are issued to the vehicles.

With respect to vehicle generation and control, there is little detailed in the literature. This is likely due to the fact that driving simulators are developed as proprietary systems or are the products of years of independent research efforts. What has been published appears to be focused on the computing approaches that have been used however the actual car following, lane changing and passing algorithms are not detailed. Some experience with Artificial Intelligence (AI) computing techniques, such as fuzzy logic has also been reported.

An alternative approach to the use of autonomous vehicles would be to use the traffic from an existing microscopic traffic simulation, such that all vehicles movement are controlled using the accepted car following and lane changing logic contained within those programs. Using this approach, specific and perhaps calibrated vehicle flows could be produced, providing the needed environment to examine behavior and traffic impacts concurrently. There is some interest in this alternate approach but to date there is very limited experience with its application.

2.2.1 Autonomous Vehicles

Autonomous vehicles are independent and self-governing. Each vehicle is provided the basic intelligence to drive on the roadway, obey the traffic rules and traffic controls, to reach a final destination. The purpose of including autonomous vehicles in a driving scenario is to provide a sense of realism to the driving setting, otherwise create the illusion of real driving. Two common approaches to providing the autonomous vehicles the intelligence to drive on their own have been to use rule-based models and state machine models.

2.2.1.1 Rule-Based. A rule-based model is comprised of a set of rules, developed using a knowledge base of driver behavior, that prescribe what decisions are made and what actions are taken given the prevalent conditions. For instance, the RUG-COV driving simulator (*110*) uses input about the road layout, traffic controls, and road users to evaluate the traffic rules for a variety of normative driving situations to arrive at the appropriate maneuvering actions.

The structure of the rule-based model can affect the efficiency of the simulation. For instance, a flat or single level structure is inefficient because it requires many rules to describe all of the decisions that can occur. This inefficiency can limit the number of vehicles that can be generated in the driving scenario. To improve the efficiency of the rule-based model approach and allow more vehicles to be generated, hierarchical structures have been used. An example of a hierarchical structure is the Michon hierarchical control structure for the driving task (*111*). The driving task is divided into three levels: 1) a strategic (planning) level to address the general planning of a trip, 2) a tactical (maneuvering) level allowing negotiation, and 3) an operational (control) level that addresses the drivers low-level control of the vehicle.

The rule-based approach is deterministic and creates vehicle behavior that is predictable unless some mechanism to produce stochastic behavior is introduced. The approach taken by Al-Shihabi and Mourant (*112*) was to use fuzzy variables integrated into four units: 1) perception unit, 2) emotions unit, 3) decision-making unit, and 4) decision-implementation unit, which together determined the behavior of the vehicles. Autonomous vehicles, generated and controlled using this framework, were expected to perform in a stochastic, human-like and less predictable manner. It was predicted that such vehicle behavior would improve the validity of the driving simulation and the credibility of the studies performed.

2.2.1.2 State Machine. A state machine is a device that stores the status of an autonomous vehicle and uses input about the prevailing conditions to change the status thereby causing the vehicle to move. In a driving simulation, each autonomous vehicle is assigned a state machine. Each low-level driving task is encoded as a state and high-level tasks require a set of lower-level states to be performed in a particular order. In essence, the states are building blocks used to construct the behavior exhibited by the autonomous vehicles.

In single-level state machines, all states are considered on the same level. The sequential logic fails to describe the construct of driving behavior and is difficult to use when various input and constraints need to be considered simultaneously, as is the case for driving. In hierarchical concurrent state machines (*113*), each state machine may contain multiple sub-state machines that execute concurrently. The hierarchical architecture allows states to be grouped to represent the construct of driving behavior and the concurrency allows multiple constraints or goals to be considered simultaneously.

The state-machine approach is also deterministic and therefore produces predictable vehicle behavior. To produce realistic, driving behavior, a hybrid state machine approach has been used (*114*). A rule-based model that incorporates probability distributions approximated from empirical data represents the tactical portion of the driving task, and hierarchical concurrent state machines represent the operational portion of the driving task.

Using only autonomous vehicles in a driving simulation has two interrelated drawbacks, both stemming from the fact that there is no control over the movement of the vehicles. The first is the difficulty determining what exactly the test driver will experience, as far as the traffic conditions. Because of the dynamic nature of traffic, it is difficult to predict when any test driver will be at a specific location and therefore it is purely coincidence or perhaps luck that the test driver experiences what is intended. The second is the difficulty of repeating a specific driving situation. In an interactive driving simulator, the test driver responds to and interacts with the autonomous vehicles. Although each run of the driving simulation starts out the same, the differences in the behavior of the test drivers and the interaction with the autonomous vehicles can produce differences in what is experienced. To control these differences greater control of the vehicles is needed.

2.2.2 Controlled Vehicles

Controlling the autonomous vehicles in driving simulators has been achieved in a number of ways. Commands may be encoded into the model through an initialization script or read from an external file and executed during the simulation run. Commands may also be attached to mechanisms such as triggers and beacons. Triggers are a type of control mechanism that when activated initiate a command or set of commands to control vehicles or some other activity in the scenario (*25*, *113*). Location triggers are attached to the roadway and are initiated when run over. They may be coded such that they are only activated by a particular vehicle or particular type of vehicle. Virtual triggers have no physical representation but are encoded to initiate at a specified time or on a specified schedule. Beacons are also a type of control mechanism that sends messages to vehicles. A beacon can be attached to the roadway or a vehicle, including the test vehicle (*113*). Specific routes (series of intersection within an origin and destination pair) may be specified or particular paths (series of location points) may be defined and assigned to specific vehicles. These methods of controlling vehicles offer a lot of flexibility that can be utilized to create highly orchestrated vehicle movements.

There are two main drawbacks to using these mechanisms to control vehicles in the simulation. First, depending upon the amount of control needed, encoding the commands, setting up the triggers and beacons, and defining the routes and paths may be very time consuming. The availability of these control mechanisms is dependent on the capabilities of the particular driving simulation. The commands may be used to change the attributes of the vehicles (acceleration, speed, headway, etc) or the movement of the vehicle (lane change, turn, merge). Therefore, innovative approaches may be required to produce the desired vehicle movements. Second, when a lot of control is being exercised, the vehicle movements may appear to be unrealistic or forced which is not desirable. The commands need to be issued such that the controlled vehicles are seamlessly integrated with the autonomous vehicles.

2.2.3 Traffic Simulation Vehicles

Another approach to generating and controlling vehicles is to use the traffic from a microscopic traffic simulation, whereby the movement of the vehicles is prescribed by the car following, lane changing, and passing logic contained within the program. Although this approach lacks the ability to create highly orchestrated vehicle movements, it does provide a driving environment with naturalistic (i.e. stochastic) vehicle behavior.

The experience with this approach is very limited. Using agent technology, INRETS (Institut National de Recherche sur les Transports et leur Sécurité) integrated the SIM^2 driving simulator into the ARCHISIM microscopic traffic simulation program. TNO, of the Netherlands, intends to make MIXIC on-line data compatible with other applications and realize a real-time link to the TNO driving simulator (*115*). TNO's efforts are motivated by the need to study individual behavior effects and traffic flow effects in a coherent manner (*116*) as demonstrated through their studies on Intelligent Speed Adaptation.

This alternate approach for generating and controlling vehicles is challenged by a number of considerations. First, the simulation rate of one tenth of a second of the current microscopic traffic simulations are not adequate for driving simulations that have refresh rates of 60 times per second. Second, the car following, lane changing, and passing models that are based on empirical studies may not be accepted by the simulation community, which has chosen to use driver behavior models that represent the cognitive function of the driver. Third, establishing a connection between two independently developed and perhaps proprietary programs may prove to be an arduous task.

2.3 High Level Architecture

The idea of using distributed computing techniques to take advantage of the synergistic effects of combining disparate simulations is not new. One major contribution to the field of distributed computing was the creation of the High Level Architecture (HLA), a framework for creating distributed simulations, to address a problem that the US Department of Defense (USDOD) had encountered. Historically, the USDOD had invested in creating new simulations for a variety of problems and as a result produced an inventory of over a thousand simulations, however, the costs of developing new simulations became unacceptable and the USDOD needed a way to reuse the existing simulations (*117*). The HLA was created to provide a general framework to support the reuse and interoperability of simulations (*118*).

The framework itself is not a product to be implemented; rather it is a set of rules and interfaces that are followed to create a distributed simulation. Within the framework, the distributed system is termed the federation and each simulation, database, or integrated application is a federate. In 2000, the Institute of Electronic and Electrical Engineers (IEEE) recognized the HLA standards as P1516 Framework and Rules, P1516.1 Federate Interface Specification, and P1516.2 Object Model Template (*119*). The framework and rules specify the responsibilities of the federation and the individual federates while the interface specifications define the nature of the communication among federates. The object model template prescribes the method for recording information in the object models required for each federate. The rules for the federation and federates are examined more closely in the following sections.

2.3.1 Federation

The federation is a collection of simulations, databases, and applications that are designed to interact together. Each federation must include a federation object model (FOM) describing the objects and interactions to be shared across the federation. It is documented according to the HLA object model template (OMT).

2.3.2 Object Model Template

The OMT has two main components: object classes and interaction classes. Objects are simulated entities that are of interest to more than one federate and endure for some interval of simulated time. The OMT defines classes of objects and each class defines a set of named data called attributes. An interaction is a collection of data sent at one time by one federate across the federation. Once the intended federates receive the interaction, the interaction no longer exists.

The OMT defines classes of interactions, and each class defines the parameters that may be sent with the interaction.

2.3.3 Federates

Each federate is a simulation, database or application included in the federation. The simulation object model (SOM) describes all the objects and interactions the federate might contribute to a federation. It is defined using the HLA OMT. The federate must be able to update and/or reflect any attributes and send and/or receive any interactions as specified in its SOM. To update the attribute the federate needs to have ownership of that attribute, therefore, the federate must also be able to transfer and/or accept ownership of the attribute. The federate should update the attribute according to the conditions described in its SOM. Each federate should be able to manage their own local time advance to facilitate coordination with the other members of the federation.

2.3.4 Runtime Infrastructure

During execution of the federate, the exchange of FOM data among federates is supported by the Runtime Infrastructure (RTI) services according to the HLA Interface Specifications. The interfaces between each federate and the RTI are shown in Figure 2.4. Each federate offers an interface to the RTI called the FederateAmbassador interface and includes the RTI services initiated by the RTI. The RTI offers an interface called the RTIAmbassador to each federate and includes the RTI services invoked by federates. Because the exchange of FOM data always occurs via the RTI, the federation has an event-based architecture also referred to as an implicit invocation or reactive integration. A federate initiates an RTI service to communicate with the RTI, and in response the RTI initiates RTI services to communicate with other federates.

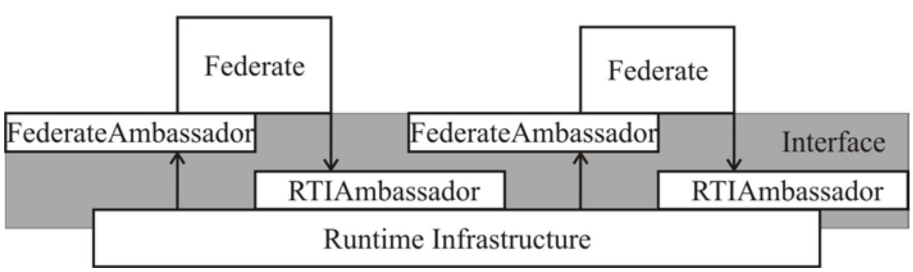


FIGURE 2.4. The interface between federates and the RTI.

There are six classes of services provided by the RTI, however a running federation can be achieved using the following four services. Federation management services include functions to create and operate the federation. Declaration management services declare what data each federate intends to provide (publish to) and require (subscribe to). Object management services are used to exchange data and include sending and receiving interactions, creating and discovering new instances of objects, and updating object attributes. Ownership management services are used to transfer the ownership of an attribute to a federate so that it can issue updates to that attribute.

The additional two classes of services deal with time management and data distribution management and are used to develop advanced federations. Time management services support synchronization by coordinating the local time advances of federates and ensuring the ordering of events. Data distribution management services further control the relationships between federates thereby refining the routing produced by the declaration management services.

2.3.5 Previous High Level Architecture Distributed Traffic Simulations

HLA was created for a library of defense simulations held and maintained by the USDOT, however the standards are applicable to a variety of simulation applications. The framework has been used in the civil domain including a couple of prototypes for transportation applications.

Klein, Schulze, Strassburger (*26*) produced a simulation of simple urban traffic based on the HLA. The federation incorporated the simulation tool Simulation Language with Extensibility (SLX) with the animation tool Skopeo, which were both extended for HLA compatibility. Three simulation federates controlled the vehicle traffic, pedestrian traffic, and traffic signal control, and a fourth animation federate provided a visual animation of the execution of the simulation. This federation was a demonstration of the interoperability of the simulation and animation federates.

To further demonstrate the interoperability aspects of HLA, a distributed driving simulation was developed based on HLA (*26*, *27*, *120*, *121*). The federation consisted of three federates. The driving simulator federate was based on a real-time driving simulator written in C++ for UNIX. The traffic simulator federate was based on a discrete event-based, psychophysical traffic simulation (*122*) implemented with SLX in a Windows environment. The animation federate was based on Skopeo and ran as an applet in a Java-capable web browser. Each simulation was extended for HLA compatibility, based on a common FOM, and the corresponding federates were developed independently. The successful execution of the simulation demonstrated the interoperability of independently developed federates and highlighted the interoperability in time management, operating platforms, programming languages, and networks.

To demonstrate the integration of on-line data into HLA federations, a public transport (streetcar) simulation was developed that included a streetcar simulation federate, an animation federate, and an on-line federate (*120*, *121*, *123*, *124*). The on-line federate provided real-time positions of streetcars. A copy of the on-line object model was used to create an off-line federate that could act as the on-line federate for testing, or to replay simulation scenarios. The streetcar simulation federate was developed using SLX, and the animation federate was developed using Skopeo and Proof Animation for Windows.

In the publications describing the development of these three distributed traffic simulations, there was very little written about the performance of the federations during execution. The creators of the simple urban traffic simulation evaluated the performance of the federation by viewing whether there were noticeable discontinuities in the animation. Under an unspecified, moderate traffic density, none were observed, however it was noted that the demands of the animation far exceed the demands of being an HLA federate and receiving data from the animation federate through the RTI.

3 LITERATURE REVIEW – PART 2

The passing maneuver is a complex and inherently dangerous maneuver where the passing driver overtakes a slower impeding vehicle by traveling at a faster speed in the opposing lane. A schematic of this maneuver is shown in Figure 3.1 and the impeding (I), passing (P), and opposing (O) vehicles are labeled. During the initial time t_1, the driver, who desires to maintain a certain speed, decides to pass a slower, impeding vehicle. If there is no immediate opportunity to pass, the driver is forced to follow the impeding vehicle until a gap in the opposing traffic is accepted. During the time in the left lane t_2, the driver overtakes the impeding vehicle by traveling at a higher speed. When adequate spacing in front of the impeding vehicle has been achieved, the driver returns to the right lane.

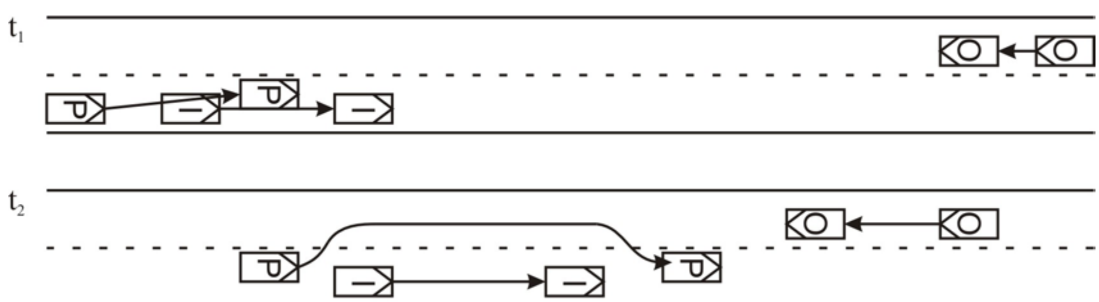


FIGURE 3.1. A schematic of the passing maneuver.

3.1 Need to Identify What Impact Trucks Have on Passing Sight Distance

One set of passing sight distance values are used in the design of rural highways and another set is used in the marking of no-passing zones. Both sets of passing sight distance values are based on maneuvers where a passenger car passes another passenger car. This shortcoming may be exacerbated if larger vehicles are permitted and the passing sight distance criteria are not adjusted accordingly. Currently there are pressures to change the federal truck size and weight limits, which depending upon how drivers respond to the changes, may impact how two-lane, two-way roads are designed and marked for passing.

3.1.1 Passing Sight Distance for Design

The passing sight distances used for design are given in *A Policy on Geometric Design of Highways and Streets* (*10*) and are shown in Table 3.1. They are based on the needed distance to complete a simple passing maneuver where, before the maneuver is started, the passing driver determines that there are no opposing vehicles that pose a conflict.

TABLE 3.1. Passing Sight Distance Values for Design

Design speed (km/h)	Assumed speeds (km/h)		Passing sight distance (m)
	Impeding vehicle	Passing vehicle	
30	29	44	200
40	36	51	270
50	44	59	345
60	51	66	410
70	59	74	485
80	65	80	540
90	73	88	615
100	79	94	670
110	85	100	730
120	90	105	775
130	94	109	815

Several assumptions about the behavior of the vehicles involved are incorporated into the passing sight distance values:

- The impeding vehicle travels at a constant speed;
- The passing vehicle follows the impeding vehicle as they enter a passing area;
- Time to perceive whether the opposing lane is clear and begin the maneuver is needed;
- The passing vehicle accelerates at the start of the pass and then continues at a uniform speed;
- The speed difference, m between the passing vehicle and impeding vehicle while the passing vehicle is in the opposing lane is 15 km/h (10 mph);
- There is an opposing vehicle present at the end of the maneuver; and
- The passing vehicle returns to the lane, leaving suitable clearance to the opposing vehicle.

The passing sight distances were determined from the summation of four elements (d_1, d_2, d_3, and d_4) of the passing maneuver, as depicted in Figure 3.2. The distance traveled by the passing vehicle (P) during the time needed for the passing driver to determine the opposing lane is clear and to begin the maneuver is

$$d_1 = 0.278 t_1 \left(\bar{s}_p - m_{pi} + \frac{\bar{a}_p t_1}{2} \right) \tag{3.1}$$

where:

t_1 is the time taken to perceive the opportunity to pass and begin the maneuver, s;

$\bar{s}_p$ is the average speed of the passing vehicle, km/h;

$\bar{a}_p$ is the average acceleration of the passing vehicle, km/h/s; and

m_{pi} is the speed difference between the passing and impeding vehicles, km/h.

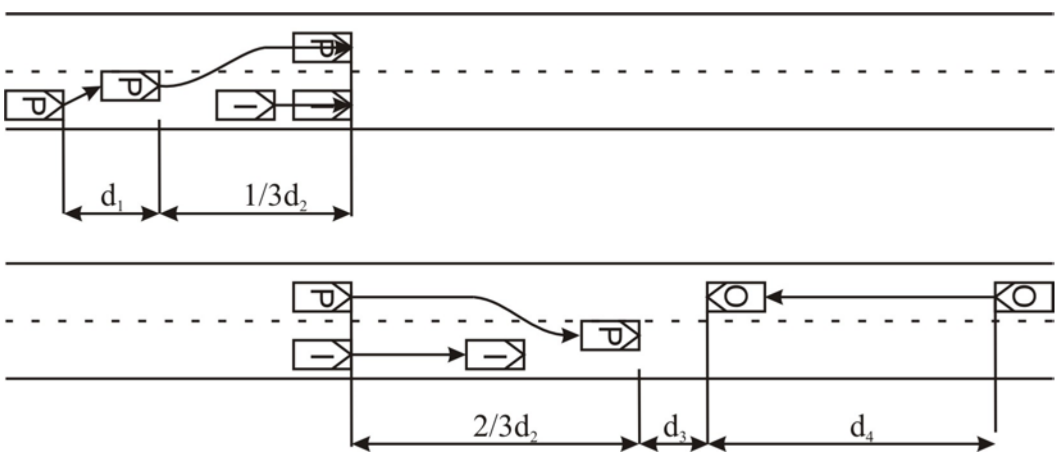


FIGURE 3.2. The elements of the passing maneuver.

The distance the passing vehicle travels in the left lane is d_2 and the corresponding time is t_2. One-third of d_2 is required for the passing vehicle to pull abreast of the impeding vehicle (I), and the remaining 2/3 d_2 is to complete the maneuver.

$$d_2 = 0.278 \bar{s}_p t_2 \tag{3.2}$$

The distance between the passing vehicle and the opposing vehicle (O) at the end of the maneuver is d_3, and the distance traveled by the opposing vehicle is d_4. Although d_4 could be considered the distance traveled by the opposing vehicle during the entire time needed to complete the passing maneuver, only a portion is included in the passing sight distance design values. The rationale for using a reduced value is to avoid overly large passing sight distances and the fact that the passing maneuver could be aborted prior to the passing vehicle pulling abreast of the impeding vehicle. Assuming that the average speed of the opposing vehicle is the same as the average speed of the passing vehicle, d_4 is given as $2/3d_2$.

The empirical values for the four elements of the passing maneuver are based on field studies conducted in the late 1930's and early 1940's and analyzed by Prisk (*9*). The results included the acceleration, average speeds, times, and clearance distances. Some extrapolation of the acceleration data was needed to obtain values for the highest speed range. The calculated distances for the four elements of the passing maneuver are shown in Table 3.2. The passing sight distance design values are taken from a plot of these calculated distances.

TABLE 3.2. Elements of the Passing Sight Distances for Design

Element	Speed range (km/h)			
	50-65	66-80	81-95	96-110
d_1 (m)	45	66	89	113
d_2 (m)	145	195	251	314
d_3 (m)	30	55	75	90
d_4 (m)	97	130	168	209
$d_1+d_2+d_3+d_4$ (m)	317	446	583	726

3.1.2 Passing Sight Distances for Marking No-Passing Zones

The minimum passing sight distances for marking are given in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*12*) and are shown in Table 3.3. These distances are used to determine where no-passing zone markings are needed. No-passing markings are started at the first point where the available sight distance is less than the passing sight distance and ended where the available sight distance first exceeds the passing sight distance. The available sight distance is calculated using a 1.07 m object and 1.07 m observation heights for vertical alignments and a 1.07 m observation height and the object obstructing the view for horizontal alignments. If the distance between two no-passing zones is less than 120 m (400 ft), that section of roadway is also painted with no-passing markings. With this approach, the passing areas are those areas that are left after the no-passing areas are marked.

TABLE 3.3. Minimum Passing Sight Distances for Marking

85th percentile or posted speed limit (km/h)	Minimum passing sight distance (m)
40	140
50	160
60	180
70	210
80	245
90	280
100	320
110	355
120	395

These passing sight distance values are a compromise between the distances for flying start passes and accelerated start passes and date back to 1940 (*13*). During a flying start pass, the passing vehicle travels more distance in the left lane as compared to an accelerated start pass. When these values were accepted, it was argued that large values would unnecessarily restrict the amount of passing opportunity. By using smaller passing sight distances for marking, the driver is required to decide whether or not it is safe to pass in the passing area. These minimum passing sight distances have been reviewed and scrutinized (*16*, *17*, *125*, *126*, *127*, *128*) yet they remain unchanged (*12*, *13*).

3.1.3 State Statutes

Adherence to the no-passing markings is regulated by the states. A review of the state statues (see Appendix C) revealed that most states prohibit drivers from traveling left of a no-passing marking, such as a double solid yellow centerline, or in the case of a one-direction, no-passing zone a broken yellow line in combination with a solid yellow line. Idaho and New Hampshire do permit drivers to remain left of the solid centerline after the end of a passing area if necessary to complete a passing maneuver. The permissive nature of the no passing marking at the end of a passing zone was referred to as the “long-zone” concept by Van Valkenburg (*129*). He recommended that the concept should be adopted given the fact that it was not always physically possible to complete the passing maneuver without crossing the solid yellow line.

In some of the statutes the clearance to the opposing vehicle at the end of the pass is specified, ranging from 100 to 300 feet (approximately 30 to 90 meters) or described as without interfering with the opposing traffic. The statutes also prohibit the impeding vehicle from accelerating while being passed by another vehicle.

3.1.4 Federal and State Truck Size and Weight Regulations

In 1956, the Federal-Aid Highway Act (*130*) was passed and the federal government began regulating the width and weight of large trucks operating on the Interstate Highway System as a means to protect its investment against the damage caused by heavy vehicles. The maximum gross vehicle weight was 33,300 kg (73,280 lb) and the single and tandem axle loads were limited to 8,200 kg (18,000 lb) and 14,600 kg (32,000 lb) respectively. The width was limited to 2.4 m (96 inches) while limits on the length and height were left up to the individual states. The weight limits were increased in 1975 to allow a gross vehicle weight of 36,400 kg (80,000 lb), single axle load of 9,100 kg (20,000 lb), and a tandem axle load of 15,500 kg (34,000 lb). These regulations were permissive in nature and the states were not compelled to strict adherence.

In 1982, the regulations became mandatory under the Surface Transportation Assistance Act (STAA) (*131*), however states could retain their previous higher weight limits through grandfather clauses. Limits on the lengths of semi trailers and trailers were included. States were required to allow tractor semi trailer combinations with semi trailers 14.6 m (48 ft) long and tractor twin-trailer combinations with trailers 8.7 m (28.5 ft) long to operate on a collection of roads classified as the National Network (NN), however, the individual states had the authority to permit longer trailers. There was no limit on the overall length, except for tractor-trailer combinations designed and used specifically to carry automobiles or boats in specially designed racks. STAA vehicles were limited to a width of 2.6 m (102 inches).

In 1991, under the Intermodal Surface Transportation Efficiency Act (ISTEA) (*132*), states were prohibited from introducing allowances for the operation of longer combination vehicles (LCV), which is any tractor multi-trailer combination that exceeds 36,400 kg (80,000 lb) or has more than two trailers or the length of any single trailer exceeds 8.7 m. This freeze was maintained in the 1998 Transportation Equity Act for the 21st Century (TEA-21) (*133*).

The current federal weight regulations (*134*) limit the gross vehicle weight to 36,400 kg (80,000 lb), the single axle load to 9,100 kg (20,000 lb), and the tandem axle load to 15,500 kg (34,000 lb), which are the same limits that were introduced in 1975. The current limits on truck size (*135*) are the same as those for STAA trucks, specifically 14.6 m (48 ft) semi trailers, 8.7 m (28.5 ft) trailers, and a width of 2.6 m (102 inches). Many states allow tractor semi trailers with 16.2 m (53 ft) long semi trailers to operate on the NN, and a few states allow even longer semi trailers, up to 18.3 m (60 ft).

3.1.5 North America Free Trade Agreement

One of the objectives of the North American Free Trade Agreement (NAFTA) (*136*) was to eliminate trade barriers and facilitate the cross-border movement of goods and services. The Land Transportation Standards Subcommittee (LTSS) was established under Article 913(5)(a)(i) and its work plan comprised of several compliance issues including standards-related measures for bus, truck and rail operations as well as the transportation of dangerous goods. Compliance issues related to the truck weights and dimensions were to be implemented no later than three years after the 1994 entry into force of the Agreement. The standard capability work program remains to be completed and continues to hinder cross-border trade. The discrepancies between the federal truck size and weight regulations in the United States (*134*, *135*), Canada (*137*), and Mexico (*138*) are shown in Table 3.4. While the LTSS is considering the use of performance criteria and thresholds for regulatory control it has also prepared a side-by-side analysis of the truck size and weight limits from 65 jurisdictions in the three countries (*139*, *140*, *141*, *142*). The LTSS has arrived at recommended truck size and weights, as included in Table 3.2, although no formal agreement has been reached. The LTSS recommended truck lengths are similar to the current US regulations with the exception of the overall truck length limits. These have been included because most truck travel in Canada and Mexico is on two-lane highways where the overall length of the truck may restrict the ability for other vehicles to pass an international truck.

TABLE 3.4. Comparison of Truck Size and Weights

Description	United States	Canada	Mexico	LTSS
Overall Tractor Semi Trailer Length, m		23.0	20.8	23.0
Overall Tractor Double Trailer Length, m		25.0	31.0	25.0
Semi Trailer Length, m	14.6	16.2		16.2
Double Trailer Length, m	8.7	20.0[a]		8.7
Width, m	2.6	2.6	2.6	2.6

Note: a) Canada uses box length, which includes two trailer lengths and the space between.

3.1.6 Reviews of the Federal Truck Size and Weight Regulations

Changing the federal truck size and weight regulation is a controversial issue. Congress has received a number of proposals from industry groups, state governments, and others. Some argue that there is an overwhelming dissatisfaction with the current situation (*143*) while others argue the current situation represents a balance between the needs of motorists, truckers, shippers, and the maintenance of a healthy freight system (*144*). In a workshop held in 2000, industry leaders had the opportunity to voice their opinions about the current regulations (*145*). The opinions included leaving the regulations as-is, changing the policies within the existing framework, and changing the framework itself.

A number of studies have been performed to try to evaluate the impact of changing the current federal truck size and weight regulations (*143*, *146*, *147*, *148*, *149*, *150*). In several of those reports, some recognition about the potential impact that changes might have on the passing maneuver was made. In 1994, the US Department of Transportation began a comprehensive truck size and weight study, and the completed study was submitted to Congress in 2000 (*150*). In this report, it was acknowledged that the distance needed to pass large trucks could be significantly larger than those for passing passenger vehicles and that the current sight distance criteria for design and marking do not take into account longer vehicles. It was noted that LCVs could require up to eight percent more passing sight distance but the source for this statistic was not identified. In Special Report 267 (*143*), conclusions were drawn from the previous Transportation Research Board (TRB) reports and previous truck size and weight studies. In this report, it was stated that liberalization of the federal regulations would change driver behavior including passing behavior and would ultimately negatively impact congestion and emissions. It was also stated that the traffic effects are well enough understood to facilitate regulation change. However, both of these statements were later questioned in a following independent evaluation (*144*).

3.2 Need to Classify the Factors that Potentially Impact Passing Sight Distance

The methods of examining the impact of different factors on the passing sight distance have included making observations in the field, conducting field experiments, and conducting experiments in controlled environments. The specific observation and recording techniques were reviewed to illustrate the difficulties and risks in capturing passing behavior.

The results of the previous studies were reviewed to summarize what is known about passing behavior. A common approach to describe the factors that influence the passing sight distance is to categorize them as driver, vehicle and environment factors. With a better understanding about passing sight distance, it is clear that the factors need to be classified according to their potential impact.

3.2.1 Study Methods

In the 1930's tremendous efforts were made to observe passing maneuvers in the field and record details about drivers' passing behavior. This task proved difficult because of the spatial and temporal variability of passing. Greenshields (*4*) photographed vehicles from a fixed observation point but captured very few passing maneuvers. Holmes (*8*) developed a method of capturing passing maneuvers, which consisted of a series of air tubes installed 50 feet apart in each lane along the roadway. A graphical time recorder was activated each time an air tube was depressed, thereby recording the progression of vehicles. Using the Holmes method, over 20,000 passing maneuvers were captured across seven states in three years (*9*). The data was captured in electronic form, however the robustness of the data was limited by the spacing of the detectors and the process of summarizing the data was lengthy. Forbes also managed to capture passing maneuvers by photographing the vehicles from a plane, (*7*), although care had to be taken in selecting the camera characteristics.

In addition to the covert field observations, another approach used by Forbes (*7*) was to ride along with the test driver in the passing vehicle and using a stopwatch, record the judgment and perception time needed to begin a pass. Forbes and Matson conducted a field experiment (*5*, *6*) where the passing maneuvers were observed from the impeding vehicle driven in the traffic. The distance to the passing vehicle was photographed from the impeding vehicle and the passing time was measured using a stopwatch. To some extent, each of these methods exposed the observer, and the test driver, to the dangers of moving traffic.

There was a resurgence of interest in the passing maneuver in the 1960's that lingered into the 1970's, which resulted in a variety of field experiments and controlled or closed-course experiments being conducted. It began with Crawford's (*151*) examination of drivers' acceptance of the gap in the opposing traffic using a controlled experiment. The speeds of the impeding, passing and opposing vehicles were controlled to produce different speed-gap size combinations. The vehicles had instrumentation, linked by radio that recorded the movement of the vehicles. The results of the controlled experiment were supported by the results of a similar field experiment. Observations were taken from the impeding vehicle driven at a constant speed. The times that particular events occurred were recorded.

In further field experiments, stopwatches (*129*, *152*), manually activated event recorders (*153*), and operations recorders (*154*) have been used to record the time that events have occurred. Speeds and distances have been captured using reference marks on the roadway (*153*) and images captured using cameras (*154*, *155*) or read from a speedometer and odometer (*129*). In one study, the observer rode as the passenger in the passing vehicle and subjectively evaluated the risk taken by the passing driver in terms of the size of the gap accepted in the opposing traffic (*156*).

In further controlled experiments, estimates of the time headway between the passing vehicle and the opposing vehicle have been compared to the actual times recorded using stopwatches (*157*, *158*). Distances have been measured using a manually activated marking pistol installed on the rear bumper of the passing vehicle (*159*). A more elaborate experimental method has included using a fifth wheel on the passing vehicle to capture distance and speed, photocells that respond to reflective tape placed across the roadway at 400 foot intervals, and instrumentation in the passing vehicle to measure lateral and longitudinal acceleration, lateral position, yaw rate, brake pressure, and steering wheel position (*160*, *161*).

The advances in video recording technology and computer technology have improved the capability of recording passing maneuvers in the field. In more recent field observation studies and field experiments video recording technology (*22*, *162*, *163*) and computer technology (*164*) have been implored. The use of these methods however, is still challenged by the temporal and spatial variations of passing and the inherent risks of observing traffic in the field.

3.2.2 Study Results

Through the various field observations, field experiments and controlled experiments, much has been learned about the passing maneuver and drivers' passing behavior. The passing sight distance can be described in terms of the contributing environment, vehicle, and driver factors as outlined in Figure 3.3.

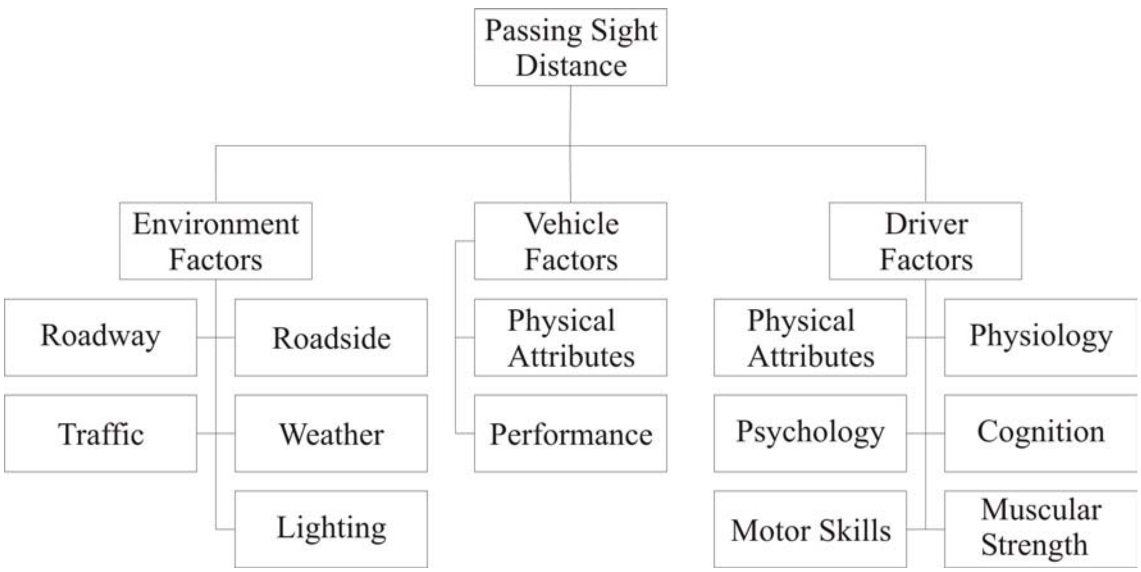


FIGURE 3.3. Classifying the passing condition factors by the source.

3.2.2.1 Environment Factors. The environment factors describe the situational elements of the passing maneuver including the characteristics of the roadway, traffic, roadside, weather, and lighting conditions.

Hostetter et al. (*154*) found that the sight distance was the predominate factor in deciding to pass however, the speed traveled while impeded was a contributing factor as was the interaction between the distance traveled and the available sight distance. Surprisingly, drivers have been observed to accept smaller passing opportunities when the opportunity was limited by sight distance as opposed to limited by the presence of an opposing vehicle (*153*). The time taken to respond to the passing opportunity was found to increase when the time to the opposing was very large (i.e. no threat from opposing traffic) or approached the critical or threshold time interval

(*151*). As the travel speeds increased, the critical time interval decreased and the response times increased.

In many field observations, and field experiments, the passing distance and passing time have been found to increase with the speed of the impeding vehicle (*5*, *9*, *22*, *151*, *155*). This result could also be presented in terms of the posted speed or design speed. Troutbeck (*162*) found that the mean passing time and distance increased when the maneuvers were performed on narrow, 6 m wide roads as compared to more common 7.4 m wide roads. The gaps in the opposing traffic that were accepted by the drivers were larger on the narrow road, however the difference in gap acceptance was attributed to the difference in the traffic volume at the two study locations. Given that fact, there is the possibility that the passing time and distance was more influenced by the traffic conditions than the road conditions.

Farber (*153*) compared passing behavior observed under nighttime conditions with behavior previously observed under daytime conditions on the same roadway sections. The mean decision time was found to be less under the nighttime conditions and the mean passing time was slightly less during the day when the passing opportunity was greater than 2,500 feet (762 m).

3.2.2.2 Vehicle Factors. Vehicle factors describe the physical attributes and performance capabilities of the vehicles. In the passing maneuver the vehicle factor may describe the passing vehicle, the impeding vehicle, or an opposing vehicle. Characteristics of the traffic, or groups of vehicles are considered environmental factors.

Passing time and distances have been observed to increase with the speed of impeding vehicle (*5*, *151*). Flying passes took more distance than accelerated passes but the difference decreased at higher speeds (*5*, *6*). The speed differential between the passing vehicle and impeding vehicle was thought to be 10 mph (16 km/h) regardless of speed however it has been shown that the speed differential was smaller with greater impeding vehicle speeds (*155*). The impact of the dimensions of the impeding vehicle has also been examined. The width of the impeding vehicles appeared to have no effect on the passing time, distance, or speed but increased the decision time (*165*). Through field observations, it has been found that the passing distance and time increased when larger impeding vehicles were passed (*22*).

Gordon and Mast (*159*) found that drivers were better at estimating their passing performance when driving their own vehicle as opposed to an unfamiliar vehicle. This result was attributed to the drivers' knowledge and experience with their own vehicle's performance.

In the same study, it is noted that the vehicle of one test driver could not be used because the 1959 Volkswagen did not have the performance capabilities to pass at 50 mph (80 km/h) within the limited distance available.

3.2.2.3 Driver Factors. Driver factors describe the drivers of the vehicles in terms of who they are, and their ability to process information, make decisions and carryout actions. The majority of the driver studies have focused on some aspect of driver judgment or estimation. One exception was the study by Brown et al. who reported that drivers who have been driving for a prolonged period of time are more likely to make risky maneuvers (*156*). This conclusion was based upon subjective characterization of the gaps that drivers accepted.

Jones and Heimstra (*152*) found drivers to be poor at deciding the last safe moment to start a passing maneuver. The estimates among subjects were highly variable and nearly fifty percent of the estimates were less than the average passing times exhibited in the practice passes. In another study (*158*), drivers were asked to indicate when the opposing vehicle was 12 seconds ahead. The time gaps were underestimated at low speeds and overestimated at high speeds however, the knowledge of opposing vehicle speed or closing rate decreased the variance in the estimates. Without knowledge about the opposing vehicle, the variance of the estimates decreased with practice. Farber and Silver (*161*) reported that drivers were sensitive to the closing rate of the opposing vehicle to the passing vehicle but that drivers did not perfectly compensate for changes, therefore the actual ability to judge the closing rate was unknown.

It was found that when the speed of the opposing vehicle was given, drivers used that information to decision whether or not to pass (*160*), however driver were poor at making the speed judgment. Drivers were sensitive to the speed of the passing vehicle but did not perfectly compensate for changes (*161*).

Farber and Silver (*161*) also reported that drivers are sensitive to the distance between the impeding vehicle and the passing vehicle as well as the distance to the end of a passing zone, and in another study concluded that drivers could judge distance (*160*). Gordon and Mast found drivers estimated passing distance better when driving their own vehicles than the experimental vehicle, however the distances were underestimated and the errors increased at high travel speeds (*159*). Forbes and Matson examined the accepted and rejected gap sizes and concluded that there was a large amount of uncertainty in the judgment of the clearance distance (*6*).

3.2.2.4 Interrelated Factors. The benefit of categorizing each factor by its source is that it is easy to identify the source of a factor and each factor only belongs to one source. However, the detriment of this approach is that the impact of the factor, and relationships between factors are neglected. For instance, a change in the grade of the roadway is obviously an environment factor but it may have an impact on the performance of the vehicle or change the way the driver behaves. To capture these types of relationships, a more beneficial approach would be to categorize the factors in terms of their potential impact. Such an approach was used in section 8.2.1.

3.3 Need to Develop a Passing Sight Distance Equation

There have been two types of models developed to describe the passing sight distance. The first type is the empirical models, which have been developed from data and describe the passing situation where one passenger car passes another passenger car. The second type is the theoretical models, which have been based on a theory or supposition. These models have been used to predict the impact of trucks.

3.3.1 Empirical Approach

The most well known empirical model of passing sight distance is the AASHTO model, based on Prisk's analysis of 3,521 passing maneuvers. Originally, the model consisted of three elements: 1) Preliminary delay, 2) Occupation of left lane, and 3) Interval for opposing vehicle (*9*). The values of these elements were calculated from the observed times, accelerations, speeds, and distances for three speed ranges. The third element has since been broken into two separate elements and they have been renamed d_1 through d_4 (*10*). Extrapolated data has been used to calculate the distances for a fourth, higher speed range. The MUTCD model is also an empirical model but the origin of the values is unknown.

3.3.2 Theoretical Approach

The majority of the theoretical models that have been developed are based on the supposition that the passing vehicle reaches a critical position, point of no return, or critical point during the passing maneuver where the passing driver decides to continue or abort the maneuver. Both Weaver and Glennon (*155*) and Van Valkenburg (*129*) independently surmised the existence of this decision point. Van Valkenburg recognized that the critical point would vary depending on the driver, characteristics of the passing vehicle, and the speeds of the impeding and opposing vehicles.

The presumption is that the driver continuously reevaluates the progress of the pass with respect to the impeding vehicle and the available passing sight distance. However, there was no empirical evidence to support this opinion. In fact, the passes completed under unsafe conditions (*5*, *6*) contradict it. Furthermore, the ability to judge when the critical point is reached or to judge the passing sight distance needed to abort the maneuver are highly questionable considering drivers have been found to be relatively poor at judging distances, speed, and closing rates, and estimating the needed passing distance.

In 1972, Herman and Lam (*14*) developed an analytical model of the passing maneuver based on this theory of a point of no return, defined as the point where the driver is better to complete rather than abort the maneuver. A decade later, Lieberman (*15*) developed an analytic model based on the kinematics of the passing maneuver. The critical position was defined as the moment that completing or aborting the passing maneuver would offer the driver the same clearance with oncoming vehicles. Building upon Lieberman's definition of critical position, Saito (*16*) developed two analytic models for the aborted passing maneuver. The models were developed under the assumption that initiation of the abort decision occurs when the passing vehicle is either trailing or abreast the impeding vehicle.

Glennon (*17*) criticized the developers of those models for failing to apply the critical position concept and to weigh the trade-offs between completing and aborting the passing maneuver. His definition of the critical position was the point in the passing maneuver where the passing sight distance needed to complete the maneuver is equal to the passing sight distance needed to abort the maneuver. He developed time-space diagrams detailing completed and aborted passing maneuvers and mathematical expressions for the critical position and critical passing sight distance. Rilett, Hutchinson and Whitney (*18*) challenged some of the assumptions used to develop the Glennon model. Their modified model allows vehicles to continue to accelerate past the critical point and in an abort maneuver decelerate to some terminal speed. Hassan, Easa and Halim (*19*, *166*) pointed out several deficiencies in the Glennon model and criticized the Rilett model for being too conservative. Lui and Herman (*167*) recognized the Lieberman model as a specific case of the previous Herman and Lam model and criticized the formulation of distance and time prediction equations. The Herman and Lam model was extended to incorporate the acceleration and deceleration of vehicles under wet and dry pavement conditions and longer impeding and/or passing vehicles.

3.3.3 Passing Models to Predict the Impact of Trucks

Lieberman (*15*) and Saito (*16*) addressed the impact of trucks by varying the length of the impeding vehicle in their models. The passing sight distances increased, reflecting the additional distance to be traveled around a longer impeding vehicle. Glennon and Harwood (*20*) used the Glennon model to investigate the impact of trucks in three passing scenarios, passenger cars passing trucks, trucks passing passenger cars, and trucks passing trucks. As expected, the longer vehicles required greater passing distance, however this result was amplified by the speed of the impeding vehicle. Rilett et al. (*18*) used their model to demonstrate that the passing sight distances were sensitive to the design speed, the length of the impeding vehicle, and the minimum time headway between the impeding vehicle and the passing vehicles. Goods et al. (*21*, *168*) used the Lieberman and Glennon models to show the speed of the impeding and passing vehicles, and the length of the impeding vehicle were most sensitive in determining passing sight distance.

In 2000, Polus, Livneh and Frischer (*22*) aimed to quantify the major components of the passing maneuver by examining approximately 1,500 passing maneuvers videotaped from vantage points and from a hovering helicopter. The speed differential, headway between the passing and impeding vehicles at the beginning of the maneuver, distance the opposing lane was occupied, tailway between the passing and impeding vehicles at the end of the maneuver, and clearance to the opposing vehicle were observed to be greater when the impeding vehicle was a tractor semi trailer. This result suggests the impact of an increase in the impeding vehicle length was not limited to the added distance traveled along the length of the impeding vehicle.

3.3.4 Future Work

In the recently published report *Review of Truck Characteristics as Factors in Roadway Design* (*169*), the current passing sight distances for design and marking were reviewed. The incompatibility between the design values and the much smaller marking values were discussed and the origins of the current criteria were critiqued. Several of the above models were mentioned but the portion of the document related to passing was heavily weighted toward the Glennon model (*17*).

Subsequently, the National Cooperation Research Program released a call for proposals for Project 15-26 “Passing Sight Distance Criteria”. Passing sight distance criteria for both design and marking are to be considered. Phase I of the project is to include 1) a review of the principles, data, assumptions, and calculations for the ASSHTO and MUTCD models, 2) an analysis of the pertinent research and practices, 3) identification of the limitations, and 4) development of recommendations for acceptance or modification of these criteria. Phase II of the project is to be focused on preparing new or modified passing sight distance criteria suitable for design and marking.

4 A METHODOLOGY FOR ADVANCING TRAFFIC SIMULATIONS

A methodology for creating and applying distributed simulations to address behavior or traffic problems is presented as a framework in Figure 4.1. It is assumed that the behavior or traffic problem lends itself to investigation through simulation techniques. The methodology is applicable for those problems where an existing simulation is not adequate and the features from multiple existing simulations combined together are desired. Problems that require investigation methods other than simulation or problems where new simulations need to be created fall outside this framework.

Within this framework, the methodology begins with the identification of the requirements needed to address the particular behavior or traffic problem. Contributing simulations are chosen based on those requirements and the distributed simulation is created. The creation of the distributed simulation includes the design, development, and evaluation processes. The final distributed simulation is then applied to the original behavior or traffic problem. Within this framework, there are several potential avenues for feedback to improve the contributing simulation and/or the distributed simulation. In this section, the steps of the methodology, and the feedback loops are discussed.

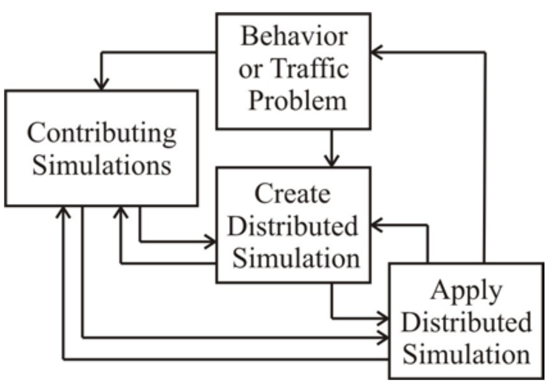


FIGURE 4.1. The general framework for advancing simulations.

4.1 Step 1: Behavior or Traffic Problem

The first step in the methodology is to identify the study requirements of the behavior or traffic problem, in terms of the elements in the model, and the simulation output.

4.1.1 Model Elements

The elements are those physical features of the real system that need to be included in the model to reasonably represent the real system and allow the behavior or traffic problem to be investigated. The elements can be categorized as static or dynamic. Static elements do not change over time whereas dynamic elements change as the simulation advances in time. Some typical static elements are the roadway alignment, roadside features, intersection geometry, and static traffic controls such as stop signs and speed limits. Some typical dynamic elements are the vehicles and other road users, and the dynamic traffic controls such as traffic signals. It is possible for some of the typical static elements to be given dynamic behavior such as reversible traffic lanes, where the direction of traffic flow is reversed some time during the simulation. It is also possible for a typical dynamic element to be modeled as a static element. For instance, vehicles may be positioned in the model and remain unchanged during the simulation.

In the simulation program, the elements are represented in the computer code as some set of variables and may also be represented as a visual construct in an animation. A point or block representation may be used. With point representation, elements have no discernable dimension whereas with block representation, the elements have defined measurements. In the animations, the elements may be drawn as wire frames or they may have textured surfaces. Advanced visualization tools can be used to produce life size images in high resolution that can be viewed in color on large screens such that they subtend a large field of view.

A very important issue concerning the elements used in the model is how each dynamic element changes and interacts with other elements. This behavior is determined by the logic contained within the simulation program. In terms of vehicle behavior, there may be logic included to describe how vehicles select travel routes, how vehicles are controlled within a lane, and how vehicles change lanes or make turning maneuvers. The behavior or traffic problem may be isolated to one specific situation where a simplified logic is sufficient however some problems may require very detailed models with complex logic. The simulations need to be chosen accordingly.

4.1.2 Simulation Output

The simulation output is the raw data from each simulation run. To address the behavior or traffic problem, the type of data and the fidelity of that data need to be specified. The data may be for a particular type of element, a group of elements, or a measure of the operation of a portion or all of the system being simulated. Not all simulation programs have the same output capabilities and therefore, must be carefully chosen.

By specifying what fidelity of output is needed to address the behavior or traffic problem, the level of detail needed in the simulation can be identified. The required output may be a detailed account of the status of individual elements during the simulation run or a summary of the status for groups of elements or the system as a whole. If disaggregate data is desired, then a microscopic simulation is needed to produce details about individual vehicles. Due to the dynamic nature of traffic systems, and the interactions that occur between individual vehicles, it is assumed that the microscopic model would be simulated using a fixed time step, whereas a macroscopic model may use event-based time advances. Typically, a microscopic simulation can output disaggregate data for every time step in the simulation run, therefore, the fidelity of the output depends on the size of the simulation time step. In some programs, the user can specify the size of the time step, ranging from seconds to a small fraction of a second. If aggregate data is sufficient, there are both microscopic and macroscopic simulation models that provide such output. The chosen simulation program must provide the specified output fidelity.

4.2 Step 2: Contributing Simulations.

A distributed simulation is a simulation that is divided into parts. The framework shown in Figure 4.1 represents the situation where the distributed simulation is created by combining existing simulations to take advantage of their capabilities. The specific simulations are selected because together they provide the capabilities needed to address the behavior or traffic problem. They have the desired model elements, contain logic appropriate to investigate the specific problem, and produce the desired output.

In addition, each simulation must have import and export capabilities to facilitate communications. A large proportion of the simulation programs available are legacy or proprietary programs. Some programs may not have import and export capabilities and are therefore not suitable for inclusion into a distributed simulation.

4.3 Step 3: Create Distributed Simulation

The creation of the distributed simulation includes the design, development, and evaluation processes. The design is the process of putting together the plan or blueprint of how to construct the distributed simulation and the development is the process of putting that plan into action. The evaluation is the process of assessing the implementation of the design and the usefulness of the final distributed simulation. Through these processes, potential improvements to the contributing simulation and the distributed simulation may be identified.

4.3.1 Design Process

The structure of a distributed simulation is modular therefore, the design of the distributed simulation focuses on specifying the communications among the individual simulations. There are many issues surrounding the communications among the simulations that need to be addressed. These issues include identifying the data flows, specifying the type and size of the data packets, defining data storages, identifying needed algorithms to manipulate the data, and specifying the communication frequency and speed. There are also initialization and synchronization issues. These data management and time management specifications should be included in the design.

4.3.1.1 Data Management. The backbone of the communications is the network of data flows linking the individual simulations. Depending upon the specific behavior or traffic problem, it may be desirable to have one-way and/or two-way data flows between pairs of simulations, therefore, the direction and routing of the data needs to be specified.

The type of data that is transferred depends upon what contribution each simulation will provide to the distributed simulation. Difficulties arise when the disparate simulation programs use difference elements to construct the model of the system, or elements that have common labels have different meaning. Consistency in the model description and the meaning of elements among simulations, or the ability to translate the meaning, is needed.

The number and size of the data packets to be transferred needs to be specified. It may be desirable to send data about a select few elements or all the elements from one simulation to another. Each piece of data may constitute a data packet or the data may be grouped together to improve the efficiency of the communications.

It is likely that the format of the data or the programming language of the disparate simulation programs will differ. It is even possible that the operating platforms differ and the simulations need to be run on separate processors. To translate the data format or convert the data into the appropriate language commands of the intended destination simulation, data storage is needed. This storage area may be appended to the individual simulation programs or could be contained within a separate program, which links the simulation pairs. Additional algorithms could also be included if manipulation of the data is required.

Data about an element may be sent only once during a simulation run or more likely every time the state of that element changes. The frequency of the transfer of data needs to be specified and issues may arise when different data flows have different frequencies. Such issues are addressed with time management techniques.

4.3.1.2 Time Management. Time management strategies are used to control the order of the data transfers and to synchronize the time advance in the independent simulations. Without the implementation of time management strategies, the simulations run independently and the data transfers are not scheduled.

The order of the data transfers is controlled so that data transferred to a simulation is received during the appropriate simulation time step. In a simulation that runs in real-time, the data received is used to calculate the state changes of the elements and must be carried out within a single time step. If the data is received after some delay, the data is old and the element states that are calculated based on that data would be for the states of a previous time step. In essence, there is a potential to momentarily reverse the simulation or take a step back in time.

Each simulation program has an internal time that is used to advance the simulation. When a number of simulations are integrated into a distributed simulation, time management strategies are used to coordinate the advance of the simulation time with the transfer of data. An individual simulation may regulate the transfer of data to other simulations and/or be constrained by the data coming from the other simulations. It is the combination of regulating and non-regulating, constrained and unconstrained simulations included in the distributed simulation that determines the needed time management strategies.

4.3.2 Development Process

During the development, the data and time management strategies are implemented. Communication with the individual simulations is established and the data storage and algorithms are created and implemented to complete the network of data flows. Measures are introduced to control the order of the data transfers and to synchronize the time advance in the individual simulations. The design may be altered to address unforeseen issues or to include minor enhancements.

4.3.3 Evaluation Process

The evaluation process occurs in combination with the development process. As each portion of the distributed system is created, it can be tested to ensure that it is working as expected. For instance, when communication with a simulation is established, the quality of that communication can be evaluated before proceeding to the next development task. Problem identification and remediation is much easier when small portions of the simulation are tested separately instead of trying to debug the completed, larger, distributed simulation. It is possible that problems will be encountered that hinder further development of the distributed simulation. It is also possible that through the development and evaluation processes, potential improvements to the contributing programs and the distributed simulation will be identified.

4.3.3.1 Output. The distributed simulation is created to produce the desired output needed to address the behavior or traffic problem. The evaluation process should be used to verify the type and fidelity of the output and to quantify any errors.

4.3.3.2 Communications. During the design process, the data management and time management strategies are specified. These strategies need to be evaluated. Through the evaluation process, delays in the transfer of information, inefficient data storage, and inappropriate manipulation of the data may be identified. The results may be used to support further development of the distributed simulation or perhaps optimize the data management or time management processes.

4.4 Step 4: Apply Distributed Simulation

The distributed simulation is created in light of a specific behavior or traffic problem. Once the final simulation has been evaluated and accepted for use, it can be applied to produce the output needed to arrive at a solution to that problem. During the application process, experience using the distributed simulation is gained and can be used to make recommendations for improvements to the contributing programs and the distributed simulation.

4.5 Benefits of the Methodology

The methodology is suitable for situations where a specific behavior or traffic problem cannot be addressed using the traditional tools and where several existing simulations in combination together provide the necessary capabilities. The inherent strength of the methodology is the synergistic effects of having several simulations running synchronously. The benefits of this methodology should be attractive to both the users and the developers of simulation tools.

4.5.1 User Benefits

Traditionally, users select one simulation program that meets the requirements needed to address a particular behavior or traffic problem. The selection is made from the population of available simulation programs that differ by the level of detail, the elements used to create the model, the type of time advance, and the program logic used to change the states of the elements. Because programs are designed and developed to simulate the operations of specific types of facilities or traffic movements, sometimes the user is forced to select a program that meets most but not all of the requirements to address the given problem.

This methodology provides the user the opportunity to select multiple simulations to meet the needed requirements. The simulations are combined together to take advantage of the combined capabilities. Essentially, a new distributed simulation is created using multiple existing simulations, thereby extending the usefulness of the current population of simulation programs.

4.5.2 Developer Benefits

The developers can view this methodology as a means to extend the lifecycle of their products by expanding their usefulness for addressing a larger variety of behavior or traffic problems. This could also mean an increase in market coverage, where simulations are used in concert with other types of simulations. For instance, the interaction between driver behavior and traffic conditions could be investigated using a distributed simulation that combines a traffic simulation, which is normally used for traffic studies with a driving simulator, which is normally used for behavior studies. A longer lifecycle and greater market coverage means more profits, which should be very attractive to the developers of commercial programs whose survival depends on making a profit.

If the idea of distributed simulation is accepted among developers, there is a great potential to advance the field of traffic simulation. The newest technologies, such as visualization tools and improved logic to control model elements, could be included into a distributed simulation without a full redesign of a particular program. It would also allow developers to concentrate their research and development efforts on one particular aspect of traffic simulation that could be incorporated into a variety of distributed simulations. There is also the potential to gain feedback from innovative applications of a distributed simulation, which could be used to improve the contributing programs, and in turn improve the distributive simulation, thus advancing the field of traffic simulation.

5 THE PROTOTYPE

The methodology, presented as a framework in Section 4, was used to create a prototype that combined a VISSIM traffic simulation and a DriveSafety driving simulation. It was hypothesized the final prototype could be used to create a specified traffic flow in DriveSafety and to capture both traffic and driver behavior data.

5.1 Step 1: Behavior or Traffic Problem

The specific problem to be addressed was to determine the impact of the length of an impeding vehicle on passing behavior. The methodology was chosen for three reasons:

1) the difficulties investigating the passing maneuver in the field;
2) the shortcomings of the existing traffic and driving simulations; and
3) the potential to use a distributed simulation comprised of existing traffic and driving simulations.

The majority of previous passing maneuver studies were conducted in the field. The observer had very little knowledge about the drivers or control over the vehicles or environment, apart from choosing the observation location, and selecting the time of day or under what weather conditions observations were taken. Another drawback of these methods was that the observer, and the drivers involved in the passing maneuver were subject to the hazards of driving. The passing maneuver is a dangerous maneuver, given that the passing vehicle travels in the opposing lane. Passes are usually conducted at highway speeds, thus the closing speed between the opposing and passing vehicle is approximately double the speed limit and such head-on collision can be quite severe.

While there are many traffic simulation programs that contain complex car following and lane changing logic, most do not simulate passing maneuvers. Microscopic traffic simulation programs that simulate the operations of rural highways, including passing maneuvers, include TWOPAS and TRARR. These programs are used to evaluate the capacity and level of service of the rural highway under various passing and no-passing marking configurations, and the design of passing lanes. For each simulation run, the details about the movement of all the vehicles during the simulation can be output. These programs do not have the capability to simulate changes in driver behavior and therefore are not suitable to predict the impact of the length of the impeding vehicle on passing behavior.

Driving simulations are used to conduct driver behavior studies. Scenarios can be created that model rural driving environments, however creating a specific or calibrated traffic flow, or having vehicles move according to accepted theories of car following and lane changing, may be extremely complicated and/or time consuming. In a passing maneuver, the driver behavior is a function of the movements of the impeding and opposing vehicles therefore, it is important to have information about those vehicles. Some driving simulation programs do not have the capability to record data about all the vehicles during the simulation. For these reasons, the driving simulation alone is not suitable to study the impact of the length of the impeding vehicle.

By combining a traffic simulation and a driving simulation, a driving scenario can be produced that has a specific traffic flow, and both traffic and driver behavior data can be recorded during each simulation run. These are ideal capabilities for conducting a passing behavior study where the passing driver can be observed in a controlled and safe driving environment and data about all the vehicles involved in the maneuver can be recorded.

5.1.1 Conceptualization of the Distributed Traffic Simulation

The conceptualization of the distributed traffic simulation, which integrates disparate traffic and driving simulations, is shown in Figure 5.1. The data about the opposing and impeding vehicles are exported from the traffic simulation and imported by the driving simulation to control the flow of the vehicles in the driving scenario. At the same time, data about the test vehicle controlled by the test driver is exported from the driving simulation and imported by the traffic simulation. The two-way, real-time exchange of data permits interaction between the impeding and opposing vehicles controlled by the traffic simulation and the test vehicle controlled by the test driver in the driving simulation.

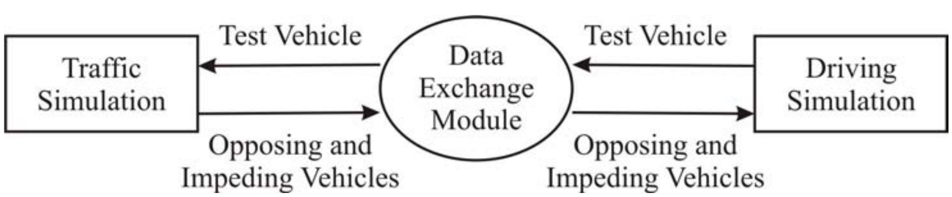


FIGURE 5.1. A conceptualization of the distributed traffic simulation.

5.1.2 Import and Export Capabilities

A basic requirement for any simulation to be included in the distributive simulation was the capability to import and export data. Many legacy and proprietary programs, which were designed for stand-alone simulations did not possess this capability and were therefore not suitable. If the data from the traffic simulation and the driving simulation differed because of the data format, reference to the separate coordinate systems used to build the models, variable names, etc. and needed to be converted or translated, these functions would occur in a data exchange model, which would also facilitate the real-time communication between the two simulations.

5.1.3 Desired Model Elements

The passing condition is described by the static elements making up the environment, and dynamic vehicles. At a minimum, both the traffic and driving simulations needed the capability to model a straight, two-lane, two-way, rural roadway. The visible environment could include elements such as trees, houses and farms that are typical for a rural setting.

In the passing experiment, the passing conditions that the test drivers experience needed to be controlled. To examine the impact of the length of the impeding vehicle on passing behavior, at least two distinctly different lengths of vehicles were needed. It was also desirable to have two distinctly different travel speeds, as speed has been shown to impact passing behavior. A specific traffic volume of opposing vehicle was needed, such that the sizes of the gaps in the opposing traffic were controlled. All the vehicles needed to interact with each other including the test vehicle driven by the test driver.

5.1.4 Desired Simulation Output

To investigate the passing behavior problem, disaggregate data about the test driver and the traffic was needed. In previous field studies, the passing time has been reported to the nearest tenth of a second. The same fidelity for the recorded behavior and traffic data was desired.

Driving simulations are microscopic, where the states of individual elements are updated using a fixed time step. The size of the time step is very small so that the test driver does not perceive discontinuities in the time advance, and interactions with vehicles and the environment are realistic. Typical refresh rates of the images are in the neighborhood of 30 to 60 times per second and some programs record the test driver's behavior at this same rate.

To create the vehicle flows in the simulated driving environment, either a macroscopic or microscopic traffic simulation could have been used, however the desire to record disaggregate traffic data required that the traffic simulation be microscopic. Such programs use fixed time steps as small as one or one tenth of a second. The details of the movements of individual vehicles are usually available for each time step.

5.2 Step 2: Select VISSIM and DriveSafety

The second step of the methodology was to select the contributing simulations. The microscopic traffic simulation program VISSIM and the driving simulation program DriveSafety were chosen because together they have the desired model elements, can produce the desired simulation output, and each can import and export data during a simulation run. The capabilities of each program are detailed in the following sections.

5.2.1 Description of VISSIM

VISSIM was developed by PTV AG of Germany as a behavior-based, multi-purpose microscopic traffic simulation program. It was a proprietary program and was commercially available in Europe through PTV AG, and in North American through Innovative Transportation Concepts, Inc. (ITC), the exclusive North American distributor of the ptv vision® software suite. VISSIM ran on a personal computer with a recommended minimum of a Pentium III processor, 128 MB memory, 1280 x 1024 screen resolution, a 3D accelerator chipset video card, and operated in a Microsoft Windows environment.

VISSIM has been be used for a variety of planning, design, and operation studies with traffic or transit simulation needs. Some sample applications have included evaluating freeway management designs, Intelligent Transportation Systems (ITS), transit signal priority plans, toll plaza designs, transit terminal designs, as well as conducting corridor studies and environmental impact studies.

5.2.2 Description of DriveSafety

DriveSafety was a fixed based, fully interactive driving simulator developed by GlobalSim, which prior to 2002 was referred to as Hyperion Technologies and KQ Corporation. The DriveSafety system was proprietary and was sold as a turnkey product, customized and configured for the needs of the individual clients. However, the real-time driving simulator software, Vection and the user interface, HyperDrive Authoring suite was common to all implementations. The system designed for the Texas Transportation Institute (TTI) was used for this research and any further details about DriveSafety refer to that customized configuration. A schematic of DriveSafety at TTI is shown in Figure 5.2.

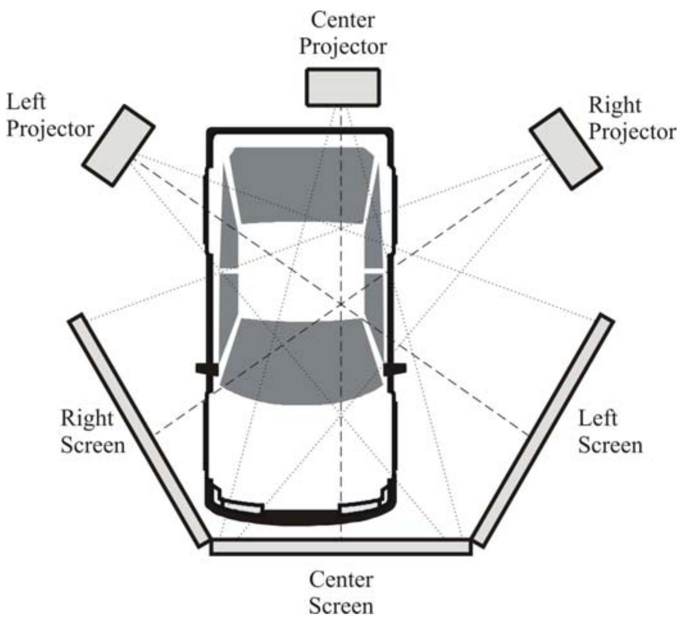


FIGURE 5.2. A schematic of the driving simulator at the Texas Transportation Institute.

There were five computer processors in the DriveSafety system. The first processor was the host, where the Vection software was run on a Linux system. Vection included the core software for simulation execution and communications, and the vehicle dynamics, scenario control, visual, audio, instrumentation, and control loading subsystems. The next three processors were the channels, each used SGI/IRIX to render the graphics sent to the corresponding projectors. The last processor contained the user interface software, the HyperDrive Authoring suite, which operated in a Microsoft Windows environment. A driving scene could be constructed by selecting elements from the available databases. A driving scenario was produced by adding Tool Command Language (Tcl) scripting commands to control the dynamic elements. The available Tcl scripting commands were listed in the HyperDrive user manual (*25*).

The computer generated driving scenarios were projected onto three screens that subtended a visual field measuring 150 degrees horizontally and 50 degrees vertically. The center of the visual field was located at the driver's head position, as depicted in Figure 5.2. The images for the rear view and side mirrors were superimposed onto the forward image. The color images were high resolution (1024 x 768) textured graphics.

The test vehicle was a full size, 1995 Saturn SL1 and had a full instrumentation package including speedometer and odometer. The accelerator, brake, and steering wheel were used to navigate through the driving scenario, interacting with the roadway and vehicles. There was a force feedback electric servomotor for steering feedback, operating at 800 Hz.

Acceleration performance tests were conducted to illustrate the acceleration capabilities of the test vehicle. From a stopped position, the accelerator was fully depressed and the speed and acceleration of the test vehicle were recorded. A sample acceleration curve is shown in Figure 5.3. Reading from this figure, it appears that the acceleration rate increased to 4.0 m/s^2, then dropped down to 3.0 m/s^2 at 30 km/h, then to 1.5 m/s^2 at 50 km/h, then to 0.8 m/s^2 at 95 km/h, and finally to zero at a maximum speed of 110 km/h. It should be noted that during the initial acceleration, the maximum acceleration was not achieved. The logic contained within the Vection software controlled the amount of acceleration to avoid slip between the road and tires.

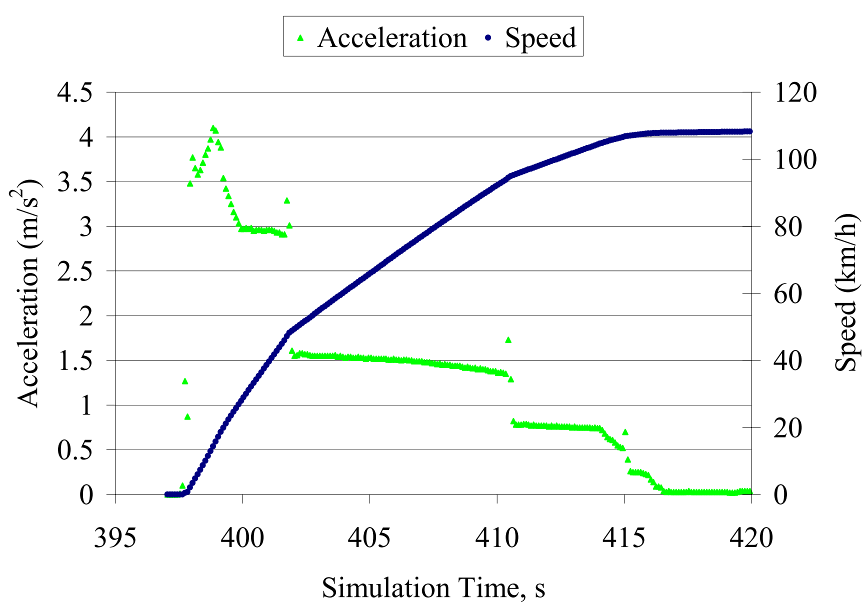


FIGURE 5.3. A sample of the acceleration capabilities of DriveSafety.

Similar tests were conducted to determine the deceleration capabilities of the test vehicle. The test vehicle was brought up to a speed of approximately 100 km/h and then the brake pedal was fully depressed. The speed and deceleration of the test vehicle was recorded. A sample deceleration curve is shown in Figure 5.4. It appears that the test vehicle had a maximum deceleration rate of a little over –8 m/s^2. Upon the initial and final moments of braking, the maximum deceleration was not achieved. It is believed that the response of the vehicle was dampened in the Vection software, thereby limiting the jerk. This also reduced the sudden vertical shift of the visual display representing the pitch of the test vehicle.

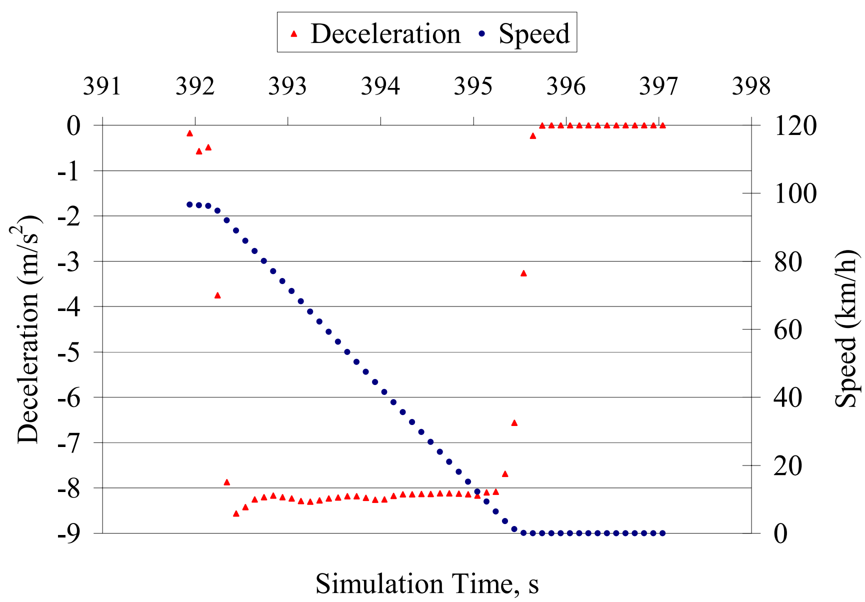


FIGURE 5.4. A sample of the deceleration capabilities of DriveSafety.

5.2.3 Model Elements

In order for a VISSIM simulation and a DriveSafety simulation to be integrated into a distributed simulation, the descriptions of the roadway models needed to be consistent. VISSIM used link-connector topography to create a model of the roadway network, and allowed the endpoints of each link and connector to be located at specific x and y coordinates. The number of lanes, lane widths, gradient, length, direction of traffic, could be defined. Links could also be defined to restrict certain vehicles. This approach was quite flexible and could be used to create a model that compared to a model created in DriveSafety. For the DriveSafety simulation, the scene was created using the HyperDrive Authoring suite by selecting existing roadway tiles from a database. Each tile typically represented 200 x 200 meters of topography including roadway and elements typical of the culture. A tile could be positioned so that a chosen corner of the tile was located at any 100 increment of the x and y coordinates. The available cultures included rural, urban, suburban, residential, industrial, and freeway settings. The availability of two-lane, three-lane, one-way, two-way, intersections, straight roadway, and curves differed by culture. In each of these programs, it was possible to develop a model of a straight, two-lane, two-way, rural roadway needed to address the passing behavior problem.

The vehicles in DriveSafety and VISSIM also needed to be consistent. In DriveSafety, up to a maximum of 256 vehicles could be included in one scenario, by selecting the different vehicles from an existing database. Vehicles were classed as emergency, construction, commercial, and passenger vehicles. All of these vehicles had two axles and the sizes and colors were fixed for the individual vehicles. For instance, the Grand Prix was 4.72 meters long and 1.556 meters wide and was available in blue, green, red, tan, and white. The commercial bus was 13.062 meters long and 2.884 meters wide and was only available in white. Any one of these vehicles could be modeled in VISSIM by defining the vehicle type, class, and category and specifying the length, width, color, location of axles, and acceleration and deceleration characteristics. By using two vehicles that differ in length, such as the Grand Prix and the commercial bus, different passing situations could be programmed such that the lengths of the impeding vehicles differ.

The decision to use a distributed simulation was, in part, based on the differences in how traffic flows were generated and how vehicles interacted in the different simulations. In DriveSafety, vehicles were either randomly generated to produce an ambient traffic flow or individually created using Tcl scripting commands. Each vehicle was created with a default set of parameter values that prescribed how the vehicles moved and interacted. The parameters included the desired speed, acceleration, deceleration, headway, and tailway. To produce variability in vehicle behaviors these parameter values needed to be changed by issuing the appropriate Tcl scripting commands. The commands could be issued in a start-up file, in a time procedure that ran at a specific time, in a location trigger activated when a vehicle passed over it, or in a virtual trigger that activated at a specified rate. Generating a specific traffic flow using DeriveSafety's traffic generation mechanisms was very difficult and time consuming, and was much easier using VISSIM. By defining the traffic volumes, traffic composition, speed distributions, and vehicle acceleration profiles for specific time intervals during the simulation, a specific and/or calibrated traffic flow could be created in a VISSIM simulation. The vehicles interacted according to the psychophysical car following logic based on Wiedemann's (*66*, *67*) work and the lane changing logic originally designed by Sparmann (*76*). These models of driving behavior were stochastic, and therefore introduced variability in the vehicle movements.

5.2.4 Simulation Output

The need for both traffic and behavior data to address the passing behavior problem was the key motivation for using a distributed simulation. The VISSIM simulation produced disaggregate data about all of the vehicles in the simulation and the fidelity of the data was limited by the size of the time step used for the simulation run. VISSIM could use a fixed simulation time step as small as one tenth of a second. The data was recorded in a vehicle record output, delineated text format file that had an .fzp extension. The available data was listed in the VISSIM user manual (*24*).

The DriveSafety simulation produced disaggregated data about the test vehicle and one other specified entity (i.e. element). The data collection rate could be specified in the range of one to 60 times per second. This was possible because the simulation had an update rate of 60 times per second. The data was recorded in a delineated text (.txt) format file. The available data was listed in the HyperDrive user manual (*25*). Information about the activation of triggers, the creation of vehicles, or the processing of external commands was recorded in a log that was accessible through the HyperDrive Authoring suite and was in a Hyper Text Markup Language (.html) format file. The information was also saved in a delineated text (.txt) format file on the host. The user could telnet into the host to retrieve the file.

5.2.5 Import and Export Capabilities

To contribute to the distributed simulation, each individual simulation needed to have data import and export capabilities. The VISSIM program was chosen because it included an external driver Application Program Interface (API) that allowed the import and export of data via a Dynamic Link Library (.dll). The Drivermodel.dll had an entry point called DriverModelSetValue used to export data from VISSIM and an entry point called DriverModelGetValue used to import data to VISSIM. A third entry point called DriverModelExecuteCommand contained four functions that were called by VISSIM.

Driver_Command_Init was called during the initialization of the VISSIM program, the Driver_Command_Create_Driver was called when an external driver vehicle was created in the simulation, Driver_Command_Move_Driver was called for each time step for the external driver vehicles, and Driver_Command_Kill_Driver was called when the external driver vehicle moved out of the road network. During the execution of a simulation, data about any vehicle could be imported or exported so long as the External Driver Model check box was selected on the Vehicle Type dialogue box. The available data about the movement of vehicles is listed in Tables 5.1 and 5.2.

TABLE 5.1. VISSIM Import Data

Data Parameter	Description
Driver_Data_Veh_Desired_Velocity	The desired non directional velocity (i.e. speed) (m/s) of the vehicle
Driver_Data_Veh_Desired_Acceleration	The desired acceleration of the vehicle

TABLE 5.2. VISSIM Export Data

Data Parameter	Description
Driver_Data_Veh_ID	A unique identifier for each individual vehicle
Driver_Data_Veh _Lane	The current lane occupied by the vehicle
Driver_Data_Veh _Lane_Angle	The current angle (rad) of the vehicle relative to the middle of the lane
Driver_Data_Veh _Lateral_Position	The current position (m) of the front of the vehicle to the middle of the lane
Driver_Data_Veh_Velocity	The current non directional velocity (i.e. speed) (m/s) of the vehicle
Driver_Data_Veh_Acceleration	The current acceleration (m/s^2) of the vehicle
Driver_Data_Veh_Max_Acceleration	Maximum acceleration (m/s^2) given current speed
Driver_Data_Veh_Desired_Velocity	The desired non directional velocity (i.e. speed) (m/s) of the vehicle
Driver_Data_Veh_X_Coordinate	The current x-coordinate of the front end of the vehicle
Driver_Data_Veh_Y_Coordinate	The current y-coordinate of the front end of the vehicle

DriveSafety was chosen because communication with external programs was possible through a socket that used Transmission Control Protocol/Internet Protocol (TCP/IP). TCP guaranteed that the data was received in the same order that it was sent. A socket program was defined in the initialization script for the DriveSafety simulation, which defined the IP address, port, and variables needed to put data to and get data from the socket.

Any of the data collection parameters could be exported and any recognized Tcl scripting commands could be imported. The data collection parameters describing the movement of the test vehicle (i.e. subject) are listed in Table 5.3. The Tcl scripting commands used to control the movement of vehicles are listed in Table 5.4.

TABLE 5.3. DriveSafety Export Data

Data Collection Parameter	Description
LaneName	Current lane occupied by subject
LanePos	Position of the center of the subject in the current lane (m)
SubjectHeading	Current heading (degrees) with respect to coordinate system
Velocity	Current non-directional velocity (i.e. speed) (m/s) of the subject
X coordinate	Current x-coordinate of the center of the test vehicle
Y coordinate	Current y-coordinate of the center of the test vehicle

TABLE 5.4. DriveSafety Import Data

Tcl Scripting Command	Description
EntityCreate	Creates entity with a unique name with the center located at the defined x and y coordinates with a zero speed
EntityJoinRoadway	Joins the named entity to the roadway so the entity can begin to move
EntitySetAcceleration	Sets the acceleration behavior of the named entity which is used when changing the speed of the vehicle
EntitySetLanePosition	Sets the position of the vehicle in the current lane
EntitySetRoadwayVelocity	Sets the roadway speed for the named entity
EntitySetSpatialState	Sets the x and y coordinates of the center of a moving, named entity

5.3 Step 3: Create the Prototype

The third step in the framework was to create the prototype. The prototype was designed to allow a test driver in DriveSafety to interact with vehicles controlled by VISSIM by establishing a two-way, real-time exchange of data between the VISSIM and DriveSafety simulations. During the development process, delays in the transfer of data were observed and this precluded the two-way real time exchange of data. In the final prototype, the vehicle data from the VISSIM simulation was transferred to the DriveSafety simulation.

5.3.1 Vehicle Control

The most accurate control of the vehicles would be achieved by updating the x and y coordinate positions. Unfortunately, using the SetSpatialState scripting command to control the vehicle positions in DriveSafety caused the vehicles to suddenly stop, change position, and start moving again. This behavior was not satisfactory. In VISSIM, The x and y coordinate data could not be imported. Therefore, an alternate approach was required.

The next best approach was to update the velocity of the vehicles. In DriveSafety, vehicle velocities could be controlled using the EntitySetRoadwayVelocity scripting command. Upon receiving this command, a vehicle would accelerate or decelerate to the specified speed. The speed data could also be imported by VISSIM.

The errors in controlling vehicle movements using the velocity data could be explained by examining the relationship between the velocity data and the x-y coordinate data. If the vehicle traveled at a constant velocity, the current (instantaneous) velocity data would reflect the change in the position during the last time step. However, if the average velocity $\overline{v}_i$, m/s, differed from the current velocity v_i, m/s, then the error in position, m would be equal to:

$$e_i = (\overline{v}_i - v_i)t \tag{5.1}$$

where t was the size of the time step, s. With this approach, every time the vehicle changed velocity, an error in the position of the vehicle would be incurred.

5.3.2 Federation

The design of the federation (i.e. prototype) was based on the HLA standards, and is depicted in Figure 5.5. The *vin* attribute referred to the unique identification number of the vehicle and the *type* attribute was a description of the vehicle. The *xposition* attribute referred to the x coordinate data and the *yposition* attribute referred to y coordinate data. According to HLA standards, the exchange of data had to occur through the RTI using implementations of the RTI services. The RTI could not store data but could convert the format of the data. A translator program was needed in the DriveSafety federate to translate the *vin*, *type*, *xposition*, and *yposition* data to the appropriate Tcl scripting commands.

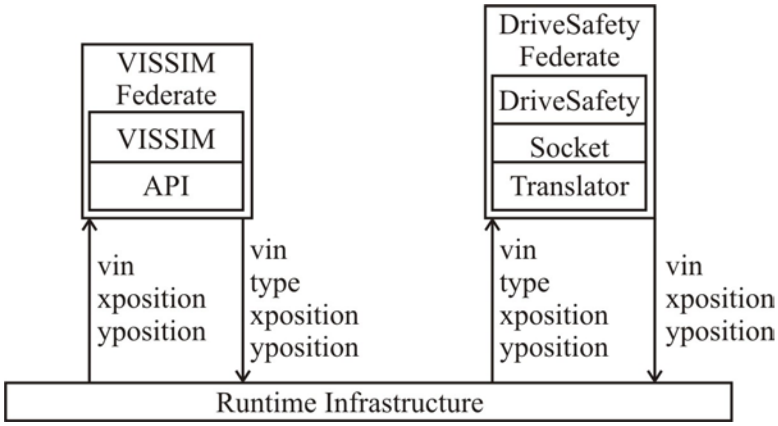


FIGURE 5.5. The design of the HLA-based prototype.

The federation included two simulation federates; the VISSIM federate and the DriveSafety federate. The federation object model (FOM) described the objects and interactions to be shared across the federation. The simulation object models (SOMs) for the VISSIM and DriveSafety federates were identical to the FOM. There was only one object class for this federation, namely the vehicle object class. It contained the attributes *vin*, *type*, *xposition*, and *yposition*. The formats of the *vin* and *type* attributes were specified as long and the formats of the *xposition* and *yposition* attributes were specified as double. The object class hierarchy for the federation is depicted in Figure 5.6 using the Unified Modeling Language graphical notation.

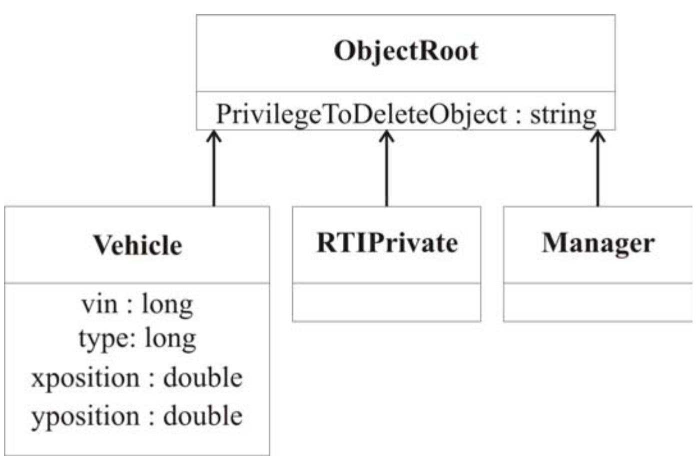


FIGURE 5.6. Depiction of the object classes in the federation.

The federation execution data (FED) file contained the FOM information needed for the RTI to function including the object classes and attributes, and the interaction classes and parameters. The FED had to include the ObjectRoot class along with the RTIprivate and Manager subclasses, and the InteractionRoot, and the RTIPrivate and Manager subclasses. For this design, there were no specified interaction classes.

The RTI initialization data (RID) file contained configuration parameters that controlled the operation of the RTI software. In this file, network information specific to the execution of this federation, such as the multicast IP addresses were stored. Both the FED and the RID files needed to accompany the source files for each federate.

In the final prototype, the vehicle data was transferred from VISSIM to DriveSafety. RTI data management services were implemented for the RTIambassador and FederateAmbassador for the VISSIM federate and the DriveSafety federate respectively. These RTI interfaces are illustrated in Figure 5.7.

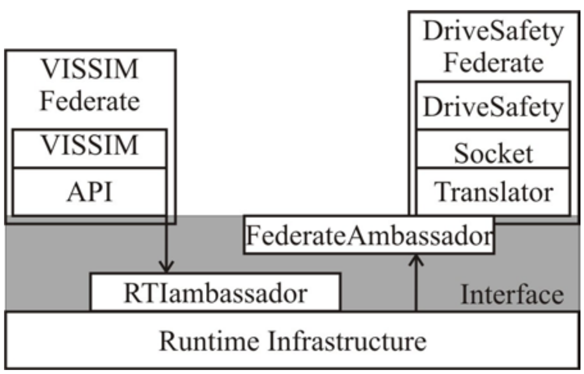


FIGURE 5.7. The RTI interfaces in the developed federation

5.3.3 RTI Services

Four RTI data management services were specified for the prototype. Federation management services were used by the federates to join the federation. Declaration management services were used by the federates to declare that they would publish and/or subscribe to data during the simulation execution. Object management services were used to register new instances of an object class, update the instance attributes, discover new instances, and receive updates of instance attributes. The ownership management services were used to share the instance attributes by transferring ownership from the VISSIM federate to the DriveSafety federate, and vice versa.

5.3.4 Advanced RTI Services

The more advanced data distribution management services and the time management services were not implemented. Because both VISSIM and DriveSafety were proprietary and there was no access to the interval time advance, the simulations were run independently. Synchronization of the simulations depended on the efficiency of the data transfers and the ordering of events relied on the first-in-first-out processing of data across the TCP/IP connections.

5.3.5 VISSIM Federate

The VISSIM federate was comprised of the VISSIM simulation file and the drivermodel.dll that is used to import/export data using the VISSIM API. The drivermodel.dll was generated in a Visual C++ environment called drivermodel.dsw. This environment was made up of the following files:

- Byte_swap.cpp — used to convert data to network form before sending to RTI
- FederateAmabassador.cpp — contains implementation of federate ambassador services
- Objects.cpp — contains the object definitions for RTI services
- DriverModel.cpp — contains the external driver routines
- Vissim_interface.cpp — has the implementation of the driver_move function
- Rti_interface.cpp — contains the implementation of RTI services
- Byte_swap.h — contains prototypes for byte_swap.cpp
- FederateAmbassador.h — contains prototypes for FederateAmabassador.cpp
- Objects.h — contains prototypes for Objects.cpp
- DriverModel.h — contains prototypes for the external driver routines
- Vissim_interface.h — contains prototypes of the driver_move function
- Rti_interface.h — contains prototypes for Rti_interface.cpp

Copies of the FED and RID files had to be placed in the same location as the files making up the drivermodel.dsw environment. To run the VISSIM federate, the drivermodel.dll and copies of the FED and RID files had to be in the same location as the VISSIM application.

During the development of the VISSIM federate, only one problem was observed. The output from the API interface did not always compare to the VISSIM data collection file. To illustrate this problem, the data from the VISSIM data collection file and the API output file are plotted in Figures 5.8 and 5.9 respectively, for a simulation of a circular roadway network with one entry point and no exit point that was run for 2000 seconds and had 1073 vehicles enter the network. During the 28th second, the API did not output any data and the performance of the API is disturbed between the 469th and 541st seconds. This data could be indicative of a problem with the API.

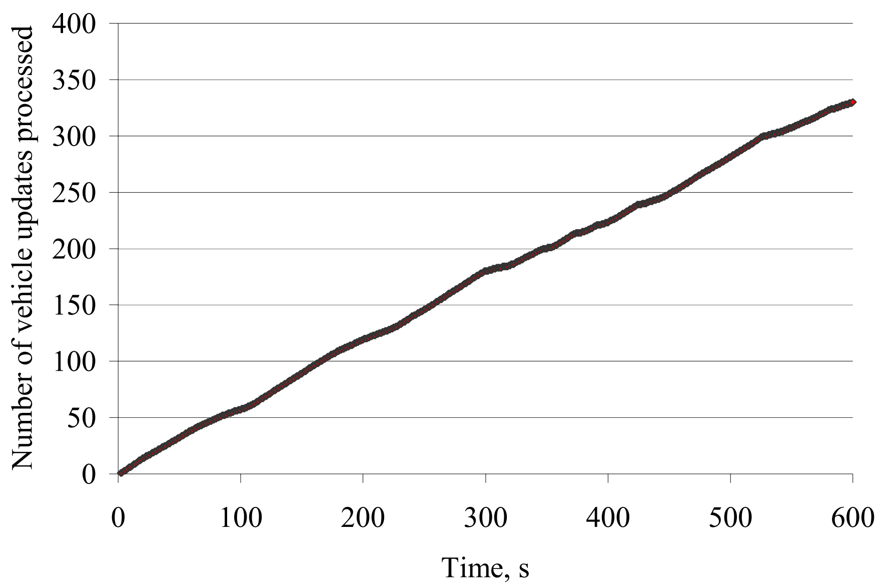


FIGURE 5.8. Data output from VISSIM.

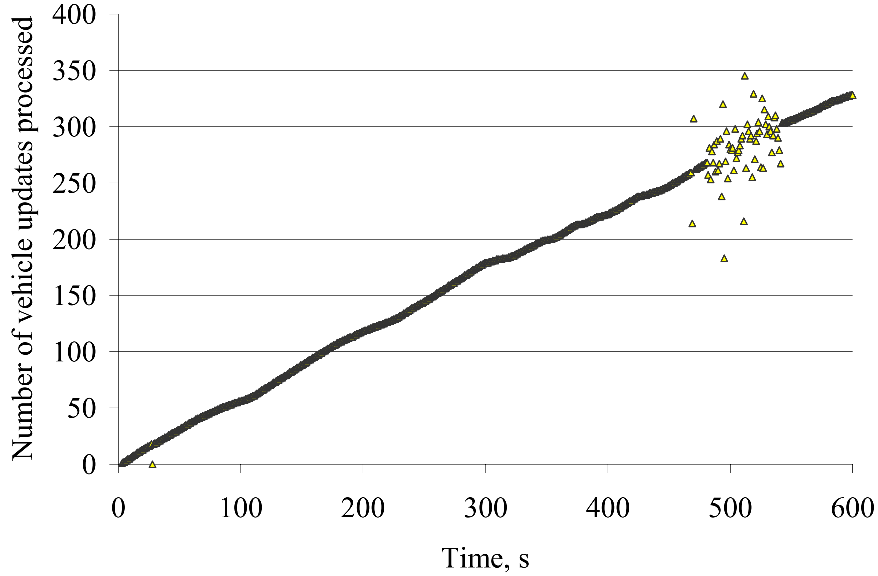


FIGURE 5.9. Data output from the VISSIM API.

5.3.6 DriveSafety Federate

The DriveSafety federate was comprised of a DriveSafety scenario created using the HyperDrive Authoring suite and executed in DriveSafety, an interface containing the TCP/IP socket program to import/export data, and a translator program that used a command generator function to translate the imported data to Tcl scripting commands. The socket program was located in the initialization script of the DriveSafety simulation, and defined the IP address, port, and two string arrays. A polling rate of 60 times per second was specified. The federate was developed as an executable file that was generated in the VC++ environment called simulator_interface.dsw. This environment was made up of the following files:

- Byte_swap.cpp — used to convert data to network form before sending to RTI
- Simulator_interface.cpp — contains the socket program
- Objects.cpp — contains the object definitions for RTI services
- Rti_interface.cpp — contains the implementation of RTI services
- FederateAmabassador.cpp — contains implementation of federate ambassador services
- Command_generator.cpp — used to translate instance attributes to Tcl scripting commands

- Byte_swap.h contains prototypes for byte_swap.cpp
- Command_generator.h contains prototypes for Command_generator.cpp
- Rti_interface.h contains prototypes for Rti_interface.cpp
- FederateAmbassador.h contains prototypes for FederateAmabassador.cpp
- Objects.h contains prototypes for Objects.cpp

Copies of the FED and RID files had to be placed in the same location as these files making up the simulator_interface.dsw environment.

During the development of the DriveSafety federate, eight problems were observed. The first problem was that during any second of the simulation, DriveSafety would process only up to thirty EntitySetRoadwayVelocity scripting commands received through the socket. As a test, one thousand EntitySetRoadwayVelocity scripting commands were sent at one time to DriveSafety. The data from the host log was plotted, as shown in Figure 5.10, revealing that a maximum of thirty commands were during each second.

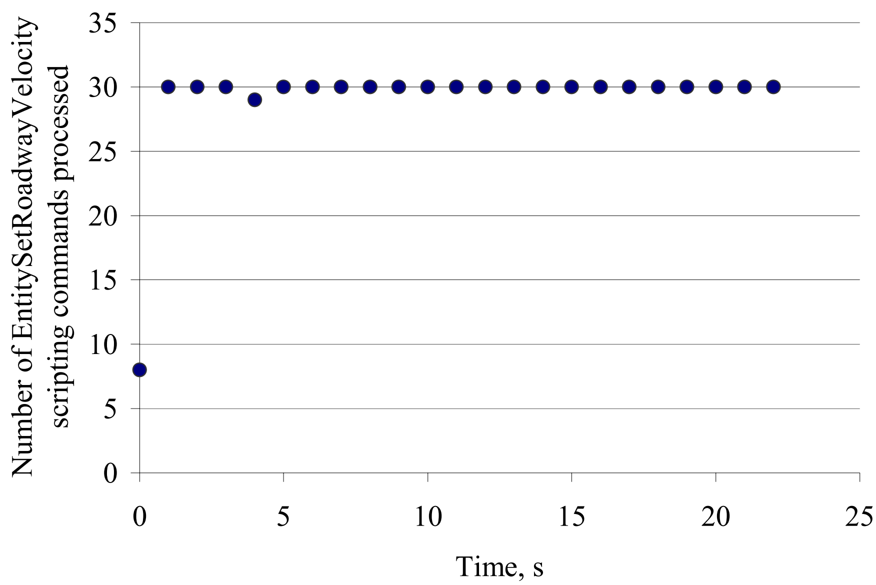


FIGURE 5.10. Processing EntitySetRoadwayVelocity commands in DriveSafety

The processing threshold had some significant consequences for the prototype development. It meant that either very few vehicles could be controlled externally or that the update rate had to be reduced. In the final prototype, the velocity of each vehicle was updated each second, which allowed a maximum of thirty vehicles to be controlled. This impacted the volume of vehicles and the size of the network that could be used in the simulation.

The second problem was that queuing was observed in the translator program. One thousand velocity updates were sent at one time to the translator program, which converted the updates to EntitySetRoadwayVelocity scripting commands and sent them to the socket program. The performance of the translator is illustrated in Figure 5.11. A large number of scripting commands were issued immediately upon receiving the velocity updates however it took 23 seconds for all one thousand scripting commands to be sent to the socket program. The default buffer size used in the socket program was changed to 100 and then to 1,000,000 with no obvious differences in performance. Fortunately, this queuing did not impact the processing of commands internal to DriveSafety (i.e. DriveSafety did not crash).

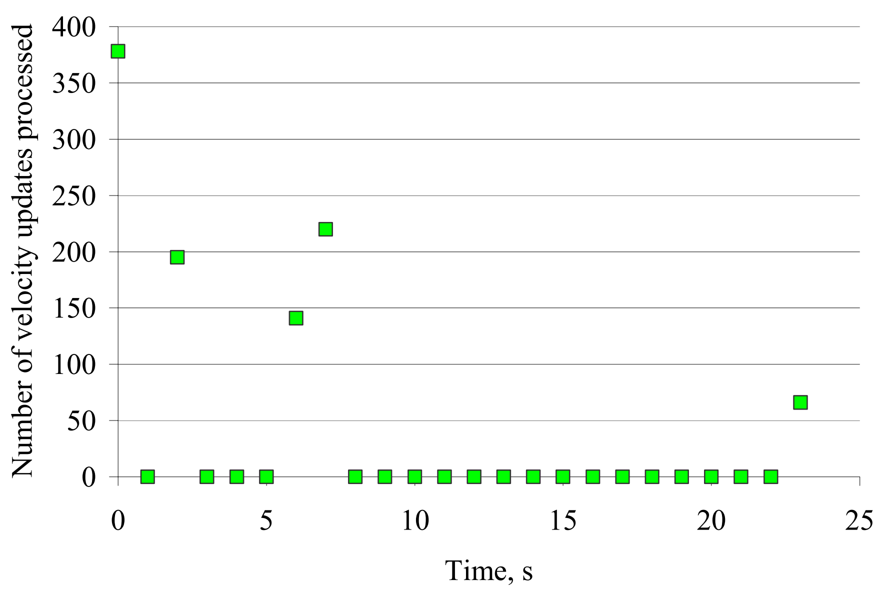


FIGURE 5.11. Data processing through the translator program.

The third problem, was that additional queuing was occurring in the translator because the translator program was written as a single-thread program and could only read or write at one time. It is hypothesized that a multi-thread translator program and separate sockets for import and export are needed if a two-way real-time connection is to be established.

The fourth problem was that the socket program used a pulling mechanism to look for new data from the translator program. The program constantly looked for new data and caused the computer-processing unit (CPU) to operate at 100% utilization for the duration of the simulation. This could potentially cause other performance problems. An improvement would be to replace the pulling mechanism with either a shared memory area, or the use of a dynamic data exchange technique (*120*).

The fifth problem was that DriveSafety did not recognize certain vehicle types when used in externally issued commands. Therefore, data about the vehicle types commercial bus and transit bus could not be transferred. The FOM, SOMs and name convention used in DriveSafety were reviewed and no explanation for this phenomenon was found. The vehicle type box truck was used instead. In DriveSafety, this vehicle is 6.31 meters long and 2.17 meters wide. A similar vehicle was defined in VISSIM.

The sixth problem was that on occasion, the starting *xposition* and *yposition* for a new vehicle sent from VISSIM to DriveSafety referenced a location outside of the roadway network. When this occurred, the vehicle failed to join the roadway and subsequent velocity updates for that vehicle were processed without producing any results. This problem was addressed by the extended the endpoints of the network in DriveSafety slightly beyond the endpoints of the network in VISSIM.

The seventh problem was that when the EntitySetRoadwayVelocity commands issued in DriveSafety required the vehicle to slow down, the brake lights would illuminate. Because the VISSIM vehicle traveled at a desired speed with some stochastic variation, the brakes lights on the vehicles in DriveSafety were observed to flash quite often. The solution was to deactivate the brake lights by issuing the EntitySetBrakeLight scripting command using a location trigger activated as each vehicle drove over it. An alternate solution would have been to adjust the tolerance for illuminating the brake lights such that the brake lights would only illuminate under large decelerations.

The eighth problem was that DriveSafety considered the externally controlled vehicles as ambient vehicles. This meant that at intersections, and other routing decision points, DriveSafety randomly directed these vehicles, causing vehicles to make unexpected turns. The solution was to place location triggers that initiated the EntitySelectTurn scripting command thereby directing vehicles to continue straight through the intersection.

5.3.7 Initialization of the Prototype

To use the federation, comparable simulations were first created in VISSIM and DriveSafety, meaning they contained the same road network and mapped to the same x and y coordinate origin. Performing the following four steps initialized the federation:

1. Run the RTI software;
2. Execute the DriveSafety federate (Simulator_interface.exe);
3. Run the DriveSafety simulation;
4. Execute the VISSIM program; and
5. Run the VISSIM simulation.

The federation was created when the DriveSafety federate was executed, and at the same time, the DriveSafety federate joined the federation. When the DriveSafety simulation was run, the socket program and translator program were initialized. The VISSIM federate joined the federation when the VISSIM program was executed. The RTI service to create a federation was called but the RTI received a message saying it was already created. The drivermodel.dll was initiated when the VISSIM simulation was run.

5.3.8 Execution of the Prototype

Each time a new vehicle was created in VISSIM, the VISSIM federate registered a new object instance and updated the attributes of that instance. The instance attributes were reflected in the FederateAmbassador and the data was sent to the translator program, which used the command generator function to generate the following Tcl scripting commands

- EntityCreate — to create a new vehicle
- EntityJoinRoadway — to join the vehicle to the roadway so that it can move
- EntitySetAcceleration — to set the acceleration and deceleration behavior of the vehicle

For each subsequent instance of the attributes, the average velocity was calculated in the FederateAmbassador using the *xposition* and *yposition* for the current and previous updates, and was sent along with the instance attributes to the translator. The translator used the command generator function to generate the EntitySetRoadwayVelocity scripting commands. They were stored in a global string array, which had a bottom-in and top-out queuing. The socket program read the Tcl scripting commands and passed them to DriveSafety over a TCP/IP socket.

The execution of the final prototype produced a driving environment that was visually comparable to the driving environments produced using DriveSafety as a stand-alone simulation. The simulation progressed without any noticeable discontinuities in the time advance. The creation of vehicles and the velocities were prescribed by the data from VISSIM however DriveSafety still maintained primary control of the vehicles. The advantage of using the prototype was that a specific traffic flow could be created. The test driver could interact with the vehicles even though a two-way real-time exchange of data was not achieved. The driver data could be collected using DriveSafety, and the traffic data could be collected using VISSIM, although the traffic data would only be an estimation of the vehicle movements observed by the test driver.

5.3.9 Communication Within the Final Prototype

In this section, the communication within the federation is examined by comparing the output files from the VISSIM simulation, the drivermodel.dll interface, the translator program, and DriveSafety simulation. The file formats are indicated on Figure 5.12. The html and fzp files were converted into a text format file and all the text format files were imported into Excel spreadsheets.

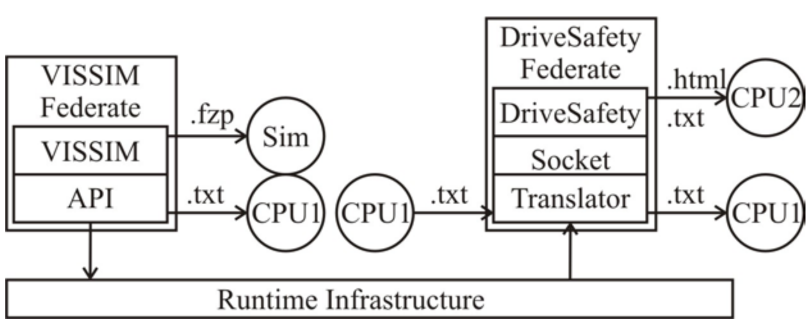


FIGURE 5.12. The data files that were available to evaluate the federation.

Comparing the output was complicated by the fact that the VISSIM simulation and the DriveSafety simulation referenced different time clocks than the drivermodel.dll and the translator program as depicted in Figure 5.12. The VISSIM simulation referenced the simulation time, which was the logical time, used to advance the simulation. The drivermodel.dll and the translator program referenced the time of the first computer-processing unit (CPU), labeled CPU1. The DriveSafety simulation output referenced the time of the second CPU, labeled CPU2

The federation was executed and the VISSIM.fzp, API.txt, Translator.txt, and DriveSafety.html files were examined. In each file, the time was recorded to the nearest second. The referenced time and the first five times recorded in each file are shown in Figure 5.13. The size of the time offsets, labeled O_1 and O_2 were unknown. It was assumed that the absolute value of the time offset was not greater than one second, which meant that the delay in transferring data between VISSIM and the API, and between the translator and VISSIM was assumed to be less than one second. The files were aligned according to the logical processing of the data being transferred from VISSIM to DriveSafety.

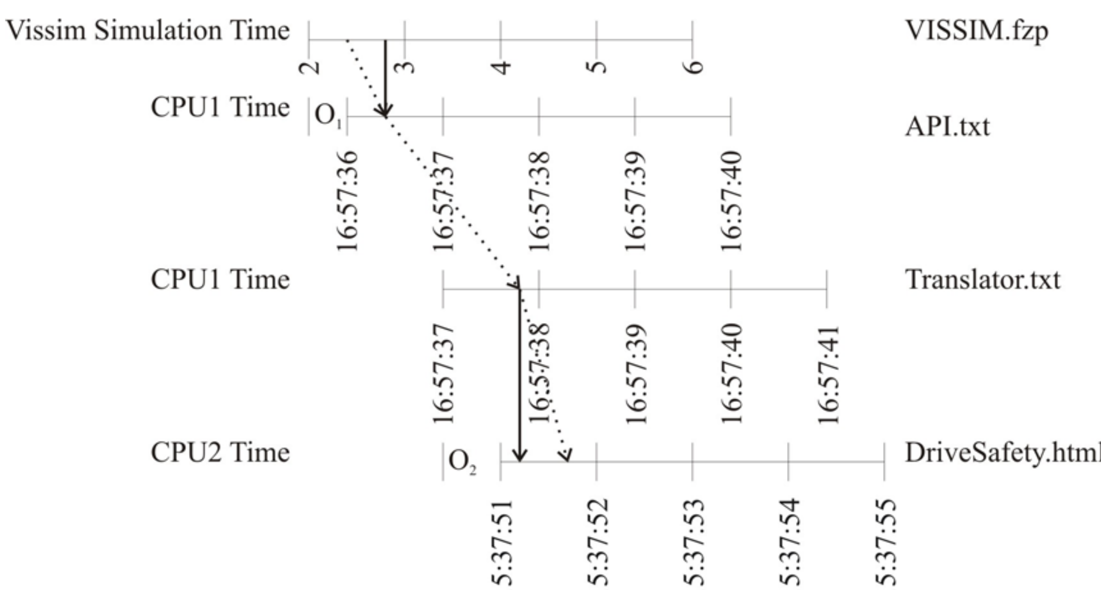


FIGURE 5.13. A depiction of the comparing the time in the output files.

To demonstrate the process of aligning the files, the first data transfer (the creation of the first vehicle) was tracked in each of the files, as indicated by the arrows in Figure 5.13. In the VISSIM.fzp file the data was recorded at time 2, in the API.txt file it was recorded at 16:57:36, in the Translator.txt file it was recorded at 16:57:37, and in the DriveSafety.html file it was recorded at 15:37:51. Because the time was recorded to the nearest second, the arrows could have been drawn anywhere within the individual time intervals. A vertical solid arrow represents a data transfer that had no time delay and a dotted arrow represents a data transfer that was delayed. This was repeated for each subsequent data transfer to ensure that the alignment of the files reflects the logical processing order.

5.3.9.1 Queuing. Queuing occurred in both the VISSIM federate and the DriveSafety federate, as previously discussed in sections 5.3.5.and 5.3.6 respectively. The queuing is apparent when comparing the number of vehicle instances (i.e. updates) processed by the VISSIM simulation, the API interface, the translator program, and the DriveSafety simulation, during a run of the prototype, as shown in Figures 5.14 though 5.17 respectively. The time used on the x-axis refers to the amount of time that passed since the transfer of the data for the first vehicle created.

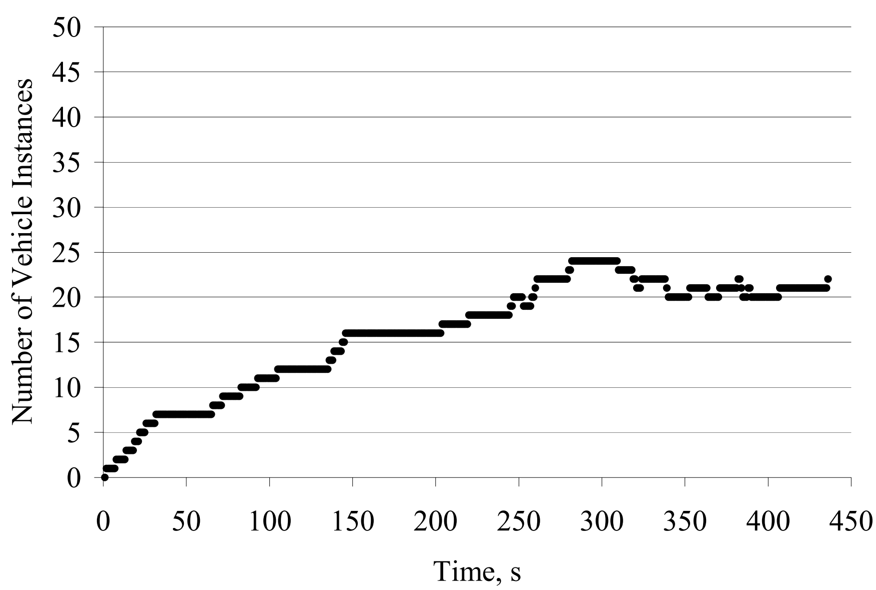


FIGURE 5.14. Number of vehicle instances recorded in the VISSIM.fzp file.

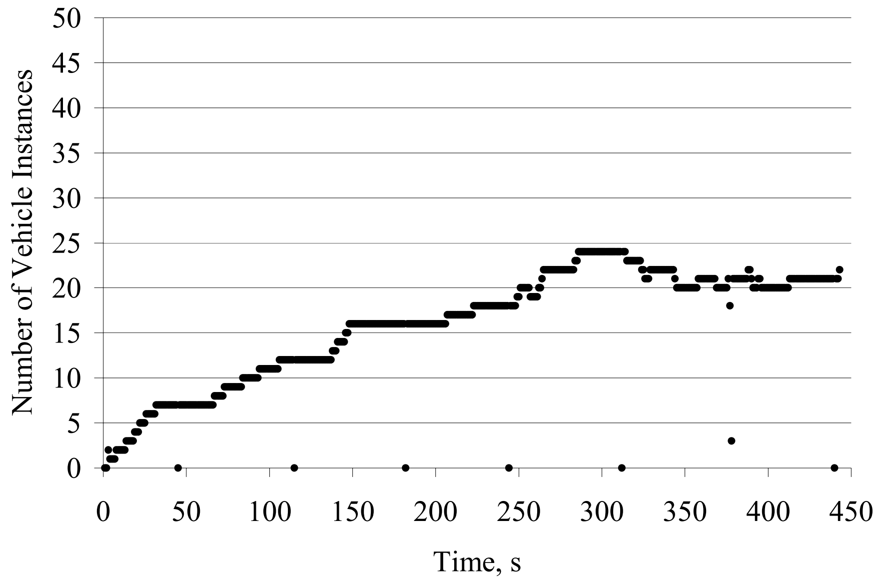


FIGURE 5.15. Number of vehicle instances recorded in the API.txt file.

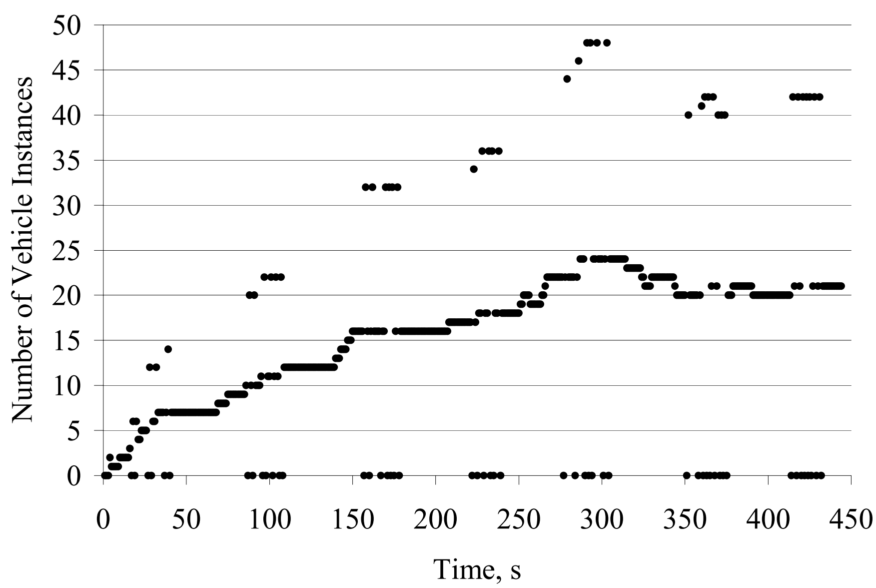


FIGURE 5.16. Number of vehicle instances recorded in the Tranlstor.txt file.

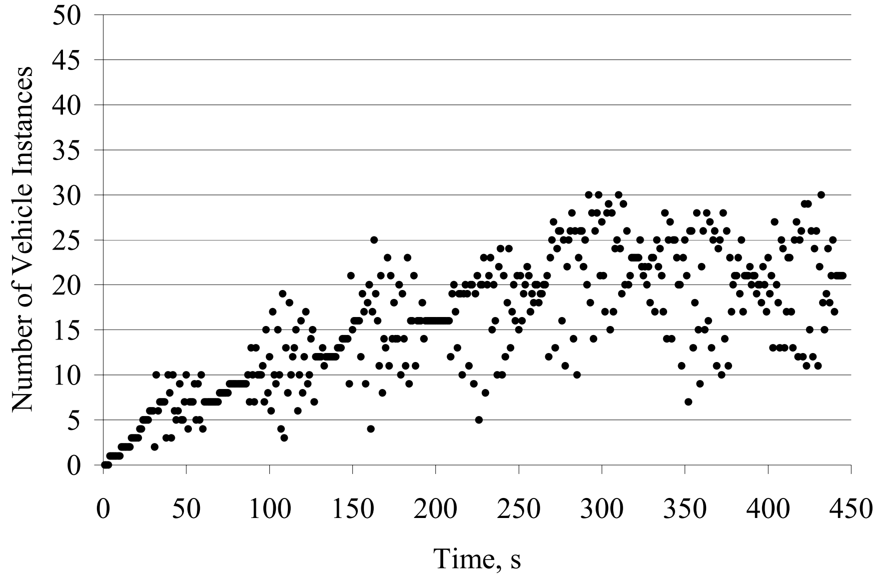


FIGURE 5.17. Number of vehicle instances recorded in the DriveSafety.html file.

If queuing had not occurred during the simulation run, the plots in Figures 5.14 through 5.17 would be identical. Therefore, any difference between any two consecutive plots is evidence of queuing. It appears that queuing occurred between VISSIM and the API, between the API and the translator, and between the translator and DriveSafety.

5.3.10 Vehicle Position Error

Errors in vehicle positions were expected because the speed data was used to control the vehicle movements, as discussed in section 5.3.1. The vehicle position error is the difference between the expected location (x_e) of the vehicle, as given by the VISSIM simulation, and the actual location (x_a) observed in the DriveSafety simulation. It can be described as the integral of the differences between the speeds of the vehicles over the time interval from zero to t, and can be estimated by:

$$\sum_{0}^{t}\left(\frac{\Delta x_e}{\Delta t}-\frac{\Delta x_a}{\Delta t}\right) \tag{5.3}$$

There were several reasons why the vehicles in DriveSafety deviated from their expected positions. The first reason was the difference in how vehicles were created. VISSIM vehicles entered the network with a speed whereas in DriveSafety vehicles were created with zero speed and joined the network from a stopped position. The second reason was the time delay that occurred while transferring vehicle instances from VISSIM to DriveSafety. The third reason was that the acceleration behavior of the vehicles in VISSIM and DriveSafety differed and would cause vehicle position errors during speed changes. The fourth reason was that the vehicles in DriveSafety might have reacted to the test vehicle thereby causing speed changes.

To illustrate the position error, the VISSIM.fzp file and the DriveSafety.html file were collected for a single simulation run and the speed outputs were compared. Starting at the VISSIM simulation time 288 seconds, the vehicle position errors for the first vehicle created were calculated as the difference in the x positions in the two files. In Figure 5.28, the vehicle position error is shown with respect to the VISSIM simulation time. A negative vehicle position error indicates that the DriveSafety vehicle was trailing behind the expected position. The speed of the vehicle is also shown. It is seen in Figure 5.18, that when the speed increased the vehicle lagged further behind the expected position.

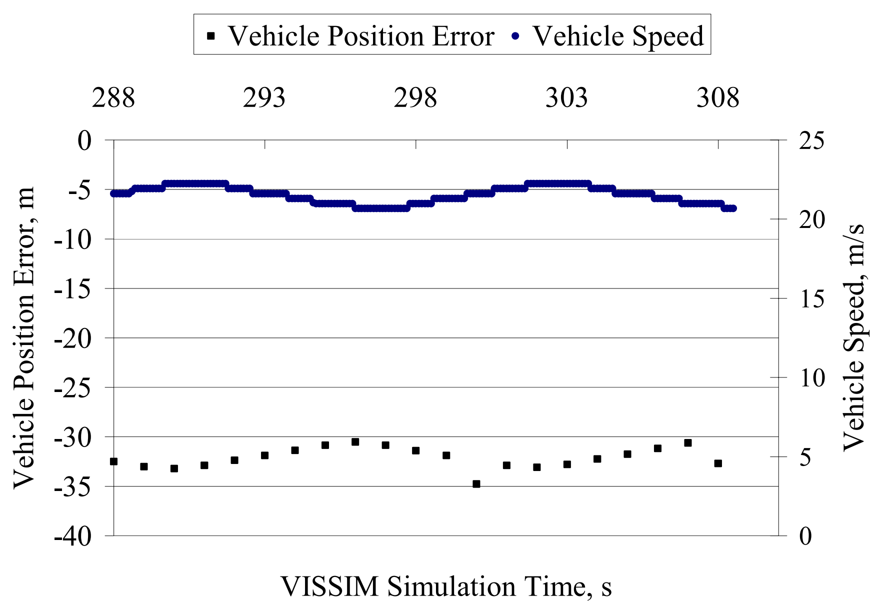


FIGURE 5.18. The vehicle position error.

5.4 Recommendations

Based on the problems encountered during the creation of the prototype, several recommendations were made. Addressing these recommendations would pave the way for a future two-way real time exchange of data in the prototype.

5.4.1 VISSIM

The sporadic queuing of data between the VISSIM simulation and the API needs to be examined. If the queuing stemmed from how the API was programmed, then changes are needed to ensure that the API exports data during every time step. Without this correction, there will be difficulties incorporating a VISSIM simulation into a distributed simulation designed for two-way real-time data exchange. It is also possible that the queuing was the result of poor CPU memory management, in which case, that issue would need to be addressed.

5.4.2 DriveSafety

In DriveSafety, vehicles were created with zero speed. A request was submitted to the developers to allow vehicles to be created with a non-zero speed. This request was addressed and the EntityCreate command was changed to include a speed parameter.

During the development of the prototype, a processing threshold of thirty EntitySetVelocity scripting commands was identified. Although 254 vehicles could be included in the simulation, only thirty could be controlled externally. This threshold limited the update rate, the number of vehicles in the simulation, and therefore the traffic flow and network size. To increase the usefulness of DriveSafety, and make it more desirable for distributed simulations, this threshold need to be increased.

The socket program used an indefinite loop to pull data, which is the least desirable method to get new data from an external source. The operation of the socket needs to be re-evaluated. The used of a shared memory or dynamic data exchange techniques would be preferable.

5.4.3 Translator Program

The translator program was developed to translate the text format information from the VISSIM API into Tcl scripting commands read by DriveSafety. This program was developed in C++ as a single thread program. To allow data to be read and written simultaneously, the program needs to be developed as a multithread program and run in a Windows type environment.

5.4.4 Prototype

The prototype included simulations creating using two proprietary programs. Each has its own internal clock to control the advance of the individual simulations. In a distributed simulation, where the data is transferred in real-time between the individual simulations, the HLA time management tools really need to be implemented to synchronize the simulations. Because of the proprietary nature of the programs this was not possible. It is recommended that in the future, greater consideration of the access to the source code and the ability to manipulate the time advance should be given when selecting the contributing simulations.

6 APPLICATION OF THE PROTOTYPE*

This passing application is only one example of how the methodology could be applied. Other prototype distributed traffic simulations could be created and used to study other specific traffic and/or behavior problems. The details of this passing experiment were submitted to the Institutional Review Board at the Texas A&M University. Approval was granted based on the experimental design, selection of test drivers, risk to the test drivers, and the experimental procedures described in the following sections. Copies of the approval letters are located in Appendix D.

6.1 Experimental Design

The experiment had a 2x2 factorial design with repeated measures on both factors, where both the type of impeding vehicle (car or truck) and the speed of the impeding vehicle (fast or slow) were fixed effects factors. The dependent factors were the time and distance traveled in the left lane during the passing maneuver. The experiment was designed to have test drivers follow an impeding vehicle on a simulated two-lane rural road and then accelerate and pass. The test drivers had to choose to accept a gap in the opposing traffic to complete the maneuver.

6.2 Test Drivers

Thirty test drivers, sixteen females and fourteen males, were recruited from Texas A&M University and the community through person-to-person contact. To avoid including drivers with little driving experience, which are generally over represented in vehicle accident statistics (*170*), each test driver had at least 5 years of driving experience. Six of these test drivers were replacements for those who either did not complete the study or failed to make the desired passing maneuvers. In the end, the data for twelve male and twelve female test drivers, ranging in age from 23 to 57 years was collected. The four passing conditions could be ordered in 24

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*Reprinted with permission from Jenkins, J., and L. R. Rilett. Application of a Distributed Traffic Simulation for a Passing Behavior Study. Presented at Transportation Research Board 83rd Annual Meeting, Washington, D. C., 2004. (Accepted for publication in *Transportation Research Record: Journal of the Transportation Research Board*, TRB, National Research Council, Washington, D.C., 2004 [in preparation]).

unique combinations. The ordering combinations were randomly assigned to the 24 test drivers to control for any ordering effects. The final schedule is located in Appendix E.

6.2.1 Risks

The test drivers were told that they may experience symptoms of simulator sickness, including eyestrain, headache, dizziness, and nausea. Only one of the thirty test drivers chose not to complete the experiment because of some discomfort. The remaining twenty-nine test drivers completed the experiment. All test drivers completed the simulator sickness questionnaire found in Appendix F and reported the severity of the simulator sickness symptoms experienced during the study. Their responses are listed in Appendix G and summarized in Table 6.1.

TABLE 6.1. Reported Severity of Simulator Sickness Symptoms

Symptom Experienced	Reported severity			
	None	Low	Moderate	High
Eye Strain	13	15	2	0
Headache	22	7	1	0
Dizziness	16	12	1	1
Nausea	22	6	1	1

6.3 Experimental Procedure

After reading and signing a copy of the consent form found in Appendix H, each test driver drove the practice scenario once and the experimental scenario four times.

6.3.1 Practice Scenario

The practice scenario, developed using DriveSafety as a stand-alone simulation, was to acclimate the test drivers to the simulated driving environment. A schematic of the practice scenario is shown in Figure 6.1. For the practice scenario, test drivers were instructed to follow the lead vehicle. As the test vehicle began to move the lead vehicle advanced and continued down the two-lane road through an industrial area at 72 km/h (45 mph) and a rural area at 88 km/h (55 mph). The instructions are included in Appendix I. The roadway was approximately 5 km long and took approximately 4 minutes to drive. The scenario ended when the test driver arrived at a stop controlled t-intersection and was instructed to place the vehicle transmission in park. All test drivers were observed to have good control of the simulated vehicle. Data was not collected to confirm this observation.

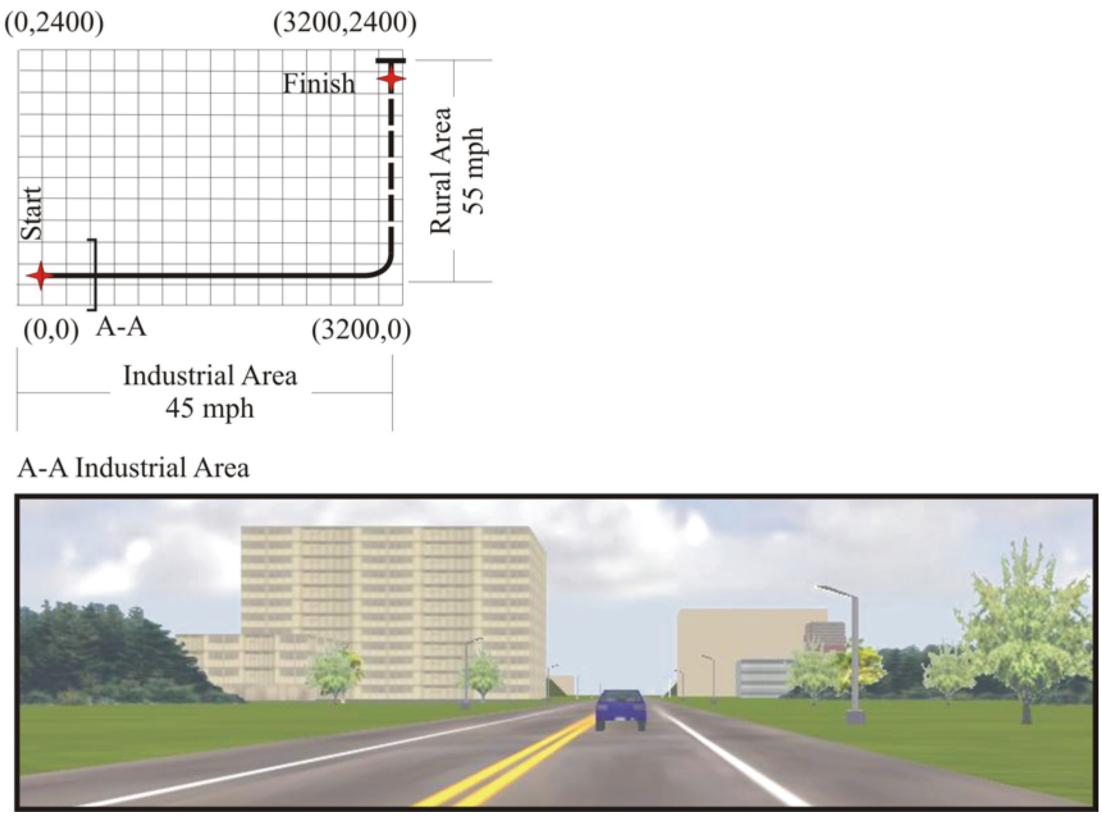

FIGURE 6.1. Schematic of the practice scenario with a sample center screen image.

6.3.2 Experimental Scenario

The experimental scenario was developed using the prototype distributed traffic simulation. The VISSIM simulation controlled the creation and the speed of all vehicles excluding the test vehicle. A schematic of the experimental scenario is shown in Figure 6.2. The scenario had over 10 km of roadway, including 4 km of road through an industrial area and 4 km of road through a rural area. The posted speed limits were 72 km/h (45 mph) in the industrial area and 88 km/h (55 mph) in the rural area. The scenario took approximately 7 minutes to drive.

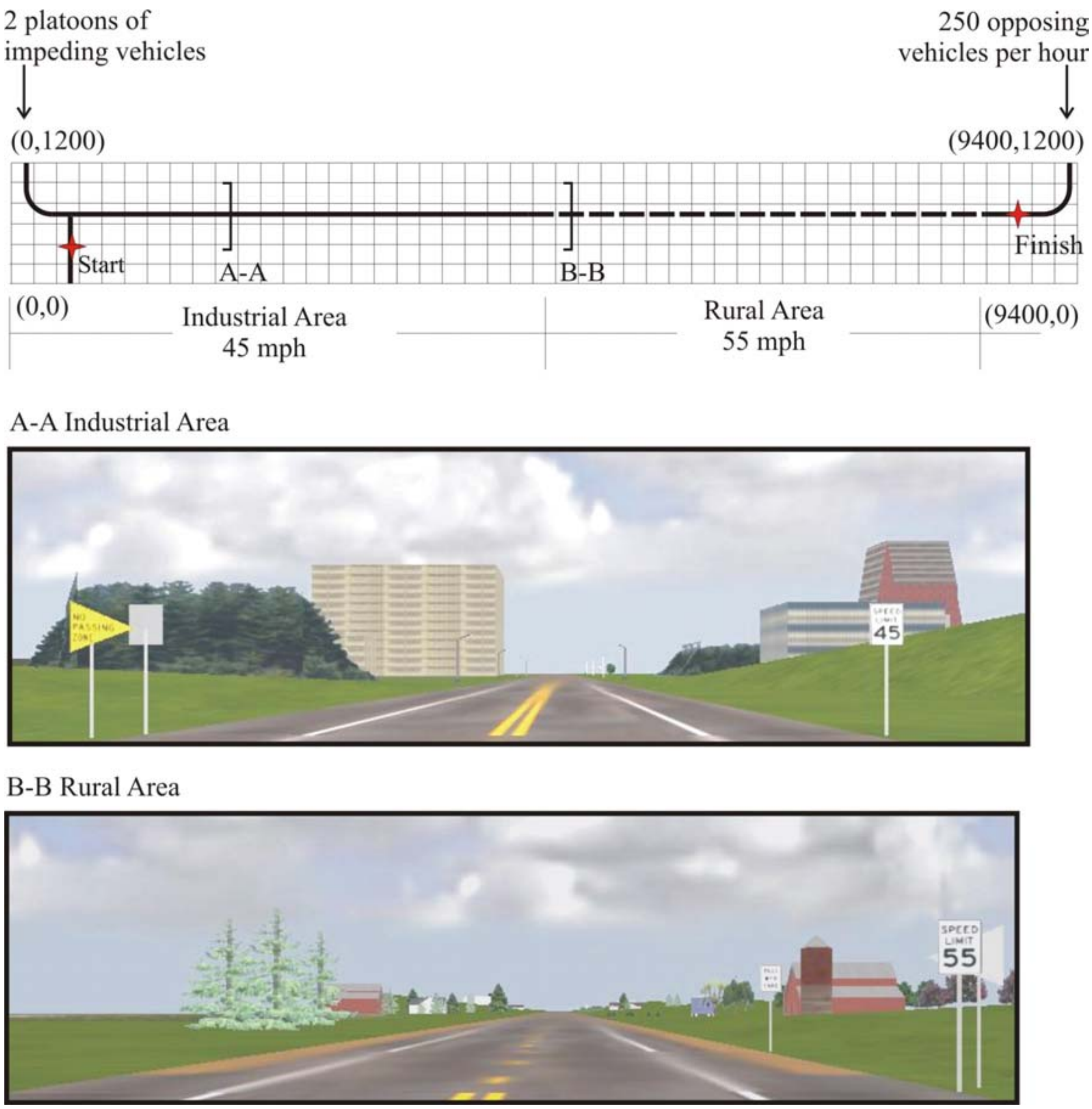

FIGURE 6.2. Schematic of the experimental scenario with sample center screen images.

As shown in Figure 6.3, two separate platoons, each with a lead car, truck, and second car, entered the network at the beginning of the simulation and traveled in the center of the test vehicle's lane. The impeding vehicles traveled at speeds less than the posted speed limit to create a passing situation. The first and second platoons were respectively programmed to travel approximately 8 km/h (5 mph) and 16 km/h (10 mph) below the speed limit. The lead car and the truck in each platoon were the impeding vehicles to be passed. The cars were 4.72 m long and the trucks were 6.31 m long. These were the lengths of the vehicles in DriveSafety and were mimicked in VISSIM.

FIGURE 6.3. Illustration of the two platoons of impeding vehicles.

To ensure that the test driver did not see vehicles magically appear and begin to drive along the roadway, it was necessary to populate the scenario from the end points of the roadway. The opposing traffic entered at a volume of 250 vehicles per hour and traveled at approximately the speed limit. The VISSIM simulation also controlled the volumes and speeds of these vehicles and the flow of opposing vehicles began at the beginning of the simulation. The industrial and rural roadway sections were sized so that the drivers would have opposing traffic when they entered the rural passing area. This was necessary to ensure that the passing did not take place at the beginning of the passing area where the speed limit changed from 45 mph to 55 mph.

The simulated environment posed a constraint on the available sight distance. Objects appeared 500 meters ahead of the test vehicle on the apparent horizon. When the opposing vehicle was 500 m or more upstream, there was ample distance for the test driver to successfully complete the passing maneuver. At higher speeds, this constraint could have limited the passing opportunity.

At the beginning of each experimental scenario, test drivers were stopped at the location labeled “Start” in Figure 6.2. They were instructed to turn right onto the roadway behind a particular vehicle in one of the two platoons that would approach from their left. Test drivers were instructed to pass the slower impeding vehicles in a safe and judicious manner, pass only in the rural passing area, and pass only one vehicle at a time. To complete a passing maneuver, the driver had to choose an acceptable gap in the opposing traffic. After driving through the rural area, the test drivers were instructed to pull over onto the shoulder and place the vehicle transmission in park. The instructions for the experimental scenario are included in Appendix I.

6.4 Data Collection

If a two-way, real-time communication had been established in the prototype, the position and speed of every vehicle would have been available directly from the VISSIM simulation output. However, the prototype operated with a one-way communication that experienced time delays in the transfer of vehicle data from VISSIM to DriveSafety. Therefore, two methods were used to collect the data, one for the impeding and passing vehicles and a second for the opposing vehicles.

6.4.1 Impeding and Passing Vehicle Data

DriveSafety had tools to collect data about the test vehicle and one named entity, in this case the impeding vehicle. These tools were use to record the time, x-y coordinate of the center of the vehicle, heading, speed, and acceleration data of the test vehicle, the gap between the impeding and passing vehicle, the linear distance between the centers of the impeding and passing vehicles, and the speed of the impeding vehicle, all at a rate of ten times per second. The quantity and quality of this data far exceeded what has been captured in the field using traditional techniques. It was possible to record the data at 60 times per second but the additional time and effort to reduce six times the amount of data did not warrant the small differences that could be obtained. Using a location trigger placed at the beginning of the rural area, the name of the impeding vehicle was queried so that it could be included in the data collection file. The location trigger also activated the recording of the data. A second location trigger placed at the end of the rural area deactivated the recording of data.

6.4.2 Opposing Vehicle Data

Data about the opposing vehicles in the experimental scenario was not available through the DriveSafety data collection tools. Instead, the vehicle locations were estimated by analyzing the activity of location triggers placed along the rural passing area that were activated every time a vehicle drove over them. The locations triggers were placed at the coordinate locations (4500,700), (5500, 700), (6500, 700), (7500,700) and (8500, 700) as identified in Figure 6.4.

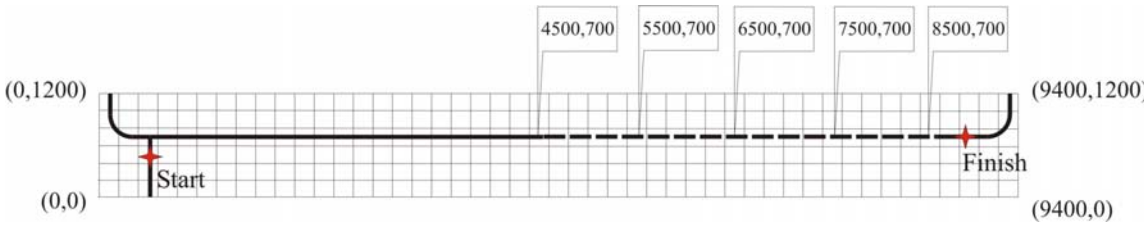

FIGURE 6.4. Coordinates of the location triggers.

The location trigger activation data was recorded in the host log of DriveSafety. Because the simulation was the same for each experimental scenario run, the data for the opposing vehicles was only reduced once. The vehicle trajectories of the opposing vehicles and the impeding vehicles are shown in Figure 6.5. These trajectories estimated the location of the center of the vehicles because the triggers were activated when the center of the vehicle crossed over the edge of the location trigger.

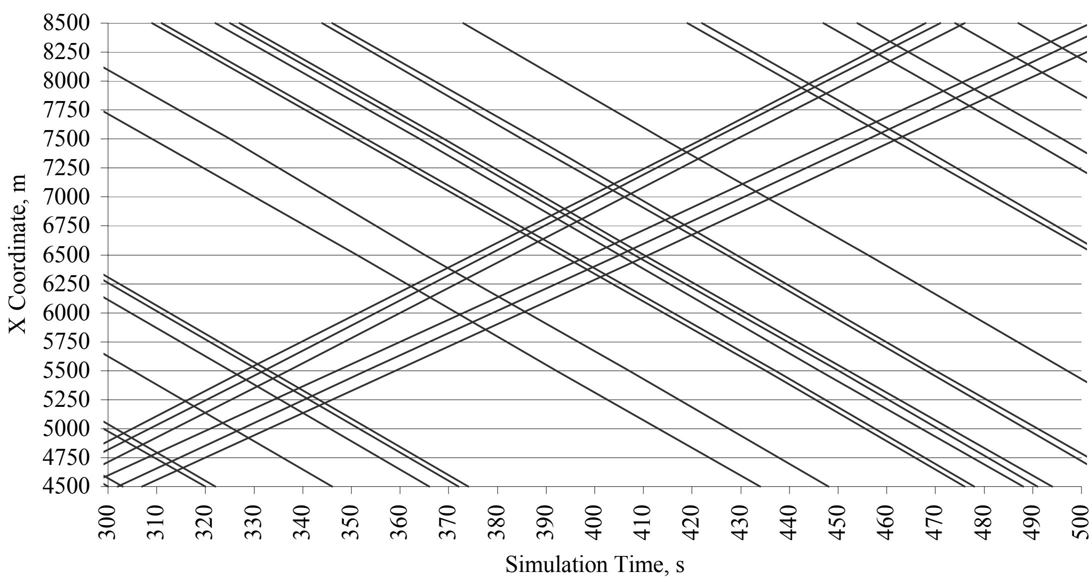

FIGURE 6.5. Estimated trajectories of the opposing vehicle using location trigger data.

Also using the data about the activation of the location triggers, a set of linear regression equations was developed to describe the estimated trajectories of each of the opposing vehicles. These equations are shown in Table 6.2.

These trajectory equations referenced the simulation time, t, of one particular simulation run. However, this time varied between experimental scenario runs so a method was needed to link these trajectories to the movement of the opposing vehicles during each passing maneuver. Because VISSIM controlled both the opposing and the impeding vehicles, the movements of the impeding vehicles observed during each simulation run could be used to align the simulation time of each experimental scenario run with the simulation time referenced in the trajectory equations. To do this the trajectory equations for the impeding vehicles were needed. These are shown in Table 6.3

TABLE 6.2. Linear Regression Equations of Opposing Vehicle Trajectories

Vehicle ID	Vehicle Description	Estimated Trajectory
v10	Purple Celica	$x_o = -24.271t + 11569$
v11	Purple Celica	$x_o = -23.923t + 11687$
v12	Purple Celica	$x_o = -23.98t + 11762$
v13	Blue Lexus	$x_o = -24.154t + 12226$
v14	Purple Celica	$x_o = -24.096t + 12265$
v15	White Grand Prix	$x_o = -24.39t + 12940$
v16	Blue Lexus	$x_o = -24.213t + 13368$
v17	Purple Celica	$x_o = -24.213t + 13561$
v18	Gray Lexus	$x_o = -24.213t + 13513$
v19	Gray Lexus	$x_o = -23.98t + 14909$
v20	Blue Lexus	$x_o = -24.271t + 15374$
v21	Blue Lexus	$x_o = -23.923t + 15898$
v22	White Grand Prix	$x_o = -23.923t + 15946$
v23	Purple Celica	$x_o = -24.154t + 16283$
v24	Gray Lexus	$x_o = -24.096t + 16337$
v25	Purple Celica	$x_o = -23.98t + 16343$
v26	Purple Celica	$x_o = -24.213t + 16830$
v27	Blue Lexus	$x_o = -24.154t + 16863$
v28	Blue Lexus	$x_o = -24.213t + 17532$
v29	Purple Celica	$x_o = -23.98t + 18553$
v30	White Grand Prix	$x_o = -24.038t + 18647$
v31	Purple Celica	$x_o = -24.095t + 19276$
v32	White Grand Prix	$x_o = -24.095t + 19444$

TABLE 6.3. Linear Regression Equations of Impeding Vehicle Trajectories

Vehicle ID	Vehicle Description	Estimated Trajectories
v1	Red Grand Prix	x_i = 21.459t - 1548.1
v2	White Box Truck	x_i = 21.551t - 1647.4
v3	Red Grand Prix	x_i = 21.551t - 1755.2
v5	Blue Grand Prix	x_i = 19.342t - 1210.8
v7	Gray Box Truck	x_i = 19.493t - 1387.8
v8	Blue Grand Prix	x_i = 19.342t - 1442.9

TABLE 6.4. Vehicle Lengths and Widths

Vehicle ID	Vehicle Description	Length To Back, m	Length To Front, m	Width ,m
Test Vehicle	Beige Saturn	2.3595	2.3595	1.556
v1	Red Grand Prix	2.359	2.359	1.556
v2	White Box Truck	3.499	2.811	2.17
v3	Red Grand Prix	2.359	2.359	1.556
v5	Blue Grand Prix	2.359	2.359	1.556
v7	Gray Box Truck	3.499	2.811	2.17
v8	Blue Grand Prix	2.359	2.359	1.556
v10	Purple Celica	1.887	2.156	1.728
v11	Purple Celica	1.887	2.156	1.728
v12	Purple Celica	1.887	2.156	1.728
v13	Blue Lexus	2.405	2.405	1.762
v14	Purple Celica	1.887	2.156	1.728
v15	White Grand Prix	2.359	2.359	1.556
v16	Blue Lexus	2.405	2.405	1.762
v17	Purple Celica	1.887	2.156	1.728
v18	Gray Lexus	2.405	2.405	1.762
v19	Gray Lexus	2.405	2.405	1.762
v20	Blue Lexus	2.405	2.405	1.762
v21	Blue Lexus	2.405	2.405	1.762
v22	White Grand Prix	2.359	2.359	1.556
v23	Purple Celica	1.887	2.156	1.728
v24	Gray Lexus	2.405	2.405	1.762
v25	Purple Celica	1.887	2.156	1.728
v26	Purple Celica	1.887	2.156	1.728
v27	Blue Lexus	2.405	2.405	1.762
v28	Blue Lexus	2.405	2.405	1.762
v29	Purple Celica	1.887	2.156	1.728
v30	White Grand Prix	2.359	2.359	1.556
v31	Purple Celica	1.887	2.156	1.728
v32	White Grand Prix	2.359	2.359	1.556

The position of the center of the impeding vehicle x_i given in the output was used with the appropriate estimated trajectory equation from Table 6.3 to calculate the simulation reference time, t. That time was then used with the appropriate estimated trajectory equations for the opposing vehicles from Table 6.2 to calculate the location of the center of the opposing vehicles, x_o.

The positions of the impeding and opposing vehicles, and their corresponding trajectory equations, referenced the center of the vehicle. To determine the gaps between opposing vehicles, the lengths of the opposing vehicles were needed. The lengths and widths for all the impeding and opposing vehicles are given in Table 6.4. Gaps between opposing vehicles were found to range from roughly 20 to 1450 m.

For each test driver, the data was put into an Excel workbook, each containing one worksheet for each experimental scenario run. A typical worksheet was twenty columns by approximately one thousand rows. Capturing similar data in the field would be very difficult. Even if photographic techniques could be implored to capture the movement of every vehicle, the data reduction efforts would be enormous.

6.4.3 Surveys, Questionnaires and Interviews

In addition to the electronically recorded data, detailed information about the test drivers could have been elicited through surveys, questionnaires, or personal interviews. Experiments such as this one, which used a simulated environment conducted in a laboratory setting, brings the researcher or experimenter face-to-face with the test drivers. Comparable interaction is not available during field studies.

6.4.4 Observations

Apart from the formal interaction between the test driver and the experimenter, the laboratory setting allowed the experimenter to gain information about the test driver through general observations. To make observations during a field study, the experimenter would need to be in close proximity to the test driver. To capture how the behavior changes or to observe the test driver for a period of time would mean that the experimenter would need to be in the same vehicle as the test driver, in a neighboring vehicle, or use some technology that has tracking capabilities, such as Global Positioning Satellite (GPS).

During the passing behavior study, several general observations were recorded. First of all, all of the test drivers were observed to have good control of the test vehicle. Some difficulties were observed making the right turn onto the industrial roadway from the start position but this did not impact the experiment. If difficulties were observed during the first experimental scenario, the test driver was given further verbal instructions on how to better negotiate the turn. Some drivers complained of some discomfort when braking at the end of the scenarios. If this was the case, the test driver was further instructed to coast to a stop to reduce their discomfort.

Second, most drivers followed the given instructions. Only one test driver failed to make a pass during an experimental drive. The data for this test driver was excluded from the analysis. Three test drivers completed passes where more than one vehicle was passed during a single maneuver. The data for these test drivers was also excluded from the analysis.

Third, a couple of behaviors were observed that support the notion that the test drivers were engrossed in the simulated driving environment. These behaviors included the tilting of the head to the left to see around the impeding vehicle, the sampling of the rear view image, and avoiding collisions. Given that the animation was presented in two dimensions, any shifting of the head did not change what was viewed. Therefore, it was interesting to see test drivers repeatedly tilted their heads to get a better look at whether there was opposing traffic present. Test drivers were also observed looking at the rear view, which was integrated in the center forward view. It appeared that drivers looked at this image when returning to the right lane. For the most part, test drivers avoided collisions with the impeding and the opposing vehicles. In six passing maneuvers, the driver decided to abort the maneuver and return to the right lane behind the original impeding vehicle. In each case, a passing maneuver was successfully completed further downstream. Only in one passing maneuver for one test driver did a collision with an opposing vehicle occur. This test driver had a lot of previous experience driving in simulated environments and admitted that there is no longer any perceived risk when driving. The data for this test driver was excluded from the analysis.

6.5 Data Reduction – Conventional Definition

The data from the experimental scenario under each of the four passing conditions for all of the 24 test drivers was examined. Each passing maneuver was labeled using the test driver number followed by the sex of the test driver and the trial number. For instance, the four passing maneuvers performed by the first test driver, who was male, would be identified by 1M1, 1M2, 1M3, and 1M4.

For each passing maneuver, the time and distance in the left lane, start gap distance, and end gap distance were calculated. The time (t_2) and distance (d_2) that the passing vehicle occupied the left lane was defined as:

- beginning when the front left wheel crossed over the centerline as the passing vehicle moved into the left lane; and
- ending when the rear left wheel crossed over the centerline as the passing vehicle moved back into the right lane.

These are the conventional definitions, and are comparable to that given by AASHTO (10) and used in previous studies (*22*, *155*). The start gap (G_S) was the distance from the front of the passing vehicle to the rear of the impeding vehicle when the passing vehicle began to occupy the left lane. It was calculated from the positions of the impeding (x_i) and passing (x_p) vehicles, taking into account of the vehicle lengths (L_i and L_p) such that:

$$G_S = \left(x_i - \frac{L_i}{2} \right) - \left(x_p + \frac{L_p}{2} \right) \tag{6.1}$$

The end gap (G_E) was the distance from the rear of the passing vehicle to the front of the impeding vehicle when the passing vehicle ceased to occupy the left lane. It was also calculated from the positions of the impeding (x_i) and passing (x_p) vehicles, taking into account the vehicle lengths (L_i and L_p) such that:

$$G_E = \left(x_p - \frac{L_p}{2} \right) - \left(x_i + \frac{L_i}{2} \right) \tag{6.2}$$

The lengths of the passing vehicle and each of the impeding vehicles were previously given in Table 6.4. Because of the fidelity of the data recorded, other definitions for the time and distance in the left lane, and gap distances could be used and easily quantified.

A cursory examination revealed that five test drivers performed at least one pass, where the test vehicle was partially in the left lane while the test driver waited for an acceptable gap in the oncoming traffic. Six test drivers performed at least one pass where the test vehicle remained in the left lane at the end of the pass until after the oncoming vehicle passed. These behaviors are inappropriate and could be regarded as potential collisions. The cause of these behaviors was not explored analytically but it was hypothesized that it could stem from how test drivers judged their lateral position on the simulated road or perceived the risk of a collision. Three test drivers exhibited both of these behaviors. The data for 8 test drivers that exhibited either behavior was excluded, leaving a total of 64 passing maneuvers for analysis. The time and distance in the left lane, start gap distance, and end gap distance for each of the 64 passing maneuvers is shown in Appendix J along with a description of the impeding vehicle.

6.5.1 Data Exploration

In preparation for the analysis of the passing data, the distributions of the response variables were tested using the Kolmogorov-Smirnov (K-S) test for normality. The results are shown in Table 6.5. At a 0.05 level of significance, the normal distribution was not a good fit for the time or distance in the left lane for this sample of passing maneuvers. To further explore these distributions, histograms of the response variable were plotted. The plots are shown in Figure 6.6 and 6.7.

TABLE 6.5. Normality Test Results for Time, Distance, and Gap Distances, N=64

Response Variable	n	Mean	σ	Absolute Extreme Difference	K-S test statistic	Significance
t_2 (sec)	64	20.05	10.76	0.202	1.617	0.011
d_2 (m)	64	490.30	237.64	0.202	1.613	0.011
G_S (m)	64	23.49	12.19	0.155	1.242	0.092
G_E (m)	64	47.37	19.25	0.137	1.099	0.178

Note: n is the sample size and σ is the standard deviation.

From the histograms, it is seen that there may be extreme outliers in the time interval labeled by 70 seconds and the distance interval labeled by 1600 meters. Both of these outliers are from passing maneuver 7F1. By removing this outlier from the data, the results of the Kolmogorov-Smirnov (K-S) test for normality at the 0.05 level of significance support that the normal distribution was a good fit for each of the response variables for this sample of 63 passing maneuvers. The results are shown in Table 6.6.

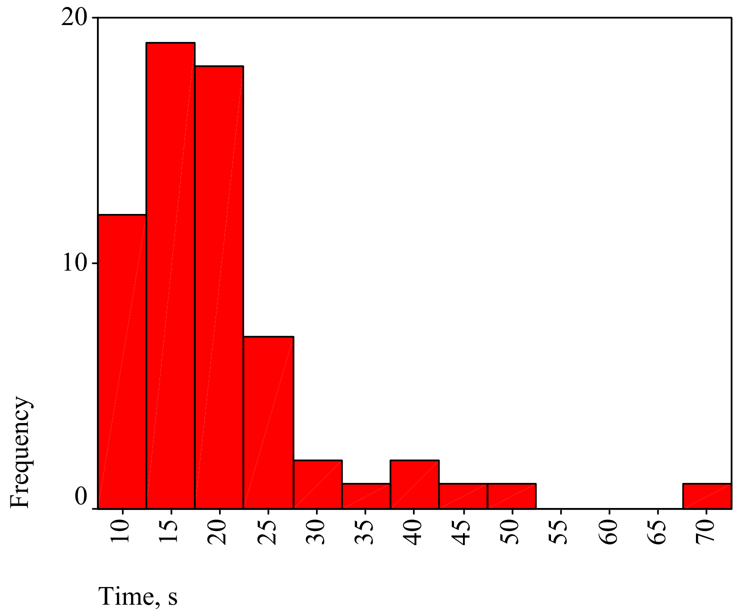

FIGURE 6.6. Histogram of the response variable, time in the left lane.

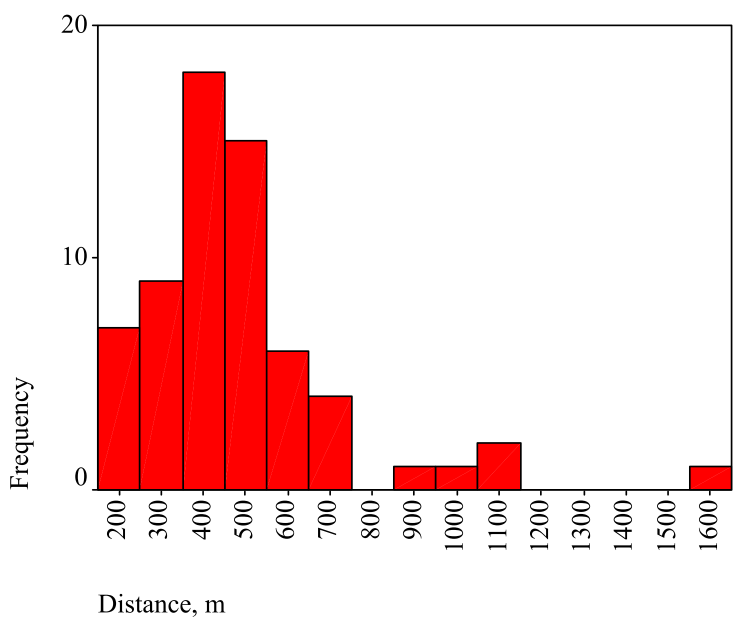

FIGURE 6.7. Histogram of the response variable, distance in the left lane.

TABLE 6.6. Normality Test Results for Time, Distance, and Gap Distances, N=63

Response Variable	n	Mean	σ	Absolute Extreme Difference	K-S test statistic	Significance
t_2 (sec)	63	19.23	8.63	0.152	1.206	0.109
d_2 (m)	63	472.28	190.43	0.153	1.216	0.104
G_S (m)	63	23.45	12.29	0.162	1.283	0.074
G_E (m)	63	47.31	19.40	0.146	1.161	0.135

Note: n is the sample size and σ is the standard deviation.

TABLE 6.7. Time, Distance, and Gap Distances – Conventional Definition

Response Variable	Impeding Vehicle	Slow Speed			Fast Speed			All Speeds		
		n	Mean	σ	n	Mean	σ	n	Mean	σ
t_2 (sec)	car	16	17.63	11.43	16	17.38	7.15	32	17.50	9.40
	truck	16	19.21	5.58	15	22.94	8.95	31	21.02	7.52
	all	32	18.42	8.89	31	20.07	8.42	63	19.23	8.63
d_2 (m)	car	16	424.4	241.0	16	449.5	168.4	32	436.9	204.9
	truck	16	456.9	123.9	15	563.9	197.5	31	508.7	169.8
	all	32	440.6	189.2	31	504.9	189.1	63	472.2	190.4
G_S (m)	car	16	22.07	13.26	16	19.58	8.05	32	20.82	10.86
	truck	16	24.40	11.02	15	28.05	15.42	31	26.16	13.23
	all	32	23.23	12.05	31	23.68	12.72	63	23.45	12.29
G_E (m)	car	16	53.31	21.45	16	49.28	20.17	32	51.29	20.58
	truck	16	49.17	20.68	15	36.82	10.60	31	43.20	17.48
	All	32	51.24	20.83	31	43.25	17.20	63	47.31	19.40

Note: n is the sample size and σ is the standard deviation.

6.5.2 Data Summary

For the 63 data samples, the averages and standard deviations of the times and distances in the left lane, start gap distances, and end gap distances are presented in Table 6.7. As expected, it appears that the time and distance in the left lane, and the start gap distance were greater when the impeding vehicle was a truck as opposed to a car or when the impeding vehicle was traveling at the faster of the two speeds. Contrary to expectation, it appears that the end gap distances were smaller when the impeding vehicle was a truck as opposed to a car or when the impeding vehicle was traveling at the faster of the two speeds. The data is analyzed in the following sections.

6.6 Data Analysis – Conventional Definition

The first step in the analysis was to examine the factor effects plots for each of the response variables: the times and distances in the left lane, and the start gap and end gap distances. These plots illustrate the interaction and the main effects of the two factors: the speed and the length of the impeding vehicle. The second step in the analysis was to test whether the observed interaction of the factor effects are significant from a statistical perspective. This test was carried out using a factor effects analysis of variance (ANOVA) model for two factor experiments with repeated measures on both factors and assumed that the response variables were normally distributed. The third step in the analysis was to determine whether the main effects of the factors were significant by using the same ANOVA model.

6.6.1 Factor Effects Plots

A factor effects plot was used to compare the mean responses given the various levels of the experiment test factors. The effects of two factors interact if the difference in the mean response for two levels of one factor is not constant across the levels of the second factor. Visually, this means that if the lines are parallel, then there is no interaction of factor effects. If the lines are not parallel, the factor effects do interact and the importance of that interaction is tested using an F-test. The main effects of the factors are also illustrated in a factor effects plot. For a two-factor effects plot, the main effect of the first factor is illustrated by the slopes of the lines for each level of the second factor. The main effect of the second factor is illustrated by the difference between the lines at each level of the first factors. The factor effect plots for the times and distances in the left lane and the start gap and end gap distance are shown in Figures 6.8 through 6.11.

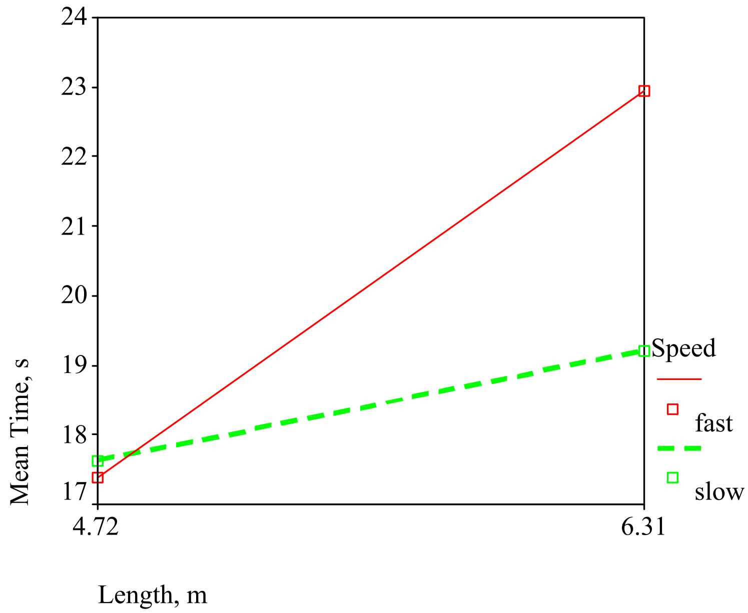

FIGURE 6.8. Factor effects plot for time in the left lane.

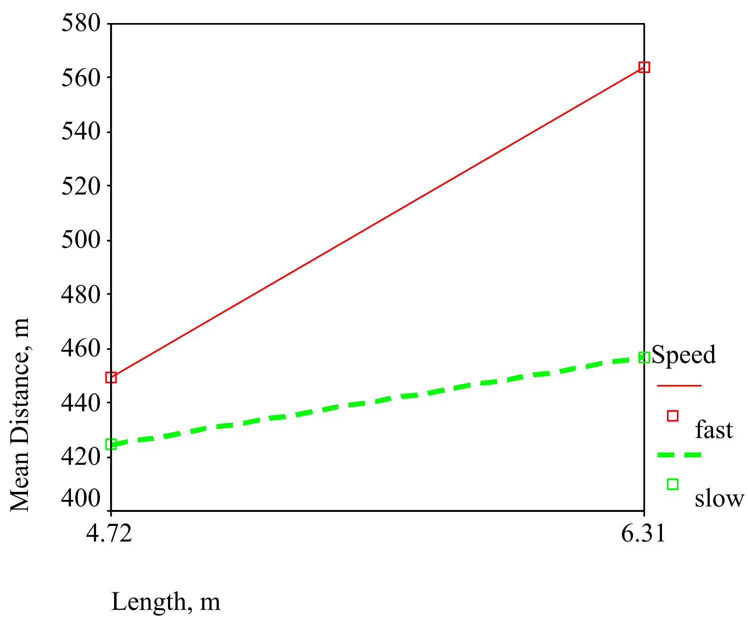

FIGURE 6.9. Factor effects plot for distance in the left lane.

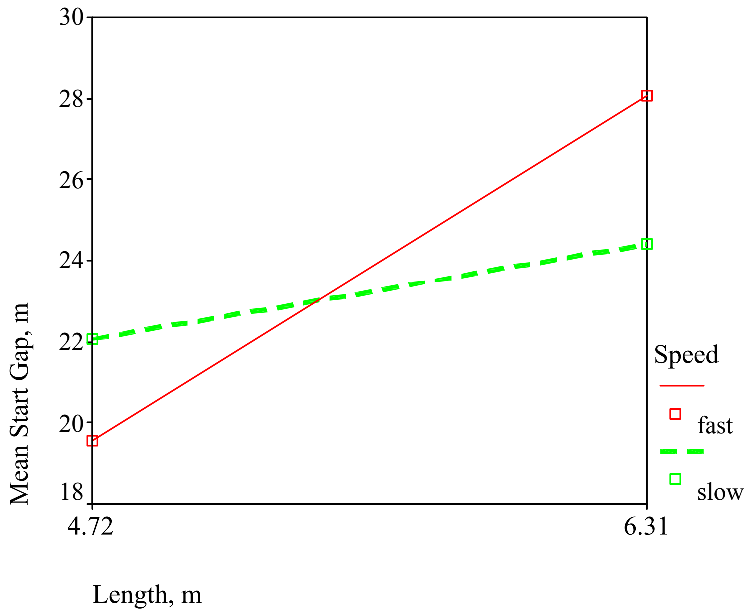

FIGURE 6.10. Factor effects plot for start gap distance.

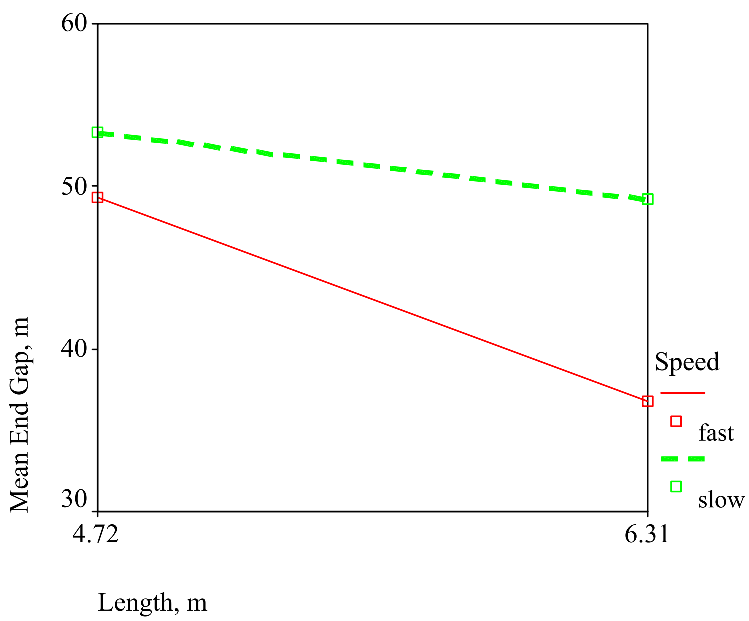

FIGURE 6.11. Factor effects plot for end gap distance.

In each of the four factor effects plots, the lines are not parallel, suggesting that the factor effects interacted. Based on the slopes of the lines and the differences between the lines at the factor levels, there appears to have been main effects of both factors for all of the response variables. These relationships were further explored by conducting F-tests for the strengths of the interaction between the factor effects as well as the main factor effects.

6.6.2 Analysis of Variance Model

The ANOVA model for two factor experiments with repeated measures on both factors, assuming no interaction between the treatments and the subjects, has the general form:

$$Y_{ijk} = \mu + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijk} \tag{6.3}$$

where Y_{ijk} is the observation for the i^{th} subject, j^{th} level of factor A and the k^{th} level of factor B;

μ is the overall mean

ρ_i is the effect due to the i^{th} subject;

α_j is the effect due to the j^{th} level of A;

β_k is the effect due to the k^{th} level of B;

$(\alpha\beta)_{jk}$ is the effect due to the j^{th} level of A and the k^{th} level of B; and

ε_{ijk} is the random error.

The corresponding ANOVA table is shown in Table 6.8.

TABLE 6.8. ANOVA Table for a Two-Factorial Experiment with Repeated Measures

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square
Subjects	$SSS = ab\sum_i(\overline{Y}_{i..} - \overline{Y}_{...})^2$	n-1	MSS
Factor A	$SSA = nb\sum_j(\overline{Y}_{.j.} - \overline{Y}_{...})^2$	a-1	MSA
Factor B	$SSB = na\sum_k(\overline{Y}_{..k} - \overline{Y}_{...})^2$	b-1	MSB
AB Interaction	$SSAB = n\sum_j\sum_k(\overline{Y}_{.jk} - \overline{Y}_{.j.} - \overline{Y}_{..k} + \overline{Y}_{...})^2$	(a-1)(b-1)	MSAB
Error	$SSTR.S = \sum_i\sum_j\sum_k(Y_{ijk} - \overline{Y}_{i..} - \overline{Y}_{.jk} + \overline{Y}_{...})^2$	(n-1)(ab-1)	MSTR.S

Applied to this experiment, factor A is the speed of the impeding vehicle and factor B is the length of the impeding vehicle. Factor A has two levels, high speed and low speed. Factor B also has two levels, the 4.72 m long passenger car and the 6.31 m long truck.

6.6.3 Tests for Interaction of Factor Effects

To test whether the interactions of the factor effects, observed in Figures 6.9 through 6.12 were significant, the following hypothesis test was performed for each response variable.

H_o : all $\alpha\beta_{jk} = 0$

H_a : at least one $\alpha\beta_{jk}$ differs from the rest

Test Statistic: $F^* = \dfrac{MSAB}{MSTR.S}$

Rejection Region: $F^* > F_{\alpha,df1,df2}$

where α is the level of significance, df1 is the degrees of freedom of factor A times the degrees of freedom of factor B, and df2 is the degrees of freedom of the error. With two levels of factor A and two levels of factor B, and a total of 63 observations, $F_{0.05,\,1,\,40}$ is about 4.12. The results of the analysis of the interaction effects are shown in Table 6.9. For each of the response variables the test statistic is less than the F value, therefore Ho is not rejected. There was no evidence of significant interaction of factor effects.

TABLE 6.9. Interaction of Effects – Conventional Definition

Response Variable	MSAB	MSTR.S	F*	Significance	Observed Power
t_2 (sec)	0.964	16.046	0.060	0.808	0.057
d_2 (m)	1418.339	7977.770	0.178	0.676	0.070
G_S (m)	143.632	49.100	2.925	0.095	0.386
G_E (m)	62.222	183.265	0.340	0.563	0.088

6.6.4 Tests for Speed Factor Effects

To test for main effects of the speed of the impeding vehicle the following test was performed:

H_o : all $\alpha_j = 0$

H_a : at least one α_j differs from the rest

Test Statistic: $F^* = \dfrac{MSA}{MSTR.S}$

Rejection Region: $F^* > F_{\alpha,df1,df2}$

where df1 is the degrees of freedom of factor A and df2 is the degrees of freedom of the error. $F_{0.05,1,40}$ is about 4.12. The results of the test for main effects of the speed of the impeding vehicle are shown in table 6.10. There was evidence to support a difference in the response variables, distance in the left lane and end gap, based on the effect of the levels of the speed of the impeding vehicle.

TABLE 6.10. Effect of the Impeding Vehicle Speed – Conventional Definition

Response Variable	MSA	MSTR.S	F*	Significance	Observed Power
t_2 (sec)	62.011	16.046	3.865	0.056	0.484
d_2 (m)	71847.809	7977.770	9.006	0.005	0.834
G_S (m)	86.659	49.100	1.765	0.192	0.254
G_E (m)	987.280	183.265	5.387	0.025	0.620

6.6.5 Tests for Length Factor Effects

To test for main effects of the length of the impeding vehicle the following test was performed:

H_o : all $\beta_k = 0$

H_a : at least one β_k differs from the rest

Test Statistic: $F^* = \dfrac{MSB}{MSTR.S}$

Rejection Region: $F^* > F_{\alpha,df1,df2}$

where df1 is the degrees of freedom of factor B and df2 is the degrees of freedom of the error. $F_{0.05,1,40}$ is about 4.12. The results of the test for main effect are shown in Table 6.11. There was evidence to support a difference in the response variables, time and distance in the left lane and start gap, based on the effect of the levels of the length of the impeding vehicle.

TABLE 6.11. Effect of the Impeding Vehicle Length – Conventional Definition

Response Variable	MSB	MSTR.S	F*	Significance	Observed Power
t_2 (sec)	408.191	16.046	25.439	<0.001	0.998
d_2 (m)	172025.608	7977.770	21.563	<0.001	0.995
G_S (m)	537.868	49.100	10.955	0.002	0.898
G_E (m)	605.864	183.265	3.306	0.077	0.427

6.7 Analysis Results – Conventional Definition

The results from the data analysis were grouped by the response variables to describe the impact of the speed and length of the impeding vehicle of passing behavior. These results are discussed in terms of what was expected and what might have caused the observed behavior to differ from those expectations.

6.7.1 Time in the Left Lane

As expected, the mean time in the left lane increased with increases in the speed and length of the impeding vehicle. These relationships were illustrated on the factor effects plot in Figure 6.8. It appeared that there was an interaction between the factors but the interaction was found not significant (F= 0.060, P=0.808).

The increase in the speed of the impeding vehicle was shown to increase the time traveled in the left lane. From the factor effects plot in Figure 6.8, it appeared that this relationship was far more pronounced when the impeding vehicle was a truck. There appeared to be very little difference in the time in the left lane when the impeding vehicle was a car. The effect of the speed was found not significant (F=3.865, P=0.056). The observed power of this test was 0.484. A larger sample size could increase the power of the test and perhaps produce a significant effect of the speed factor.

The lack of significance in the effect of the speed could be attributable to the small difference between the fast and slow impeding vehicle speeds. One of the limitations of the prototype was the presence of speed limit signs in the rural simulation environment. The impeding vehicle needed to be traveling slower than the speed limit so that the test driver would pass the vehicle but the difference could not be unrealistically large. Therefore, the fast and slow vehicles were programmed to travel within 8 km/h (5 mph) and 16 km/h (10 mph) under the speed limit respectively. Removing or changing the speed limit signs would provide the opportunity to use a wider range of impeding vehicle speeds. A wider range of speeds could result in larger and perhaps significant effects for the time in the left lane.

The effect of the length was significant ($F=25.439$, $P<0.001$). The time traveled in the left lane was observed to be sensitive to the small difference in length between the 4.72 m long passenger car and the 6.31 m truck.

6.7.2 Distance in the Left Lane

It was also expected that an increase in the speed or length if the impeding vehicle would increase the distance traveled in the left lane. This relationship was illustrated in the factor effects plot in Figure 6.9 and there appeared to be an interaction in the effects of the speed and length of the impeding vehicle. This interaction was not significant ($F=0.178$, $P=0.676$).

The speed ($F=9.006$, $P=0.005$) and length ($F=21.563$, $P<0.001$) of the impeding vehicle significantly increased the distance traveled in the left lane. The powers of these tests were 0.834 and 0.995 respectively for the effects of the speed and length of the impeding vehicle.

6.7.3 Start Gap Distance

It was expected that the test driver would leave a greater start gap distance when the impeding vehicle traveled at the faster of the two speeds or when the impeding vehicle was a truck as opposed to a car. These relationships were observed in the factor effects plot in Figure 6.10 and there appeared to have been an interaction between the factor effects. However, this interaction was not significant ($F=2.925$, $P=0.095$).

The effect of the speed of the impeding vehicle ($F=1.765$, $P=0.192$) was not significant. It was surprising to see that when the impeding vehicle was a car, subjects left greater start gaps at the faster speed than at the slower speeds. The opposite behavior was expected. The observed power for the test of the effect of the speed of the impeding vehicles was 0.254. A larger sample size could increase the power of the test and perhaps produce a significant effect of the speed factor. The small differences in the speeds of the impeding vehicle may have also played a role. Larger increases in the speed may also significantly affect the start gap distance.

The effect of the length of the impeding vehicle ($F=10.955$, $P=0.002$) was significant with an observed power of 0.898. Whether the impeding vehicle was traveling at the slower or faster speeds, the start gap was larger for the longer impeding vehicles. The distance in the left lane was sensitive to the small difference in the lengths of the impeding vehicles.

6.7.4 End Gap Distance

It was also expected that the test driver would leave greater end gap distance when the impeding vehicle traveled at the faster of the two speeds or when the impeding vehicle was a truck as opposed to a car. The factor effects plot in Figure 6.11 illustrated the opposite relationships. The observed end gap decreased with increases in the speed and length of the impeding vehicle and there appeared to be an interaction between these effects. The interaction was not significant (F=0.340, P=0.563).

The effect of the speed of the impeding vehicle (F=5.387, P=0.025) was significant, however the observed end gap distances were smaller at the faster speeds, which is contrary to expectation. The effect was more pronounced when the impeding vehicle was a truck as opposed to a car, however the effect of the length of the impeding vehicle (F=3.306, P=0.077) was not significant.

These unexpected relationships may be explained by the design of the experimental scenario. The impeding vehicles were the leading car and following truck in each of the fast and slow traveling platoons. When a truck was passed, the test driver needed to return to the right lane in between the truck and the lead vehicle in the platoon. When the lead vehicle was passed, the test driver returned to the right lane in front of the lead vehicle and there was no other vehicle ahead to restrict the end gap distance the test driver allowed. Therefore, the smaller end gap distances observed for the faster and longer vehicles might be the consequence of whether or not a vehicle was present ahead of the impeding vehicle.

6.8 Data Reduction – Alternate Definition

To avoid including overly large start gap and end gap distances, the passing data was reduced using an alternate definition of the time and distance in the left lane. The time ($\dot{t}_2$) and distance ($\dot{d}_2$) that the passing vehicle occupies the left lane was defined as:

- beginning when the center of the vehicle crossed over the centerline as the passing vehicle moved into the left lane; and
- ending when the center of the vehicle crossed over the centerline as the passing vehicle moved back into the right lane.

The start gap ($\dot{G}_S$) was the distance from the front of the passing vehicle to the rear of the impeding vehicle when the center of the passing vehicle crossed the centerline to move into the left lane. The end gap ($\dot{G}_E$) was the distance from the rear of the passing vehicle to the front of the impeding vehicle when the center of the passing vehicle crossed the centerline to move back into the right lane.

The data from the experimental scenario under each of the four passing conditions for all of the 24 test drivers was examined. The time and distance in the left lane, start gap distance, and end gap distance for each of the 96 passing maneuvers is shown in Appendix K along with a description of the impeding vehicle.

6.8.1 Data Exploration

The Kolmogorov-Smirnov (K-S) test for normality was applied to the data in Appendix K and the results are shown in Table 6.12. At a 0.05 level of significance, the normal distribution was not a good fit for the start gap or end gap distances for this sample of passing maneuvers.

TABLE 6.12. Normality Test Results for Time, Distance, and Gap Distances, N=96

Response Variable	n	Mean	σ	Absolute Extreme Difference	K-S test statistic	Significance
$\dot{t}_2$ (sec)	64	20.05	10.76	0.202	1.617	0.011
$\dot{d}_2$ (m)	64	490.30	237.64	0.202	1.613	0.011
$\dot{G}_S$ (m)	64	23.49	12.19	0.155	1.242	0.092
$\dot{G}_E$ (m)	64	47.37	19.25	0.137	1.099	0.178

Note: n is the sample size and σ is the standard deviation.

To further explore these distributions, box plots of the start gap and end gap distances were plotted. The plots are shown in Figure 6.12 and 6.13. From the box plots, there appears to be 2 extreme outliers; one in the start gap distance interval labeled by 65 meters and one in the end gap distance interval labeled by 80 meters. These come from passing maneuvers 24F3 and 23F2, respectively. These maneuvers were excluded from further analysis.

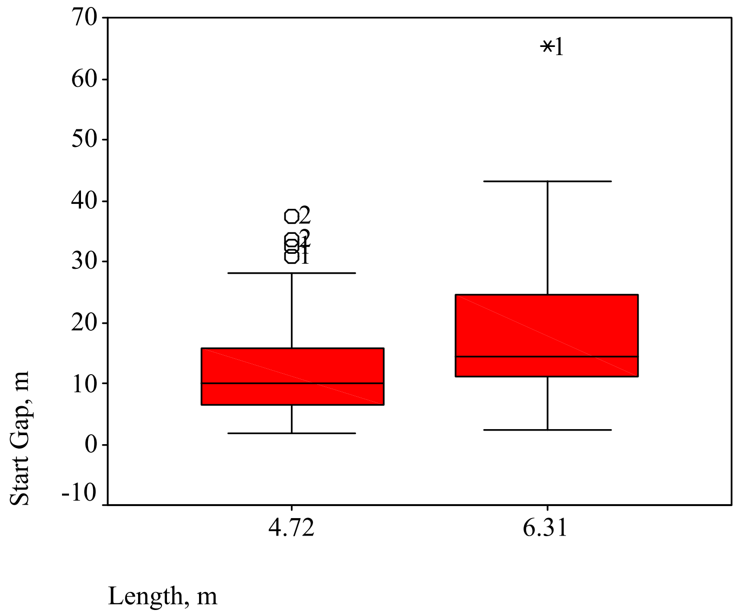

FIGURE 6.12. Box plots of start gap distances.

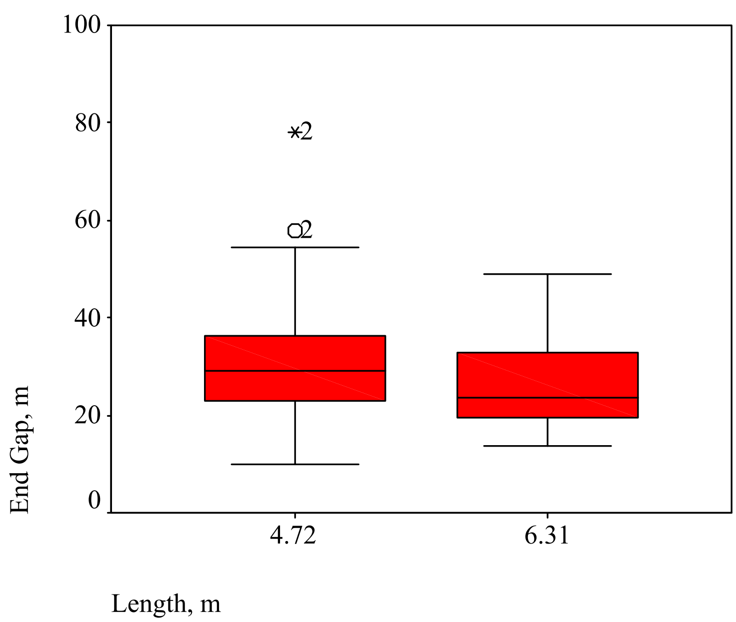

FIGURE 6.13. Box plots of end gap distances.

To ensure that the response variables were normally distributed, passing maneuvers 29F4 and 23F3 were removed. The results of the Kolmogorov-Smirnov (K-S) test for normality for the remaining 92 passing maneuvers are shown in Table 6.13. At the 0.05 level of significance, the results of the K-S tests support that the normal distribution was a good fit for each of the response variables for this sample of 92 passing maneuvers.

TABLE 6.13. Normality Test Results for Time, Distance, and Gap Distances, N=92

Response Variable	n	Mean	σ	Absolute Extreme Difference	K-S test statistic	Significance
$\dot{t}_2$ (sec)	92	10.21	2.45	0.063	0.601	0.862
$\dot{d}_2$ (m)	92	263.49	61.54	0.067	0.646	0.798
$\dot{G}_S$ (m)	92	14.54	8.91	0.141	1.357	0.050
$\dot{G}_E$ (m)	92	27.42	8.73	0.080	0.772	0.591

Note: n is the sample size and σ is the standard deviation.

TABLE 6.14. Time, Distance, and Gap Distances – Alternate Definition

Response Variable	Impeding Vehicle	Slow Speed			Fast Speed			All Speeds		
		n	Mean	σ	n	Mean	σ	n	Mean	σ
$\dot{t}_2$ (sec)	car	22	8.59	1.38	24	9.60	2.21	46	9.12	1.91
	truck	23	10.89	1.75	23	11.73	2.99	46	11.31	2.46
	all	45	9.76	1.95	47	10.64	2.81	92	10.21	2.45
$\dot{d}_2$ (m)	car	22	219.2	32.2	24	256.8	57.3	46	238.8	50.2
	truck	23	268.9	39.4	23	307.3	75.0	46	288.1	62.3
	all	45	244.6	43.6	47	281.5	70.6	92	263.4	61.5
$\dot{G}_S$ (m)	car	22	11.12	7.87	24	12.47	8.46	46	11.82	8.12
	truck	23	15.46	8.52	23	19.04	9.13	46	17.25	8.92
	all	45	13.33	8.40	47	15.69	9.31	92	14.54	8.91
$\dot{G}_E$ (m)	car	22	30.64	9.36	24	27.68	9.06	46	29.10	9.27
	truck	23	27.78	7.48	23	23.70	7.96	46	25.74	7.91
	All	45	29.18	8.47	47	25.73	8.74	92	27.42	8.73

Note: n is the sample size and σ is the standard deviation.

6.8.2 Data Summary

The averages and standard deviations of the times and distances in the left lane, start gap and end gap distances are presented in Table 6.14. As expected, it appears that the time and distance in the left lane were greater when the impeding vehicle was a truck as opposed to a car or when the impeding vehicle was traveling at the faster of the two speeds. The start gap distance was also greater when the impeding was a truck or traveling at the faster speed. Contrary to expectation was the decrease in the end gap distances when the impeding vehicle was a truck as opposed to a car or when the impeding vehicle was traveling at the faster of the two speeds.

6.9 Data Analysis – Alternate Definition

The effects of the speed and length of the impeding vehicle on each of the response variables was examined using factor effects plots and then tested using F-tests for the ANOVA model presented in section 6.6.2.

6.9.1 Factor Effect Plots

The factor effect plots for the time and distance in the left lane, start gap and end gap distances are shown in Figures 6.14 through 6.17.

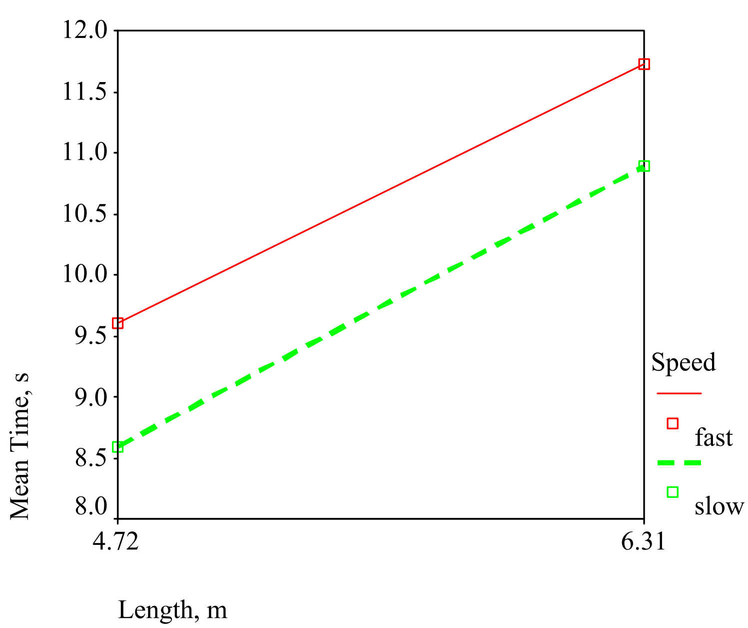

FIGURE 6.14. Alternate factor effects plot for time in the left lane.

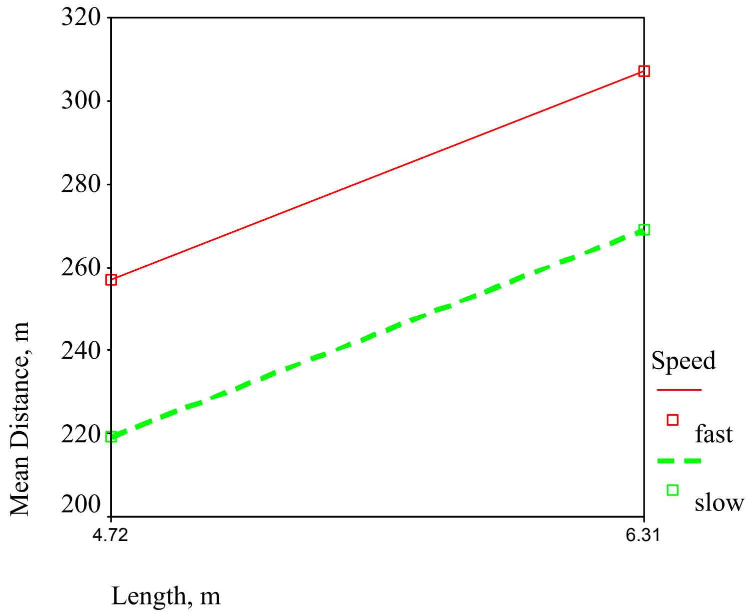

FIGURE 6.15. Alternate factor effects plot for distance in the left lane.

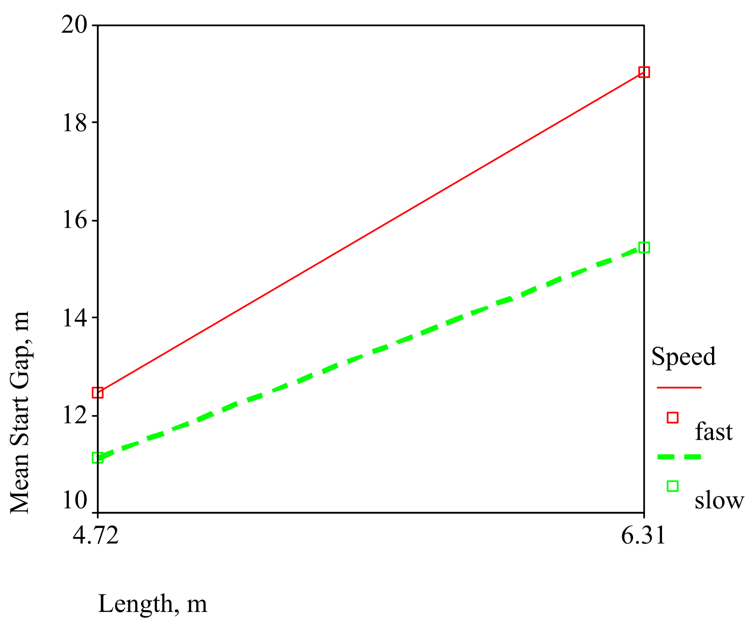

FIGURE 6.16. Alternate factor effects plot for start gap distances.

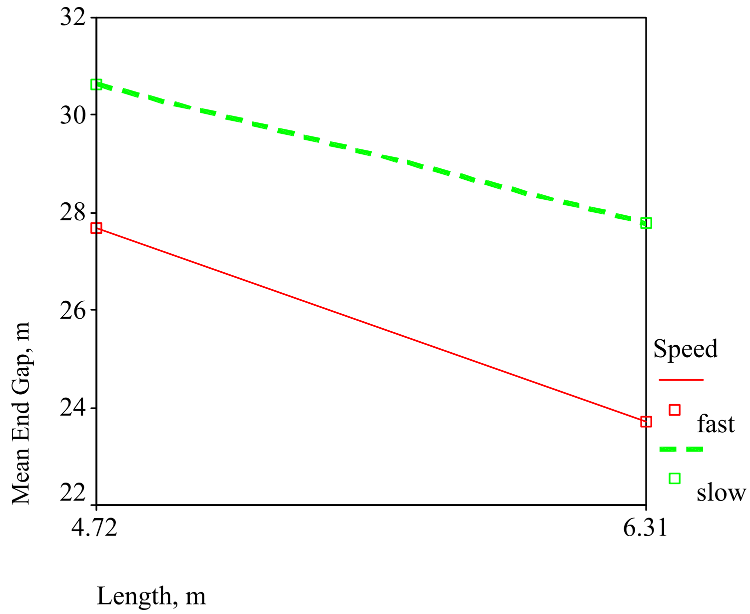

FIGURE 6.17. Alternate factor effects plot for end gap distances.

From the factor effects plots, there appears to have been little if any interaction between the effects of the speed of the impeding vehicles and the effects of the length of the impeding vehicle. These relationships were further explored by conducting F-tests for the strengths of interaction between the factor effects as well as the main factor effects.

6.9.2 Tests for Interaction of Factor Effects

The same procedures for testing the interaction of factor effects that was used in section 6.6.3 were applied. The results of the ANOVA are shown in Tables 6.15. The interaction of the factor effects were not significant given that $F_{0.05,\,1,\,65}$ is slightly less than 4.

TABLE 6.15. Interaction of Effects – Alternate Definition

Response Variable	MSAB	MSTR.S	F*	Significance	Observed Power
$\dot{t}_2$ (sec)	0.039	2.907	0.013	0.908	0.052
$\dot{d}_2$ (m)	71.663	1624.004	0.044	0.834	0.055
$\dot{G}_S$ (m)	69.995	24.458	2.862	0.095	0.385
$\dot{G}_E$ (m)	11.962	38.600	0.310	0.580	0.085

6.9.3 Tests for Speed Factor Effects

The main effects of the impeding vehicle speed were tested using the procedures outlined in Section 6.6.4 and the results are shown in Table 6.16. The effect of the impeding vehicle speed was significant for the distance in the left lane and the end gap distance.

TABLE 6.16. Effects of the Impeding Vehicle Speed – Alternate Definition

Response Variable	MSA	MSTR.S	F*	Significance	Observed Power
$\dot{t}_2$ (sec)	10.920	2.907	3.757	0.057	0.480
$\dot{d}_2$(m)	23017.263	1624.004	14.173	<0.001	0.960
$\dot{G}_S$(m)	63.742	24.458	2.606	0.111	0.356
$\dot{G}_E$(m)	322.094	38.600	8.344	0.005	0.812

6.9.4 Tests for Length Factor Effects

The main effects of the impeding vehicle length were tested using the procedures outlined in Section 6.6.5 and the results are shown in Table 6.17. The effect of the impeding vehicle speed was significant for each of the response variables.

TABLE 6.17. Effects of the Impeding Vehicle Length – Alternate Definition

Response Variable	MSB	MSTR.S	F*	Significance	Observed Power
$\dot{t}_2$ (sec)	106.393	2.907	36.602	<0.001	1.000
$\dot{d}_2$(m)	54454.633	1624.004	33.531	<0.001	1.000
$\dot{G}_S$(m)	671.732	24.458	27.465	<0.001	0.999
$\dot{G}_E$(m)	300.498	38.600	7.785	0.007	0.785

6.10 Results of the Data Analysis – Alternate Definition

The results of the alternate data analysis are presented in the following sections grouped by the various response variables.

6.10.1 Time in the Left Lane

It was expected that an increase in the speed or length of the impeding vehicle would increase the time traveled in the left lane. In the factor effect plot in Figure 6.14, the time in the left lane was shown to increase for greater speeds and vehicle lengths. There was no significant interaction of these effects (F=0.013, P=0.908).

As the speed increases, the time in the left lane increases. This relationship was not significant (F=3.757, P=0.057) but the observed power of the test was 0.480. Increasing the sample size would increase the observed power of the test and might produce a significant effect of the speed factor. The lack of significance in the effect of the speed could also be attributable to the small difference between the fast and slow impeding vehicle speeds as discussed in section 6.7.1.

The effect of the length was significant (F=36.602, P<0.001). The time traveled in the left lane was observed to be sensitive to the small difference between the 4.72 m long passenger car and the 6.31 m truck.

6.10.2 Distance in the Left Lane

It was also expected that an increase in the speed or length of the impeding vehicle would increase the distance traveled in the left lane. In the factor effects plot in Figure 6.15, the distance in the left lane was shown to increase with increases in the speed and length of the impeding vehicle. There was no significant interaction of these effects (F=0.044, P=0.834), however increasing the speed (F=14.173, P<0.001) and the length (F=33.531, P<0.001) of the impeding vehicle significantly increased the distance traveled in the left lane.

6.10.3 Start Gap Distance

It was expected that the test driver would leave a greater start gap distance when the impeding vehicle traveled at the faster of the two speeds or when the impeding vehicle was a truck as opposed to a car. In the effects plot in Figure 6.16, there appeared to be some interaction between the effects of the speed and the length of the impeding vehicle. The interaction was not significant (F=2.862, P=0.095).

The test drivers left a greater start gap distance for the faster impeding vehicles but the effect was not significant (F=2.606, P=0.111). The test drivers also left a greater start gap distance for the longer vehicles. The effect of the impeding vehicle length was significant (F=27.465, P<0.001).

6.10.4 End Gap Distance

It was also expected that the test driver would leave greater end gap distance when the impeding vehicle traveled at the faster of the two speeds or when the impeding vehicle was a truck as opposed to a car. In the factor effects plot in Figure 6.17 it is seen that the reverse relationship occurred. The test drivers left significantly larger end gap distances when the impeding vehicle was traveling at the slower speed (F=8.344, P=0.005) or when the impeding vehicle was a car (F=7.785, P=0.007). This is likely explained by the design of the experimental scenario and the presence or absence of a vehicle in front of the impeding vehicle, as discussed in section 6.7.4. There was no significant interaction of these effects (F0.310, P=0.580).

6.11 Comparison of Data Analyses (Conventional and Alternate Definitions)

Two definitions were used to define the time and distance in the left lane and the start and end gap distances. This was possible because the comprehensive data that was captured during the passing study, and estimated from the VISSIM data, detailed the movements of all the vehicles for every tenth of a second. In both approaches, the position of the passing vehicle was referenced to the centerline of the roadway. Using the conventional definition, the front left and the rear left wheels of the passing vehicle were referenced, while using the alternate definition, the center of the vehicle was referenced.

In both analyses, the interaction between the speed effects and the length effects was not significant. For the main effects, the p-values for each of the response variables are included in Table 6.18. There were no differences in the significance of the main effects however there were changes in the p-values.

TABLE 6.18. Comparison of Results – Conventional and Alternate Definitions

Conventional Definition			Alternate Definition		
Response Variable	Speed Effect	Length Effect	Response Variable	Speed Effect	Length Effect
t_2 (sec)	0.056	<0.001*	$\dot{t}_2$ (sec)	0.057	<0.001*
d_2 (m)	0.005*	<0.001*	$\dot{d}_2$ (m)	<0.001*	<0.001*
G_S (m)	0.192	0.002*	$\dot{G}_S$ (m)	0.111	<0.001*
G_E (m)	0.025*	0.007*	$\dot{G}_E$ (m)	0.005*	0.007*

Significant effects are indicated with an asterisk.

6.12 Nonparametric Analysis

In sections 6.5.1 and 6.8.1, outliers in the passing data were removed from the data sets to obtain distributions of the response variables that resembled a normal distribution. This was necessary because when applying of the ANOVA procedures, it was assumed that each group of data was an independent random sample from a normal population. A preferred alternative to excluding the outliers and using ANOVA procedures was to analyze the data using nonparametric techniques.

The Friedman test is the nonparametric equivalent of a one-sample repeated measures design, which was used to test that

H_o: all experimental conditions had identical effects

H_a: at least on experimental condition tended to yield larger effects than another experimental condition.

The k variables were ranked from 1 to k and the ranks were used to calculate the test statistic T, which was then compared to the Chi-squared distribution, with (k-1) degrees of freedom. If there was evidence that the experimental conditions were not identical, then differences were tested using the Wilcoxon signed rank test. The differences were considered significant when the p-value was less than or equal to 0.05. These tests were applied to the passing data summarized using both the conventional and alternate definitions.

6.12.1 Conventional Definition

The time and distance in the left lane, start gap distance, and end gap distance for each of the 64 passing maneuvers shown in Appendix J were analyzed using the Friedman and Wilcoxon nonparametric tests. The resulting p-values are shown in Table 6.19. Although the p-values varied from those found using the ANOVA procedures, the significance of the effects was comparable.

TABLE 6.19. Nonparametric Results Using the Conventional Definition

Response Variable	Group Differences	Speed Effect	Length Effect
t_2 (sec)	0.001*	0.085	0.001*
d_2 (m)	<0.001*	0.012*	0.001*
G_S (m)	0.003*	0.866	0.001*
G_E (m)	0.013*	0.050*	0.010*

Significant effects are indicated with an asterisk.

6.12.2 Alternate Definition

The time and distance in the left lane, start gap distance, and end gap distance for each of the 96 passing maneuvers shown in Appendix K were analyzed using the Friedman and Wilcoxon nonparametric tests. The resulting p-values are shown in Table 6.20. Although the p-values varied from those found using the ANOVA procedures, the significance of the effects was comparable.

TABLE 6.20. Nonparametric Results Using the Alternate Definition

Response Variable	Group Differences	Speed Effect	Length Effect
$\dot{t}_2$ (sec)	<0.001*	0.208	<0.001*
$\dot{d}_2$ (m)	<0.001*	0.003*	<0.001*
$\dot{G}_S$ (m)	<0.001*	0.103	<0.001*
$\dot{G}_E$ (m)	0.025*	0.002*	0.002*

Significant effects are indicated with an asterisk.

6.12.3 Results of the Nonparametric Analyses

Using the Friedman and Wilcoxon nonparametric tests, the impact of the speed of the impeding vehicle on the distance in the left lane and the end gap distance, and the impact of the length of the impeding vehicle on the distance and time in the left lane, as well as both the start gap and end gap distances was found to be significant. The significance of the effects was comparable using the conventional and alternate definitions, although the p-values varied. The significance of the effects was also comparable to those found using the ANOVA procedures.

6.13 Transferability of Results

There are concerns about the transferability of simulator study results to the real world. Drivers in a simulated environment may behave differently than in the real world, may be affected by the symptoms of simulator sickness, and may have difficulties controlling the simulated vehicles or maneuvering in the simulated environment. To determine whether this prototype was suitable for studying passing behavior, the results using both the conventional and the alternate definitions were compared to the field observations reported by Polus et al. (*22*).

6.13.1 Results Using the Conventional Definition

In this section, the passing data summarized using the conventional definition was compared to the previously reported field data. The means, standard deviations, and sample sizes for the time and distance in the left lane and the start and end gap distances are shown in Table 6.21.

The average time in the left lane and the average distance traveled in the left lane were approximately double that of the field observations. Similarly, the average start gap distance was approximately triple that of the field observations and the average end gap distance was approximately double that of the field observations.

TABLE 6.21. Comparing the Conventional Definition Results with Field Observations

Response Variable	Results			Field Observations		
	Mean	σ	n	Mean	σ	n
Time in left lane (s)	19.23	8.63	63	10.9	3.4	527
Distance in left lane (m)	472.28	190.43	63	253.7	80.9	507
Start gap distance (m)	23.45	12.29	63	7.4	6.1	462
End gap distance (m)	47.31	19.40	63	21.3	9.7	451

Note: n is the sample size and σ is the standard deviation.

To test whether the underlying populations of these samples are the same, tests for the difference of means were performed.

$$H_o : \mu_x - \mu_y = 0$$

Test Statistic: $z = \dfrac{\bar{x} - \bar{y} - 0}{\sqrt{\dfrac{s^2{}_x}{n} + \dfrac{s^2{}_y}{m}}}$

where the population variances were estimated by the sample variances (s^2) with sample sizes n and m. The observed test statistics were:

$|z| = 7.59$ for the time in the left lane;

$|z| = 9.01$ for the distance in the left lane;

$|z| = 10.20$ for the start gap distance; and

$|z| = 10.46$ for the end gap distance.

In each case, the null hypothesis was rejected at an approximate significance level of 0.05 ($z_{0.025}$ = 1.96), and the conclusion was that the simulation data and the field data were from different populations.

6.13.2 Results Using the Alternate Definition

In this section, the passing data summarized using the alternate definition was compared to the previously reported field results. The means, standard deviations, and sample sizes for the time and distance in the left lane and the start gap and end gap distances are shown in Table 6.22.

The analysis results, based on the alternate definition, compare better to the field observations reported by Polus et al. (*22*) than do the results based on the conventional definition. The average time in the left lane and the average distance traveled in the left lane appear to be comparable to the field observations. The average start gap distance is approximately double that of the field observations and the average end gap distance is slightly greater than the field observations.

TABLE 6.22. Comparing the Alternate Definition Results with Field Observations

Response Variable	Alternate Results			Field Observations		
	Mean	σ	n	Mean	σ	n
Time in left lane (s)	10.21	2.45	92	10.9	3.4	527
Distance in left lane (m)	263.49	61.54	92	253.7	80.9	507
Start gap distance (m)	14.54	8.91	92	7.4	6.1	462
End gap distance (m)	27.42	8.73	92	21.3	9.7	451

Note: n is the sample size and σ is the standard deviation.

To test whether the underlying populations of these samples are the same, the same test used in the previous section were applied to test for the difference of means. The observed test statistics were:

$|z|$ = 2.34 for the time in the left lane

$|z|$ = 1.33 for the distance in the left lane

$|z|$ = 7.35 for the start gap distance

$|z|$ = 6.01 for the end gap distance

At an approximate level of significance of 0.05 ($z_{0.025} = 1.96$), there was evidence that the mean distance in the left lane was the same therefore the null hypothesis was not rejected. However, the null hypothesis was rejected for the time in the left lane, and the start gap and end gap distances. The simulation data and field data were from different populations.

From the results of the passing study, using both definitions, and comparisons with previous field observations, it appears that the drivers left more space between vehicles when in the simulated environment. Three possible reasons for these differences between the simulation data and the field data are discussed in the following sections.

6.13.3 Distance Judgments in Real and Simulated Environments

The first reason for the differences is the difficulties drivers have judging the perceived distance in real and simulated environments. In a fixed-based driving simulator, such as the one used in this research, a test driver views the two-dimensional image from a fixed point. There are no vestibular cues and the perception of depth, or stereopsis resulting from binocular disparity is not possible. The test driver must rely on monocular cues for depth perception. These cues include atmospheric perspective, relative height, relative size, shadows, texture gradient, occlusion, and motion parallax (*59*) and are provided by how the images are drawn.

Pertinent to this experiment, is a comparative study, which investigated the judgment of the safe distance to a lead vehicle. The distance judgments made in the simulated environment were underestimated compared to those made while driving in the real world (*171*). In several other comparative studies, the tendency to underestimate distances has been shown to be more severe in virtual environments as compared to the real world (*172*, *173*, *174*). If the test drivers in this passing study underestimated the distance to the impeding vehicle, that would account for the large start gap and end gap distances, and consequently the large distances and times in the left lane.

6.13.4 Lateral Position

The second reason for the differences could stem from the lateral position of the test vehicle. In the passing study, five test drivers performed at least one pass, where the test vehicle was partially in the left lane while the test driver waited for an opportunity to pass. Six test drivers performed at least one pass where the test vehicle remained in the left lane at the end of the pass until after the opposing vehicle passed. Although the data for these test drivers was removed from the analysis, they may be indicative of a more generalized problem.

The images in the simulated environment were two-dimensional. To better see around the impeding vehicle required driving the vehicle further to the left and perhaps crossing the centerline. In a real environment, this is a risky behavior but in the simulated environment there is no imminent threat from the opposing vehicles. Because of the lack of consequences, drivers may have been encouraged to accept what would normally be considered risky or inappropriate situations.

6.13.5 Bias in Field Data

The third reason for the differences could be from how the data was collected in the field. Considering the difficulties accurately pinpointing when and where the vehicle first begins to cross the centerline as it moves into the left lane or returns to the right lane, it is possible that the field data reflects a passing maneuver that falls somewhere between the conventional and alternate definitions. This reason is supported by the fact that the mean distance in the left lane for the alternate definition and the field data were the same.

7 PASSING BEHAVIOR

The data collected during the passing study was further examined to illustrate the variability in how the passing maneuver is performed and the variability in the types of passing maneuvers.

7.1 Driver Variability

During the passing study, the sex of the test driver was collected. It was recorded on the simulator sickness questionnaire and used in the naming convention adopted for the data files, as described in Section 6.5. The effect of the sex of the test drivers was examined using the data in Appendix J. The data was grouped by the sex of the test drivers and the differences in the time and distance in the left lane, and the start and end gap distances were evaluated using the Friedman test and the Wilcoxon nonparametric, signed ranks test. Compared to the male test drivers, the time in the left lane (P=0.067), distance in the left lane (P=0.067), start gap distance (P=0.909), and end gap distance (P=0.006) were greater for the female test drivers. The difference in the end gap distance was significant, at a 0.05 level of significance.

7.2 Position of the Passing Vehicle Relative to the Impeding Vehicle

To avoid a collision, the driver maintained some minimum or safe distance away from the impeding vehicle. The variability in the start gap and end gap distances was examined.

7.2.1 Start Gap

The start gap (G_S) was the distance from the front bumper of the passing vehicle to the rear bumper of the impeding vehicle at the moment the passing vehicle began to enter the left lane. It was calculated from the positions of the impeding (x_i) and passing (x_p) vehicles, taking account of the vehicle lengths (L_i and L_p) such that:

$$G_S = \left(x_i - \frac{L_i}{2} \right) - \left(x_p + \frac{L_p}{2} \right) \qquad (7.1)$$

The frequency distribution of the start gap distance is shown in Figure 7.1. Using the Kolmogorov-Smirnov test (Z=1.242), the start gap distance was shown to resemble a normal distribution with a mean of 23.5 m and a standard deviation of 12.19 m.

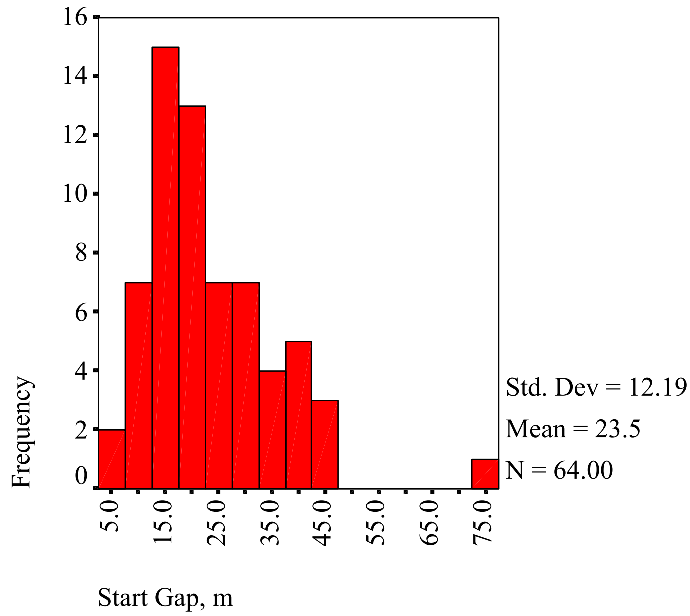

FIGURE 7.1. Frequency distribution of the start gap distances.

7.2.2 End Gap

The end gap (G_E) was the distance from the rear bumper of the passing vehicle to the front bumper of the impeding vehicle at the moment the passing vehicle completely returned to the right lane. It was also calculated from the positions of the impeding (x_i) and passing (x_p) vehicles, taking account of the vehicle lengths (L_i and L_p) such that:

$$G_E = \left(x_p - \frac{L_p}{2} \right) - \left(x_i + \frac{L_i}{2} \right) \tag{7.2}$$

The frequency distribution of the end gap is shown in Figure 7.2. Using the Kolmogorov-Smirnov test (Z=1.099), the end gap distance was shown to resemble a normal distribution with a mean of 47.4 m and a standard deviation of 19.25 m.

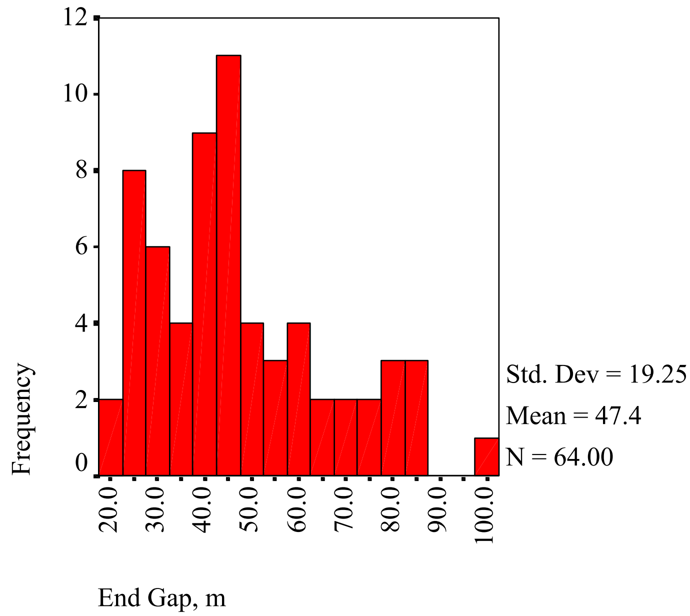

FIGURE 7.2. Frequency distribution of the end gap distances.

7.3 Speed of the Passing Vehicle

The driver controlled the longitudinal position of the vehicle through speed inputs. The speed of the passing vehicle can be described in terms of the absolute speed gain that was attained during the passing maneuver. It can also be described as the maximum speed difference with respect to the impeding vehicle or relative to the speed limit. The variability of the speed of the passing vehicle was examined using each of these descriptions.

7.3.1 Speed Gain

The speed gain of the passing vehicle was calculated by a comparison of its maximum and minimum speeds. The minimum speed occurred when acceleration began (s_p(accel)), and the maximum speed occurred when deceleration began (s_p(decel)). The speed gain (Δs_p) was calculated as:

$$\Delta s_p = s_p(\text{decel}) - s_p(\text{accel}) \tag{7.3}$$

The distribution of the speed gain of the passing vehicle for the 96 passing maneuvers is shown in Figure 7.3. Using the Kolmogorov-Smirnov test (Z=0.853), the speed gain was shown to resemble a normal distribution with a mean of 7.7 m/s and a standard deviation of 2.29 m/s.

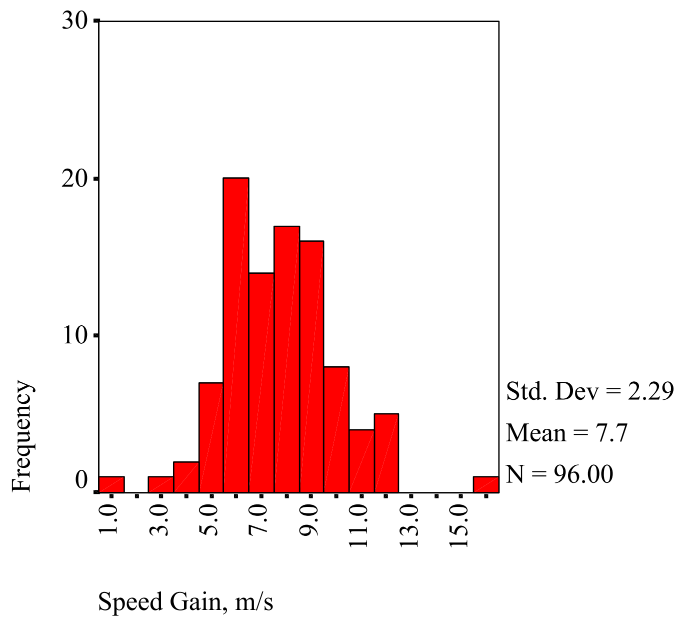

FIGURE 7.3. The frequency distribution of the speed gain of the passing vehicle.

The range in speed gain was quite large, with the speed of the passing vehicle increased as much as 16 m/s (57.6 km/h or 36 mph). The speed of the passing vehicle needed to be compared to the speed of the impeding vehicle to get a better feel for how the passing maneuver was performed.

7.3.2 Maximum Speed Difference

The maximum speed difference was the maximum speed of the passing vehicle relative to the speed of the impeding vehicle. The passing vehicle reached its maximum speed at the moment it began to decelerate. The speed of the passing vehicle (s_p(decel)) and the impeding vehicle (s_i(decel)) at that moment were compared to determine the speed of the passing vehicle relative to the impeding vehicle (S_{pi}(decel)), such that

$$S_{pi}(\text{decel}) = s_p(\text{decel}) - s_i(\text{decel}) \tag{7.4}$$

The distribution of the maximum speed difference is shown in Figure 7.4. Using the Kolmogorov-Smirnov test (Z=0.851), the maximum speed difference was shown to resemble a normal distribution with a mean of 7.8 m/s and a standard deviation of 1.90 m/s.

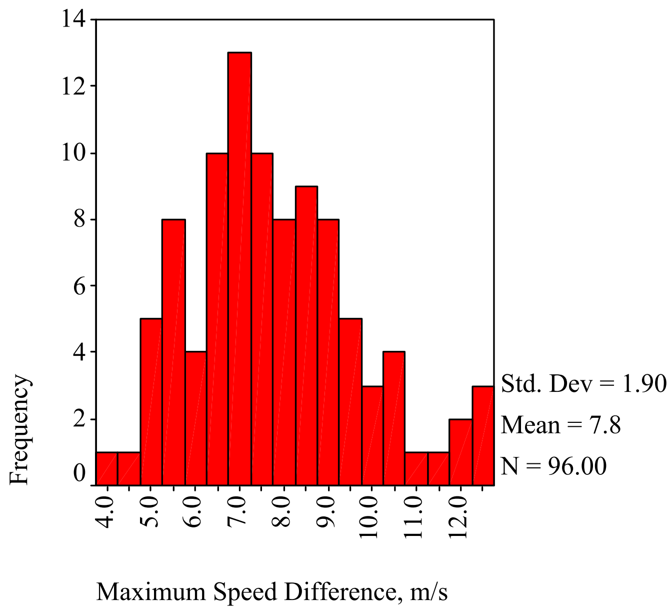

FIGURE 7.4. The frequency distribution of the maximum speed differences.

Considering that the impeding vehicles were traveling between 19 m/s (43 mph) and 22.2 m/s (50 mph), and the speed limit was 24.4 m/s (55 mph), the range in the maximum speed difference was quite large. During some passes, the passing vehicle reached a speed as much as 50% faster than the impeding vehicle. These speed differences suggest that the speed limit was exceeded during many of the passing maneuvers.

7.3.3 Exceeding the Speed Limit

The frequency of the maximum speed (s_p(decel))of the passing vehicle was plotted and is shown in Figure 7.5. In each of the 96 passing maneuvers, the passing vehicle exceeded the 24.4 m/s

(55 mph) speed limit. In 29 passing maneuvers, the speed limit was exceeded by at least 4.4 m/s (10 mph) and in one passing maneuver the speed limit was exceeded by 9.4 m/s (21 mph).

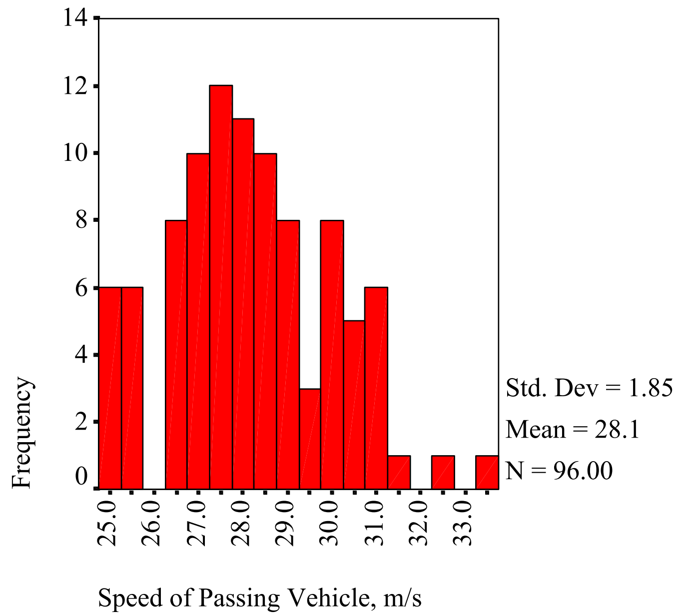

FIGURE 7.5. The frequency distribution of passing vehicle maximum speeds.

The speed of the passing vehicle has been described as the absolute speed gain, the maximum speed difference with respect to the impeding vehicle, and the maximum speed in excess of the speed limit. The speed of the passing vehicle was directly related to the acceleration and deceleration behavior of the driver. As the magnitude and duration of the acceleration increased, the speed increased. To further explore the variation in how the passing maneuver was performed, the acceleration and deceleration behavior was examined.

7.4 Acceleration and Deceleration Behavior.

For each of the 96 passing maneuvers, the data was examined to identify when the passing driver began to accelerate and began to decelerate. Each was identified in relation to the following instances.

1. The passing vehicle began to enter the left lane;
2. The passing vehicle was completely in the left lane;

3. The passing vehicle was abreast of the impeding vehicle;
4. The passing vehicle began to enter the right lane; and
5. The passing vehicle was completely in the right lane.

These instances are illustrated and numbered accordingly in Figure 7.6. The beginning of the acceleration is shown in green and beginning of the deceleration is shown in red.

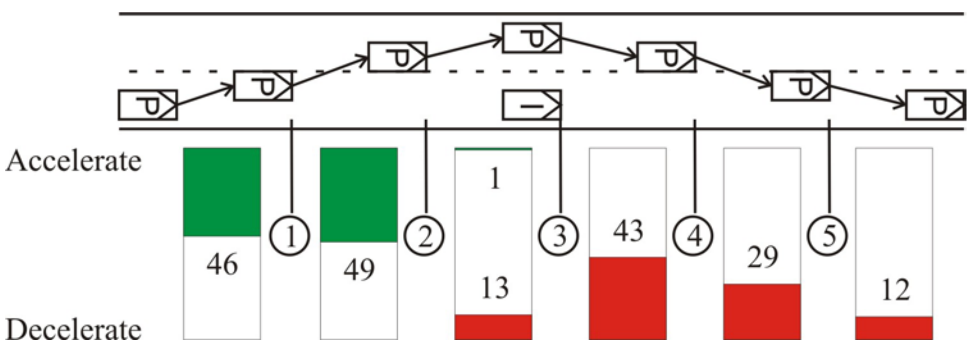

FIGURE 7.6. The order tasks were performed during the passing maneuvers.

In 46 passes the acceleration began prior to the vehicle moving into the left lane (before instance 1) and in 49 passes the acceleration began as the vehicle moved into the left lane (between instances 1 and 2). For one pass, acceleration did not begin until the vehicle was completely in the left lane (between instances 2 and 3).

In 13 passes, deceleration began prior to the vehicle coming abreast with the impeding vehicle (between instances 2 and 3). In 43 passes, deceleration began prior to the vehicle moving back into the right lane (between instances 3 and 4), followed by 29 passes where deceleration began as the vehicle moved back into the right lane (between instances 4 and 5). In 12 passes the drivers began to decelerate only after completely returning to the right lane (after instance 5). To further explore the acceleration behavior of the drivers, the duration and magnitude of the acceleration was examined. The results are presented in the following two sections.

7.4.1 Acceleration Duration

The acceleration duration was calculated as the time between the moment acceleration began (t_p(accel)) and the moment deceleration began (t_p(decel)). The frequency distribution of the acceleration duration is shown in Figure 7.7. Using the Kolmogorov-Smirnov test (Z=0.670), the duration of acceleration was shown to resemble a normal distribution with a mean of 13.3 s and a standard deviation of 4.04 s.

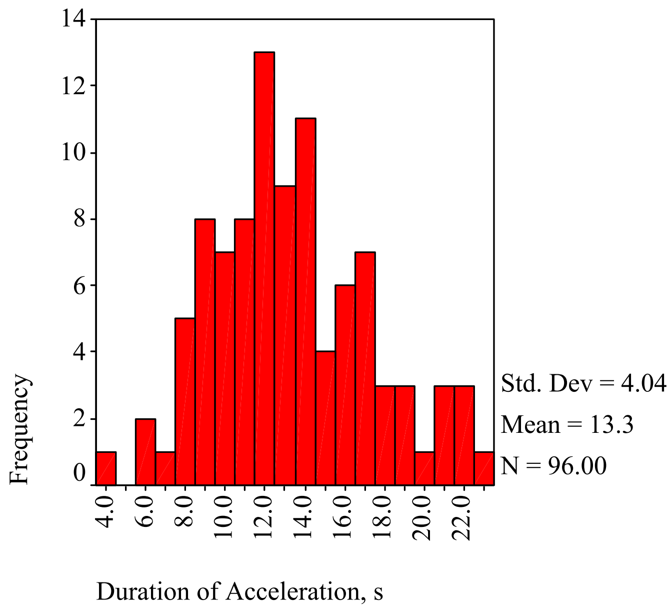

FIGURE 7.7. Frequency distribution of the duration of acceleration.

7.4.2 Acceleration Magnitude

The acceleration magnitude was limited by the performance capabilities of the simulation vehicle. The acceleration performance was shown in Figure 4.8. At the speed limit of 24.4 m/s (55 mph or 88 km/h) the maximum acceleration was approximately 1.5 m/s^2. The acceleration magnitude was represented by the average acceleration of the passing vehicle ($\bar{a}_p$). It was calculated using the speed gain (Δs_p) of the passing vehicle and the acceleration duration such that:

$$\bar{a}_p = \frac{\Delta s_p}{t\ (decel) - t\ (accel)} \tag{7.5}$$

The distribution of average acceleration achieved over the duration of acceleration is shown in Figure 7.8. Using the Kolmogorov-Smirnov test (Z=0.670), the average acceleration was shown to resemble a normal distribution with a mean of 0.60 m/s^2 and a standard deviation of 0.17 m/s^2.

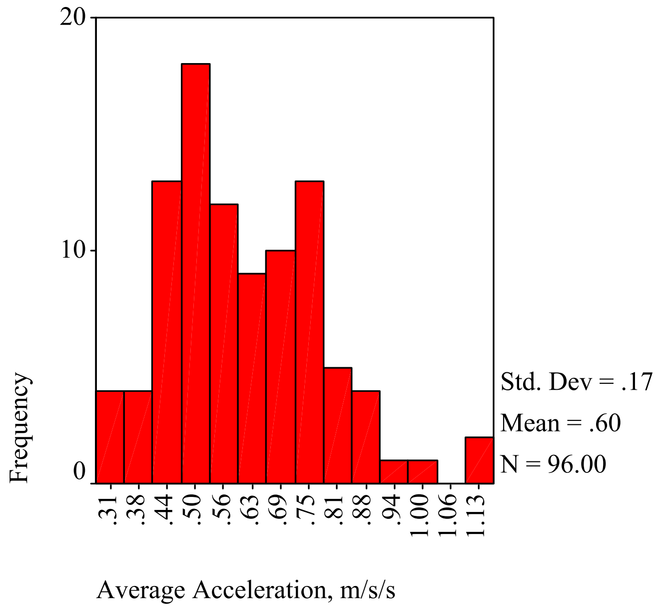

FIGURE 7.8. Frequency distribution of the magnitude of acceleration.

7.4.3 Discussion

The data from 96 passing maneuvers collected during the passing study was explored. In each pass, the driver moved from the right lane to the left lane, overtook the impeding vehicle by traveling at a higher speed, and moved back into the right lane. However, the drivers' control of the vehicle varied, as described by the range in the end gap and start gap distances, speed gain, maximum speed difference, and acceleration duration and magnitude.

A portion of the variation may have been attributable to differences in the passing conditions. Even though each driver was given the same experiment where the vehicle, roadway, traffic, and environment conditions were controlled, the passing conditions that were experienced were the result of the driver's own behavior. For instance, the driver chose what distance to follow the impeding vehicle and what gap to accept in the opposing traffic. Two drivers maintaining different car following distances and choosing different sized gaps would experience different passing conditions. It is for that reason that the driver behavior data was used to examine the variability in the type of passing maneuver.

7.5 Variability in the Types of Passing Maneuver

Historically, passing maneuvers have been classified by the beginning and end of the maneuver whereby the beginning is described as a flying start (*5*) or accelerated start (*5*) and the end is described as a voluntary return (*5*) or forced return (*5*). An accelerated start has also been described as a delayed start (*9*), and a forced return has also referred to as a hurried return (*5*, *9*). Using this classification system, the observer judges which category each passing maneuver belongs. Because the descriptions are, by necessity qualitative, their own passing behavior and their interpretation of the individual passing situations when making these judgments would likely bias their judgments.

By using two categories, for the description of the beginning and end of the maneuver, it is assumed that these categories are distinctly different. In the following sections, the data for 96 passing maneuvers recorded during the passing experiment was explored. By examining the driver behavior at the beginning and end of the maneuver, it was found that the categories are not distinct or easily distinguishable.

7.5.1 Start of the Passing Maneuver

A flying start is when the passing vehicle does not significantly slow down as it approaches and overtakes the impeding vehicle. An accelerated start is when the passing vehicle is traveling at about the same speed as the impeding vehicle and accelerates to overtake the impeding vehicle. The passing vehicle may have traveled behind the impeding vehicle for some time or may have recently approached and slowed to await a passing opportunity.

The difficulty with this classification is determining which definition best describes the start of each passing maneuver. A flying start would have a high relative speed between the passing and impeding vehicles and the amount of speed gained during the pass would be low. Conversely, an accelerated start would have a low relative speed and a high speed gain. To examine the relationship between the relative speed and the speed gain, the data from the passing study was explored.

For each passing maneuver, the moment the passing vehicle began to accelerate was found, and the speeds of the passing (s_p(accel)) and impeding (s_i(accel)) vehicles was used to calculate the speed of the passing vehicle relative to the impeding vehicle (S_{pi}(accel)) as follows:

$$S_{pi}(\text{accel}) = s_p(\text{accel}) - s_i(\text{accel}) \qquad (7.6)$$

The maximum speed of the passing vehicle during the pass, otherwise the speed at the moment when the passing vehicle begins to decelerate (s_p(decel)) after overtaking the impeding vehicle, was found and the speed gain (Δs_p) was calculated as:

$$\Delta s_p = s_p(\text{decel}) - s_p(\text{accel}) \qquad (7.7)$$

A plot of the relative speed versus the speed gain is shown in Figure 7.9.

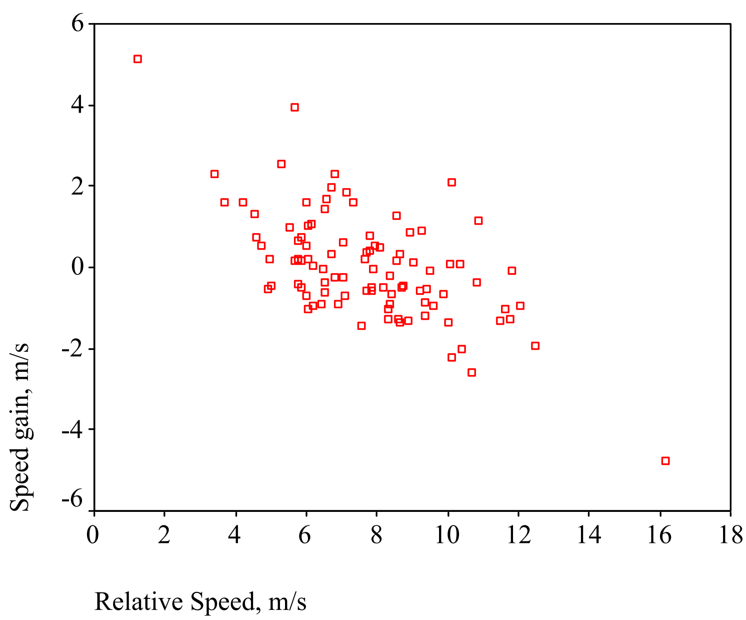

FIGURE 7.9. Relative speed (S_{pi}(accel)) versus speed gain (Δs_p).

Because the passing study was designed to elicit accelerated starts, the majority of the data passing maneuvers began with a low relative speed. However, there appears to have been a relationship between the relative speed and the speed gain. To examine this relationship, a linear regression analysis was performed. The regression line is described by the following equation:

$$\Delta s_p = 7.748 - 1.058\, S_{pi}\,(\text{accel}) \tag{7.8}$$

Using a regression ANOVA, it was found that at a 0.05 level of significance, the relative speed explains a good amount of the variation in the speed gain ($F_{1,94} \approx 3.95$). The results of the regression ANOVA are shown in Table 7.1.

TABLE 7.1. Regression ANOVA Results

Model	Sum of Squares	df	Mean Square	F-statistic
Regression	192.861	1	192.861	59.151
Residual	306.485	94	3.260	
Total	499.347	95		

This relationship does not support the idea that there are two distinctly different categories to describe the beginning of the passing maneuver. Instead, this relationship is evidence that there is a continuum between accelerated and flying starts. To further examine this continuum, additional passing data is needed; including passes that start with large relative speeds. In addition, it is also desirable to confirm these findings with field data. The simulated environment may have influenced the passing behavior during the study and that may have had an impact on the strength of the relationship between the relative speed and the speed gain.

7.5.2 End of the Passing Maneuver

Historically, the presence of an opposing vehicle has been used to determine whether the end of the pass was voluntary or forced. It was assumed that with an opposing vehicle, the passing vehicle was hurried or forced to return to the right lane and without an opposing vehicle, the passing vehicle returned to the right lane voluntarily. A crude interpretation of these definitions, could lead to a voluntary return pass being mistakenly classified as forced return pass when an opposing vehicle is present but does not pose a threat.

To examine the perceived threat of an opposing vehicle on the completion of a passing maneuver, the data from the passing study was explored. It was assumed that the passing vehicle decelerated only when the driver was comfortable with the clearance to the opposing vehicle and confident that the pass would be completed. Therefore, the correlation between the clearance (C(decel)) with the opposing vehicle and the relative position X_{pi}(decel) with the impeding vehicle at the moment of deceleration was investigated.

For each passing maneuver, the moment the passing vehicle began to decelerate after overtaking the impeding vehicle was identified. The head-on clearance (C(decel)) was calculated from the estimated position of the opposing vehicle ($\hat{x}_o$(decel)) (refer to section 6.4.2) and the position of the passing vehicle (x_p(decel)), as:

$$C(\text{decel}) = \hat{x}_o(\text{decel}) - \left[x_p(\text{decel}) - \tfrac{L_p}{2}\right] \tag{7.9}$$

The $\frac{L_p}{2}$ term was the distance from the center to the front bumper of the passing vehicle, and was needed because the position was recorded with reference to the center of the vehicle. The relative position (X_{pi}(decel)) was calculated from the positions of the front bumpers of the impeding (x_i(decel)) and passing (x_p(decel)) vehicles as follows:

$$X_{pi}(\text{decel}) = \left[\left(x_p(\text{decel}) + \tfrac{L_p}{2}\right) - \left(x_i(\text{decel}) + \tfrac{L_i}{2}\right]\right. \tag{7.10}$$

A plot of the clearance with the opposing vehicle versus the relative position with the impeding is shown in Figure 7.10. The data points where the clearance was greater than 500 m, the opposing vehicle was not visible to the test driver, as discussed in section 6.3.2. The passes represented by these data points, were voluntary return passes because there was no threat of an opposing vehicle when the driver began to decelerate. Some drivers began to decelerate before attaining a positive relative position with the impeding vehicle, and completed the maneuver given the available clearance to the opposing vehicle. In these cases, the threat of the opposing vehicle was low and the return to the right lane was voluntary. The remaining passing maneuvers were more difficult to categorize. The correlation between the clearance with the opposing vehicle and the relative position with the impeding vehicle for passes where the impeding vehicle posed some threat is shown in Figure 7.11. The lane that was occupied at the time of deceleration is labeled.

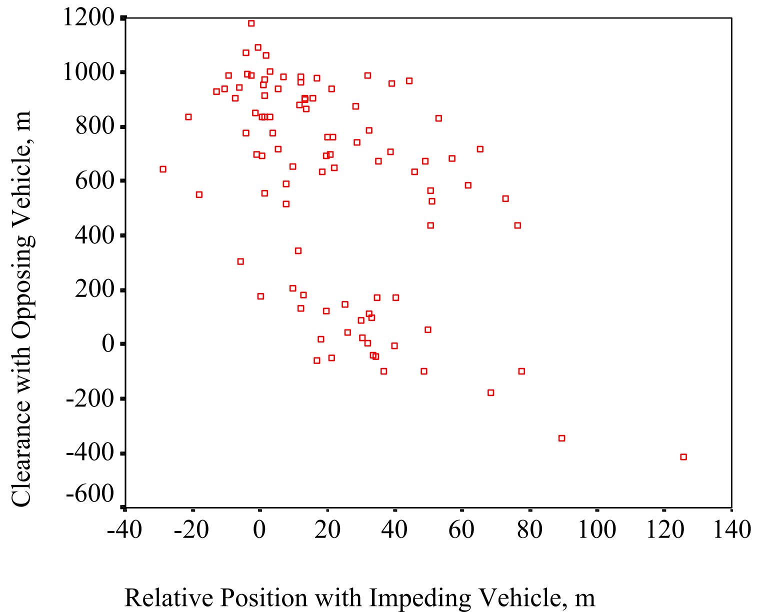

FIGURE 7.10. Clearance versus relative position at the moment of deceleration.

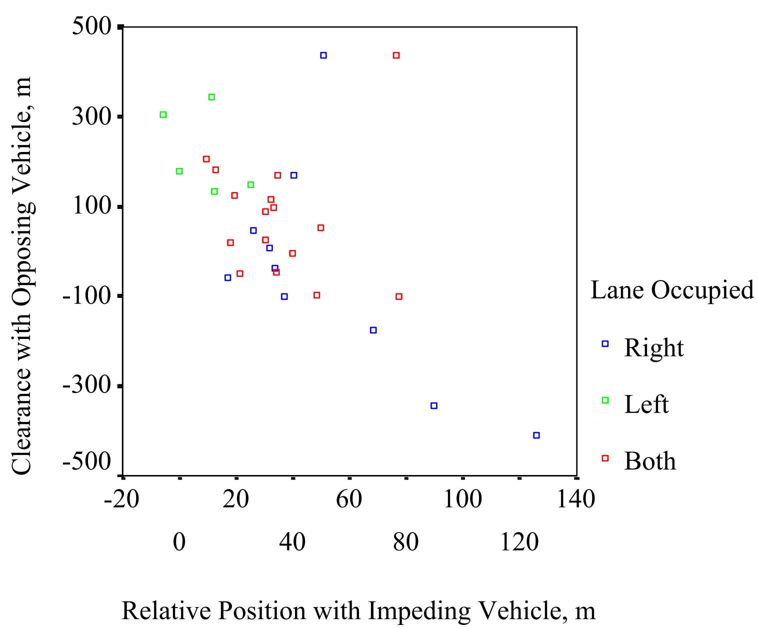

FIGURE 7.11. Lane occupied at the moment of deceleration.

With the assumption that the driver decelerated only when comfortable with the clearance to the opposing vehicle and confident that the pass would be completed, it was expected that every driver would decelerate prior to the opposing vehicle passing by and prior to returning to the right lane. There were a couple unexpected behaviors that occurred that should be pointed out. Some drivers did not decelerate until after the opposing vehicle had passed, as noted by those data points where the clearance is negative. Even though the impeding vehicle had been successfully overtaken and the threat of the opposing vehicle was gone, both of which should have elicited the driver to decelerate, some drivers continued to travel at a high speed. In addition, some drivers had not completely returned to the right lane by the time the opposing vehicle passed by even though they were well ahead of the impeding vehicle. The reasons for these behaviors were not clear. It could have been linked to the difficulties drivers have estimating speed, distance, and lateral position in a simulated environment, the perceived risk, or it could have actually been the habit of these drivers to behave this way.

In Figure 7.11, there appears to have been a correlation between the clearance with the opposing vehicle and the relative position with the impeding vehicle at the time of deceleration. This relationship was explored using Pearson correlation coefficients, which is a measure of the linear association between two variables. Using the Kolmogorov-Smirnov test, the distributions of the clearance with the opposing vehicle values (Z=0.574) and the relative position with the impeding vehicle values (Z=1.040) were tested and found to resemble a normal distribution. The correlation matrix for these two variables is shown in Table 7.2. A value of –0.546, is interpreted as a negative correlation that is mildly strong. It was significant at the 0.001 level of significance.

TABLE 7.2. Pearson Correlation Matrix for Deceleration Behavior.

		Clearance with opposing vehicle	Relative position with impeding vehicle
Clearance with opposing vehicle	Pearson Correlation Sig. (2-tail) N	1 . 31	-0.546 0.001 31
Relative position with impeding vehicle	Pearson Correlation Sig. (2-tail) N	-0.546 0.001 31	1 . 31

It was assumed that driver decelerated when the clearance with the opposing vehicle and the relative position with the impeding vehicle were such that the driver felt the passing maneuver could be completed. Using the data taken at the moment of deceleration, a linear correlation between the clearance with the opposing vehicle and the relative position with the impeding vehicle at the time of deceleration was found. This correlation is evidence of a continuum from the forced to the voluntary types of endings of the passing maneuver. To further examine this correlation and the assumption about the perceived threat of the opposing vehicle, additional data is needed. Considering drivers have greater difficulty making accurate distance and speed judgments in a simulated environment as opposed to a real environment, the additional data needs to be collected in the field in a covert manner.

Another factor that likely played a role in the behavior at the end of a passing maneuver was the presence of a vehicle ahead of the impeding vehicle. Although this vehicle would not have posed a threat to the passing vehicle in the same way that an opposing vehicle does, it did limit the opportunity for the passing vehicle to return to the right lane. Therefore the relationship between the clearance with the opposing vehicle and the relative distance to the impeding vehicle may actually be more complicated and include the size of the gap available ahead of the impeding vehicle. Additional data is needed to examine this relationship.

8 PASSING EQUATION

The original behavior problem that was approached using the methodology was to identify what impact the length of the impeding vehicle has on the passing distance. In this section, an equation for the total passing distance is derived that explicitly includes the length of the vehicles.

8.1 Elements of the Passing Maneuver

The passing maneuver can be broken down into four physical elements, each expressed as a separate distance. These distances are shown in Figure 8.1. The distance d_1 is the distance traveled by the passing vehicle in the right lane as the driver prepares to enter the left lane. This distance is traveled during the time interval t_1. The distance the passing vehicle travels in the left lane is d_2 and occurs during the time interval t_2. The clearance between the passing vehicle and the opposing vehicle when the passing vehicle returns to the right lane is d_3. The distance traveled by the opposing vehicle during the time intervals t_1 and t_2 is d_4. The total passing distance is the sum of the four elements, $d_1+d_2+d_3+d_4$. This definition of the passing maneuver elements differs slightly from the AASHTO definition (*10*), which describes d_4 as $2/3d_2$.

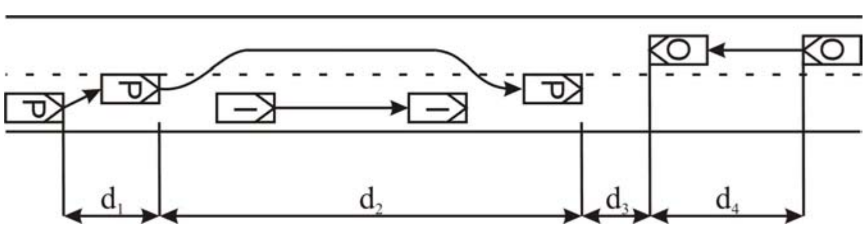

FIGURE 8.1. Elements of the passing maneuver.

8.1.1 Assumptions

In developing a mathematical equation for the total passing distance, the following three assumptions were made.

1. The impeding and opposing vehicles maintain constant speeds during t_1 and t_2;

2. The passing vehicle maintains a constant speed over t_1; and
3. The passing vehicle increases speed linearly over t_2.

These assumptions reflect the behavior of an accelerated start and forced return passing maneuver that was observed during the passing behavior study. These assumptions are far less restrictive than the assumptions used in previous models. For instance, the speed of the impeding vehicle was often assumed to be traveling less than the speed limit, and the passing vehicle travels approximately at the same speed and during t_1 accelerates to the speed limit. The opposing vehicle was assumed to be traveling at the same speed as the impeding vehicle or at the speed limit.

In previous models, the passing maneuver has been described by the acceleration of the passing vehicle. This passing equation was developed using the speed of the vehicles. Of course, the acceleration of the passing vehicle should be checked for reasonableness to ensure that the performance of the passing vehicle was not exceeded given the environment.

8.1.2 Passing Maneuver Variables

The following variables were used to develop the equations that describe the elements of the passing maneuver and the total passing distance (D).

- t_1 = time taken for the passing driver to decide to pass and move the vehicle towards the left lane, s
- t_2 = time the passing vehicle occupies the left lane, s
- L_v = length of vehicle v, m
- s_v = speed of vehicle v, m/s
- $\bar{s}_v$ = average speed of vehicle v, m/s
- $\bar{a}_v$ = average acceleration rate of vehicle v, m/s^2.
- G_s = gap between the passing and impeding vehicles at the start of t_2, m
- G_e = gap between the passing and impeding vehicles at the end of t_2, m
- C = clearance between the passing and oncoming vehicles at the end of t_2, m
- $G_S+L_i+L_p+G_E$ = space interchange needed to be gained by the passing vehicle, m

8.1.3 Element d_1

In an accelerated pass, the passing driver uses the time interval t_1, to perceive the opportunity to pass, decide the course of action, and begin to execute the pass by steering the vehicle to the left edge of the lane. Alternately, the driver may first move over to the left edge of the lane in preparation for making a pass, and upon perceiving an opportunity and deciding to accept the gap in the opposing traffic, begin to move into the left lane. The passing vehicle travels at an average speed ($\bar{s}_p$) during t_1, and travels a distance

$$d_1 = \bar{s}_p t_1 \quad (8.1)$$

During t_1, the oncoming vehicle travels at an average speed of $\bar{s}_o$ and a distance of $\bar{s}_o t_1$. These distances are shown on Figure 8.2.

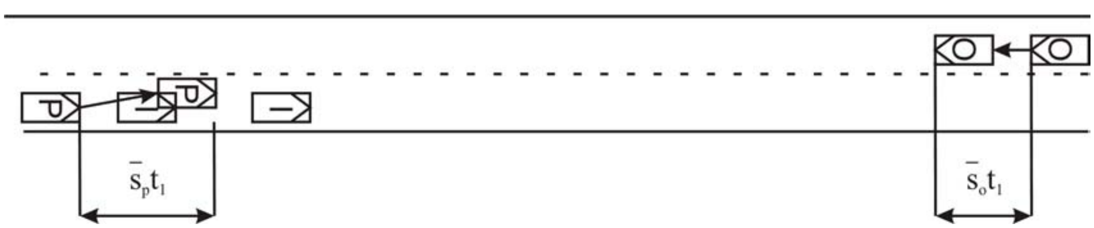

FIGURE 8.2. Distances traveled during t_1.

The time interval t_1 has been referred to as the perception and reaction time and the time for initial acceleration. This time is not calculated; rather it is observed in the field or measured during controlled experiments.

8.1.4 Element d_2

During the time interval t_2, the passing vehicle travels a distance of d_2 in the left lane. If the average speed of the passing vehicle is known then d_2 can be calculated as

$$d_2 = \bar{s}_p t_2 \quad (8.2)$$

It is more likely that d_2 and t_2 were measured and $\bar{s}_p$ can be calculated from the same relationship. To understand how the passing conditions impact d_2 and t_2, each needed to be written in terms of how the passing vehicle overtakes the impeding vehicle. To overtake the impeding vehicle, the passing vehicle must travel the distance traveled by the impeding vehicle ($\bar{s}_i t_2$) plus a distance equal to the sum of the lengths of the vehicles and the gap distances left between vehicles at the start and end of t_2. Therefore, the distance traveled by the passing vehicle is

$$d_2 = G_S + L_i + \bar{s}_i t_2 + L_p + G_E \tag{8.3}$$

During t_2, the distance traveled by the opposing vehicle is $\bar{s}_o t_2$. These distances are shown on Figure 8.3.

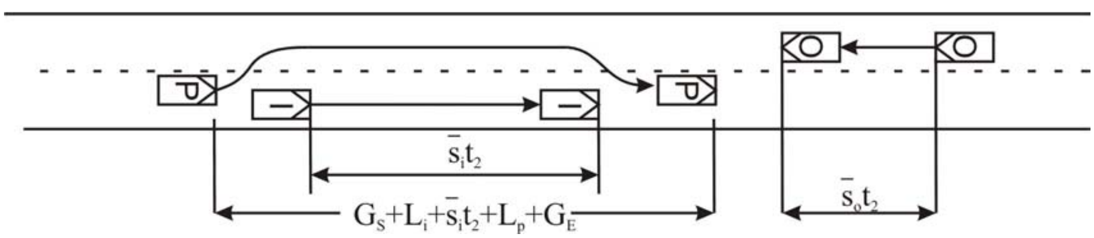

FIGURE 8.3. Distances traveled during t_2.

In a forced return pass, it was assumed that the passing vehicle continually increases speed from s_p to $s_p+\Delta s_p$ while in the left lane and does not begin to decelerate until after t_2. If the average speed over t_2 is known for both the passing and impeding vehicles, then

$$t_2 = \frac{G_S + L_i + L_p + G_E}{\bar{s}_p - \bar{s}_i} \tag{8.4}$$

This equation is the ratio of the distance to be gained by passing vehicle with respect to the impeding vehicle and the rate at which the passing vehicle gains distance. If the average speed of the passing vehicle is not known, it can be approximated by

$$\bar{s}_p = s_p + \frac{\Delta s_p}{2} \tag{8.5}$$

If the passing vehicle is traveling at the same speed as the impeding at the beginning of t_2, then equation 7.4 reduces to

$$t_2 = \frac{G_S + L_i + L_p + G_E}{\frac{\Delta s_p}{2}} \tag{8.6}$$

In this situation, the speed gain (Δs_p) is comparable to the speed difference (m) used in previous models.

When t_2 is calculated using equation 8.4 or 8.6, it can then be used in equation 8.3 to calculate d_2. Alternatively, equations 8.2 and 8.5 can be combined so that d_2 can be calculated as:

$$d_2 = \left(s_p + \frac{\Delta s_p}{2} \right) t_2 \tag{8.7}$$

A check on the average acceleration of the passing vehicle ($\bar{a}_p$) is needed to ensure that the performance capabilities of the vehicle are not exceeded under the given conditions. The average acceleration is calculated as

$$\bar{a}_p = \Delta s_p / t_2 \tag{8.8}$$

If $\bar{a}_p$ is found to be too large, then the speed gain is too large or the time interval is too small. Decreasing the speed gain or increasing the time interval can reduce the average acceleration.

8.1.5 Element d_3

The distance d_3 is the clearance (C) between the passing and opposing vehicles at the end of time interval t_2.

$$d_3 = C \tag{8.9}$$

The clearance distance is shown in Figure 8.4.

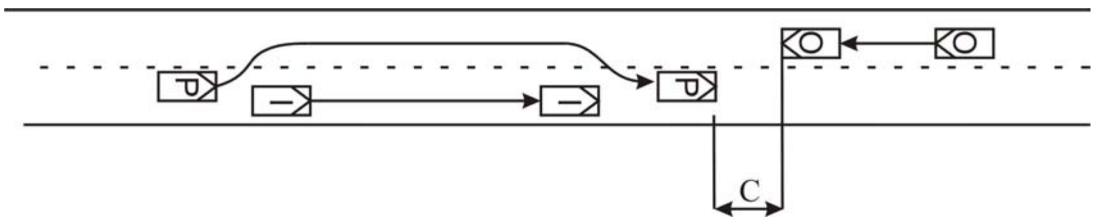

FIGURE 8.4. The clearance distance.

The clearance is observed in the field or recorded in a controlled experiment. To ensure that the passing vehicle maintains a safe distance from the opposing vehicle, a minimum clearance distance, equal to a time separation of one second has been previously suggested (*5*, *6*). The clearance values in the AASHTO design values range from 30 to 90 meters for a speed range of 50-110 km/h.

8.1.6 Element d_4

The distance d_4 is the sum of the distances traveled by the opposing vehicle during time intervals t_1 and t_2. Traveling at an average speed $\bar{s}_o$, the distance traveled is

$$d_4 = \bar{s}_o(t_1 + t_2) \tag{8.10}$$

This distance is the sum of the two elements shown in Figure 8.5.

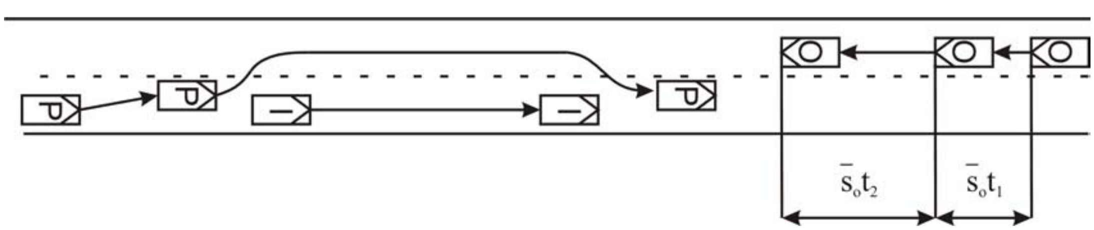

FIGURE 8.5. Distance traveled by opposing vehicle.

For the AASHTO design values, d_4 is calculated as $2/3d_2$, and the rationalization for not using the total distance traveled by the opposing vehicle is that during t_1 and the first 1/3 of t_2, the passing vehicle can abort the maneuver. It is also assumed that the opposing vehicle travels at the passing speed of the passing vehicle.

8.1.7 Total Passing Distance

The passing distance (D) is the sum of the elements d_1 through d_4. By combining equations 8.1, 8.3, 8.9, and 8.10, the passing distance is calculated as

$$D = \bar{s}_p t_1 + G_S + L_i + \bar{s}_i t_2 + L_p + G_E + C + \bar{s}_o (t_1 + t_2) \qquad (8.11)$$

If the time interval t_2 is not known, it is calculated from the speed of the passing vehicle using equations 8.4 or 8.6 and the average acceleration of the passing vehicle is checked using equation 8.8.

8.2 Factors Impacting the Passing Maneuver

The passing study was a controlled experiment where the length and speed of the impeding vehicle was varied. The drivers were somewhat controlled since participation in the study was limited to drivers with at least five years driving experience. Therefore, the observed variation in how the passing maneuver was performed and what type of passing maneuver was completed was the result of differences in driver behavior and testing conditions. In the real world, there is limited control of the passing conditions and the test drivers.

The equation presented in Section 8.1.7 includes variables for the length and speed of the vehicles and the spacing between vehicles that can be changed to reflect a variety of passing conditions. Because variables are not included for every conceivable change in the passing conditions, the traditional method for classifying factors by their source is not appropriate. This method was outlined in section 3.2.2. An alternate method for classifying the factors was needed, where the factors are classified by their potential to impact the passing maneuver. In the following sections, an alternative classification system is presented.

8.2.1 Classification by Impact

In the case of the passing maneuver, there are two expected types of impacts that a factor can have; a factor may impact the mechanics of the maneuver or impact the behavior of the driver performing the passing maneuver. These groups are not mutually exclusive. A factor may impact both the passing mechanics and passing behavior as outlined in Figure 8.6.

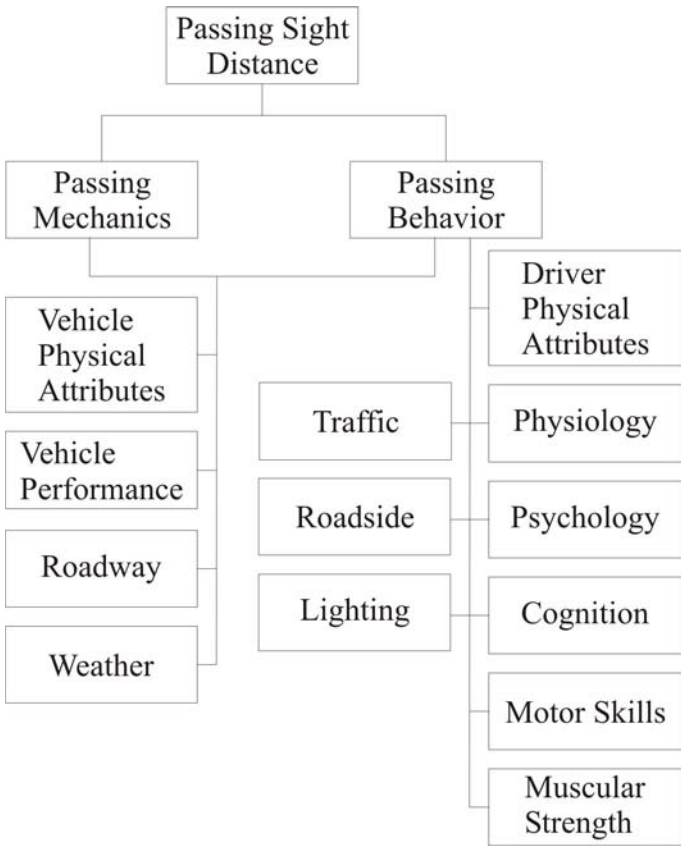

FIGURE 8.6. Classifying passing condition factors by the type of impact.

Unlike the system where the factors are easily classified by their source, classification by impact requires some insight into the potential impact of the factors and where insight is not possible perhaps some rationalization of what type of impact is reasonable. For this reason, this classification system is best illustrated by discussing how some of the factors could impact the passing mechanics and/or the passing behavior. Three examples will be discussed.

8.2.1.1 Physical attributes of the vehicles. The first example is drawn from the physical attributes of the vehicles involved in the passing maneuver, specifically the lengths of the vehicles. If the opposing vehicle is a long truck, there is no impact on the mechanics of the passing maneuver. The passing vehicle has the same distance to gain on the impeding vehicle and has the same acceleration performance available to complete the pass. However, the behavior of the driver may change in light of the large opposing vehicle. The driver may choose a different size gap in the opposing traffic or may change how the available acceleration performance is utilized.

If the impeding vehicle or the passing vehicle is a long truck, the mechanics of the passing maneuver is changed. The passing vehicle has a greater distance to gain on the impeding vehicle. Additionally, the behavior of the driver may change. In the case where the impeding vehicle is a long truck, the passing driver may leave more space around the large vehicle or compensate for the addition distance to be gained by utilizing more of the available acceleration performance. In the case where the passing vehicle is a long truck, the passing driver will hopefully choose a larger gap in the opposing traffic to compensate for the additional time that will be spent in the left lane.

8.2.1.2 Roadway Characteristics. The second example is drawn from the characteristics of the roadway, specifically the design of a vertical curve. Assuming that there is adequate passing sight distance to perform a pass on an incline, the incline itself can impact the mechanics of the passing maneuver and the perhaps the behavior of the passing driver. The impact to the passing mechanics could be observed as an increase in the time spent in the left lane, as the result of a reduction in the available acceleration performance of the passing vehicle given such an incline. The change in the passing behavior could be a decrease in the space left between vehicles. The driver may choose to accept a greater gap in the opposing traffic or allow a smaller clearance to the opposing vehicle to compensate for the additional time in the left lane.

8.2.1.3 Driver Psychology. The third example deals with the risk taking nature of drivers. The risk the driver is willing to accept does not impact the mechanics of the passing maneuver but most certainly does impact the passing behavior. Drivers who are thrill seekers are more likely to accept smaller gaps in the opposing traffic and leave less space between vehicles than those drivers who are not willing to take high risks. Although the risk taking nature of the driver may be influenced by the performance of the vehicle being driven, the reverse is not true. The nature of the driver does not change the available performance of the vehicle.

8.2.2 Incorporating the Factors that Potentially Impact the Passing Maneuver

There are many driver, vehicle, and environment factors that impact the passing distance. Since it is not reasonable to include each factor as a separate variable in the passing equation, they were grouped according to their potential impact on the passing distance. The different variables included in the passing equation are discussed in the following two sections.

8.2.2.1 Passing mechanics variables. The variables in the passing equation that describe the mechanics of the passing maneuver relate to the distance to be gained by the passing vehicle and the rate at which that distance can be gained. These are the lengths of the impeding and passing vehicles, the speeds of all of the vehicles, and the available acceleration of the passing vehicle, which limits the possible speed gain during the pass. An impact to the mechanics of the passing maneuver may by some degree be compensated for by a change in passing behavior.

8.2.2.2 Passing behavior variables. All of the variables in the passing equation with the exception of the speeds of the impeding and opposing vehicles, the acceleration performance of the passing vehicle, and the lengths of the passing and impeding vehicles change depending on how the driver chooses to perform the passing maneuver. The driver chooses what gap to accept in the opposing traffic, the spacing to leave between the passing and impeding vehicles, and the speed, which together determines the clearance at the end of time interval t_2.

8.3 Validation

The purpose of validating the passing equation was to ensure that it adequately describes the observed passing behavior. The data from the passing study was compared to the results using the passing equation.

For the 64 passing maneuvers, summarized using the conventional definition, the time in the left lane t_2, and distance in the left lane d_2 are listed in Appendix J. The observed times and distances were compared to those estimated using the following passing equations for t_2 and d_2 respectively.

$$t_2 = \frac{G_S + L_i + L_p + G_E}{\bar{s}_p - \bar{s}_i} \qquad (8.12)$$

$$d_2 = G_S + L_i + \bar{s}_i t_2 + L_p + G_E \quad (8.13)$$

The vehicle lengths L_i and L_p, start gap distances G_S, end gap distances G_E, average speed of the passing vehicle $\bar{s}_p$, and average speed of the impeding vehicle $\bar{s}_i$, needed to calculate t_2 and d_2 are also listed in Appendix L.

The estimation error is a measure of how well the passing equation can be used to estimate the observed distance and time in the left lane. The error was calculated as

$$E = \frac{Estimated - Observed}{Observed} \times 100 \quad (8.14)$$

The results are tabled in Appendix M and plotted in Figures 8.7 and 8.8. The estimation errors for both t_2 and d_2 are less than 1% suggesting that the passing equation adequately describes the observed passing behavior.

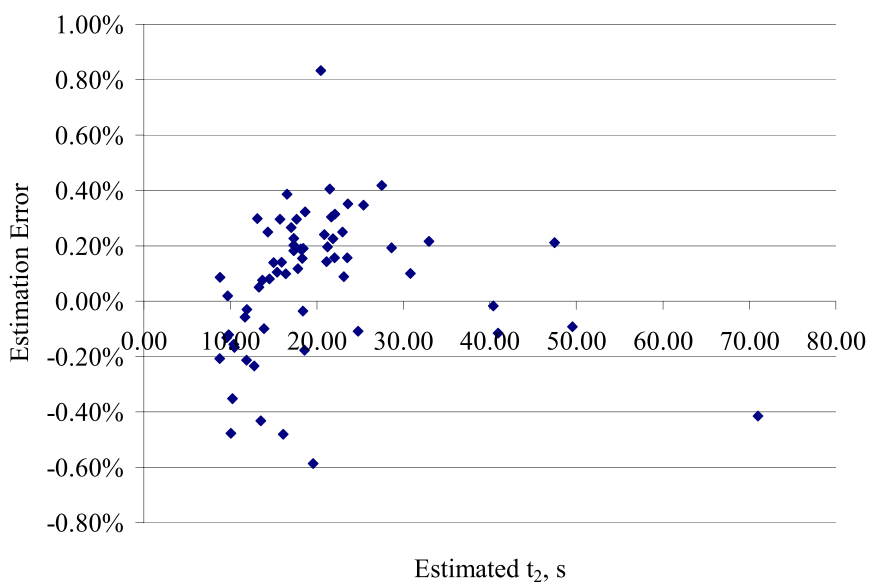

FIGURE 8.7. Estimation error for t_2.

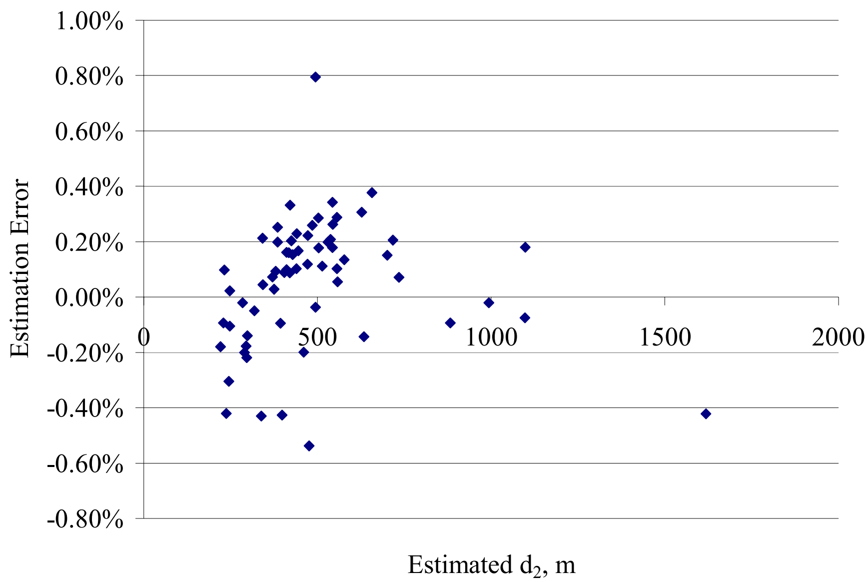

FIGURE 8.8. Estimation error for d_2.

8.4 Calibration

The passing equation was developed using data from the passing behavior study. To calibrate the passing equations for the time and distance in the left lane, the AASHTO design values were used.

8.4.1 AASHTO Data

The AASHTO design values (*10*) are based on Prisk's evaluation of 2,417 observed passes collected during the late 1930's and early 1940's (*9*) using the Holmes' method (*8*). Prisk identified 676 of those passes as delayed start and hurried return to arrive at distances in the left lane, reflecting the 80th percentile of the observed distances. The distances are grouped into 10 mph speed ranges and the passing vehicle is assumed to slow to within approximately 5 mph of the impeding vehicle and accelerate by 10 mph before entering the left lane. The passing vehicle is assumed to travel at a constant speed to overtake the impeding vehicle. This interpretation of the passing behavior differs from what was observed during the passing behavior study and subsequently used to develop the passing model. Prisk did not provide details about the lengths of the vehicle directly but were supposedly incorporated in to the space interchange distances along with the gap distances.

For the accelerated start and hurried return passes, the time in the left lane ranged from 9.3 to 10.4 seconds. Using the average speed of the passing vehicle, the distance in the left lane is calculated using equation 8.2. The values of t_2 and d_2 for four speed ranges are shown in Table 8.1. The speed of the passing vehicle is assumed to be 15 km/h greater than the impeding vehicle.

TABLE 8.1. AASHTO Design Values for t_2 and d_2.

Speed range (km/h)	50-65	66-80	81-95	96-110
$\bar{s}_p$ (km/h)	56.2	70.0	84.5	99.8
t_2 (s)	9.3	10.0	10.7	11.3
d_2 (m)	145	195	251	314

8.4.2 Results

To calibrate the equations, the space interchange, calculated as the sum of the lengths of the passing and impeding vehicles and the gap distances, was adjusted in Equation 8.3 to obtain a 15 km/h speed difference between the passing and impeding vehicles given the values of t_2 and d_2 presented in Table 8.1. The results are shown in Table 8.2

TABLE 8.2. Model Calibration Results

Speed range (km/h)	50-65	66-80	81-95	96-110
$\bar{s}_p$ (km/h)	56.2	70.0	84.5	99.8
$\bar{s}_p$ (m/s)	15.61	19.44	23.47	27.72
t_2 (s)	9.3	10.0	10.7	11.3
d_2 (m)	145	195	251	314
$\bar{s}_i$ (m/s)	11.44	15.28	19.31	23.56
$\bar{s}_i$ (km/h)	41.2	55.0	69.5	84.8
$G_S+L_i+L_p+G_E$ (m)	38.6	42.2	44.4	47.8
$\bar{s}_p - \bar{s}_i$ (km/h)	15	15	15	15

The equations were successfully calibrated to the AASHTO design values for t_2 and d_2. As expected, the speed of the impeding vehicle ($\bar{s}_i$) and the size of the space interchange ($G_S+L_i+L_p+G_E$) increased with greater passing vehicle speeds. This relationship and others were explored through a sensitivity analysis.

8.5 Sensitivity Analysis

The purpose of the sensitivity analysis was to examine the relationship between individual variables in the passing equation and the calculated t_2 and d_2 values. The sensitivity of t_2 and d_2 to the variables that reflect the mechanics of the passing maneuver, such as the speeds and lengths of the impeding and passing vehicles were explored first. This was followed by an examination of the sensitivity of t_2 and d_2 to the variables that reflect passing behavior, such as the gap distances and speed gain of the passing vehicle.

The base condition used for the sensitivity analysis is described by the following variable values; vehicle speeds (20 m/s), speed gain of passing vehicle (4.17 m/s), speed difference between the passing and impeding vehicles (0 m/s), total vehicle length (9.44 m), and total gap distance (20 m).

8.5.1 Impeding and Passing Vehicle Speeds

The impeding and passing vehicle speeds were the speeds of the individual vehicles at the beginning of t_2. The speed gain (4.17 m/s), speed difference (0 m/s), total vehicle length (9.44 m), and total gap distance (20 m) were held constant. An equal increase in the speeds of the impeding and passing vehicles increased the distances in the left lane but the time in the left lane remained unchanged. These relationships are illustrated in Figure 8.9.

The relationship between the value of t_2 and the vehicle speeds was expected. When the space interchange is constant, the passing vehicle has the same amount of distance to gain. If that distance is gained at the same rate, equal to the difference between the average speeds of the passing and impeding vehicles, then it takes the same time to make up the space interchange.

The relationship between the vehicle speed and d_2 was also expected. Given the same space interchange, and therefore the same t_2, the impeding and passing vehicles travel further at higher speeds. For every unit increase in speed, the change in d_2 is equal to the magnitude of t_2 since d_2 is proportional to $s_i t_2$. A change in vehicle speeds also impacts d_1 and d_4. The response in d_1 is proportional to the change in speed of the passing vehicle, while the response in d_4 is proportional to the change in the opposing vehicle speed.

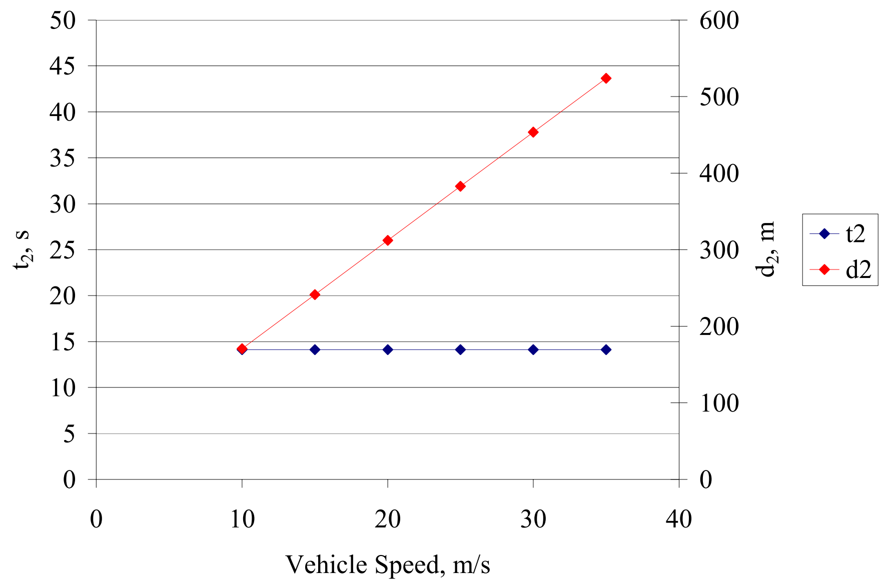

FIGURE 8.9. Sensitivity to the impeding and passing vehicle speeds.

8.5.2 Impeding and Passing Vehicle Lengths

The total vehicle length is the sum of the length of the passing vehicle and the length of the impeding vehicle ($L_i + L_p$). To examine the sensitivity to the total vehicle length, the lengths of the vehicles were varied, while the vehicle speeds (20 m/s), speed gain (4.17 m/s), speed difference (0 m/s), and total gap distance (20 m) were held constant. The results are shown in Figure 8.10.

The sensitivity of t_2 and d_2 were also examined where the speed of the impeding vehicle varied from 10 to 30 m/s, and the speed gain (4.17 m/s), speed difference (0 m/s), and total gap distance (20 m) were held constant. The total vehicle length was varied from 9.44 to 29.2 m. These lengths reflect passing conditions, where there are two passenger cars, a passenger car and a semi tractor-trailer, and two semi tractor-trailers. The results are shown in Figure 8.11. The increase in t_2 resulting from an increase in the total vehicle length is the same across the vehicle speeds. However, as the speed of the passing vehicle increases the distance in the left lane increases.

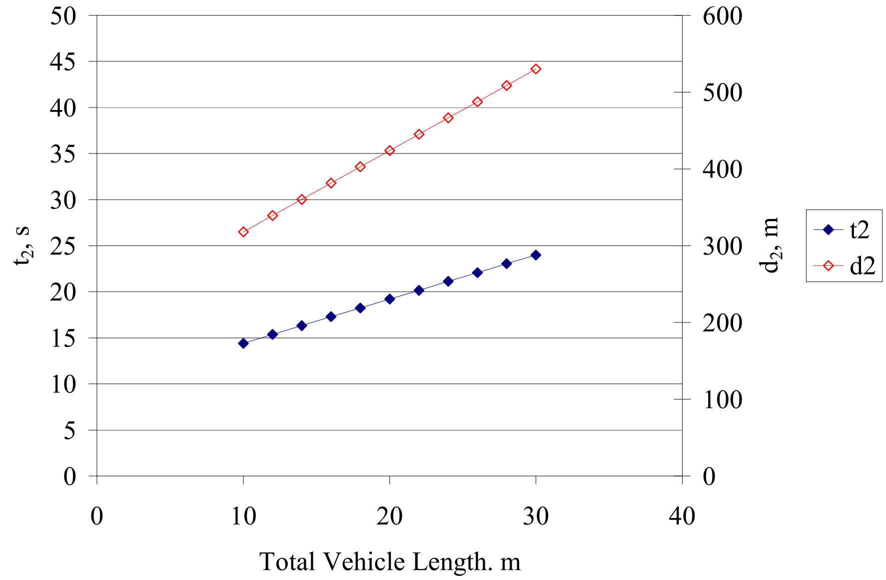

FIGURE 8.10. Sensitivity to the total vehicle length.

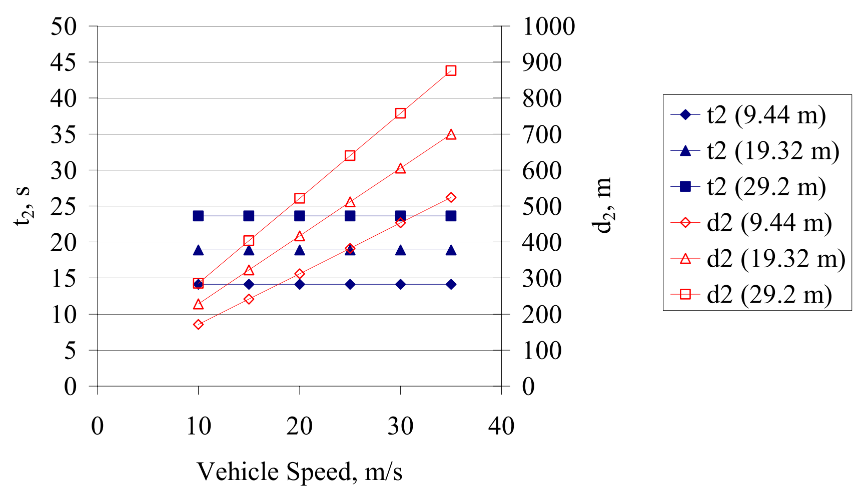

FIGURE 8.11. Sensitivity to the impeding and passing vehicle lengths and speeds.

8.5.3 Gap Distances

The total gap distance is the sum of the start gap and end gap distances (G_S+G_E) that the passing driver chooses to leave between the passing vehicle and the impeding vehicle. To examine the sensitivity of t_2 and d_2, the total gap distances were varied, while the vehicle speeds (20 m/s), speed gain (4.17 m/s), speed difference (0 m/s), and total vehicle length (9.44 m) were held constant. The total gap distance was varied from 20 to 40 m. The results are shown in Figure 8.12.

The differences in t_2 and d_2 in response to changes the total gap distance are identical to the differences in response to changes in the total vehicle length. This is because whether the total vehicle length or the total gap distance increases, the result is an increase to the space interchange and therefore an increase in t_2 and d_2. For a unit increase in the total gap distance, t_2 increases by the reciprocal of the difference in the average speeds of the impeding and passing vehicles ($\left(\bar{s}_p - \bar{s}_i\right)^{-1}$), and d_2 increases by the change in the total gap distance plus the product of the impeding vehicle speed and the time in the left lane ($\left(\Delta\sum G\right) + \bar{s}_i t_2$).

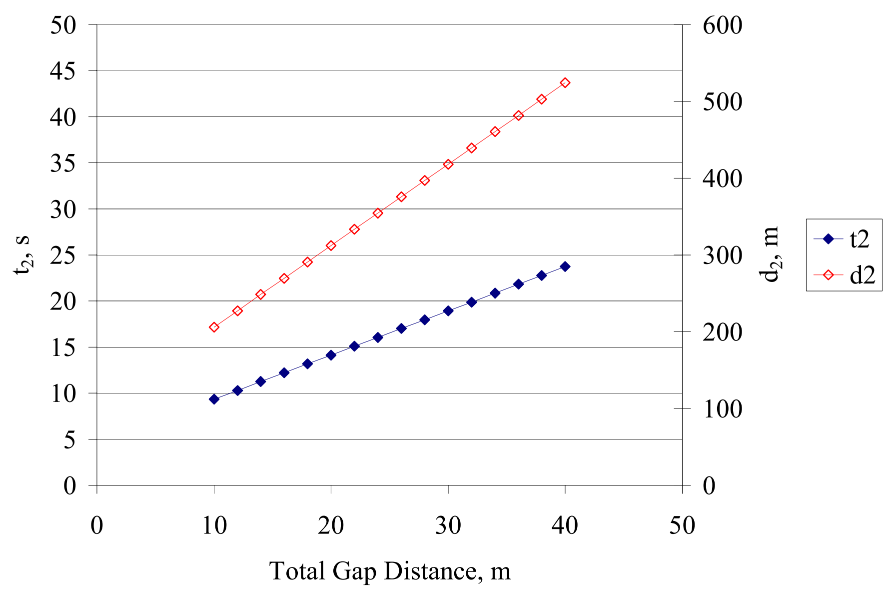

FIGURE 8.12. Sensitivity to the total gap distance.

The sensitivity of t_2 and d_2 were also examined where the speed of the impeding vehicle varied from 10 to 30 m/s, and the speed gain (4.17 m/s), speed difference (0 m/s), and total vehicle length (9.44 m) were held constant. The results are shown in Figure 8.13.

The increase in t_2 resulting from an increase in the total gap distance is the same across the vehicle speeds. However, as the speed of the passing vehicle increases the distance in the left lane increases. These results are the same as those for an increase in total vehicle length.

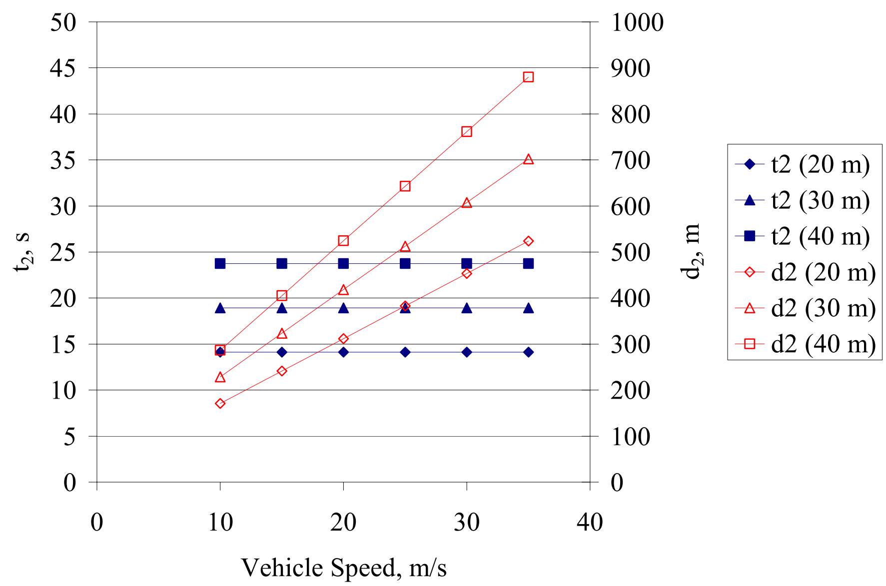

FIGURE 8.13. Sensitivity to the total gap distance and vehicle speeds.

8.5.4 Speed Difference

The speed difference is the difference in the speeds of the passing and impeding vehicles at the beginning of t_2. The driver controls the amount of speed difference by choosing whether to accelerate prior to entering the left lane. The sensitivity of t_2 and d_2 were first examined where the speed of the impeding vehicle is 20 m/s, and the speed gain (4.17 m/s), total vehicle length (9.44 m), and total gap distance (20 m) were held constant. The speed difference is varied from 0 to 15 m/s. As the speed difference increases, both t_2 and d_2 decrease but at a decreasing rate. The results are shown in Figure 8.14.

As the speed difference increases, the rate at which the passing vehicle makes up the needed distance also increases. Because t_2 is inversely proportional to the rate the needed distance is gained, t_2 decreases at a decreasing rate. Thus, the passing vehicle spends less time and therefore travels less distance in the left lane.

The sensitivity of t_2 and d_2 were also examined where the speed of the impeding vehicle varied from 10 to 30 m/s, and the speed gain (4.17 m/s), total vehicle length (9.44 m), and total gap distance (20 m) were held constant. The speed difference was varied from 0 to 10 m/s. The sensitivity of t_2 is the same across vehicle speeds but the sensitivity of d_2 increases with higher vehicle speeds. The results are shown in Figure 8.15.

The change in t_2 for all impeding vehicle speeds is the result of the change in the rate that the distance needed is gained. This relationship was illustrated in Figure 8.14 and occurs for all impeding vehicle speeds in Figure 8.15. The decrease in d_2 is larger for higher impeding vehicle speeds because d_2 is proportional to the product of the impeding vehicle speed and t_2.

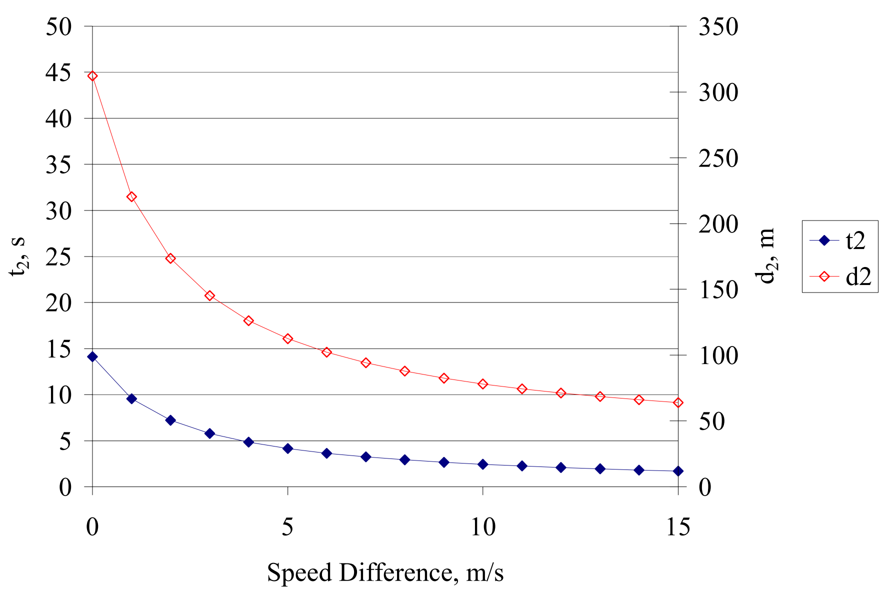

FIGURE 8.14. Sensitivity to the speed difference.

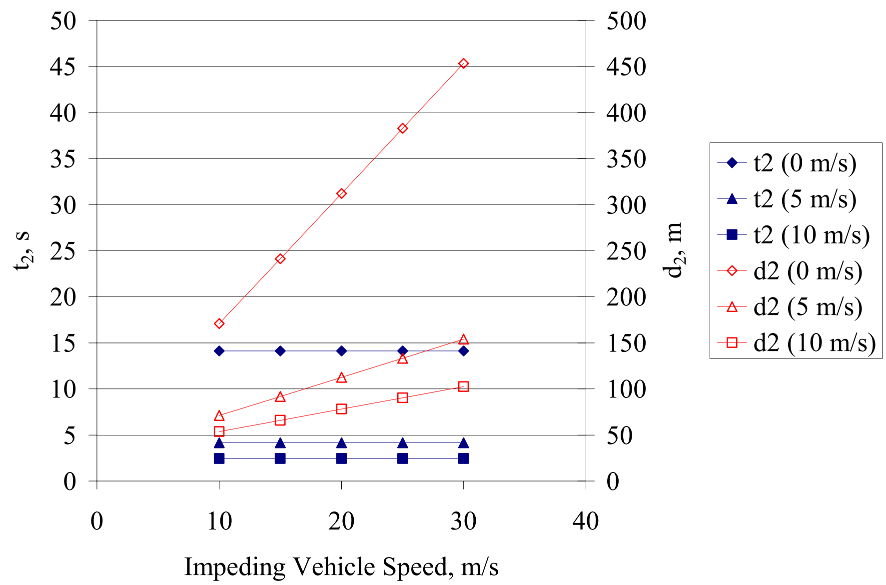

FIGURE 8.15. Sensitivity to the speed difference and impeding vehicle speed.

8.5.5 Speed Gain

The speed gain, which is controlled by the passing driver, is the difference in the speed of the passing vehicle during the time interval t_2. To examine the sensitivity of t_2 and d_2, the speed gain was varied, while the vehicle speeds (20 m/s), speed difference (0 m/s), total vehicle length (9.44 m), and total gap distance (20 m) were held constant. The speed gain was varied from 2 to10 m/s. The results are shown in Figure 8.16.

As the speed gain increases, the rate at which the passing vehicle makes up the needed distance also increases. Thus, the passing vehicle spends less time and therefore travels less distance in the left lane. Because t_2 is inversely proportional to the rate the needed distance is gained, t_2 decreases at a decreasing rate.

The sensitivity of t_2 and d_2 was also examined where the speed of the impeding vehicle varied from 10 to 30 m/s, and the speed difference (0 m/s), total vehicle length (9.44 m), and total gap distance (20 m) were held constant. The speed gain was varied from 2 to 10 m/s. The results are shown in Figure 8.17.

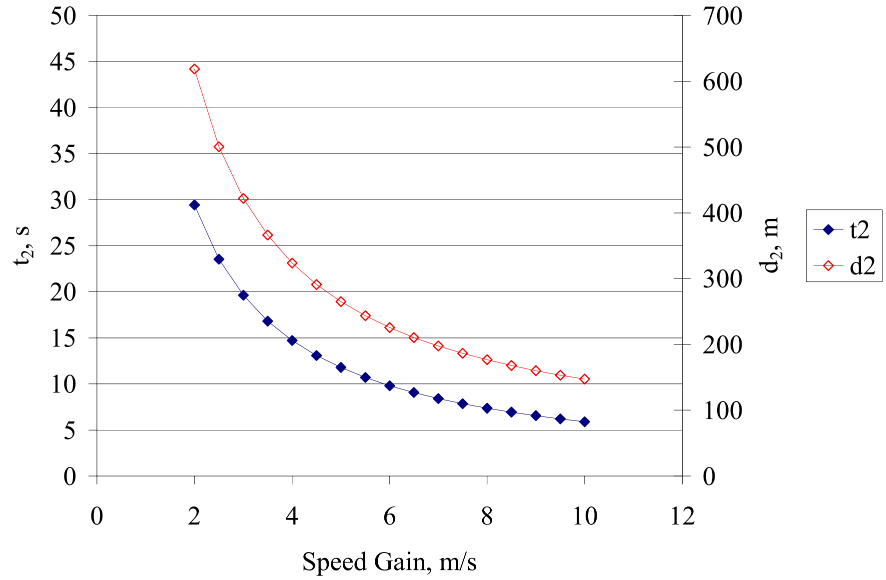

FIGURE 8.16. Sensitivity to the speed gain.

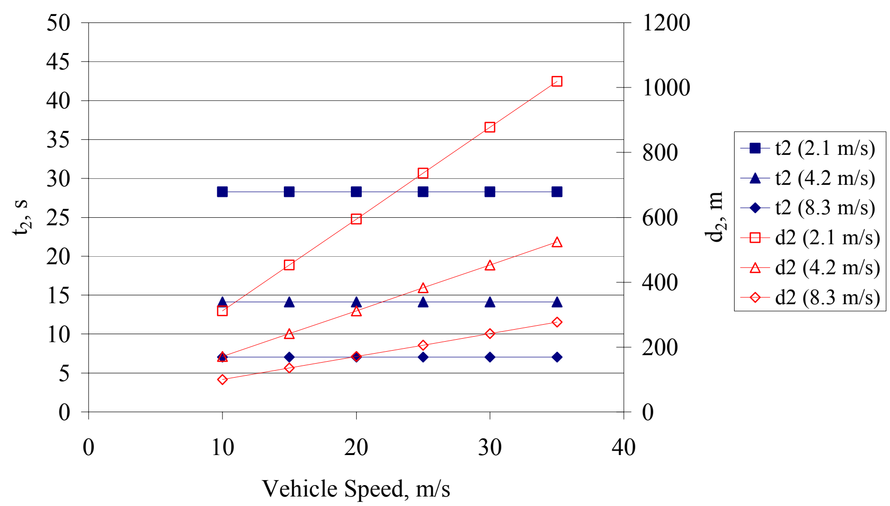

FIGURE 8.17. Sensitivity to the speed gain and vehicle speeds.

The change in t_2 for all impeding vehicle speeds is the result of the change in the rate that the distance needed is gained. This relationship was illustrated in Figure 8.16 and occurs for all impeding vehicle speeds in Figure 8.17. The decrease in d_2 is larger for higher impeding vehicle speeds because d_2 is proportional to the product of the impeding vehicle speed and t_2.

The differences in t_2 and d_2 in response to the speed gain are similar to the differences in response to changes in the speed difference. Both the speed difference and speed gain contribute to the rate at which the passing vehicle gains the needed distance. To produce the same response in d_2 and t_2, the speed gain would need to be twice the change in the speed difference.

8.5.6 Summary

The passing distance is highly variable. In the passing equation, there are variables that reflect the mechanics of the passing maneuver and variables that reflect passing behavior. Increases in the speeds of the vehicles result in increases in d_1, d_2 and d_4. Increases to the total vehicle length or total gap length result in increases to t_2 and d_2. The driver can compensate for the increases in d_2 by increasing the speed difference at the beginning of t_2 or the speed gain during t_2. Of course an increase in speed difference is also an increase in the speed of the passing vehicle during t_1 and results in an increase in d_1. The impact of the increase in the individual variable values on t_2, d_1, d_2, and d_4 are summarized in Table 8.3.

TABLE 8.3. Summary of Responses to Increases in Model Variables

Variable increased	Response in passing maneuver			
	t2	d1	d2	d4
Vehicle speeds		↑	↑	↑
Total vehicle length	↑		↑	
Total gap distance	↑		↑	
Speed difference	↓	↑	↓	
Speed gain	↓		↓	

It should be noted that the clearance distance, d_3 is not included in the sensitivity analysis. This distance is the result of the difference between the gap that is chosen in the opposing traffic and some portion of the sum of d_1, d_2 and d_4. The portion depends on when the acceptance of the gap occurs. It may be argued that the gap is accepted at the beginning of t_1, when the driver perceives the opportunity to pass and begins the actions to execute the maneuver. Alternatively, it could be argued that the gap is reassessed during the maneuver, and the gap is accepted sometime during t_2.

8.6 Predicting the Impact of Increasing the Impeding Vehicle Length

Through the sensitivity analysis, an increase in the total vehicle length was shown to positively impact both the time and distance the passing vehicle travels in the left lane. The increase in t_2 is equal to the distance to be gained during the maneuver divided by the rate at which the passing vehicle gains that distance.

$$t_2 = \frac{\text{distance to be gained}}{\text{rate distance is gained}} \tag{8.15}$$

The rate can be represented as the difference in the average speeds of the impeding and passing vehicles. The increase in t_2 is then multiplied by the speed of the impeding vehicle and added to the increase in the length of the impeding vehicle to determine the impact on d_2. The increase in d_2 represents the change in the mechanics of the passing maneuver.

The relationship between the gain rate and d_2 for total vehicle lengths of 9.4, 19.3, and 29.2 m is shown in Figure 8.18. These total vehicle lengths represent the passing conditions where there are two passenger cars, a passenger car and a semi tractor-trailer, and two semi tractor-trailers.

Increasing the gain rate decreases the distance the passing vehicle travels in the left lane. The passing driver can increase speed, thereby increasing the gain rate to compensate for the added distance to be gained caused by an in crease in the total vehicle length. For instance, at a gain rate of 3 m/s, a passing passenger car travels approximately 240 meters in the left lane to overtake another passenger car. If the impeding vehicle is a semi tractor-trailer, a passing passenger car can still overtake the impeding vehicle in the same distance if the gain rate is increased to 5 m/s. If both vehicles are semi tractor-trailers, the gain rate needs to be increased to 6 m/s for the passing vehicle to overtake the impeding vehicle in the same distance.

An increase in the gain rate may be achieved in two ways: by increasing the speed difference by accelerating during t_1 or by increasing the speed gained during t_2. Either way will help to compensate for the impact of an increase to the total vehicle length on the distance and time in the left lane. However, if the driver increases speed during t_1, there is also an increase in d_1 and the total passing distance (D).

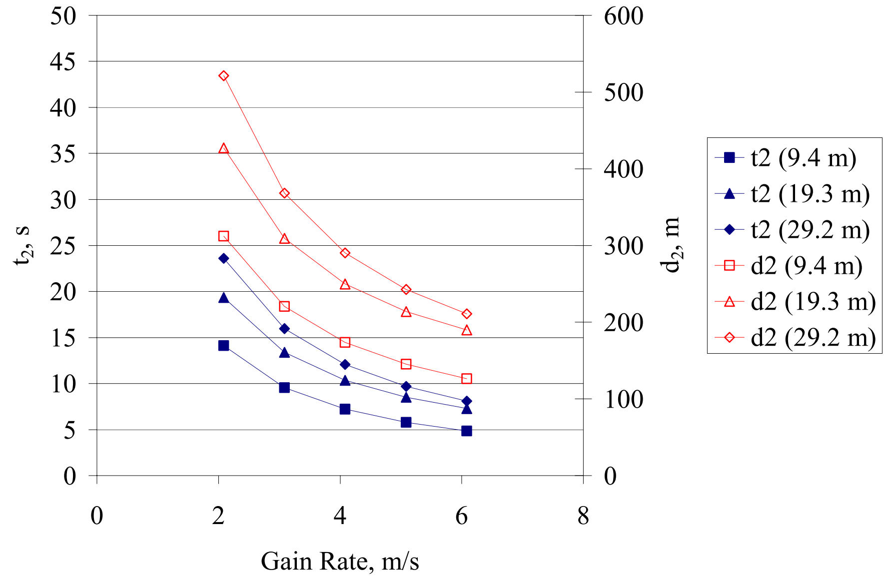

FIGURE 8.18. Sensitivity to gain rate and vehicle lengths.

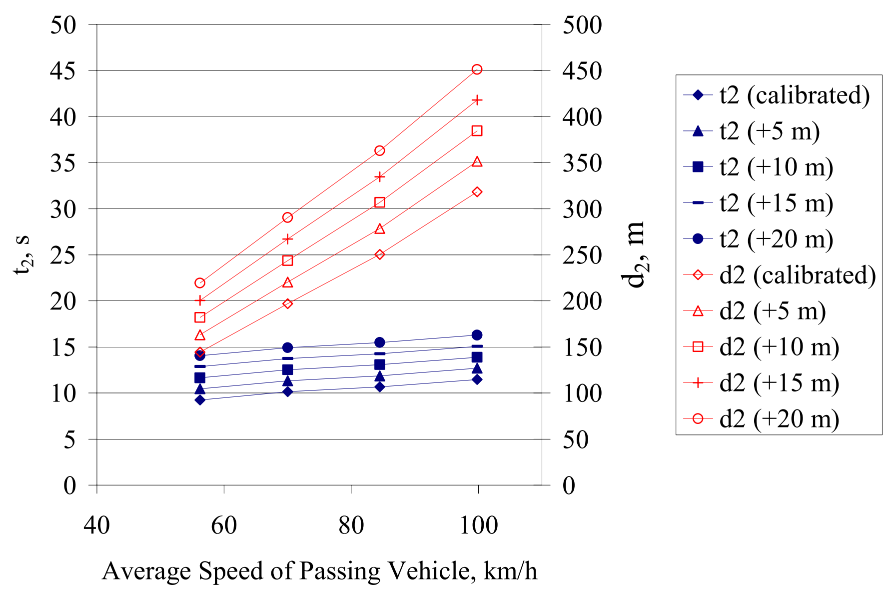

FIGURE 8.19. Predicted impact of vehicle length on AASHTO design values.

An important consideration is that the increase in the gain rate is limited by the performance of the passing vehicle under the specific passing conditions. Vehicles with poor acceleration capabilities may not be able to achieve the higher gain rates. Steep grades may also prevent vehicles from achieving a high gain rate. In addition, some drivers may not be comfortable with large gain rates, especially if the speed limit is exceeded. Therefore, compensating for the impact of the increase in the total vehicle length on the time and distance in the left lane is dependent on vehicle, environment, and driver factors.

Using the passing model, calibrated for the ASSHTO design variables, the increase in the length of the impeding vehicle was examined. The predicted increase in d_2, shown in Figure 8.19, represents changes only in the mechanics of the passing maneuver and not changes in passing behavior.

Under the passing conditions described by the ASSHTO design values, a one meter increase in the total vehicle length is predicted to cause an increase in t_2 of 0.24 seconds. This impact is the same regardless of the average speed of the passing vehicle. However, the impact on d_2 depends on the average speed of the impeding vehicle. The marginal changes in t_2 and d_2 are summarized in Table 8.4.

TABLE 8.4. Marginal Changes in t_2 and d_2 for Total Vehicle Length.

Average passing vehicle speed, km/h	Marginal change in t_2, s	Marginal change in d_2, m
56.2	0.24	3.74
70	0.24	4.67
84.5	0.24	5.64
99.8	0.24	6.66

The marginal differences only represent the changes in the mechanics of the passing maneuver. It is possible that the passing driver may behave differently depending on the type of impeding vehicle. Perhaps the length, width, type of cargo or some other characteristic about the impeding vehicle is perceived in such a way that the passing driver leaves more space. An increase in the total gap distance would also add to the space interchange thereby increasing the time and distance traveled in the left lane. Polus et al. reported that the gap distances were larger when the impeding vehicles were trucks or buses rather than passenger cars (*22*). If the behavior observed in Israel is similar to the behavior in the United States of America, then the marginal differences presented in Table 8.4 are underestimated.

8.6.1 Passing Sight Distance Design Practices

The current passing sight distance values are published in A Policy on Geometric Design of Highways and Streets (*10*). The distances are shown in Table 3.1. They are based the passing driver determining at the start of the passing maneuver that the opposing traffic lane is clear to successfully complete a passing maneuver. The passing situation is a passenger car overtaking another passenger car on a level roadway. It has been suggested that the increase in the vehicle length would require greater passing distance. On unfavorable grades, such as steep inclines, it is recommended that the passing sight distances should be increased.

The passing equations have been calibrated to the AASHTO values and include variables that represent the mechanics of the passing maneuver and passing behavior that can be adjusted to describe a variety of passing conditions. These equations are much more valuable than the AASHTO representation of passing distances because they can be calibrated to a variety of conditions and used to predict the impact to the passing distance given changes to the mechanics of the passing maneuver. For instance, when large trucks are being considered as the impeding vehicle, not only is the length of the vehicle a concern but also the performance of the vehicle. If the passing maneuver occurs on a grade, an impeding truck may lose speed on a positive grade or gain speed on a negative grade. This would change the average speed of the impeding vehicle and could be incorporated into the equations to predict the impact of t_2 and d_2.

The passing equations can also be used to identify what changes in driver behavior are needed to compensate for changes in factors that impact the mechanics of the passing maneuver. Using the same example of a change in the grade and an impeding truck, on a positive grade the speed gain needed by the passing vehicle would decrease whereas on the negative grade the needed speed gain would increase. Depending on the performance of the passing vehicle and other passing conditions, the larger speed gain may not be achievable.

8.6.2 No-Passing Zones Marking Practices

The current passing sight distance values for marking no-passing zones are published in the Manual on Uniform Traffic Control Devices (*12*). The distances are shown in Table 3.3. The passing sight distance values used for marking are less than those used in design. The inconsistency between the passing sight distances for design and for marking are a concern because there is a potential that a section of roadway designed with inadequate passing sight distance may be marked for passing.

Glennon (*17*) suggested that a critical passing sight distance should be provided at the end of every passing area. This distance is described as the passing sight distance needed at the critical point or point of no return, which is the moment when the same sight distance is needed to abort or complete the pass with the same amount of safety. The measure of the safety is the clearance to the opposing vehicle at the end of the aborted or completed pass. To calculate the critical passing sight distance, it is assumed that the driver can decide when the critical point or point of no return has been reached. This is a complicated decision and given the difficulties of judging distance, speed, time to collision, it is unlikely that drivers can accurately determine when the critical point has been reached. Nonetheless, the notion that there should be a connection between the passing sight distances for design and marking is credible. The exact relationship between the passing sight distances for design and marking needs to be determined to ensure that the passing and no-passing areas operate as the roadway was designed.

Under the current marking practices, the minimum passing sight distance is available at any point within the passing area. The worse case scenario is that the passing maneuver has not been completed when the end of the passing area is reached. If it is assumed the passing and opposing vehicles are traveling at the speed limit during the passing maneuver, and the opposing vehicle enters the line of sight, the minimum passing sight distances are equivalent to approximately a five second time to collision. To ensure a one second clearance at the end of the maneuver, the pass needs to be completed or aborted within about four seconds. In most states, the driver is not allowed to drive left of a solid, yellow centerline therefore, the pass must be completed prior to the end of the passing area. What limits the size of the passing area is a minimum allowable distance of 120 m between no-passing areas. In practice, some engineers find it prudent to increase this minimum allowable distance (*126*), which is reasonable because a passing maneuver cannot be performed in a 120 m section of highway. Perhaps the minimum allowable distance should be the same as the minimum sight distance, however there still needs to be some link to the passing sight distance used for design.

Once the relationship between the passing sight distances for design and marking is established, the passing equation could be adjusted to produce a passing model for marking that is sensitive to changes in the passing conditions. Changes to factors that impact the mechanics of the maneuver and passing behavior could then be incorporated into the marking practices. For instance, maybe longer minimum passing sections are needed on positive grades and in areas where there are a large percentage of trucks. Compared to a level roadway with only passenger cars as impeding and passing vehicles, these types of passing conditions require greater passing distances; therefore providing a longer minimum passing area would be prudent.

8.7 Evaluating Passing Behavior

In the field, it is difficult to track both the passing and impeding vehicle with enough accuracy so as to obtain the speed profiles of the vehicles over the duration of the maneuver. With the passing equation, the speed of the passing vehicle at the beginning and end of the maneuver can be used in combination with the observed time and distance in the left lane to describe what type of passing maneuver was performed. The average speed observed in the field is calculated as

$$\bar{s}_p(\text{observed}) = \frac{d_2}{t_2} \tag{8.16}$$

The estimated average speed, as considered in the passing equation, is calculated as

$$\bar{s}_p(\text{predicted}) = s_p + \frac{\Delta s_p}{2} \tag{8.17}$$

If the observed and estimated average speeds of the passing vehicle are equal, then the passing vehicle increased speed linearly over the time interval t_2. In other words the acceleration was constant over t_2. If during t_2, the acceleration decreased, the observed average speed would be greater than the estimated average speed. Similarly, if during t_2 the acceleration increased, the observed average speed would be less than the estimated average speed.

Using this relationship, and the assumption that the acceleration behavior represents the perceived threat of the opposing vehicle, confidence in completing the pass, and opportunity to move back into the right lane, some comments can be made about the type of passing maneuver being observed.

In the situation where the observed average speed is greater than the estimated average speed, the driver was more aggressive in the beginning of the pass and less aggressive at the end of the pass. This behavior suggests that the driver had confidence that the pass could be completed and perceived the threat of the opposing vehicle to be low and therefore, decreased acceleration. In the situation where the observed average speed is less than the estimated average speed, the driver was less aggressive during the beginning of the pass and more aggressive during the end of the pass. This behavior suggests that sometime during the pass the driver's perception of the threat of the opposing vehicle increased given the percentage of the pass that has been completed or that the opportunity to return to the right lane was challenged. The driver responded by increasing acceleration to ensure the pass was completed successfully.

This type of evaluation could be beneficial for identifying problem areas for passing. If a consistent passing behavior is observed, it may indicate a problem inherent in the specific location. For instance, if drivers are consistently increasing acceleration late in the pass, this behavior may indicate that the sight distance is inadequate and drivers are not seeing an opposing vehicle until well into the pass. It could also indicate that a driveway or other potential conflict is present that is not seen until late into the maneuver. The results of such an investigation might support the need for additional signage for hidden driveways or perhaps a change in the passing markings.

9 SUMMARY

The methodology, presented as a general framework for improving simulations through distributed computing, was used to create a prototype. The methodology was motivated by the need to capture behavior in traffic simulations and the need to create specific traffic flows in driving simulations. The prototype was designed based on HLA and the RTI was to facilitate the two-way real-time communication between a VISSIM simulation and a comparable DriveSafety simulation.

Problems were encountered, which constrained the development of the prototype and its usefulness. The major problems included:

1. Queuing during the export of data from VISSIM;
2. Queuing of data in the translator program; and
3. A processing threshold of thirty vehicle speed updates per second in DriveSafety.

With delays in the transfer of data, a two-way real-time data transfer was not feasible. These problems will need to be solved before the prototype can be further developed. The translator program will need to be rewritten as a multithread application, which will allow simultaneous read and write capabilities. The processing threshold in DriveSafety, which limited the update rate, number of vehicles, and therefore the traffic volume and size of the network being simulated, will need to be addressed. If this threshold is not remedied, the usefulness of prototypes such as the one developed for this research cannot be fully explored.

In the final prototype, vehicle information from VISSIM was transferred to DriveSafety to generate vehicles and control their speed during the simulation. This prototype was successfully applied to a passing study, where the impact of the length of the impeding vehicle on passing behavior was investigated. Using the data from VISSIM, two platoons of impeding vehicles were generated in DriveSafety and their speeds were controlled for the duration of the simulation. An opposing traffic flow of 250 vehicles per hour was also generated and controlled in the same manner. Details about the movement of the test vehicle, controlled by the test driver, were recorded directly in the DriveSafety data collection file. Details about the movement of the impeding and opposing vehicles were estimated by comparing the data from the VISSIM data collection file, and the log of trigger activations in DriveSafety. Had a two-way real-time data exchange been achieved, the traffic data could have been read directly from the VISSIM data collection file.

The passing study was designed as a repeated measure, 2x2 factorial, where the impeding vehicles differed by length and by speed. The length on the impeding vehicle was found to significantly impact the time and distance in the left lane as well as the start gap and end gap distances. These results support the notion that the impact was not limited to the additional length of the impeding vehicle that the passing vehicle needed to gain during the maneuver. The impact was also a result of changes in the behavior of the passing driver, as indicated by the difference in gap distances.

The variation in passing behavior was further explored by examining the data collected during the passing study. The variations in start gap and end gap distances, speed gain, speed difference, maximum speed, and acceleration behavior was examined. The variation in the types of passing maneuvers was also examined. A relationship between the speed difference and speed gain was identified and can be used to describe the start of the pass. A relationship between the location of the passing vehicle with respect to the impeding vehicle and the clearance distance at the time the passing vehicle first decelerates was also identified. This relationship can be used to describe the end of the pass and perhaps also describe how the passing driver perceives the threat of the opposing vehicle in terms of the successful completion of the pass. This relationship may be more complex, and need to account for the opportunity to return to the right lane.

Using some of the insight gained during the passing study and the subsequent examination of the passing data, a series of passing equations were developed to describe the four elements of the passing maneuver. The equations were brought together to form the following equation describing the total passing distance.

$$D = \bar{s}_p t_1 + G_S + L_i + \bar{s}_i t_2 + L_p + G_E + C + \bar{s}_o (t_1 + t_2) \quad (9.1)$$

The variables that reflect the mechanics of the passing maneuver include the speeds and lengths of the vehicles. The variables that reflect passing behavior include the gap distances and speed gain of the passing vehicle used to calculate t_2. The sensitivity of t_2 and d_2 to these variables was examined. Increases to the vehicle length and gap distances increased t_2 and increases in the speed difference and speed gain decreased t_2. Increases in the vehicle speeds, vehicle lengths, and gap distances increased d_2, and increases in the speed difference and speed gain decreased d_2.

The equations for t_2 and d_2 were validated using the data from the passing study and calibrated using the AASHTO passing sight distance criteria. The calibrated equations were used to predict the impact of longer impeding vehicles. With a one meter increase in the length of the impeding vehicle, the marginal increase in t_2 was 0.24 seconds and the marginal increase in d_2 was 3.74 meters at an average passing vehicle speed of 56.2 km/h and 6.66 meters at an average passing vehicle speed of 99.8 km/h.

9.1 Contributions

The contributions of this research derive from the two focus areas: the development of a methodology to combine microscopic traffic simulation programs with driving simulator programs, and the application of a prototype distributed traffic simulation to study the impact of the length of an impeding vehicle on passing behavior.

9.1.1 Methodology

Although distributed simulation is not a new idea, it has failed to receive much attention in the area of transportation, especially in the civil domain. Some efforts in Europe, specifically in Germany and the Netherlands, have been reported but this research appears to be the first reported in the United States.

Since the methodology was generic in nature, it could be used to develop a variety of distributed simulations for a variety of traffic or behavior problems. In fact, a distributed simulation comprised of two contributing simulations could be expanded upon to incorporate multiple simulations, or other applications. Ultimately, a distributed simulation could be developed as an open traffic environment linking together an assortment of traffic simulations, databases, data acquisition tools, analyses programs, and visualization tools.

This methodology should be attractive to the users of traffic simulation because it increases the number of tools available for traffic and behavior analysis. It should also be attractive to developers because this is one avenue to increase the life and usefulness of their products and at the same time it provides the opportunity to create very specific programs that can be incorporated into larger simulations.

A distributed simulation, combining a traffic simulation and a driving simulation, is a good data collection tool. The laboratory setting is a safe and easily controlled environment and provides direct contact with the test drivers. A lot of data can be captured about the test driver, vehicle, and environment. Similar access to the test driver is not available in field studies and if it is even possible to capture very detailed data about the vehicle and environment, the methods are likely quite costly, difficult, and dangerous to implement.

9.1.2 Application

Historically, the passing maneuver has been studied by making observations in the field, conducting experiments in the field, or conducting experiments on closed courses. This is the first reported study in the United States to investigate passing behavior in a simulated environment.

The motivation behind using the prototype to study passing behavior was the potential that federal truck size and weight regulations will change and the current inconsistency between the passing sight distance criteria for designing two lane highways and marking no passing zones. To ensure the safe operation of the two-lane two-way highways, it is necessary that the impact of longer trucks be understood and considered in the design and marking of the highways. One of the benefits of the simulated environment is the ability to simulate vehicles that do not exist. Although it was not done for this research, vehicles longer than what is permitted under the current federal regulations could be used to examine the impact of these long vehicles.

There are concerns about the validity of using the simulated environment and the potential for test drivers to behave differently than they do in the real world. From the results of the passing study and the comparison of the summarized data to field data reported by Polus et al. (22), there is hope that simulated environments are suitable for passing studies and that the results are transferable to the real world. The data summarized using the conventional definition for the occupation of the left lane did not compare well to the field data, however, the data summarized using the alternate definition was much better. In fact, it was found that the means of the distance in the left lane from the simulated study and the field study were comparable.

9.1.3 Passing Equation

The passing equation has several uses. It can be used to evaluate the passing sight distance criteria for design and marking no-passing zones. It can also be used to evaluate the passing behavior observed in the field. By comparing the actual average speed of the passing vehicle to the estimated average speed of the passing vehicle, calculated using the passing equation, conclusions can be drawn about the acceleration of the passing vehicle. For example, if the actual average speed is greater than the estimated, than the majority of the increase in speed occurred during the beginning of the pass. This type of comparison requires only a few field observations and could be used to identify problem areas for passing.

9.2 Future Research

This research was multidiscipline in nature and literature was drawn from simulation, distributed computing, transportation, human factors, and psychology publication sources. It is not surprising then, that the recommended future research extends over several areas.

9.2.1 Distributed Computing

The first recommendation is to continue the efforts to advance the field of distributed computing. This recommendation is obvious considering computer technology, web technology, and networking technology are areas of strong investment. A good source for the current research is the journal *Simulation: Transactions of The Society for Modeling and Simulation International*.

The story behind the High Level Architecture is a good example of the benefits of distributed computing. Without the funding to create new simulations, and a vast library of old simulations, HLA was developed as a framework to provide the reuse of simulations and the interoperability among simulations. The old simulations became a new resource to be reused to address new problems.

Distributed computing has been implemented in many industrial domains including manufacturing, supply chains, and emergency planning. The experience in transportation is very limited apart from the use of HLA for the simulation of military operations. This means that there is a wealth of opportunity to examine the potential of distributing computing within the field of transportation.

9.2.2 Simulation

The second recommendation is to examine the validity of transportation simulations and the transferability of the study results to the real world. It is all too easy to use a simulation as a black box but this approach can lead to erroneous interpretation of the simulation results. The results of traffic and/or driving simulations reflect the logic incorporated into the models, the assumptions and simplifications that were made, and the methods of introducing randomness. In the case of a driving simulation, the captured behavior may be influenced by the characteristics of the animation, interface, and testing environment. The test driver's reaction to the driving environment, in terms of the symptoms of simulator sickness, may also influence the behavior of the driver. Research is needed to validate the host of different traffic and driving simulations.

9.2.3 Behavior Analysis

The third recommendation is to continue examining passing behavior and the impact of trucks and other driver, vehicle and environment factors. Further detailed passing data is needed to determine what type of response is expected under a variety of passing conditions. Additional data is also needed to verify the continuum between the flying and accelerated starts as well as the continuum between the voluntary and forced returns. One interesting area will be to determine how the opportunity to return to the right lane needs to be incorporated into the relationship describing the end of the passing maneuver.

The fourth recommendation is to enhance the deterministic passing equation to reflect the dynamic and stochastic behavior of drivers. This could be achieved by generating the values for the behavior variables using a random number generator and the distributions for the response variables observed during the passing study. It would then be possible to generate a sample of passing distances and times that could be used to predict behavior or evaluate passing sight distance criteria.

9.2.4 Traffic Analysis

The fifth recommendation is to define the relationship between the criteria for designing two lane highways and marking no passing zones, and determine what passing conditions should be reflected by those criteria. The current inconsistency in the criteria is concerning as sections of roadway not designed for passing may be subsequently marked as passing areas. The safety implications of this inconsistency are clear; the markings suggest to the driver that it is safe to pass while the design of the road requires that the driver judge whether or not it is truly safe to pass. These criteria could change dramatically depending upon whether the criteria are based on a flying start and voluntary return pass, or an accelerated start and hurried return pass, or some combination thereof. The final criteria will impact the capacity of two lane highways, as the opportunity to pass may change. This in turn may change the passing behavior of drivers and require further investigation into the interactions between passenger cars and trucks, and the results should be incorporated into traffic simulations.

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APPENDIX A

GLOSSARY AND ACRONYMS

AASHTO	American Association of State Highway Transportation Officials
algorithm	step-by-step problem-solving procedure
animation	the computer generated visual representation of the simulation run
blocking vehicle	the vehicle ahead of the opposing vehicle
car following	the act of maintaining a safe distance to the vehicle ahead while traveling in single file
clearance	the distance between the front bumpers of the opposing and passing vehicles when the passing vehicle has returned to the right lane
end gap	the gap between the passing and impeding vehicles when the rear left tire of the passing vehicle crosses over the centerline as the passing vehicle returns to the right lane
federate	a member of a federation, usually a simulation, database or other application
federation	a group of federates that communicate among each other
FHWA	Federal Highway Administration
gap	the distance between the rear bumper of the lead vehicle and the front bumper of the following vehicle when the two vehicles are consecutive and traveling in the same direction
HCM	Highway Capacity Manual
headway	the distance between the front bumpers of two consecutive vehicles traveling in the same direction
HLA	High Level Architecture
ISTEA	Intermodal Surface Transportation Efficiency Act
impeding vehicle	the vehicle which obstructs the forward movement of another faster vehicle in the same lane
lane changing	the act of moving from the current lane to the adjacent lane by accepting a gap in the traffic in the destination lane
logic	the sequence of instructions that define how the program operates
LTSS	Land Transportation Standards Subcommittee

macroscopic	the smallest detail is the group of vehicles or drivers
microscopic	the smallest detail is the individual vehicle or driver
model	a simplified description or representation of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics
MUTCD	Manual on Uniform Traffic Control Devices
NAFTA	North American Free Trade Agreement
NCHRP	National Cooperative Highway Research Program
NN	National Network
opposing vehicle	the vehicle in the opposing lane that constrains the occupation of that lane during a passing maneuver
overtaking maneuver	the act of moving ahead of another vehicle
passing maneuver	the act of overtaking another vehicle by traveling at a faster speed in the opposing lane of a two-lane, two-way road. Also referred to as a pass.
passing vehicle	the vehicle which moves ahead of another vehicle by traveling at a faster speed in the opposing lane
refresh rate	the frequency at which an animation is updated
simulation	updating the state of a model through time to represent the operation of the system, theory or phenomenon
simulation rate	the number of time steps calculated each real second
simulation run	a single execution of the model simulated through a given length of time using a set time step and simulation rate
STAA	Surface Transportation Assistance Act
start gap	the gap between the impeding and passing vehicles when the front left tire of the passing vehicle crosses over the centerline as the passing vehicle enters the left lane
TEA-21	Transportation Equity Act for the 21st Century
time step	the size of the time interval used to update the state of the model
traffic logic	the sequence of instructions that govern how vehicles move and interact
traffic model	a model specific to a traffic system, theory or phenomenon
USDOD	United States Department of Defense
USDOT	United States Department of Transportation

APPENDIX B

SYMBOLS

t	time, s
t_1	time taken for the passing driver to decide to pass and move the vehicle towards the left lane, s
t_2	time the passing vehicle occupies the left lane, s
L_v	length of vehicle v, m
x_v	x-coordinate location of vehicle v, m
x_v	y-coordinate location of vehicle v, m
s_v	speed of vehicle v, m/s
$\bar{s}_v$	average speed of vehicle v, m/s
Δs_v	speed gain of vehicle v, m/s
a_v	acceleration rate of vehicle v, m/s^2.
$\bar{a}_v$	average acceleration rate of vehicle v, m/s^2.
G_s	gap between the passing and impeding vehicles at the start of t_2, m
G_e	gap between the passing and impeding vehicles at the end of t_2, m
C	clearance between the passing and oncoming vehicles at the end of t_2, m
$G_S+L_i+L_p+G_E$	space interchange or distance needed to be gained by the passing vehicle, m
E	error measurement, percent
m	speed difference, the maximum difference between the impeding and passing vehicles assuming that they were traveling near the same speed at the beginning of the maneuver, m/s

APPENDIX C

STATE STATUTES REGULATING PASSING BEHAVIOR

	State Statute	
State	Overtaking/Driving Left of Center	No-Passing Zones
Alabama	32-5A-82, 32-5A-84, 32-5A-85	32-5A-86
Alaska	13ACC02.060, 13ACC02.065	13AAC02.075
Arizona	28-723, 28-725, 28-726	289-727
Arkansas	27-51-306, 24-51-307	
California	21750, 21751, 21752	
Colorado	42-4-1003, 42-4-1005	
Connecticut	14-232, 14-235	14-234
Delaware	4116, 4118, 4119	4120
District of Columbia		
Florida	316.083, 316.085, 316.087	316.0875
Georgia	40-6-42, 40-6-44	40-6-46
Hawaii	291C-43, 291C-45, 291C-46	291C-47
Idaho	49-632, 49-634, 49-635	
Illinois	625ILCS5/11-703, 625ILCS5/11-705, 625ILCS5/11-706	625ILCS5/11-707
Indiana	IC9-21-8-5, IC9-21-8-7, IC9-21-8-7.5, IC9-21-8-8	IC9-21-4-12, IC9-21-4-13
Iowa	321.299, 321.303	321.304
Kansas	8-1516, 8-1518	8-1520
Kentucky	189.340, 189.345, 189.350	
Louisiana	RS32:73, RS32:75, RS32:76	RS 32:77
Maine	2070	2085
Maryland	21-303, 21-305	21-307
Massachusetts	89-2, 89-4	
Michigan	257.636, 257.638, 257.639	257.640
Minnesota	169.18.3	
Mississippi	63-3-609, 63-3-611	
Missouri	304.016	
Montana	61-8-323, 61-8-325	61-8-326
Nebraska	60-6.133, 60-6.135, 60-6.136	60-6,137
Nevada	NRS484.295, NRS484.299	NRS 484.301
New Hampshire	265:18, 265:20, 265:21	265:22
New Jersey	39:4-85, 39:4-86, 39:4-87	39:4-201.1
New Mexico	66-7-310, 66-7-312	66-7-315
New York	1122, 1125	71-7A-S1126
North Carolina	20-149, 20-150	
North Dakota	39-10-11, 39-10-13, 39-10-14	39-10-15
Ohio	4511.27, 4511.29, 4511.30	4511.31
Oklahoma	47-11-303, 47-11-305,47-11-306	47-11-307
Oregon	811.305, 811.410	811.420

	State Statute	
State	Overtaking/Driving Left of Center	No-Passing Zones
Pennsylvania	3303, 3305, 3306	3307
Rhode Island	31-15-4, 31-15-6, 31-15-7	31-15-8
South Carolina	56-5-1840, 56-5-1860, 56-5-1880	56-5-1890
South Dakota	32-26-26, 32-26-31, 32-26-36,	32-26-37, 32-26-38, 32-26-39
Tennessee	55-8-117, 55-8-119	55-8-121
Texas	545.053, 545.054	545.055
Utah	41-6-55, 41-6-57	41-6-59
Vermont	23-1033, 23-1035	23-1036
Virginia	46.2-838, 46.2-843, 46.2-854, 46.2-856	
Washington	RCW46.61.110, RCW46.61.120, RCW46.61.125	RCW46.61.130
West Virginia	17C-7-3, 17C-7-5, 17C-7-6	§17C-7-7
Wisconsin	346.07, 346.09	349.12
Wyoming	31-5-203, 31-5-204, 31-5-205	31-5-207

APPENDIX D

INSTITUTIONAL REVIEW BOARD APPROVALS

VPR Office of the Vice President for Research

Office of Research Compliance

Administration and Special Programs

Academy for Advanced Telecommunication and learning Technologies

Institute for Scientific Computation

Laboratory Animal Resources and Research

Microscopy and Imaging Center

Office of Business Administration

Office of Graduate Studies

Office of Sponsored Projects

Texas A&M University Research Park

February 19, 2003

MEMORANDUM

TO: Jacqueline Jenkins
Texas Transportation Institute
MS 3135

SUBJECT: Review of IRB Protocol "Southwest University Transportation Center (SWUTC)" 2003-0011

Approval Date: **February 19, 2003 – February 18, 2004**

The Institutional Review Board – Human Subjects in Research, Texas A&M University has reviewed and approved the above referenced protocol. Your study has been approved for one year. As the principal investigator of this study, you assume the following responsibilities:

Renewal: Your protocol must be re-approved each year in order to continue the research. You must also complete the proper renewal forms in order to continue the study after the initial approval period.

Adverse events: Any adverse events or reactions must be reported to the IRB immediately.

Amendments: Any changes to the protocol, such as procedures, consent/assent forms, addition of subjects, or study design must be reported to and approved by the IRB.

Informed Consent/Assent: All subjects should be given a copy of the consent document approved by the IRB for use in your study.

Completion: When the study is complete, you must notify the IRB office and complete the required forms.

Gaile S. Cannella

Dr. Gaile S. Cannella, Chair
Institutional Review Board –
Human Subjects in Research

Texas A&M University

1112 TAMU
318 Administration Building
College Station, Texas
77843-1112

979.845.8585
FAX 979.862.3176

VPR Office of the Vice President for Research

Office of Research Compliance

Administration and Special Programs

Academy for Advanced Telecommunication and learning Technologies

Institute for Scientific Computation

Laboratory Animal Resources and Research

Microscopy and Imaging Center

Office of Business Administration

Office of Graduate Studies

Office of Sponsored Projects

Texas A&M University Research Park

May 2, 2003

MEMORANDUM

TO:	Jacqueline Jenkins Texas Transportation Institute MS 3135
SUBJECT:	Southwest University Transportation Center (SWUTC) 2003-0011
Approval Date:	February 19, 2003 to February 18, 2004

The Institutional Review Board – Human Subjects in Research, Texas A&M University has reviewed and approved the above referenced protocol. Your study has been approved for one year. As the principal investigator of this study, you assume the following responsibilities:

Renewal: Your protocol must be re-approved each year in order to continue the research. You must also complete the proper renewal forms in order to continue the study after the initial approval period.

Adverse events: Any adverse events or reactions must be reported to the IRB immediately.

Amendments: Any changes to the protocol, such as procedures, consent/assent forms, addition of subjects, or study design must be reported to and approved by the IRB.

Informed Consent/Assent: All subjects should be given a copy of the consent document approved by the IRB for use in your study.

Completion: When the study is complete, you must notify the IRB office and complete the required forms.

Gaile S. Cannella

Dr. Gaile S. Cannella
Institutional Review Board –
Human Subjects in Research

Amended protocol to include changes specified in memo to the IRB Office

Texas A&M University

1112 TAMU
318 Administration Building
College Station, Texas
77843-1112

979.845.8585
FAX 979.862.3176

APPENDIX E

ORDERING COMBINATION SCHEDULE

The vehicle indicated in each trial is the impeding vehicle for that trial. The letter in the parenthesis indicates whether the impeding is part of the faster or slower platoon.

Subject	Sex	Trial 1	Trial 2	Trial 3	Trial 4
~~1~~	~~M~~	~~white truck (F)~~	~~gray truck (S)~~	~~red car (F)~~	~~blue car (S)~~
~~2~~	~~F~~	~~white truck (F)~~	~~blue car (S)~~	~~red car (F)~~	~~gray truck (S)~~
3	M	blue car (S)	gray truck (S)	white truck (F)	red car (F)
~~4~~	~~F~~	~~gray truck (S)~~	~~white truck (F)~~	~~red car (F)~~	~~blue car (S)~~
5	M	white truck (F)	red car (F)	blue car (S)	gray truck (S)
6	M	red car (F)	gray truck (S)	white truck (F)	blue car (S)
7	F	white truck (F)	red car (F)	gray truck (S)	blue car (S)
~~8~~	~~M~~	~~gray truck (S)~~	~~white truck (F)~~	~~blue car (S)~~	~~red car (F)~~
~~9~~	~~F~~	~~red car (F)~~	~~gray truck (S)~~	~~blue car (S)~~	~~white truck (F)~~
10	F	red car (F)	white truck (F)	gray truck (S)	blue car (S)
11	M	blue car (S)	red car (F)	white truck (F)	gray truck (S)
12	F	blue car (S)	gray truck (S)	red car (F)	white truck (F)
13	F	blue car (S)	white truck (F)	gray truck (S)	red car (F)
14	M	blue car (S)	white truck (F)	red car (F)	gray truck (S)
15	M	red car (F)	white truck (F)	blue car (S)	gray truck (S)
16	M	red car (F)	blue car (S)	white truck (F)	gray truck (S)
17	F	white truck (F)	gray truck (S)	blue car (S)	red car (F)
18	M	gray truck (S)	blue car (S)	red car (F)	white truck (F)
19	M	gray truck (S)	red car (F)	blue car (S)	white truck (F)
20	M	blue car (S)	red car (F)	gray truck (S)	white truck (F)
21	F	gray truck (S)	red car (F)	white truck (F)	blue car (S)
22	F	red car (F)	blue car (S)	gray truck (S)	white truck (F)
23	F	white truck (F)	blue car (S)	gray truck (S)	red car (F)
24	F	gray truck (S)	blue car (S)	white truck (F)	red car (F)
25 (rep 9)	M	red car (F)	gray truck (S)	blue car (S)	white truck (F)
~~26 (rep 1)~~	~~F~~	~~white truck (F)~~	~~gray truck (S)~~	~~red car (F)~~	~~blue car (S)~~
27 (rep 2)	F	white truck (F)	blue car (S)	red car (F)	gray truck (S)
28 (rep 8)	M	gray truck (S)	white truck (F)	blue car (S)	red car (F)
29 (rep 1)	F	white truck (F)	gray truck (S)	red car (F)	blue car (S)
30 (rep 4)	F	gray truck (S)	white truck (F)	red car (F)	blue car (S)

Note: those subjects that are crossed out were replaced. For instance subject 1 was replaced by subject 26 who in turn was replaced by subject 29.

APPENDIX F

SIMULATOR SICKNESS QUESTIONNAIRE

From previous studies conducted in the Driving Environment Simulator, 1 in 10 participants experience a level of discomfort that compels them to stop driving. Symptoms include eyestrain, headache, dizziness, and nausea.

Did you complete the study? ❑Yes ❑No

By checking the appropriate boxes, please indicate what level of discomfort you experienced while in DriveSafety.

Eye Strain	❑None	❑Low	❑Moderate	❑High
Headache	❑None	❑Low	❑Moderate	❑High
Dizziness	❑None	❑Low	❑Moderate	❑High
Nausea	❑None	❑Low	❑Moderate	❑High

Your response will help to determine the risk for future participants. Thank you.

APPENDIX G

SIMULATOR SICKNESS DATA

Subject	Sex	Completed	Eye Strain	Headache	Dizziness	Nausea
~~1~~	~~M~~	~~Yes~~	~~None~~	~~None~~	~~Low~~	~~Low~~
~~2~~	~~F~~	~~Yes~~	~~Low~~	~~None~~	~~Low~~	~~Low~~
3	M	Yes	Low	None	Low	None
~~4~~	~~F~~	~~No~~	~~None~~	~~Low~~	~~Moderate~~	~~Low~~
5	M	Yes	Low	None	None	None
6	M	Yes	Moderate	Low	None	Low
7	F	Yes	Low	Low	Low	Low
~~8~~	~~M~~	~~Yes~~	~~None~~	~~None~~	~~None~~	~~None~~
~~9~~	~~F~~	~~Yes~~	~~None~~	~~None~~	~~None~~	~~None~~
10	F	Yes	None	None	None	None
11	M	Yes	None	None	None	None
12	F	Yes	Low	Low	Low	None
13	F	Yes	Low	Low	None	None
14	M	Yes	None	None	Low	None
15	M	Yes	Low	None	None	None
16	M	Yes	Low	None	None	None
17	F	Yes	Low	None	High	High
18	M	Yes	Low	Low	Low	None
19	M	Yes	Low	None	None	None
20	M	Yes	Low	None	None	None
21	F	Yes	Low	None	None	None
22	F	Yes	Moderate	None	Low	None
23	F	Yes	None	Moderate	None	None
24	F	Yes	None	None	Low	Low
25 (rep 9)	M	Yes	None	None	None	None
~~26 (rep 1)~~	~~F~~	~~Yes~~	~~None~~	~~None~~	~~None~~	~~None~~
27 (rep 2)	F	Yes	Low	Low	Low	Moderate
28 (rep 8)	M	Yes	Low	None	Low	None
29 (rep 1)	F	Yes	None	None	Low	None
30 (rep 4)	F	Yes	None	None	None	None

Totals	Completed	Eye Strain	Headache	Dizziness	Nausea
	29 Yes 1 No	13 None 15 Low 2 Moderate 0 High	22 None 7 Low 1 Moderate 0 High	16 None 12 Low 1 Moderate 1 High	22 None 6 Low 1 Moderate 1 High

APPENDIX H

INFORMED CONSENT

This research experiment is being conducted by Jacqueline Jenkins, of the Texas Transportation Institute (TTI). It is funded by the Southwest University Transportation Center (SWUTC) and is a component of Ms. Jenkins' Ph.D. dissertation. If I have questions, I may contact Dr. Larry Rilett at TTI, Texas A&M University, College Station, TX 77843-3136, (979) 845-9880, Rilett@tamu.edu.

Purpose: The purpose of this study is to observe the behavior of drivers performing passing maneuvers.

Participants: Twenty participants, an equal number of males and females, each between the age of 21 and 35 years with at least five years driving experience and a valid driver's license have been selected to participate. I meet those requirements. The experiment is taking place in Room 320, Gilchrist Building. The study is scheduled to begin in March 2003 and will be completed by the end of the 2003 spring semester. I have been instructed to read this form and ask any questions before agreeing to participate. My decision whether or not to participate will not affect my current or future relations with the TTI, Texas A&M University, or Texas A&M University System. A copy of this form will be given to me prior to proceeding with the experiment.

Procedures: If I agree to be in this study, I will be asked to complete the following three tasks:

1. Drive through one practice scenario, starting at a slow speed and increasing to 55 mph over approximately 5 minutes of driving on a rural roadway, to become familiar with the handling and control of the simulator vehicle and to become adapted to the simulated environment;
2. Drive through one test scenario, a 20 mile stretch of rural roadway at 55 mph, approximately 25 minutes of driving. I will pass slower, impeding vehicles in a safe, judicious manner. Time, distance, velocity and acceleration data about my vehicle will be recorded; and
3. Complete a questionnaire about experiencing any symptoms of simulator sickness.

The total time will not exceed one hour, and the time spent driving will be approximately 30 minutes. I may choose to withdraw from the study at any time for any reason.

Risk: I understand that while driving DriveSafety I may experience symptoms of simulator sickness that include eye strain, nausea, headache, and dizziness. One in ten participants experience a level of discomfort that compels them to stop driving. I understand that I may choose to withdraw from the study at any time.

Benefit: I will not receive any personal benefit from participating in this study.

Anonymity: I understand that any data collected during the experiment will be coded to ensure anonymity. If I do not to complete the experiment, or if the experimenter decides that the data is not valuable to the study, my data will be destroyed and a replacement participant will be recruited.

Compensation: I will not receive any compensation for my participation in this study.

Approval: I understand that this research study has been reviewed and approved by the Institutional Review Board - Human Subjects in Research, Texas A&M University. For research-related problems or questions regarding subjects' rights, I can contact the Institutional Review Board through Dr. Michael W. Buckley, Director of Support Services, Office of Vice President for Research at (979) 845-4067.

Consent: I have read and understand the explanation provided me. I have had my questions answered to my satisfaction, and I voluntarily agree to participate in this study. I have been provided a copy of this consent form.

________________________________ ___________

Signature of Research Participant Date

________________________________ ___________

Signature of Principal Investigator Date

APPENDIX I

INSTRUCTIONS

DriveSafety is an interactive simulator, which means the driving scenario you experience reacts to your steering and pedal inputs to provide a realistic driving experience. Please drive in a normal fashion and obey all traffic laws.

Practice Scenario: Your task is to become familiar with the handling and control of the simulator vehicle and to become adapted to the simulated environment. When the scenario begins, place the vehicle into *drive*, and follow the car traveling in front of you. The lead vehicle will slowly increase its speed to 55 mph. Please continue to follow the lead car. This scenario takes approximately five minutes to drive. At the end of the scenario, indicated by the stop sign, stop the vehicle and place it into *park*.

Experimental Scenario: Your task is to drive through the experimental scenario, passing slower impeding vehicles in a realistic and judicious manner. The scenario has a 20 mile section rural road, with a 55 mph speed limit. When the scenario begins, place the vehicle into drive and turn onto the roadway. When you encounter slower impeding vehicles, overtake these vehicles using the oncoming lane. Pay attention to oncoming vehicles. Do not make unsafe passing maneuvers. This scenario takes approximately 25 minutes to drive. At the end of the scenario, indicated by the stop sign, the stop sign, stop the vehicle and place it into *park*.

APPENDIX J

SUMMARY OF PASSING DATA – CONVENTIONAL DEFINITION

Maneuver	Impeding Vehicle			t_2	d_2	G_S	G_E
	Description	Speed	Length (m)	(s)	(m)	(m)	(m)
3M1	Blue car	Slow	4.72	18.40	427.99	19.53	46.90
3M2	Gray truck	Slow	6.31	18.10	416.38	23.44	32.20
3M3	White truck	Fast	6.31	27.40	654.55	25.01	42.42
3M4	Red car	Fast	4.72	17.30	444.40	16.76	45.09
6M1	Red car	Fast	4.72	25.30	625.15	26.14	46.92
6M2	Gray truck	Slow	6.31	16.40	404.52	35.59	37.70
6M3	White truck	Fast	6.31	22.00	555.17	34.24	38.64
6M4	Blue car	Slow	4.72	9.80	248.16	17.59	31.19
7F1	White truck	Fast	6.31	71.30	1625.52	25.67	51.44
7F2	Red car	Fast	4.72	40.40	993.67	19.41	99.71
7F3	Gray truck	Slow	6.31	20.80	529.46	41.45	71.08
7F4	Blue car	Slow	4.72	49.60	1098.40	47.00	81.75
10F1	Red car	Fast	4.72	18.40	494.28	10.36	78.13
10F2	White truck	Fast	6.31	30.80	734.63	18.60	44.78
10F3	Gray truck	Slow	6.31	22.00	542.34	17.72	84.91
10F4	Blue car	Slow	4.72	41.00	883.78	13.60	66.85
11M1	Blue car	Slow	4.72	9.70	247.82	7.41	47.39
11M2	Red car	Fast	4.72	13.70	370.14	30.62	35.07
11M3	White truck	Fast	6.31	10.40	298.75	29.67	33.62
11M4	Gray truck	Slow	6.31	11.90	284.13	12.60	29.39
13F1	Blue car	Slow	4.72	17.80	439.40	14.70	75.87
13F2	White truck	Fast	6.31	23.10	557.22	11.73	43.06
13F3	Gray truck	Slow	6.31	21.20	503.18	18.62	59.65
13F4	Red car	Fast	4.72	16.50	419.63	10.76	45.50
14M1	Blue car	Slow	4.72	8.80	221.63	17.88	25.77
14M2	White truck	Fast	6.31	21.40	540.96	18.09	60.28
14M3	Red car	Fast	4.72	17.00	438.91	21.82	47.23
14M4	Gray truck	Slow	6.31	21.60	500.94	17.22	62.65
17F1	White truck	Fast	6.31	23.50	575.86	28.69	41.70
17F2	Gray truck	Slow	6.31	20.30	490.50	26.59	57.51
17F3	Blue car	Slow	4.72	18.30	471.42	22.89	86.79
17F4	Red car	Fast	4.72	15.40	419.41	19.64	57.78
18M1	Gray truck	Slow	6.31	9.60	229.87	9.10	23.64
18M2	Blue car	Slow	4.72	10.30	245.97	5.90	31.28
18M3	Red car	Fast	4.72	16.20	399.85	8.58	32.89
18M4	White truck	Fast	6.31	19.70	478.55	15.67	29.24
21F1	Gray truck	Slow	6.31	21.80	542.16	20.29	87.30
21F2	Red car	Fast	4.72	13.90	393.77	16.19	75.02
21F3	White truck	Fast	6.31	11.70	318.55	33.02	24.37
21F4	Blue car	Slow	4.72	11.90	290.34	12.03	39.49

Maneuver	Impeding Vehicle			t_2 (s)	d_2 (m)	G_S (m)	G_E (m)
	Description	Speed	Length (m)				
22F1	Red car	Fast	4.72	8.80	232.29	10.90	27.74
22F2	Blue car	Slow	4.72	10.10	238.70	13.74	21.76
22F3	Gray truck	Slow	6.31	12.80	296.95	17.37	21.43
22F4	White truck	Fast	6.31	13.60	340.24	16.65	22.95
24F1	Gray truck	Slow	6.31	15.90	379.56	40.67	25.10
24F2	Blue car	Slow	4.72	13.10	341.72	41.07	38.02
24F3	White truck	Fast	6.31	24.80	634.69	75.77	22.83
24F4	Red car	Fast	4.72	14.50	374.82	34.80	23.31
27F1	White truck	Fast	6.31	28.60	699.96	38.74	41.02
27F2	Blue car	Slow	4.72	15.00	410.81	43.24	68.94
27F3	Red car	Fast	4.72	10.50	294.86	31.96	34.66
27F4	Gray truck	Slow	6.31	22.90	536.47	32.35	50.89
28M1	Gray truck	Slow	6.31	15.70	384.33	16.21	51.31
28M2	White truck	Fast	6.31	18.60	461.43	28.22	23.47
28M3	Blue car	Slow	4.72	13.30	343.36	22.81	53.48
28M4	Red car	Fast	4.72	14.30	384.22	22.34	44.77
29F1	White truck	Fast	6.31	47.40	1096.53	29.57	41.39
29F2	Gray truck	Slow	6.31	23.50	553.95	44.01	44.48
29F3	Red car	Fast	4.72	18.60	483.70	18.98	54.39
29F4	Blue car	Slow	4.72	17.60	471.01	39.97	81.56
30F1	Gray truck	Slow	6.31	32.90	715.60	17.18	47.53
30F2	White truck	Fast	6.31	21.10	512.80	17.08	42.55
30F3	Red car	Fast	4.72	17.30	423.53	14.03	40.18
30F4	Blue car	Slow	4.72	17.30	410.01	13.75	55.86

APPENDIX K

SUMMARY OF PASSING DATA – ALTERNATE DEFINITION

Maneuver	Impeding Vehicle			$\dot{t}_2$ (s)	$\dot{d}_2$ (m)	$\dot{G}_S$ (m)	$\dot{G}_E$ (m)
	Description	Speed	Length (m)				
3M1	Blue car	Slow	4.72	12.40	294.83	16.11	28.73
3M2	Gray truck	Slow	6.31	13.90	327.98	19.38	24.15
3M3	White truck	Fast	6.31	13.40	342.77	26.15	19.30
3M4	Red car	Fast	4.72	12.20	317.24	13.17	30.61
5M1	White truck	Fast	6.31	12.00	316.71	19.20	20.71
5M2	Red car	Fast	4.72	6.70	184.62	12.60	18.84
5M3	Blue car	Slow	4.72	6.70	175.23	14.31	17.94
5M4	Gray truck	Slow	6.31	9.70	247.65	9.21	24.04
6M1	Red car	Fast	4.72	11.00	292.68	15.30	29.44
6M2	Gray truck	Slow	6.31	10.80	281.71	28.31	32.65
6M3	White truck	Fast	6.31	14.10	382.33	31.03	34.51
6M4	Blue car	Slow	4.72	7.00	182.85	10.67	23.60
7F1	White truck	Fast	6.31	14.60	383.46	15.18	39.63
7F2	Red car	Fast	4.72	12.20	338.16	10.36	54.35
7F3	Gray truck	Slow	6.31	9.90	269.13	31.63	33.17
7F4	Blue car	Slow	4.72	8.20	227.14	10.20	47.66
10F1	Red car	Fast	4.72	10.80	277.76	6.25	27.57
10F2	White truck	Fast	6.31	13.70	358.79	10.25	40.55
10F3	Gray truck	Slow	6.31	12.40	306.03	11.83	38.81
10F4	Blue car	Slow	4.72	9.10	234.77	3.20	45.05
11M1	Blue car	Slow	4.72	7.30	188.12	2.96	33.26
11M2	Red car	Fast	4.72	5.60	163.88	6.82	24.67
11M3	White truck	Fast	6.31	8.50	246.20	22.46	26.79
11M4	Gray truck	Slow	6.31	10.40	250.66	9.04	25.65
12F1	Blue car	Slow	4.72	9.00	219.28	4.73	27.50
12F2	Gray truck	Slow	6.31	11.90	281.32	9.54	27.81
12F3	Red car	Fast	4.72	6.10	154.29	3.41	9.93
12F4	White truck	Fast	6.31	7.80	208.07	9.24	18.01
13F1	Blue car	Slow	4.72	8.30	212.81	3.70	40.25
13F2	White truck	Fast	6.31	9.30	245.19	13.40	20.39
13F3	Gray truck	Slow	6.31	11.60	292.49	10.15	42.21
13F4	Red car	Fast	4.72	11.00	286.75	7.56	32.07
14M1	Blue car	Slow	4.72	7.10	177.55	14.37	13.88
14M2	White truck	Fast	6.31	9.70	251.69	13.63	18.41
14M3	Red car	Fast	4.72	10.90	284.86	19.19	22.69
14M4	Gray truck	Slow	6.31	11.50	268.83	14.36	19.87
15M1	Red car	Fast	4.72	10.10	262.60	7.20	26.18
15M2	White truck	Fast	6.31	12.20	305.61	12.56	21.71
15M3	Blue car	Slow	4.72	8.40	206.01	9.61	21.48
15M4	Gray truck	Slow	6.31	12.00	275.63	8.01	21.52

Maneuver	Impeding Vehicle			$\dot{t}_2$ (s)	$\dot{d}_2$ (m)	$\dot{G}_S$ (m)	$\dot{G}_E$ (m)
	Description	Speed	Length (m)				
16M1	Red car	Fast	4.72	8.00	225.35	6.61	36.56
16M2	Blue car	Slow	4.72	7.50	196.98	6.57	35.26
16M3	White truck	Fast	6.31	11.40	303.82	24.31	21.51
16M4	Gray truck	Slow	6.31	11.00	272.72	17.08	27.84
17F1	White truck	Fast	6.31	13.20	356.58	24.07	36.57
17F2	Gray truck	Slow	6.31	14.10	348.52	22.80	38.62
17F3	Blue car	Slow	4.72	11.10	282.37	16.54	38.52
17F4	Red car	Fast	4.72	11.10	302.18	15.66	36.96
18M1	Gray truck	Slow	6.31	7.10	174.27	5.21	18.57
18M2	Blue car	Slow	4.72	8.80	211.03	1.80	26.24
18M3	Red car	Fast	4.72	7.80	203.41	1.79	23.48
18M4	White truck	Fast	6.31	7.90	205.59	2.32	20.22
19M1	Gray truck	Slow	6.31	10.70	255.43	6.68	27.16
19M2	Red car	Fast	4.72	10.30	257.71	3.68	22.24
19M3	Blue car	Slow	4.72	9.40	234.15	13.25	29.54
19M4	White truck	Fast	6.31	12.00	305.75	14.53	20.51
20M1	Blue car	Slow	4.72	7.50	204.06	7.93	40.40
20M2	Red car	Fast	4.72	7.80	215.23	7.58	27.34
20M3	Gray truck	Slow	6.31	7.80	208.13	13.23	28.01
20M4	White truck	Fast	6.31	7.90	212.56	12.88	16.73
21F1	Gray truck	Slow	6.31	10.60	270.35	14.53	36.39
21F2	Red car	Fast	4.72	7.30	198.36	9.71	22.46
21F3	White truck	Fast	6.31	8.40	233.18	25.73	13.86
21F4	Blue car	Slow	4.72	8.90	218.24	6.49	26.76
22F1	Red car	Fast	4.72	6.40	169.41	4.93	18.80
22F2	Blue car	Slow	4.72	7.60	181.87	8.57	13.68
22F3	Gray truck	Slow	6.31	9.90	234.67	11.45	17.51
22F4	White truck	Fast	6.31	10.90	276.46	13.91	17.32
23F1	White truck	Fast	6.31	16.30	414.76	34.17	20.44
23F2	Blue car	Slow	4.72	14.50	396.35	26.75	78.19
23F3	Gray truck	Slow	6.31	17.30	444.38	43.05	48.92
23F4	Red car	Fast	4.72	13.20	361.94	32.48	33.63
24F1	Gray truck	Slow	6.31	9.60	237.03	24.20	15.07
24F2	Blue car	Slow	4.72	8.90	242.21	28.12	28.62
24F3	White truck	Fast	6.31	19.60	511.99	65.22	13.96
24F4	Red car	Fast	4.72	10.80	288.08	30.91	16.60
25M1	Red car	Fast	4.72	10.60	286.12	10.05	36.45
25M2	Gray truck	Slow	6.31	10.80	256.08	11.86	21.67
25M3	Blue car	Slow	4.72	7.60	196.22	5.73	35.93
25M4	White truck	Fast	6.31	8.90	228.50	7.91	16.35
27F1	White truck	Fast	6.31	19.70	503.62	36.04	35.29
27F2	Blue car	Slow	4.72	9.20	252.06	33.63	28.68
27F3	Red car	Fast	4.72	7.60	213.34	24.76	16.05
27F4	Gray truck	Slow	6.31	8.80	241.39	16.00	30.57

Maneuver	Impeding Vehicle			$\dot{t}_2$ (s)	$\dot{d}_2$ (m)	$\dot{G}_S$ (m)	$\dot{G}_E$ (m)
	Description	Speed	Length (m)				
28M1	Gray truck	Slow	6.31	10.40	265.50	11.16	37.91
28M2	White truck	Fast	6.31	11.60	306.71	24.83	18.16
28M3	Blue car	Slow	4.72	8.80	238.87	15.64	41.27
28M4	Red car	Fast	4.72	10.20	283.33	21.98	33.63
29F1	White truck	Fast	6.31	13.70	365.10	31.58	26.94
29F2	Gray truck	Slow	6.31	13.70	340.89	38.95	23.11
29F3	Red car	Fast	4.72	10.70	292.37	19.42	32.05
29F4	Blue car	Slow	4.72	13.50	368.41	37.43	57.91
30F1	Gray truck	Slow	6.31	11.80	279.66	10.92	26.73
30F2	White truck	Fast	6.31	12.50	314.80	12.55	21.31
30F3	Red car	Fast	4.72	12.10	304.16	7.87	31.74
30F4	Blue car	Slow	4.72	10.20	246.23	10.45	29.80

APPENDIX L

PASSING DATA USED TO VALIDATE THE PASSING EQUATION

Maneuver	t_2 (s)	d_2 (m)	L_i (m)	L_p (m)	G_S (m)	G_E (m)	$\bar{s}_p$ (m/s)	$\bar{s}_i$ (m/s)
3M1	18.40	427.99	4.72	4.72	19.53	46.90	23.25	19.14
3M2	18.10	416.38	6.31	4.72	23.44	32.20	23.00	19.32
3M3	27.40	654.55	6.31	4.72	25.01	42.42	23.88	21.03
3M4	17.30	444.40	4.72	4.72	16.76	45.09	25.68	21.57
6M1	25.30	625.15	4.72	4.72	26.14	46.92	24.70	21.45
6M2	16.40	404.52	6.31	4.72	35.59	37.70	24.66	19.53
6M3	22.00	555.17	6.31	4.72	34.24	38.64	25.22	21.41
6M4	9.80	248.16	4.72	4.72	17.59	31.19	25.33	19.38
7F1	71.30	1625.52	6.31	4.72	25.67	51.44	22.80	21.55
7F2	40.40	993.67	4.72	4.72	19.41	99.71	24.59	21.41
7F3	20.80	529.46	6.31	4.72	41.45	71.08	25.44	19.52
7F4	49.60	1098.40	4.72	4.72	47.00	81.75	22.15	19.36
10F1	18.40	494.28	4.72	4.72	10.36	78.13	26.86	21.54
10F2	30.80	734.63	6.31	4.72	18.60	44.78	23.84	21.43
10F3	22.00	542.34	6.31	4.72	17.72	84.91	24.64	19.49
10F4	41.00	883.78	4.72	4.72	13.60	66.85	21.56	19.36
11M1	9.70	247.82	4.72	4.72	7.41	47.39	25.55	18.93
11M2	13.70	370.14	4.72	4.72	30.62	35.07	27.02	21.54
11M3	10.40	298.75	6.31	4.72	29.67	33.62	28.73	21.57
11M4	11.90	284.13	6.31	4.72	12.60	29.39	23.88	19.42
13F1	17.80	439.40	4.72	4.72	14.70	75.87	24.68	19.07
13F2	23.10	557.22	6.31	4.72	11.73	43.06	24.11	21.27
13F3	21.20	503.18	6.31	4.72	18.62	59.65	23.73	19.53
13F4	16.50	419.63	4.72	4.72	10.76	45.50	25.42	21.45
14M1	8.80	221.63	4.72	4.72	17.88	25.77	25.19	19.15
14M2	21.40	540.96	6.31	4.72	18.09	60.28	25.26	21.10
14M3	17.00	438.91	4.72	4.72	21.82	47.23	25.81	21.20
14M4	21.60	500.94	6.31	4.72	17.22	62.65	23.19	18.99
17F1	23.50	575.86	6.31	4.72	28.69	41.70	24.50	21.04
17F2	20.30	490.50	6.31	4.72	26.59	57.51	24.15	19.51
17F3	18.30	471.42	4.72	4.72	22.89	86.79	25.75	19.25
17F4	15.40	419.41	4.72	4.72	19.64	57.78	27.23	21.60
18M1	9.60	229.87	6.31	4.72	9.10	23.64	23.95	19.39
18M2	10.30	245.97	4.72	4.72	5.90	31.28	23.89	19.35
18M3	16.20	399.85	4.72	4.72	8.58	32.89	24.70	21.54
18M4	19.70	478.55	6.31	4.72	15.67	29.24	24.30	21.45
21F1	21.80	542.16	6.31	4.72	20.29	87.30	24.86	19.43
21F2	13.90	393.77	4.72	4.72	16.19	75.02	28.33	21.08
21F3	11.70	318.55	6.31	4.72	33.02	24.37	27.23	21.38
21F4	11.90	290.34	4.72	4.72	12.03	39.49	24.40	19.27

22F1	8.80	232.29	4.72	4.72	10.90	27.74	26.40	20.94
22F2	10.10	238.70	4.72	4.72	13.74	21.76	23.65	19.18
22F3	12.80	296.95	6.31	4.72	17.37	21.43	23.20	19.30
22F4	13.60	340.24	6.31	4.72	16.65	22.95	25.02	21.28
24F1	15.90	379.56	6.31	4.72	40.67	25.10	23.86	19.04
24F2	13.10	341.72	4.72	4.72	41.07	38.02	26.06	19.33
24F3	24.80	634.69	6.31	4.72	75.77	22.83	25.58	21.16
24F4	14.50	374.82	4.72	4.72	34.80	23.31	25.84	21.18
27F1	28.60	699.96	6.31	4.72	38.74	41.02	24.46	21.30
27F2	15.00	410.81	4.72	4.72	43.24	68.94	27.38	19.28
27F3	10.50	294.86	4.72	4.72	31.96	34.66	28.08	20.82
27F4	22.90	536.47	6.31	4.72	32.35	50.89	23.42	19.31
28M1	15.70	384.33	6.31	4.72	16.21	51.31	24.47	19.48
28M2	18.60	461.43	6.31	4.72	28.22	23.47	24.80	21.42
28M3	13.30	343.36	4.72	4.72	22.81	53.48	25.81	19.37
28M4	14.30	384.22	4.72	4.72	22.34	44.77	26.85	21.51
29F1	47.40	1096.53	6.31	4.72	29.57	41.39	23.13	21.40
29F2	23.50	553.95	6.31	4.72	44.01	44.48	23.56	19.34
29F3	18.60	483.70	4.72	4.72	18.98	54.39	25.99	21.55
29F4	17.60	471.01	4.72	4.72	39.97	81.56	26.74	19.32
30F1	32.90	715.60	6.31	4.72	17.18	47.53	21.75	19.45
30F2	21.10	512.80	6.31	4.72	17.08	42.55	24.30	20.95
30F3	17.30	423.53	4.72	4.72	14.03	40.18	24.48	20.80
30F4	17.30	410.01	4.72	4.72	13.75	55.86	23.69	19.13

APPENDIX M

VALIDATION RESULTS

Maneuver	Observed		Estimated		Estimation Error	
	t_2 (s)	d_2 (m)	t_2 (s)	d_2 (m)	t_2	d_2
3M1	18.40	427.99	18.44	428.646	0.19%	0.15%
3M2	18.10	416.38	18.13	417.047	0.19%	0.16%
3M3	27.40	654.55	27.52	657.02	0.42%	0.38%
3M4	17.30	444.40	17.34	445.142	0.20%	0.17%
6M1	25.30	625.15	25.39	627.069	0.35%	0.31%
6M2	16.40	404.52	16.42	404.878	0.10%	0.09%
6M3	22.00	555.17	22.03	555.74	0.16%	0.10%
6M4	9.80	248.16	9.79	247.899	-0.12%	-0.11%
7F1	71.30	1625.52	71.01	1618.66	-0.41%	-0.42%
7F2	40.40	993.67	40.39	993.465	-0.02%	-0.02%
7F3	20.80	529.46	20.85	530.513	0.24%	0.20%
7F4	49.60	1098.40	49.55	1097.58	-0.09%	-0.08%
10F1	18.40	494.28	18.39	494.099	-0.04%	-0.04%
10F2	30.80	734.63	30.83	735.154	0.10%	0.07%
10F3	22.00	542.34	22.07	543.765	0.31%	0.26%
10F4	41.00	883.78	40.95	882.948	-0.12%	-0.09%
11M1	9.70	247.82	9.70	247.874	0.02%	0.02%
11M2	13.70	370.14	13.71	370.408	0.08%	0.07%
11M3	10.40	298.75	10.38	298.33	-0.16%	-0.14%
11M4	11.90	284.13	11.90	284.071	-0.03%	-0.02%
13F1	17.80	439.40	17.82	439.848	0.12%	0.10%
13F2	23.10	557.22	23.12	557.522	0.09%	0.05%
13F3	21.20	503.18	21.24	504.074	0.20%	0.18%
13F4	16.50	419.63	16.56	421.025	0.39%	0.33%
14M1	8.80	221.63	8.78	221.231	-0.21%	-0.18%
14M2	21.40	540.96	21.49	542.812	0.40%	0.34%
14M3	17.00	438.91	17.05	439.913	0.27%	0.23%
14M4	21.60	500.94	21.67	502.373	0.30%	0.29%
17F1	23.50	575.86	23.54	576.635	0.16%	0.13%
17F2	20.30	490.50	20.47	494.399	0.83%	0.80%
17F3	18.30	471.42	18.33	471.981	0.15%	0.12%
17F4	15.40	419.41	15.42	419.777	0.10%	0.09%
18M1	9.60	229.87	9.59	229.655	-0.13%	-0.09%
18M2	10.30	245.97	10.26	245.22	-0.35%	-0.31%
18M3	16.20	399.85	16.12	398.144	-0.48%	-0.43%
18M4	19.70	478.55	19.58	475.976	-0.59%	-0.54%
21F1	21.80	542.16	21.85	543.129	0.23%	0.18%
21F2	13.90	393.77	13.89	393.396	-0.10%	-0.10%
21F3	11.70	318.55	11.69	318.394	-0.06%	-0.05%
21F4	11.90	290.34	11.87	289.757	-0.21%	-0.20%

22F1	8.80	232.29	8.81	232.518	0.09%	0.10%
22F2	10.10	238.70	10.05	237.697	-0.48%	-0.42%
22F3	12.80	296.95	12.77	296.301	-0.23%	-0.22%
22F4	13.60	340.24	13.54	338.777	-0.43%	-0.43%
24F1	15.90	379.56	15.92	379.914	0.14%	0.09%
24F2	13.10	341.72	13.14	342.446	0.30%	0.21%
24F3	24.80	634.69	24.77	633.78	-0.11%	-0.14%
24F4	14.50	374.82	14.51	374.924	0.08%	0.03%
27F1	28.60	699.96	28.66	701.02	0.19%	0.15%
27F2	15.00	410.81	15.02	411.216	0.14%	0.10%
27F3	10.50	294.86	10.48	294.336	-0.17%	-0.18%
27F4	22.90	536.47	22.96	537.586	0.25%	0.21%
28M1	15.70	384.33	15.75	385.296	0.30%	0.25%
28M2	18.60	461.43	18.57	460.509	-0.18%	-0.20%
28M3	13.30	343.36	13.31	343.512	0.05%	0.04%
28M4	14.30	384.22	14.34	384.985	0.25%	0.20%
29F1	47.40	1096.53	47.50	1098.51	0.21%	0.18%
29F2	23.50	553.95	23.58	555.543	0.35%	0.29%
29F3	18.60	483.70	18.66	484.953	0.32%	0.26%
29F4	17.60	471.01	17.65	472.054	0.30%	0.22%
30F1	32.90	715.60	32.97	717.072	0.22%	0.21%
30F2	21.10	512.80	21.13	513.374	0.14%	0.11%
30F3	17.30	423.53	17.34	424.393	0.23%	0.20%
30F4	17.30	410.01	17.33	410.671	0.18%	0.16%

VITA

Jacqueline Marie Jenkins

The University of British Columbia
Department of Civil Engineering
2324 Main Mall
Vancouver, B.C. Canada V6T 1Z4

Education
Ph.D., Civil Engineering, Texas A&M University, August 2004
M.E., Civil Engineering, Texas A&M University, May 2000
Ba.Sc., Civil Engineering, University of Waterloo, April 1996

Academic Awards and Honors
Southwest Region University Transportation Center Dr. William J. Harris Award, 2003
Eno Transportation Foundation Fellowship, 2003
Transportation Association of Canada Stantec Scholarship, 2001
National Dean's List, 2001
Institute of Transportation Engineers (ITE) District 9 Student Paper Award, 2001
AAA Foundation for Traffic Safety Fellowship, January 1999 to December 2002

Professional Experience
Graduate Research Assistant, Texas Transportation Institute, Jan. 1999 to Dec. 2003
Collision Investigator, Ryerson Vehicle Safety Research Center, Sep. 1997 to Dec. 1998
Junior Engineer, Marshall Macklin Monaghan, Apr. 1996 to Sep. 1997
Co-op Student, Marshall Macklin Monaghan, Sep. to Dec. 1995
Co-op Student, Toronto Transit Commission, Jan. to Apr. 1995, May to Aug. 1994
Co-op Student, ITX Technologies, Sep. to Dec. 1993
Summer Student, City of Ottawa, May to Aug. 1993, May to Aug. 1992

Professional Registration
Professional Engineers of Ontario, License #90481979

Honor Societies
Chi Epsilon, National Civil Engineering Honor Society, 2001
Phi Kappa Phi, Honor Society for Academic Excellence, 2001

Professional Memberships
American Society of Civil Engineers (ASCE)
Institute of Transportation Engineers (ITE)
- President, Texas A&M University Student Chapter of ITE, 2001
- Corresponding Secretary, Texas A&M University Student Chapter of ITE, 1999

Society of Automotive Engineers (SAE)