MODELING AND ANALYSIS OF IMPACTS OF RIGHT-TURN LANE LENGTHS

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Modeling and Analysis of Effects of Right Turn Lane Lengths

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ABSTRACT

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Turn lanes have been studied for several decades, with focus being on left-turn lanes and for urban areas. The need for right-turn lanes has been studied using the impact of such turn lanes on both safety and operational efficiency. However, the impacts of different right-turn lane lengths have not been studied well. The determinations of right-turn lane lengths have been based primarily on the deceleration of the right-turning vehicles, which happens to be one of the many factors that should influence such decisions. In this study the impacts of the right-turn lanes on two-lane roads with no controls on major roads have been modeled and analyzed. In particular, the impacts on the space mean speed and the delays have been studied using both the analysis of field data from several intersections around Minnesota and the analysis of the results from simulation models developed using CORridor SIMulation (CORSIM®).

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CHAPTER 1. INTRODUCTION

1.1. Background and Motivation

The use of turn lanes has become an important part of highway access management in many communities today. Even though the major emphasis has been on left-turn lanes, there are many important issues and design considerations that relate to right-turn movements and right-turn lanes at intersections and driveways. Much of the focus regarding turn lanes has been in urban areas, but now many turn lane related issues, particularly those related to right-turn lanes, have emerged as an important consideration in rural areas along major transportation corridors. The requirement for right-turn lanes has at times become a debatable issue between transportation professionals at Department of Transportation (DOT) and the developers. Often times, the bases for requiring the developers to build right-turn lanes have been challenged. The past studies on right-turn lanes have focused on analyzing whether there should be right-turn lane or not, and have led to development of criteria or warrants in form of volume thresholds for requiring right-turn lanes. Different states have used different volume thresholds and even criteria for establishing the need for right-turn lanes. There are still outstanding questions related to right-turn lane design as to how long taper should be and how long full width lane should be under different circumstances, which have not been adequately studied. A better understanding of these issues is needed. Resolution of such concerns will address important gap in knowledge and practice, resolve any conflicts between transportation professionals and developers when deciding regarding having a right-turn lane, and lead to improved practice of designing and implementing right-turn lanes.

1.2. Problem Statement

The use of right turn lanes follows the warrants needed for it. Typically, right turn movements are addressed at intersections and driveways in form of radius treatment, taper, or taper with full width lanes of different lengths. Offset right-turn lanes have also recently been used. The bases for deciding on the need for right-turn lanes are related to business access, cost, safety, and operational efficiency. There have been studies in past to study the need for right-turn lane based on geometric context, accident history, approach traffic volume, percentage of right-turning vehicles in approach traffic volume, speed, and type of right-turn treatment at the intersection or driveway. Such studies have tried to demonstrate the difference between the shared right-turn movement and the right-turn movements using exclusive turn lanes in terms of safety and operational impacts. There are still outstanding questions regarding the appropriateness of right-turn lane lengths. Typically, the lengths of the taper and full width turn lane have been based on the speeds on the intersection approaches, controls at the intersections, decelerating characteristics of right-turning vehicles, and speed at which right-turn movement takes place. There is more to be done to develop a fuller understanding of the effectiveness of differing lengths for broad range of conditions in terms of meeting safety and operational efficiency objectives. Use and analysis of field data for developing this understanding is very important, but can also be challenging and limiting. Some of such limitations can be handled effectively using simulation models in conjunction with the field data. Simulation model allows analysis of broad range of conditions, which might be difficult to do with analysis of field data alone. Nonetheless, field data are very useful in calibrating and validating simulation models, which in turn can provide credible analyses and results from simulation models for advancing knowledge and improving practice.

1.3. Objectives

The objectives of this research were two-fold:

- To collect and analyze field data related to right-turn lanes and their lengths, and develop statistical models for understanding operational impacts in form of speeds and delays of following through vehicles; and
- To develop simulation model to better understand the impacts of right-turn lanes of different lengths for variety of contexts on traffic operations in terms of delays and speeds of the following through vehicles.

1.4. Scope

The scope of the research was confined to use of right turn-lanes on two-lane roads with no control on major roads. The research and analyses were based on data collected at several intersections around the state of Minnesota. The research conducted here was focused on the operational impacts of different right turn treatments (shared as well as exclusive right-turn lanes of different lengths). The offset right-turn lanes were not studied. In particular, space mean speed and total delays to the following through vehicles were of interest. Both the data from field and simulation model were analyzed. The simulation was done using the simulation model developed by Federal Highway Administration (FHWA) called CORridor SIMulation (CORSIM®). The simulation model was calibrated and validated using field data. The analyses were conducted over 15-minute periods for calibration, validation, as well as different modeled scenarios.

1.5. Organization of Thesis

This thesis is organized into five chapters and includes a list of references and appendices. Chapter 2 provides review and synthesis of issues and the state-of-the-practice related to right-turn lanes, particularly related to the operational impacts and the lengths of right turn lanes. Chapter 3 describes the analysis of right-turn lanes and their lengths using field data. Chapter 4 provides discussion of the simulation model developed and the analyses using the results from the simulation models and related statistical models. Chapter 5 provides the key conclusions and recommendations resulting from this research.

CHAPTER 2. REVIEW OF RESEARCH AND PRACTICE RELATED TO RIGHT-TURN LANES

This chapter provides review and synthesis of issues, research, and state-of-practice related to use of right-turn lanes. First, treatments for right-turn movements are identified. Next, operational impacts are identified and discussed. Then, right-turn lane related operational studies are reviewed. Finally, warrants and guidelines related to right-turn lanes are synthesized.

2.1. Right-Turn Movement Contexts and Treatments

There are varying treatments at intersections and driveways to deal with right-turn movements, which are applied in different contexts and conditions. The treatments that are of focus in this research are the ones dealing with shared lanes (see (a), (b), and (c) in Figure 2.1) and exclusive lanes (see (d) and (e) in Figure 2.1).

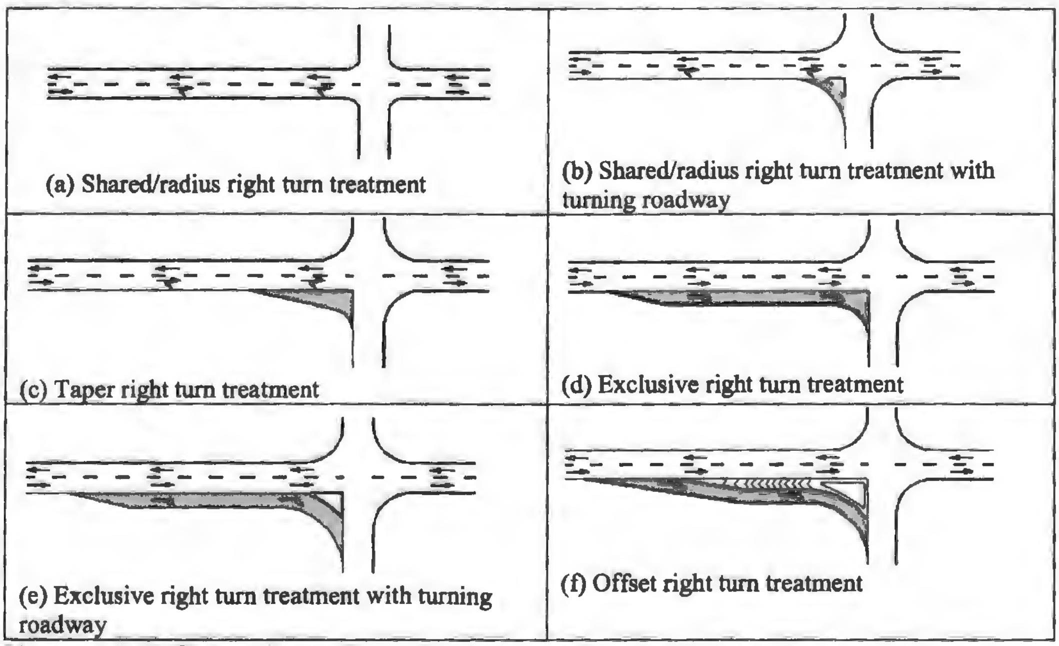

Figure 2.1. Different Right-Turn Contexts and Treatments.
Source: (Ale 2007)

Usually for low-volume and low-speed contexts just radius treatments are necessary. As traffic volume and speed increases, and the right turning vehicles increase, the need for turn lane arises. A large right turning vehicle such as a truck, while moving in the exclusive lane, can potentially obstruct the line of sight of the vehicle yielding at the minor cross road, which can lead to unsafe conditions and accidents. To address this problem, a new configuration of exclusive treatment called offset right turn treatment (see (f) in Figure 2.1) has been used. As the full-width lane is offset further from the traveled lane, the configuration allows unobstructed line of sight to yielding vehicle at the cross road.

2.2. Operational Impacts of Right-Turn Movements

Right turning movements take place at a lower speed. Thus, the right turning vehicles have to decelerate from the mainline speed to a speed considered safe for turning. The speed of the right turning vehicles is influenced by the curb radii and other conditions. The through vehicle following the right-turning vehicle has to slow down to maintain a safe distance from the leading right turning vehicle. Sometimes this impact can be translated to other through vehicles that follow the through vehicle following the right turning vehicle. Sometimes more than one vehicle may be turning right, which can extend the impact more.

This slowing down can result in safety and delay problems. There is deceleration of right turning vehicle to achieve turning speed. The following through vehicles decelerate to react to the slowing of the right-turning vehicles. There is formation of a speed-change cycle (see Figure 2.2, where V_i and a_i represent speeds and decelerations of following through vehicles). In addition, conflicts are generated due to this speed-change cycle.

Figure 2.2. Impact on Through Vehicles due to Right-Turning Vehicles.

Having a right-turn lane mitigates some of these effects as the right turning vehicle moves out of the through traffic stream quicker and at a higher speed. This, in turn, slows following through vehicles less and therefore delay experienced is less. The savings from reduced delay and other operational costs and enhanced safety can be balanced against the cost of incorporating turn lane in the project improvement. This balance can also be influenced by approach volume and number of right-turning vehicles in approach volume. Among the operational impacts are primarily the impacts on speed, the resulting delay to following through vehicles, and the increased cost from additional consumption of fuel. In this thesis the focus has been on delay and speed. A better understanding of the impacts on these two aspects can then also help in better estimating the energy and cost impacts.

Delay can be defined as the difference between the ideal travel time and the travel time under constraining conditions imposed by the slowing of the right turning vehicles. Several factors can affect the magnitude of the delay. Among these factors are posted speed limit, magnitude and variability in traffic demand, likelihood of right-turning traffic, geometric context at the location of interest, nature of control, nature of traffic on cross road, type of right-turn treatment, length of right turn lane, driver behavior and vehicle characteristics in through and turning traffic, and the presence of accesses in the vicinity. Driver and vehicle characteristics affect the car following behavior, which in turn affect the deceleration and acceleration of the vehicle and how close a vehicle follows the leading right turning vehicle. Intuitively, it can be concluded that higher traffic demand and especially higher right-turning traffic will cause more delays and will also increase likelihood of accidents, especially rear-end accidents.

Type of environment also tends to influence the operational impacts. The focus in this research is to assess the effectiveness of the right-turn lanes in both high- and low-speed environment on two-lane road where the major road had no controls. The low speed environment is typically found in urban environment whereas the high-speed is more a characteristic of rural environment. The rural areas are typically characterized by relatively much lower volume and high speed throughout the day. There are no discernible peak and off-peak periods. The headways between vehicles arriving at a point along a major road are random and the numbers of right-turning vehicles are very low. Consequently, the issue is most commonly a problem of speed differential between a right-turning vehicle and following through traffic and how it delays the through traffic in general. The urban areas have discernible peak periods, higher volume, lower speed, and vehicle arrivals are more frequent and even come in platoons when there is upstream signal. Due to increased development there are more movements, including turning movements. The lack of space and use of additional control may dictate the choice of length based on taper and storage and the deceleration is left on through lane. As a result, more delays can be experienced. However, speeds tend to be low so differential speed may be less. But, traffic levels are higher leading to accumulation of delays by more through vehicles being impacted by more right-turning traffic. This certainly poses challenges for adequately understanding the operational impacts under different conditions.

Type of right turn treatment also affects the operation and safety in certain ways. All reasonable combinations of curb return radii and throat width produce high speed differentials. Accident potential increases exponentially as speed differential increases. Thus, turn lanes are needed if acceptable (safe) speed differentials are to be achieved on major urban and rural streets. The use of long curb radii does not decrease the speed differential. However, it reduces the dispersion of the vehicle trajectories which drivers steer when entering an intersection or a driveway and potentially facilitates an easier entry maneuver. The use of a taper on the upstream side of the driveway or intersection does not significantly influence the speed of the vehicle making the driveway or intersection maneuver. However, the taper results in a reduction in exposure time (the time which the turning vehicle is blocking the through traffic lane). Lack of turn lane can increase delay and potential for accident. However, this could be insensitive up to a certain volume level or threshold.

2.3. Right-Turn Lane Related Operational Studies

Harmelink (1967) did a pioneering Canadian study and utilized a probabilistic model along with some field studies to establish left turn lane warrants for two-lane and four-lane highways at unsignalized T- intersections. Alexander (1970) conducted study in Indiana at ten different field sites, three having right-turn lanes and seven having no right-turn lanes. Primary data collected at these sites were approach volume, number of right-turns in approach volume, and average speed of through vehicles that were not delayed. The study applied regression approach to develop a delay (seconds/vehicle) equation using independent variables such as approach volume, number of right-turns in approach volume, and average speed of through vehicles that were not delayed. In addition, the study developed economic warrant for right-turn deceleration lane based on the tradeoff of savings in delay to through vehicles with the cost of construction, operation, and maintenance of turn-lanes.

Stover, Adkins, and Goodknight (1970) collected data on deceleration rate and right-turn speed using time-lapse photography at one field location. These data were used to calibrate a simulation model, which was used to compute the delay due to right-turning vehicles. The study found that the delay by right-turning vehicles increases exponentially as the volume in the driveway increases and the difference in speed in through traffic and driveway entrance increases.

Cottrell (1981) compiled existing research in 1981 and derived graphs, which delineated warranting volume thresholds at unsignalized intersections on both two- and four-lane rural roadways for multiple treatments: full turning lanes, a taper, and a radius. The volume thresholds were established based on a synthesis of relationships among the field data using regression approach, standards employed by many other states, and judgment. The variables considered include approach volume, posted roadway speed limit, and right-turn volume. This study has been the basis for guidelines used by many DOTs for determining the need of exclusive right-turn lanes or taper right-turn treatments.

Mounce (1983) used simplistic model analysis to formulate several probability statements to estimate the number of mainline through vehicles affected by right-turn movements at driveways. The study developed estimates for excess fuel consumption as function of driveway entrance speed. The study found that right-turn lane at driveway entrance could save over 30,000 gallons of fuel annually when the product of through lane hourly volume and right-turn lane hourly volume exceed 500,000.

McCoy et al. (1984) developed exponential equation to express delay savings in seconds per vehicle for left- turn lanes as a function of opposing volume, approach volume, and free-flow approach speed. This study used micro simulation software, Network Simulation (NETSIM), for the computation of operational effects, such as delay, fuel consumption, and stops. Due to errors in a series of NETSIM runs used for the simulation of right-turn lanes, the study adopted the delay savings equation developed for left-turn lanes for the right-turn lanes as well. For the computation of delay savings due to right-turn lanes, the same equation was used by replacing left-turn percentages with right-turn percentages and opposing volume set to zero. The warrants for turn lanes for rural two-lane highways on uncontrolled approaches in Nebraska were established by studying the operational effects of delay, fuel consumption, and stops.

Neuman (1985) reported the work carried out for a comprehensive study of intersection channelization, as a part of National Cooperative Highway Research Program (NCHRP) 279 study. One of the key assertions made in this report was that the safety impacts of right-turn movements are less critical than those of left-turn movements. This assertion was made based on the premise that right turns involve fewer and less severe conflicts, and tend to have lesser influence on the through traffic. However, the study reported that there are conditions for which added costs of providing exclusive right-turn lanes are fully justified by the improvements to traffic flow. The report contains the guidelines for determining the need for right-turn lanes, which were essentially adapted from Cottrell (1981).

McCoy et al. (1993) successfully simulated the uncontrolled approach with "shared" and "exclusive right-turn lane" using NETSIM software and established the delay equation for an uncontrolled approach for cases with and without a right-turn lane for two-lane and four-lane roads. It was found that the delay to through vehicles due to right-turning vehicles was affected significantly by the approach speed of the roadway, volumes at the approach, volumes of right-turning vehicles, the interactive term expressed as the product of volumes of right-turning vehicles, and the presence/absence of right-turn lane. The study developed warrant guidelines for right-turn lanes for urban two- and four-lane highways in Nebraska through cost-benefit analysis that took into account both operational and safety benefits the right-turn lanes were determined to provide to road users. The study, however, noted that the safety effects of right-turn lanes were not adequately quantified in the past mainly due to the limitations of available crash data. The safety effectiveness of right-turn lanes was, therefore, determined based on a relationship previously established between speed differentials and crashes, in which the underlying message is that the chance of being involved in a crash increases as the speed of a vehicle deviates from the average speed of traffic (Solomon 1964). The speed differentials between right-turning vehicles and through vehicles at intersection approaches without a right-turn lane were first estimated, which were then used to determine the expected number of rear-end crashes at such approaches.

Stover (1996b) developed a discussion paper on right-turn lanes for the Oregon Department of Transportation. Stover (1996b) also discussed the warrants in use in the Colorado Department of Transportation. Hasan and Stokes (1996) developed an equation for delay to through vehicles due to the effect of right-turning vehicles during their work for the development of guidelines for right-turn treatments, at unsignalized intersections and driveways, on the Kansas State highway system. According to the equation developed in this study, delay (seconds per right-turning vehicle) was a function of roadway speed and Directional Design Hour Volume (DDHV). Hasan and Stokes (1996) adapted these probability statements developed by Mounce (1983) to develop analytical models to predict the number of through vehicles that are affected by right turns (same as right-turn, same-direction conflicts, including the associated secondary conflicts) at radius right-turn treatments at approaches to unsignalized intersections and driveways on both two- and four-lane roadways. Hasan and Stokes (1996) also followed the cost-benefit approach to develop the volume warrants for right-turn treatments at the approaches to unsignalized intersections and driveways on rural two- and four-lane highways in Kansas. The safety benefits of providing right-turn lanes were quantified by adopting the same methodology formulated by McCoy et al. (1993).

McCoy and Bonneson (1996) developed volume warrants for free right-turn lanes at approaches to unsignalized intersections on rural two-lane highways based on the estimated operational cost savings achievable by providing free right-turn lanes. The study found that the safety effects of free right-turn lanes were not significant, and, therefore, the safety benefits were not incorporated in the cost-benefit analysis performed to determine the volume thresholds for free right-turn lanes.

Bonneson (1998) developed a deterministic/analytical model to predict the delay due to right-turning vehicles from the outside of a through lane of Major Street to through vehicles. To verify the developed model, the study compared computed delay with the delay obtained from the model developed by other researchers in the past using NETSIM software. This study illustrated that delay increases with the increasing flow rate in the outside through traffic lane, increasing major-street running speed, an increase in the portion of right-turns, or a decrease in the right-turn speed.

Wolfe and Lane (2000) collected field data from 15 intersections to study geometric delays due to the right-turning vehicles at the intersection, taking into account the radius of curvature of turns. The study concluded that with the decrease of radius curvature of travel way, the delay by right-turning vehicles to the through vehicles increases. The study put forward an analytical equation of the total time impacted by right- turning vehicles, taking into consideration deceleration time, clearance time, acceleration time of the through vehicle, the headway between adjacent vehicles, and a minimum headway of 1.9 seconds.

Harwood et al. (2002) provided a detailed safety effectiveness of left and right-turn lanes; however, the analysis for right-turn lanes is not as detailed as for left-turn lanes. Hadi and Thakkar (2003) used speed differentials as surrogate safety measures to evaluate the need for right-turn turn lanes at unsignalized intersections based on the data obtained from simulations as well as the field data collected from two locations in Florida. Wolfe and Piro (2003) developed a model for the delay of through vehicles by right-turning vehicles based on differences in the through and right -turning vehicles' speed, the total volume, and the right lane volume. The study was based on data collected from 12 intersections.

From a safety perspective, the operational impacts on through traffic caused by vehicles slowing down to turn may be translated into potential crashes related to speed differential. Speed differential related crashes are typically rear-end crashes. Previous studies did not specifically look at highways with traffic volumes below 4000 Average Annual Average Daily Traffic (AADT). It is commonly perceived that at volumes below 4000 AADT, the impact of right-turning traffic does not impact through traffic.

2.4. Warrants and Guidelines for Right-Turn Lanes

As mentioned earlier, right-turn lanes are provided at approaches of roadway intersections to facilitate the right-turn movements and to improve the traffic safety as well as the operational efficiency for the prevailing or anticipated road and traffic conditions. American Association of State Highway and Transportation Officials (AASHTO) has produced numerous guidelines for the geometric design of roads, streets, intersections, and interchanges, and addressed the need for auxiliary lanes as well. AASHTO (2004) presents a summary table of points on Harmelink (1967)'s graphed curves for two-lane highways. Interpretation of the table is difficult and many states have adopted forms of the graphs for two-lanes and remain consistent with AASHTO by excluding Harmelink (1967)'s four-lane highway curves.

AASHTO (2004) indicates that the length of a left- or right-turn lane is the sum of the following three components: (a) deceleration distance, (b) queue storage length, and (c) taper. Ideally, all deceleration is expected to occur after turning vehicle has cleared the through traffic lane. However, whether this happens in actuality is dependent of different geometric and operational conditions.

Common practice is to accept some deceleration in the through traffic lane. A reduction of more than 15 km/h (10 mph) on major roadways could be a concern. However, more deceleration while the turning vehicle still occupies part of the through lane may be acceptable on minor roadways or very low volume roads. In this research focus was on the approaches on major road which had no controls. Where access points are closely spaced, as in urban environments, the length of a turn lane may be limited to storage plus taper, which will require all or at least much of the deceleration to occur on the through traffic lane. Provision for deceleration clear of the through-traffic lanes is a desirable objective on arterial roads and streets and should be incorporated into design whenever feasible. The total length required is that needed for a safe and comfortable stop from the design speed of the highway. Minimum deceleration lengths for auxiliary lanes on grades of 2 percent or less, with an accompanying stop condition, for design speeds of 30, 40, and 50 mph are 235, 315, and 435 feet, respectively (AASHTO 2004). These lengths exclude the length of taper, which should be typically approximately 8 to 15 ft longitudinally to one foot transversely. The lengths given in AASHTO are accepted as a desirable goal and are expected to be provided where practical and feasible. However, the appropriateness of this from operational efficiency standpoint will be dependent on the type of geometric and operational conditions that exist. It was intended to study this aspect in greater detail using field data as well as data from simulation model by understanding how the right turning vehicles affect the through vehicles under different conditions.

Turning lanes at intersections tend to reduce accidents (crashes). Typically, state transportation departments review crash rates in determining the need for turn lanes and most review roadway volumes. States generally refer to American Association of State

Highway Transportation Officials (AASHTO) for guidance on highway design; however, most states have adopted volume warrants or guidelines at unsignalized intersections that supplement the AASHTO guidance, which is partial for left turn lanes and inadequate and even absent for right turn lanes. There appears to be greatest need for unsignalized intersections and driveways.

A review of several state DOT turn lane policies provided interesting insights. Ohio Department of Transportation (DOT) policies recognize that exclusive right-turn lanes are less critical in terms of safety than left turn lanes, right turn lanes can significantly improve the level of service of signalized intersections, and that right-turn lane can also provide a means of safe deceleration for right-turning traffic on high-speed facilities and separate right-turning traffic at stop-controlled intersections. As a general suggestion, Ohio DOT considers an exclusive right turn lane when the right turn volumes exceed 300 vehicles per hour (vph). It must be noted that a right-turn volume of 300 vph is extremely high.

In Iowa right turn lanes may be warranted if right turning traffic flow rate is greater than 30 vph and the approach volume is greater than 400 vph (IADOT 1995). Connecticut and Montana use the right-turn graph presented in Neuman (1985). The Oregon DOT uses a graph based on a series of discussion papers (Stover 1996a, 1996b). The volume criteria for a right turn lane compare the approaching design hourly volume in the outside lane with the right-turn design hourly volume. The right-turn lane volume warrants are based on Neumann (1985). Alaska requires right turn lane when the right-turn volume exceeds 25 vph. Idaho requires right-turn lanes when the design hourly volume (DHV) exceeds 200 vph and the right-turn volume exceeds 5 vph. Michigan DOT requires right-turn lane when the cross street average daily traffic (ADT) exceeds 600 vehicle per day (vpd). Utah requires right-turn lane when the DHV exceeds 300 vph and the cross street ADT exceeds 100 vpd. Virginia requires right-turn lanes when the DHV exceeds 500 vph and the cross street ADT exceeds 40 vph or when the cross street volume exceeds 120 vph on high-speed highways. Wisconsin requires right-turn lane when the highway ADT exceeds 2500 and the cross street ADT exceeds 1000. South Dakota DOT follows the policy Oregon DOT follows and also has provision to use right-turn lanes in locations where five or more accidents have taken place (SDDOT 2007). North Dakota DOT determines the need for turn lanes after conducting a traffic operation analysis, which is conducted by the Planning Division of NDDOT or by a consultant (NDDOT 2004). The current Mn/DOT Road Design Manual (Mn/DOT 2000) recommends a right-turn lane when the highway ADT exceeds 1500 in a rural area and the design speed is 45 mph or higher (Mn/DOT 2000). This volume threshold is lower than all the other states cited above who based the need for right-turn lanes on the highway AADT. Even the states that based the need for a turn lane on cross street traffic set the cross street volume threshold higher. Several of these states recommend some sort of right-turn treatment at lower volumes, primarily for the purpose of facilitating the turning vehicle to more quickly clear the through lane.

The provisions of right-turn lanes as a strategy for improving the traffic safety at unsignalized intersections and the various related strategy attributes have been documented in NCHRP Report 500 (Neuman et al. 2003). Gluck et al. (1999), as a part of NCHRP 420 study, reported on the impact of access management techniques, which also looks into the role and the use of right-turn lanes as a part of the broader strategy for access management for a corridor. The NCHRP Report 491 (McGee et al. 2003) and the NCHRP Report 500 (Neuman et al. 2003) suggest carrying out cost-benefit analyses to justify intersection improvements. The ultimate decision for right turn lanes is based on operational, safety, access, and cost considerations, which makes it a multi-faceted problem.

2.5. Summary

The previous sections reviewed and summarized various different right turn related studies and the findings related to safety effects due to use of right turn lane. This review was important to obtain an insight into the nature of impacts observed or determined by past studies. The review was also important in understanding what were the significant factors used in studying the operational impact of right-turn lanes and what methods were used to study the operational impacts. In general, data on approach volume, number of right turns in approach volume, approach speed, speed differential, and type of right-turn treatments seem to impact the operational impact of right turning vehicles. Operational impacts due to right turning vehicles have been studied using field data analysis, analytical methods, simulation analysis, or a combination of these methods. The considerations for right turn lane when approach volume is less than 4000 AADT are not well understood or established. It is commonly perceived that at volumes below 4000 AADT, the impact of right-turning traffic does not impact through traffic. The warrants for right turn lane vary by states and bases for developing the warrants also differ. The effect of different turn lane lengths on the operational impact has not been an emphasis or studied adequately. In this thesis the focus is primarily on the operational considerations.

CHAPTER 3. MODELING AND ANALYSIS USING FIELD DATA

The literature review provided good insights regarding what factors influence the operational impacts of the right-turning vehicle under different conditions. To develop better understanding, field data were collected at several locations around Minnesota. The description of methodology, data collection, data reduction, and analysis using field data are provided in this Chapter. This chapter is related to the development of statistical models that can provide a good fit for the set of field data and have a good prediction. Using multiple regression, the dependent variables, space mean speed and delays, were related to independent variables, such as posted speed, approach volume, percentage or number of right-turning vehicles in approach volume, pocket length (taper length plus length of full width lane), and their interactive terms.

3.1. Methodology

The intent was to develop predictive space mean speed and delay models using the field data. This was carried out using several steps. Appropriate sites were identified. This thesis is based on a larger project sponsored by Minnesota Department of Transportation (Mn/DOT). As a result, the selection of data collection sites was based on operational, safety, access, and cost considerations; however, it was influenced more by safety considerations. Out of 5400 locations that were studied for crashes, a random selection was made for the initial data collection sites. These sites were then surveyed initially for appropriateness and broader representation. All the sites were on two-lane major roads with no controls. A detailed discussion regarding site selection procedure used is discussed in Ale (2007) and Varma et al. (2008). The data collection sites were spread all over

Minnesota and provide a good representation of the broad range of conditions that was of interest.

Numerous field data that were critical in development of speed and delay models were collected at the data collection sites that were identified. The models to predict the space mean speeds of the through vehicles, the total delay (in vehicle-minutes) encountered by following through vehicles, and delay (in seconds per vehicle) by individual following through vehicles were developed as multiple regression models by using the method of least squares. For regression theories and assumptions, model building techniques, variables screening methods, model fit assessments and other regression-related issues, Mendenhall and Sincich (2003) may be referred. The general form of a multiple regression model is shown below.

$$y = \beta_0 + \beta_1.x_1 + \beta_2.x_2 + ... + \beta_k.x_k + \varepsilon; \qquad 3.1$$

where y = dependent variable;

β_0 = intercept parameter;

$\beta_1, \beta_2, \ldots, \beta_k$ = model coefficients;

$x_1, x_2, \ldots, x_k$ = independent variables, including interaction or higher order terms; and

ε = random error.

Models were developed based on the field data and using Minitab 15® software. The appropriateness and the predicting capabilities of field data based models were examined. Of particular interest in the model development was examining the effects of different pocket lengths. The pocket lengths are referred in this thesis as sum of taper length and length of full-width turn lanes. For a shared or radius treatment the pocket length was therefore zero.

The developed field data based models were validated by using the "Jack-knifing" method. The "Jack-knifing" method involves the calculation of predicted value $y'_{(i)}$ value for the i^{th} observation when the regression model is fit with the data point for y_i not considered in the sample. The measures of model validity, such as $R^2_{Jackknife}$ and $MSE_{Jackknife}$, were calculated using the equations given below.

$$R^2_{Jackknife} = 1 - [(\sum(y_i - y'_{(i)})^2) / (\sum (y_i - mean(y))^2)]; \quad 3.2$$

$$MSE_{Jackknife} = (\sum (y_i - y'_{(i)})^2) / (N-(K+1)); \quad 3.3$$

where, The term $(y_i - y'_{(i)})^2$ is also known as Prediction Sum of Squares (PRESS);

N represents the number of data or samples used in developing the model; and

K represents the number of variables (including the interaction terms) in the model.

The models were considered validated if $R^2_{Jackknife}$ was less than but close to the R^2 of the fitted model and the $MSE_{Jackknife}$ was greater than but close to the MSE of the fitted model. These jackknife measures give a more conservative (and more realistic) assessment of the ability of the model to predict future observations than the usual measures of model adequacy (Mendenhall & Sincich, 2003).

3.2. Data Collection

Field sites were selected to cover broad range of conditions that were relevant to the right turn lane contexts of interest. Traffic volume, spot speed, and time stamp data were collected at 14 intersections. The time stamp data were useful in developing headway profiles and in assessing space mean speed profiles for approach link to the intersection.

Time stamp data were also useful in developing travel time information. Spot speed data were collected using radar speed device. The volume data were collected using the JAMAR TDC-12 devices. The time stamped data were collected using the JAMAR TDC-12 devices and laptops with Traffic Tracker software.

The data collection locations were spread throughout Minnesota and involved both four-leg and three-leg (or T) intersections. The posted speed at these locations varied from 30 mph to 55 mph. There were both shared/radius treatments and exclusive turn lane treatment, with varying taper and full-width turn lane lengths. Depending upon traffic condition, especially right-turn volumes, data were collected in some cases from both approaches (for 4-legged intersections) and in other cases from only one approach of the intersection (for 3-legged intersections). Morning and evening hours were selected for collecting time-stamp data as well as speed and volume data. The physical inventory of each data collection site was done to get the intersection geometry including turn lane dimensions, lane widths, and intersection configuration. Instruments like radar guns, TDC-12, and laptops were used for data recording. Data were collected from the unsignalized and uncontrolled approach of the main street for both 4-legged and 3-legged intersections. Figure 3.1 and Tables 3.1 to 3.3 identify the locations and provide specific details regarding the data collection sites.

The field data were collected in the summers of 2007 and 2008 (see Table 3.3). The various field data collected include the following: intersection geometry (type, number of intersecting legs, skew angles, pavement widths, and turn lanes), right-turn treatment type

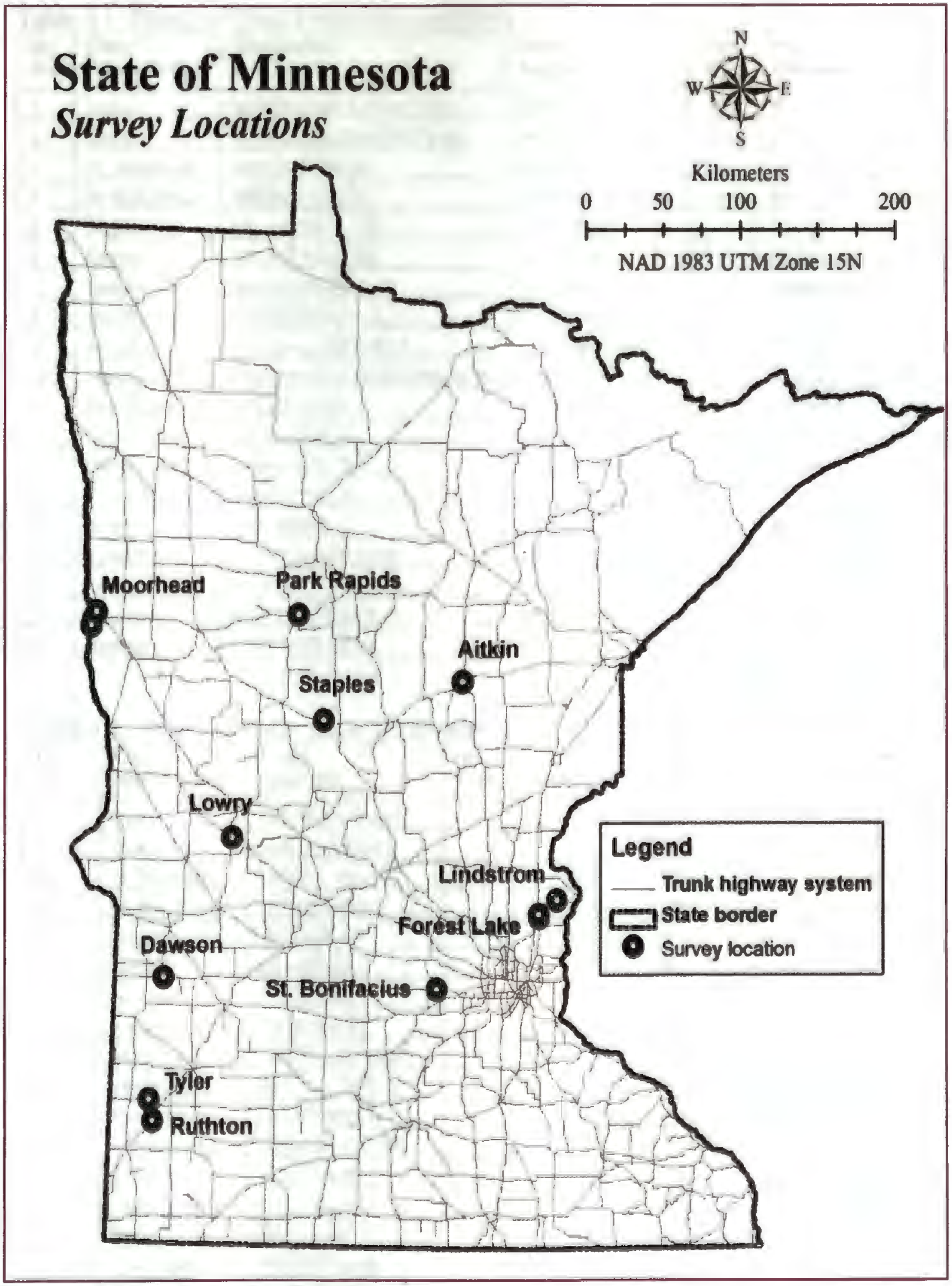

Figure 3.1. Data Collection Locations.
Source: (Varma et al. 2008)

Table 3.1. Details of Data Collection Locations.

Int No.	City / Nearest City	Intersection Description	Study Approach	Int. Type	Right-turn Treatment	Speed (mph)
1	Aitkin	MNTH-210/CR-54 & CR-56	MNTH-210 West	+	Radius	55
2	Aitkin	MNTH-210/CR-54 & CR-56	MNTH-210 East	+	Radius	55
3	St. Bonifacius	MNTH-7/CR-10	MNTH-7 West	+	Exclusive	55
4	St. Bonifacius	MNTH-7/CR-10	MNTH-7 East	+	Exclusive	55
5	Staples	US-10/12th St. NE	US-10 West	+	Radius	30
6	Staples	US-10/12th St. NE	US-10 East	+	Radius	30
7	Dawson	US-212/4th St.	US-212 East	+	Radius	30
8	Moorhead 1	US-75/46th Ave. S.	US-75 North	T	Exclusive	55
9	Moorhead 2	12th Ave. S/15th St. S	12th Ave. S. West	T	Radius	30
10	Moorhead 3	28th Ave. N. (CR-18)/34th St. N	28th Ave. N West	T	Radius	55
11	Park Rapids	MNTH-34/CR-4	MNTH-34 East	T	Exclusive	55
12	Forest Lake 1	US-61/240th St.	US-61 North	+	Shared	55
13	Forest Lake 2	US-61/250th St.	US-61 North	+	Exclusive	55
14	Forest Lake 2	US-61/250th St.	US-61 South	+	Exclusive	55
15	Tyler	US-14/CR-8	US-14 East	T	Exclusive	35
16	Lindstrom	MNTH-8/Akerson St.	MNTH-8 West	+	Exclusive	30
17	Lowry	M55/CR 114	M55 - West	T	Radius	30
18	Ruthton	MNTH-23/CR-10	MNTH-23 North	+	Exclusive	55
19	Ruthton	MNTH-23/CR-10	MNTH-23 South	+	Exclusive	55

Table 3.2. Details of Right Turn Treatments at Data Collection Locations.

Int No.	City / Nearest City	Study Approach	Int. Type	Taper Length (ft)	Full Width Lane Length (ft)	Total Length (ft)
1	Aitkin	MNTH-210 West	+	0	0	0
2	Aitkin	MNTH-210 East	+	0	0	0
3	St. Bonifacius	MNTH-7 West	+	180	250	430
4	St. Bonifacius	MNTH-7 East	+	200	240	440
5	Staples	US-10 West	+	0	0	0
6	Staples	US-10 East	+	0	0	0
7	Dawson	US-212 East	+	0	0	30
8	Moorhead 1	US-75 North	T	170	240	410
9	Moorhead 2	12th Ave. S. West	T	0	0	0
10	Moorhead 3	28th Ave. N West	T	0	0	0
11	Park Rapids	MNTH-34 East	T	157	142	299
12	Forest Lake 1	US-61 North	+	0	0	0
13	Forest Lake 2	US-61 North	+	185	280	465
14	Forest Lake 2	US-61 South	+	200	240	440
15	Tyler	US-14 East	T	75	160	235
16	Lindstrom	MNTH-8 West	+	173	188	361
17	Lowry	M55 - West	T	0	0	0
18	Ruthton	MNTH-23 North	+	186	276	462
19	Ruthton	MNTH-23 South	+	180	280	460

Table 3.3. Time for Data Collection.

Serial	Location	Date	Time Stamp and Spot Speed Studies
1	Aitkin		Morning and Afternoon
2	Dawson	29-May-07	Morning
3	Forest Lake (1)	22-May-07	Morning
4	Forest Lake (2)	30-May-07	Morning and Afternoon
5	Lindstrom	22-May-07	Afternoon
6	Lowry	25-May-07	Afternoon
7	Moorhead (1)	1-Jun-07	Morning
8	Moorhead (2)	5-Jun-07	Morning
9	Moorhead (3)	5-Jun-07	Afternoon
10	Park Rapids	31-May-07	Afternoon
11	Ruthton	24-May-07	Morning and Afternoon
12	St. Bonifacius	23-May-07; 29-May-07	Morning and Afternoon
13	Staples (1)	31-May-07	Morning
14	Staples (2)	31-May-07	Morning
15	Staples (3)	31-May-07	Morning
16	Tyler	25-May-07	Morning

(including right-turn pocket length and right-turn taper length in case of exclusive right-turn lane treatment), posted speed limit for the study approach, approach traffic volumes, and right-turn traffic volumes during 15-minute time intervals.

Volume data were collected at 15-minute time intervals using JAMAR TDC-12 device for the study approach of interest. In addition, spot speed and time stamped data were collected at specific locations, which varied for shared and exclusive right turn treatments. Time Stamp Data were collected using JAMAR's Traffic Data Collector (TDC-12). Spot Speeds were collected using Laser and Radar Guns. For shared or radius right turn treatments time stamp data were collected at points B and A, and spot speeds were collected at points X, B and A (see Figure 3.2). For exclusive right-turn treatments time stamp data were collected at points B, C and A, and spot speeds were collected at points X, B, C and A (see Figure 3.3).

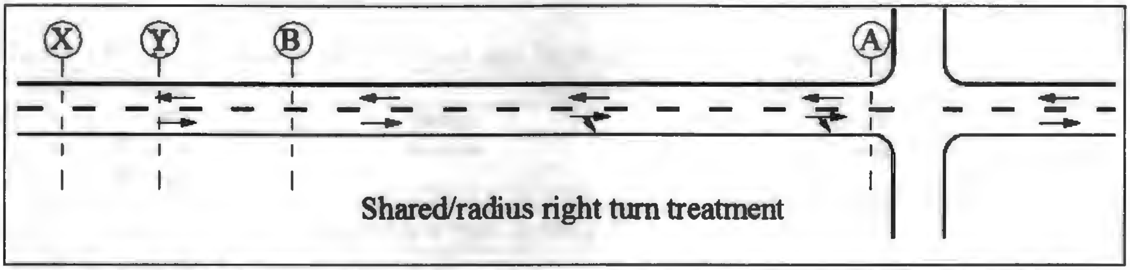

Figure 3.2. Data Collection for Shared/Radius Right Turn Treatments.
Source: (Varma et al. 2008)

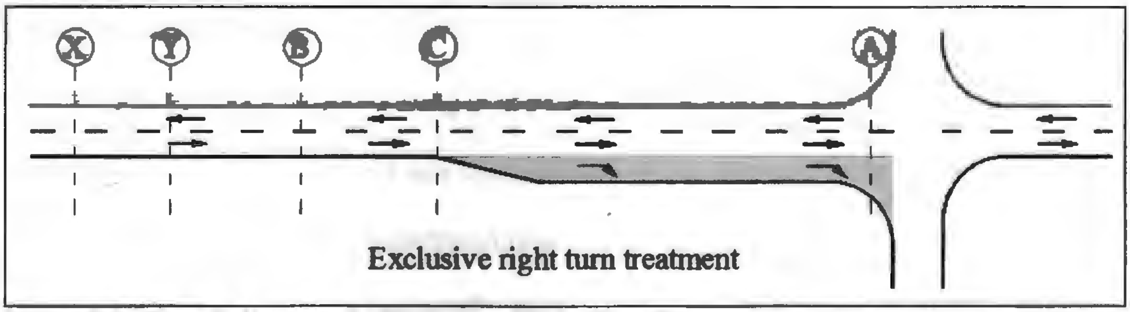

Figure 3.3. Data Collection for Exclusive Right Turn Treatments.
Source: (Varma et al. 2008)

The time-gap data were collected by using TDC-12's at points A, B or C simultaneously in a time-synchronized manner by two or three observers, as applicable, for a minimum time period of two hours. On the other hand, the spot-speed data, collected by using Laser/Radar guns, were observed by two observers together; one to direct the Laser/Radar gun towards the traffic and the other to record the observed spot speeds. A minimum of eighty spot-speed observations were collected at each of these points (A, B, X or C, see Table 3.4 below). Whenever possible, every care was taken by the spot-speed observers to be hidden or inconspicuous from the traffic on the study approach to avoid affecting the traffic behavior.

Table 3.4. Specifications of Time-Gap and Spot-Speed Data Collection Points.

Point	Data Type	Right-turn Treatment Type	
		Radius	Exclusive Lane
A	Time gap, Spot speed	Stop bar	Stop bar
B	Time gap, Spot speed	200 ft from point A at 'low' speed approach 500 ft from point A at 'high' speed approach	Start of the right-turn lane taper
C	Time gap, Spot speed	-	200 ft from point B at 'low' speed approach 500 ft from point B at 'high' speed approach
X	Spot speed	More than 800 ft from stop bar	More than 800 ft from stop bar

Note: Low speed means less than or equal to 40 mph and High Speed is Greater than 40 mph

3.3. Data Reductions

Field data were reduced using post processing of TDC data that were collected. The recorded data from the field was uploaded into computers same day they were collected. Records were first transferred into computers in their original file formats. Later, the data was processed in Excel®. The processed, final data included average spot speeds, free-flow speeds, space mean speeds, and the data related to site geometry. Final tables were developed from the processed data.

The intent of data collection was also to fulfill the data requirement for calibration and field validation of the simulation models that are discussed in next chapter. Data processing and reduction included the steps involved in the processing of lane geometry data, records from TDC-12, data from traffic tracker software on laptop, and the radar gun. The intent was to make the data readily usable for statistical modeling and analysis, and also for calibration and validation of simulation model. Lane geometry data was recorded from the site and compiled with intersection drawings. Later, the data was tabulated making it readily usable for developing statistical models and base simulation models. For spot speeds, the values observed from the radar gun were noted in the field book. The records were then entered into Excel® to compute the averages. The spot speeds included the free-flow speed and the spot speed of vehicles at A, B and C, and also the spot speeds of right-turning vehicles.

Records from TDC-12 were downloaded as a Petra Pro® data file. In order to process the data, the data was exported into EXCEL®. The data from the traffic tracker was readily downloadable in EXCEL® without any transformation. These data were in the form of time records for each vehicle at position A and B for shared case, and A, B and C for exclusive case, as shown earlier in Figures 3.2 and 3.3. The data were processed to calculate the travel time for all vehicles, the travel times for right-turning vehicles and through vehicles, the number of right-turning and through vehicles, the space mean speed of through vehicles, the space mean speed of right-turning vehicles and the delay for through vehicles in terms of vehicle-minutes as well as seconds per through vehicles.

The time of travel from B to A in the shared case (see Figure 3.2) was computed by taking the difference in time stamps at points B and A. The time of travel from C to A in the exclusive case (see Figure 3.3) was determined by the difference in time stamps at C and A. Total travel time for through vehicles was calculated as the summation of individual times of travel of all through vehicles. Similarly, total travel time for right-turning vehicles was determined as the summation of individual time of travel of all right-turning vehicles . Following four important equations were used to determine the total travel time for through vehicles under free-flow conditions (Equation 3.4), the space mean speeds (Equation 3.5), total delay for through vehicles (Equation 3.6), and average vehicle delay (Equation 3.7).

Total time for travel for through vehicles in free-flow speed

$$= (\text{link length}/\ \text{free-flow speed}) * \text{Number of through vehicles} \qquad 3.4$$

Space mean speed (for through or right-turning vehicles)

= (Number of through or right-turning vehicles * Link length)/
Total time for travel for through or right-turning vehicles 3.5

Total Delay (vehicle-minutes) for through vehicles

= Total time of travel for through vehicles –
Total time for travel for through vehicles in free-flow speed 3.6

Delay (seconds/through vehicle)

= (Delay (vehicle-minutes) * 60)/ (Number of through vehicles) 3.7

3.4. Models

The least squares prediction models, using field data, was developed based on approximately eighty independent observations. The data for 15-minute time intervals were used in developing models. Three different models were developed for through vehicle's space mean speed, total delay to through vehicles, and average vehicle delay to through vehicles. The dependent variables in the three models were the average space mean speed in miles per hour (mph), total vehicle delay in vehicle-minutes, and average vehicle delay in seconds per through vehicle, respectively, observed during a 15-minute time interval. The independent variables considered were posted roadway speed limit, total approach volume (during 15-minute time interval), right-turn volume or right turn percentage (during 15-minute time interval), pocket length (taper plus full width lane length), and the interaction terms. Stepwise regressions were carried out first to identify the significant independent variables, including the interaction and the higher order terms. After removing insignificant variables from the model-building process, the prediction model that finally fitted the best was determined. If interaction terms turned out to be significant then the individual terms were retained in the model, despite the individual terms not having significant probability values.

3.4.1. Model 1: Field Data Based Space Mean Speed Statistical Model

The space mean speed prediction model that finally best fitted the field data is provided below as Equation 3.8. The model was for determining the space mean speed of the through vehicles.

$$\text{SMS-TH} = 3.376 + 0.87176*(\text{SPEED}) + 0.03462*(\text{VOL}) - 6.183*(\text{RT\%}) + 0.00759*(\text{POC}) - 0.00016682*(\text{POC})*(\text{VOL}) + 0.06454*(\text{RT\%})*(\text{POC}) \qquad 3.8$$

$[S = 4.66709, R^2 = 84.10\%, \text{Adj. } R^2 = 82.80\%]$

where SMS-TH = space mean speed of through vehicles (in mph);

SPEED = posted speed for the approach (in mph);

VOL = approach volume during 15-minute time interval;

RT% = percentage of vehicles in 15-minute approach volume turning right; and

POC = pocket length (taper length plus full-width lane length).

The parameter estimates and the residual plots of the field data based space mean speed statistical model are presented in Table 3.5 and Figure 3.4, respectively.

Table 3.5. Parameter Estimates of Field Data Based Space Mean Speed Statistical Model.

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	3.37600	2.616	1.29	0.201
(SPEED)	0.87176	0.06865	12.70	0.000
(VOL)	0.03462	0.02469	1.40	0.165
(RT%)	-6.1830	5.916	-1.05	0.299
(POC)	0.007591	0.006747	1.13	0.264
(POC)*(VOL)	-0.00016682	0.00006183	-2.70	0.009
(RT%).(POC)	0.06454	0.02463	2.62	0.011

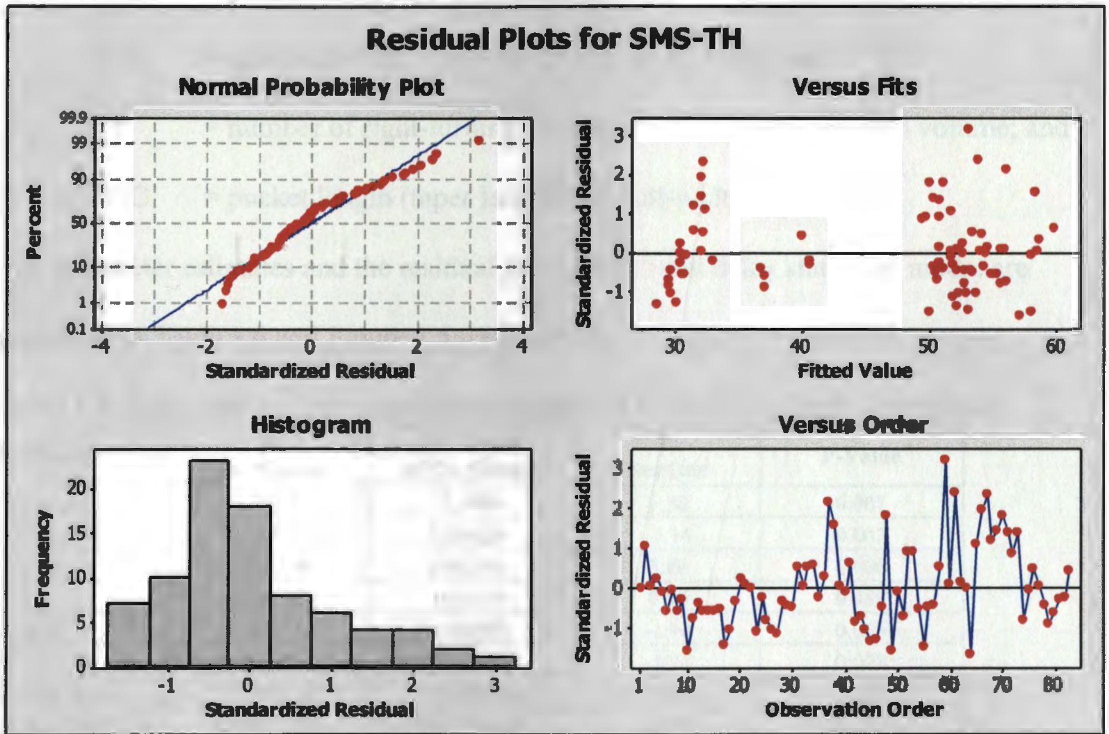

Figure 3.4. Residual Plots for Field Data Based Space Mean Speed Statistical Model.

3.4.2. Model 2: Field Data Based Total Delay Statistical Model

The total vehicle delay (in vehicle-minutes) prediction model that finally best fitted the field data is provided below as Equation 3.9. This model is for determining the cumulative delay (in vehicle-minutes) encountered by through vehicles on the approach link leading to the intersection.

$$\begin{aligned} TD = {} & 1.2555 - 0.029184*(SPEED) + 0.011338*(VOL) + 0.01635*(RT) \\ & - 0.007116*(POC) - 0.0004142*(RT)*(VOL) \\ & + 0.00002251*(POC)*(VOL) + 0.00014267*(POC)*(SPEED) \qquad 3.9 \end{aligned}$$

$[S = 0.607431, R^2 = 57.30\%, \text{Adj. } R^2 = 53.30\%]$

where TD = total delay (in vehicle-minutes) by through vehicles during the 15-minute time interval;

SPEED = posted speed for the approach (in mph);

VOL = approach volume during 15-minute time interval;

RT = number of right-turning vehicles in 15-minute approach volume; and

POC = pocket length (taper length plus full-width lane length).

The parameter estimates and the residual plots of the total delay statistical model are presented in Table 3.6 and Figure 3.5, respectively.

Table 3.6. Parameter Estimates of Field Data Based Total Delay Statistical Model.

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	1.2555	0.3586	3.50	0.001
(SPEED)	-0.029184	0.009287	-3.14	0.002
(VOL)	0.011338	0.002941	3.86	0.000
(RT)	0.01635	0.02350	0.70	0.489
(POC)	-0.007116	0.003673	-1.94	0.056
(RT)*(VOL)	-0.0004142	0.0001517	-2.73	0.008
(POC)*(VOL)	0.00002251	0.00001099	2.05	0.044
(POC)*(SPEED)	0.00014267	0.00006968	2.05	0.044

3.4.3. Model 3: Field Data Based Vehicle Delay Statistical Model

The vehicle delay (in seconds per vehicle) prediction model that finally best fitted the field data is provided below as Equation 3.10. This model predicts the average delay in seconds through vehicle encounter on the approach leading to right turn movement at intersection.

$$VD = 3.1735 - 0.06463*(SPEED) + 0.006622*(VOL) - 7.735*(RT\%) - 0.012190*(POC) - 0.05830*(RT\%)*(VOL) + 0.24074*(RT\%)*(SPEED) + 0.00025765*(POC)*(SPEED) \quad 3.10$$

$[S = 0.55896, R^2 = 38.60\%, \text{Adj. } R^2 = 32.7\%]$

where VD = average through vehicle delay in seconds;

SPEED = posted speed for the approach;

VOL = 15-minute approach volume;

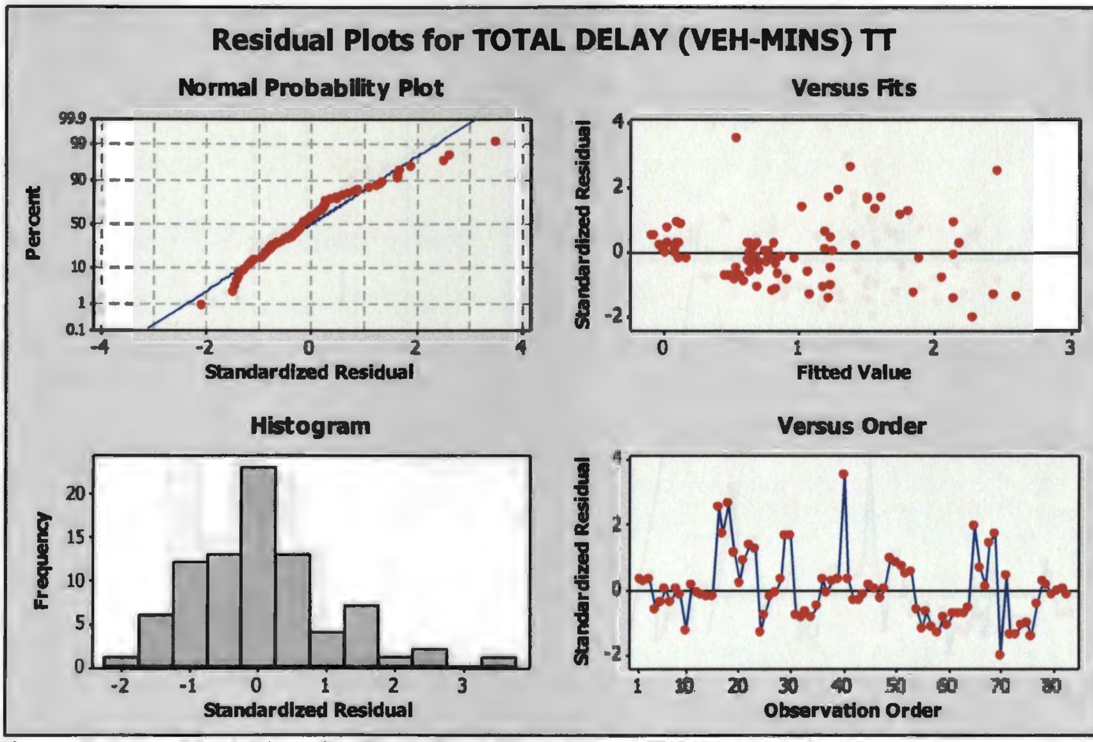

Figure 3.5. Residual Plots for Field Data Based Total Delay Statistical Model.

RT% = percentage of vehicles in 15-minute approach volume turning right; and

POC = pocket length (taper length plus full-width lane length)

The parameter estimates and the residual plots of the space mean speed prediction model are presented in Table 3.7 and Figure 3.6, respectively.

Table 3.7. Parameter Estimates of Field Data Based Vehicle Delay Statistical Model.

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	3.1735	0.4144	7.66	0.000
(SPEED)	-0.06463	0.01115	-5.79	0.000
(VOL)	0.006622	0.002664	2.49	0.015
(RT%)	-7.735	2.230	-3.47	0.001
(POC)	-0.012190	0.003353	-3.64	0.001
(RT%)*(VOL)	-0.05830	0.01709	-3.41	0.001
(RT%)*(SPEED)	0.24074	0.05561	4.33	0.000
(POC)*(SPEED)	0.00025765	0.00006235	4.13	0.000

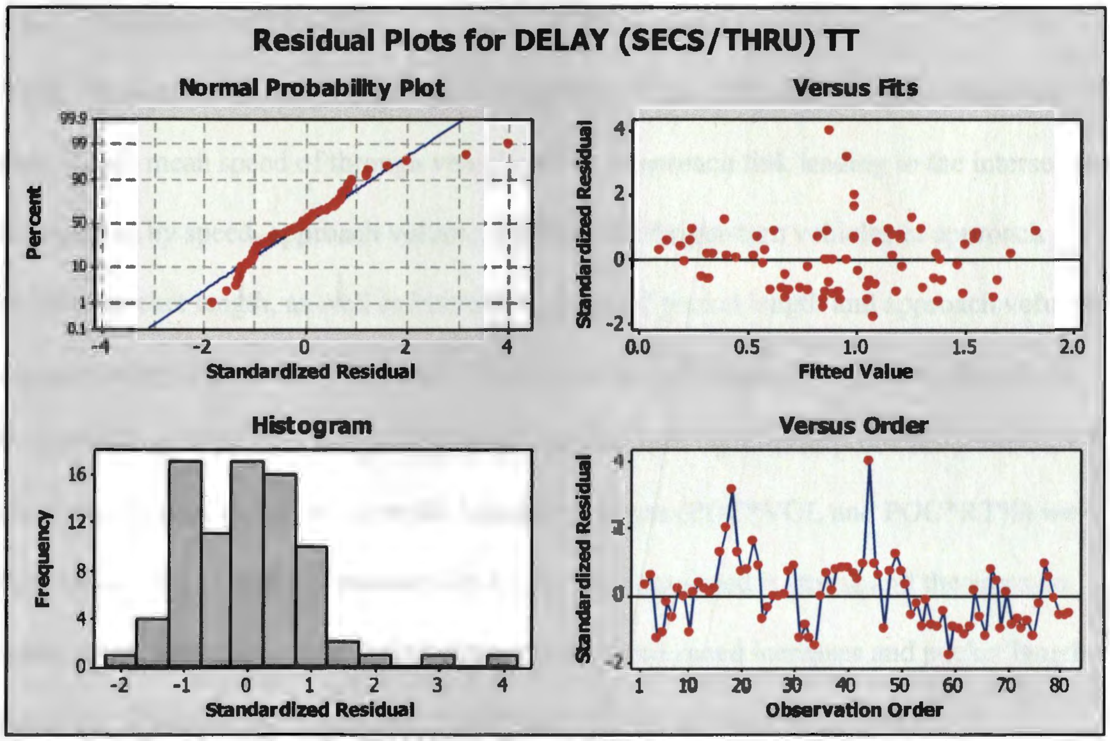

Figure 3.6. Residual Plots for Field Data Based Vehicle Delay Statistical Model.

3.5. Validation of Models

As stated before for the validation of the statistical models developed based on multiple regression of field data, the "Jack-knifing" method was used. The models related to space mean speed, total vehicle delay (in vehicle-minutes), and average vehicle delay (seconds per vehicle) were validated. The models were considered validated if $R^2_{jackknife}$ was less than R^2 of the fitted model and the $MSE_{jackknife}$ was greater than the MSE of the fitted model (see Table 3.8). The statistical models that were developed were checked only for adequacy in terms of fitness to the sample data. The test for validity was done to assess how much these models were successful at predicting when there was no data splitting or no new data were collected.

3.6. Discussion of Results

There are some interesting insights developed from these models developed using field data. Space mean speed of through vehicles on the approach link leading to the intersection is impacted by speed, approach volume, percentage of right-turn vehicles in approach volume, pocket length, as well as interaction terms of pocket length and approach volume, and percentage right turn in approach volume and pocket length. It was interesting to see that percentage right turn and pocket length did not have significant probability values, but the overall model improved when the interaction terms (POC*VOL and POC*RT%) were introduced. The strength of relationship for space mean speed is strong and the signs do make sense. The space mean speed increases as posted speed increases and pocket length increases. The increase in right turn percentage decreases space mean speed.

Table 3.8. Validation of Field Data Based Statistical Models.

Model	Dependent Variable	PRESS	R^2 (fitted model)	$R^2_{jackknife}$	MSE (fitted model)	$MSE_{jackknife}$
Model 1	Space Mean Speed	1993.89	84.10%	80.84%	21.800	26.2354
Model 2	Total Delay (vehicle-minutes)	35.4033	56.30%	45.31%	0.3737	0.4720
Model 3	Vehicle Delay (seconds/vehicle)	28.1337	38.60%	24.22%	0.3124	0.3854

Total delay to through vehicles on the approach link leading to the intersection is influenced by posted speed limit, approach volume, right turn volume, and pocket length. Total delay decreases with increasing posted speed limit. Total delay increases with increase in approach volume and right turn volume. Total delay decreases with increase in pocket length. The relationship of total delay was not as strong as was observed for space mean speed model.

Vehicle delay in seconds per vehicle is influenced by posted speed limit, approach volume, right turn volume, and pocket length. Vehicle delay decreases with increase in posted speed and increase in pocket length. Vehicle delay model was not as strong, but all variables included in the model were quite strong.

The models related to space mean speed, total vehicle delay (in vehicle-minutes), and average vehicle delay (seconds per vehicle) were found to be valid as $R^2_{jacknifc}$ was less than R^2 of the fitted model and the $MSE_{jackknifc}$ was greater than the MSE of the fitted model (see Table 3.8).

The models identified significant variables influencing space mean speed, total delay, and vehicle delay. These models can be improved by developing simulation model and developing statistical models using results from the simulation models. This is particularly true for determining the vehicle delays.

3.7. Summary

Type and amount of field data that were collected over nineteen different intersection approaches around Minnesota resulting in 80 independent data was described and discussed. These data were then analyzed to develop space mean speed model and delay models. The models for space mean speed and for total delay provided several insights. The model for average delay for individual vehicle was not as robust. It was also evident that field data analysis was limited and challenging. Thus, the need to use simulation models, based on field data related calibration and validation, was realized and pursued.

CHAPTER 4. MODELING AND ANALYSIS USING SIMULATION

The literature review and field data analysis together provided additional insights regarding what factors influence the operational impacts of the right-turning vehicle under different conditions and to what degree. However, getting complete understanding by field data alone was challenging and limiting. To develop a more comprehensive understanding, simulation model was developed using field data, and the data from simulation models were analyzed. The description of methodology, calibration of simulation model, validation of results from simulation model, and analysis using data from simulation model are provided in this Chapter.

4.1. Overall Methodology

The overall methodology involved several steps. First, a base model was developed. Next, the developed model was calibrated and validated. Finally, statistical model was developed from the data generated from numerous scenarios modeled using thousands of simulation. Simulation was useful in understanding and identifying the nature and extent of operational impacts under many more varying conditions. This understanding was also used in field data collection setup, which was then used for calibration purposes. CORSIM® was used to model and simulate right-turn movements under various conditions.

The CORSIM and VISSIM models have been comprehensively reviewed in the past (ITS 2000; Bloomberg and Dale 2000; Gettman and Head 2003). There are advantages as well as disadvantages associated with each of them. Benekohal et al. (2001) compared the delay from HCM®, SYNCHRO®, PASSER II®, PASSER IV® and CORSIM® for urban arterial and addressed CORSIM® as a standard in comparison among other software, due to its microscopic nature. Moen et al. (2000) compared the procedure for delay calculation of CORSIM® and VISSIM® and identified that CORSIM® calculates the delay for each vehicle by subtracting the travel time at the desired, free-flow speed from the actual travel time. Gafarian and Halati (1986) defined NETSIM as a stochastic microscopic traffic simulation model with a sampling interval of one second. Dowling et al. (2004) defined microscopic models as those capable of simulating the characteristics and interaction of individual vehicles using various algorithms, like car following, lane changing, and gap acceptance. Benekohal and Ayacin (2001) indicated that in NETSIM, the car following model was designed so that in each second's advancement of the lead vehicle, the follower vehicle was moved to the location so that the follower vehicle should be able to stop without collision, if the lead vehicle decelerated with a maximum deceleration rate. Siddiqui (2003) used NETSIM software for urban network as a basis to provide logical and sequential calibration and validation of micro simulation traffic models. In terms of validation, Sacks et al. (2002) found that CORSIM® output might match with field observations if it is carefully tuned and calibrated.

4.2. Simulation Model Development

Unlike the analysis that involves real world traffic, which almost always consists of some vehicles already present on the road network, the traffic simulation models, including the CORSIM® models, usually start at time 'zero' with no vehicle present on the road network. The terms 'warm-up period' or 'initialization period' of a simulation model refer to the artificial time period required for the model to reach the expected real-world steady state condition from an empty state. At the initial stage of traffic simulation, the system is expected to run faster as it takes time to build up congestion and delays. It is important that such initial bias is removed from the analysis, especially when the simulation outputs are compared with the real world observations as in model calibrations and model validations. A detail analysis is generally required to determine the warm-up period in case of traffic simulation involving complex road network.

4.2.1. Base and Preliminary Models

The base model was developed for shared case and exclusive case. The exclusive case was first studied for a particular intersection to carry out calibration and validation. In the preliminary stage, the simulation model development was aimed at understanding the principles of micro simulation in general and that are adopted in CORSIM® software, in particular. It started with creating a network on Traffic Network Editor (TRAFED) using links and nodes, and feeding the input variables like speed, total volumes, and the volumes of right-turning vehicles into the network. In the beginning of the study, the networks were simulated based on default values for relevant parameters. Several simulation runs were made to know what initialization period to choose, what types of error checking to perform, and the appropriate number of simulation runs required to get valid results. These sensitivity analyses, based on the preliminary base models, were very useful in identifying what data to collect for model calibration. In addition, speed profile examination provided insight about where the data should be collected in order to obtain speed data where the speed of traveling vehicles was not impacted by right-turning vehicles.

The base models were developed in couple of stages. In the beginning of the study, preliminary models were developed with link and nodes in TRAFED with assumed dimensions. The configuration of these models was like the link-node diagram shown in

Figure 4.1. The main purpose of the preliminary models was to carry out the exploratory analysis that could aid in development of better models.

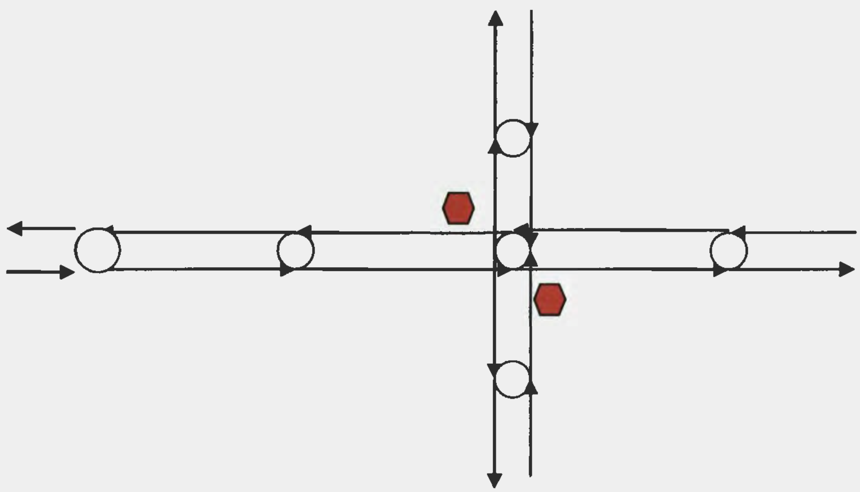

Figure 4.1. Link-Node Diagram in CORSIM® for 4-Legged Intersections.

The base models were run with low and high values of variables like speed, volume and, right-turning percentages. Errors in feeding inputs were checked by running trial simulations and making sure there were no error messages in the dialogue box, as well as in TRF files after running. If an error was found, then models were run again after eliminating the errors.

4.2.2. Calibration

The general concept was to develop simulation models for intersections with shared and exclusive right-turn treatments that would, in general, represent all intersections with shared and exclusive right-turn treatments similar to the surveyed intersections. When a sensitivity analysis was performed on the default model, several parameters in the NETSIM set up within CORSIM were altered and the effect was observed in output values of speeds and delays. However, most parameters were found to have no effect on speed and delay. The percentage multiplier of free-flow speed, the time to react to a sudden deceleration of the lead vehicle, the deceleration rate of the lead vehicle, the deceleration rate of the follower vehicle, and allowable right-turning speed had some effect. The driver type in CORSIM® is divided into 10 categories ranging from 1 to 10 based upon the aggressiveness. Driver Type 1 is a timid driver and Driver Type 10 is the most aggressive driver. CORSIM® assigns different percentage multipliers of free-flow speed according to driver types. The default multiplier ranges from 75 to 125. It is possible to develop the distribution of the free-flow speed multiplier according to the driver type categorized based upon field measured free-flow speeds. The percentage multiplier of free-flow speed was found to be a very sensitive factor that can bring considerable change in Measures of Effectiveness (MOEs). Time to react to a sudden deceleration is also considered to be a very sensitive factor. However, it is generally not used if the desired calibration can be achieved by altering other parameters. Sample study locations are shown below in Figure 4.2 for Aitkin and St. Bonifacius.

1) Aitkin (MNTH-210/CR-54 & CR-56)

Four-legged intersection on MNTH-210 with CR-54/CR-56 near Aitkin with west approach in view (low volume-high speed-shared right turn treatment)

2) St. Bonifacius (MNTH-7/CR-10)

Four-legged intersection on MNTH-7 with CR-10 near Saint Bonifacius viewed from west approach (high volume-high speed-exclusive right turn treatment)

Figure 4.2. Locations used for Calibration.

After several attempts, the driver type distribution that provided the best calibration for shared and exclusive cases were determined and are shown below in Figures 4.3 and 4.4. The models were calibrated by examining the results of space mean speed for both through and right-turn vehicles on the approach link to the intersection. The networks for the shared and exclusive cases were built according to the context found at Aitkin (for shared case) and Saint Bonifacius (for exclusive case). The calibration results are shown in Table 4.1. There was close match between both the space mean speed for through and right turning vehicles using field data and simulation results.

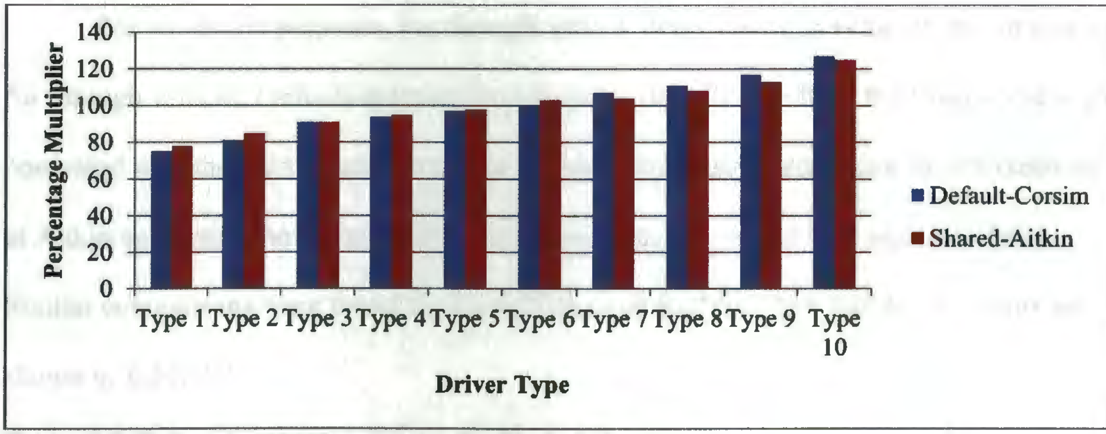

Figure 4.3. Driver Type Distribution for Shared Treatment.

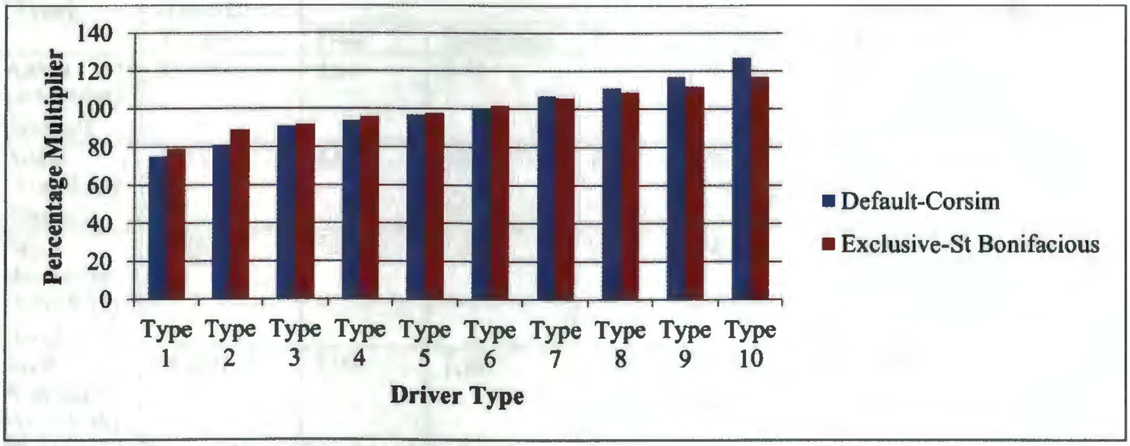

Figure 4.4. Driver Type Distribution for Exclusive Treatment.

Table 4.1. Calibration Results.

Location (Time)	Type	Approach Volume	Through Volume	SMS-Through (mph)		SMS – Right Turn (mph)	
				Field	Simulation	Field	Simulation
Aitkin (4:45-5:00)	Shared	27	25	56.36	56.47	31.02	33.9
Aitkin (5:00-5:15)	Shared	40	37	52.5	52.41	44.7	44.6
Saint Bonifacius (5:20-5:35)	Exclusive	69	63	59	59.44	38.56	36.42
Saint Bonifacius (5:35-5:50)	Exclusive	64	59	60	59.43	37.76	36.87

4.2.3. Validation

For validation purposes, the through vehicle delay (seconds/vehicle), the total delay for through vehicles (vehicle-minutes) and the total (travel) time from the simulations were compared with the field-measured values. These comparisons were done for intersections at Aitkin and Saint Bonifacius. There was closer match for travel time and total delay. Similar comparisons were found for Forest Lake and Ruthton. The Validation results are shown in Table 4.2.

Table 4.2. Validation Results.

Location (Time) [Type]	Approach Volume (Through Volume)	Travel Time (minutes)		Total Delay-Through (Vehicle-Minutes)		Vehicle Delay -- Through (seconds/vehicle)	
		Field	Simulation	Field	Simulation	Field	Simulation
Aitkin (4:45-5:00) [Shared]	27 (25)	3.16	2.74	0.1	0.1	0.31	0.24
Aitkin (5:00-5:15) [Shared]	40 (37)	4.05	3.99	0.26	0.24	0.21	0.39
Saint Bonifacius (5:20-5:35) [Exclusive]	69 (63)	7.59	7.52	0.60	0.83	0.64	0.89
Saint Bonifacius (5:35-5:50) [Exclusive]	64 (59)	7.07	7.10	0.35	0.85	0.38	0.91

4.2.4. Modeled Scenarios

After observing spot speed profiles (which are discussed in Section 4.2.5), it was determined what was the extent of the impact of right turning vehicle. It was decided that the length of the test approach link should be kept at 800 ft. The length of the immediate following link was kept 500 ft. and the rest of the links were kept at 200 ft. In the case of exclusive right-turn treatment, the length of the pocket was varied depending on the context where data were collected. Ten runs were made for each combination using run-time extension codes.

The calibrated and validated model was used for simulating various modeling scenarios. For comparison purposes the network was kept consistent for both shared and exclusive cases. In other words the approach link lengths were kept same for both the shared and exclusive cases. The only difference was the presence of pocket length of different lengths in the approach link for the exclusive cases. The networks used for modeling various scenarios for the shared and exclusive cases are shown in Figures 4.5 and 4.6, respectively. The pocket length varied in the exclusive cases. Simulations were carried out for pocket lengths of 150 ft, 300 ft (which is shown in Figure 4.6), 480 ft, and 600 ft. Hence, the network was modified each time new pocket length was used. However, in all instances, for both shared and exclusive cases the approach link to the intersection that was of interest was kept the same as 800 ft. This allowed for better comparison of operational performances in terms of space mean speed and the delays.

The intent was to simulate a wide variety of conditions and generate speed and delay data for those conditions (see Table 4.3), which could then be analyzed for better understanding and also for development of predictive statistical models. Ten runs were

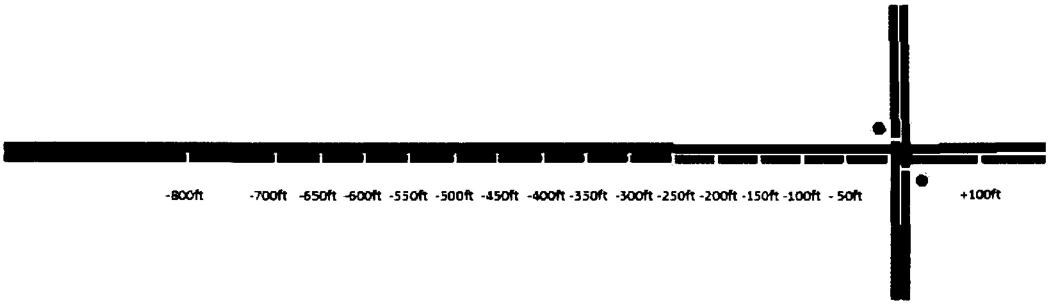

Figure 4.5. Network for Simulating Modeling Scenarios for Shared Cases.

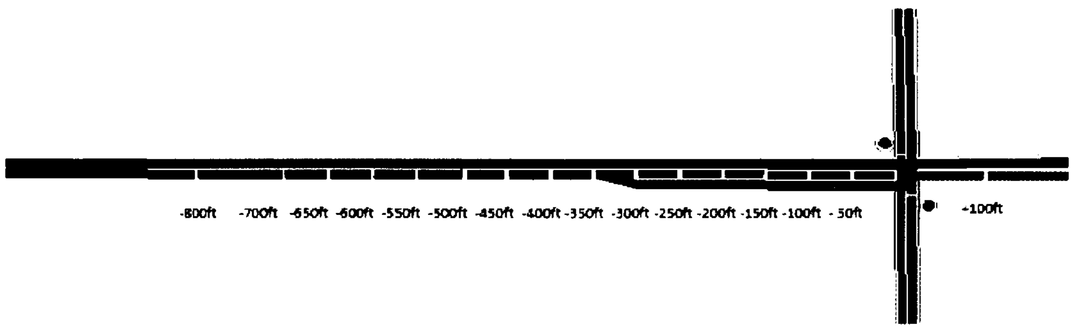

Figure 4.6. Network for Simulating Modeling Scenarios for Exclusive Cases.

made for each scenario. As a result, 2400 simulations were carried out to generate data on spot speed of through vehicles at different detector locations, space mean speed of through vehicles on approach link, total delay for all through vehicles on approach during 15-minute period of analysis (in vehicle-minutes), and through vehicle delay (in seconds per through vehicle) for all the scenarios of interest. A considerable amount of post processing using SAS® and EXCEL® was done to get the final data of interest.

Table 4.3. List of Independent Variables and their Levels.

Variables	Levels
VOL--Volume (15-min approach volume)	4 Levels (corresponding to rate of flow of 100 vph, 200 vph, 300 vph, 400 vph)
SPEED—Posted Speed (in mph)	3 Levels (30 mph, 45 mph, 55 mph)
RT%--Percentage of right-turning	4 Levels (1%, 5%, 10%, 15%)

Table 4.3 Continued

vehicle in 15-minute Approach Volume RT—Number of Right-Turning Vehicle in 15-minute Approach Volume (this could be calculated from RT% and VOL variables)	
POC—Pocket Length, which was sum of taper length and full-width turn lane length)	5 levels (0 ft, 150 ft, 300 ft, 480 ft, 600 ft). Shared treatment is corresponding to POC

4.2.5. Speed Results from Simulation

Simulation results for spot speed profiles at different detectors are shown in Figures 4.7 to 4.18 and also in Figures C.1 to C.16 in Appendix C. Simulation results for space mean speeds are shown in Figures 4.19 to 4.20 and Figure C.17 in Appendix C.

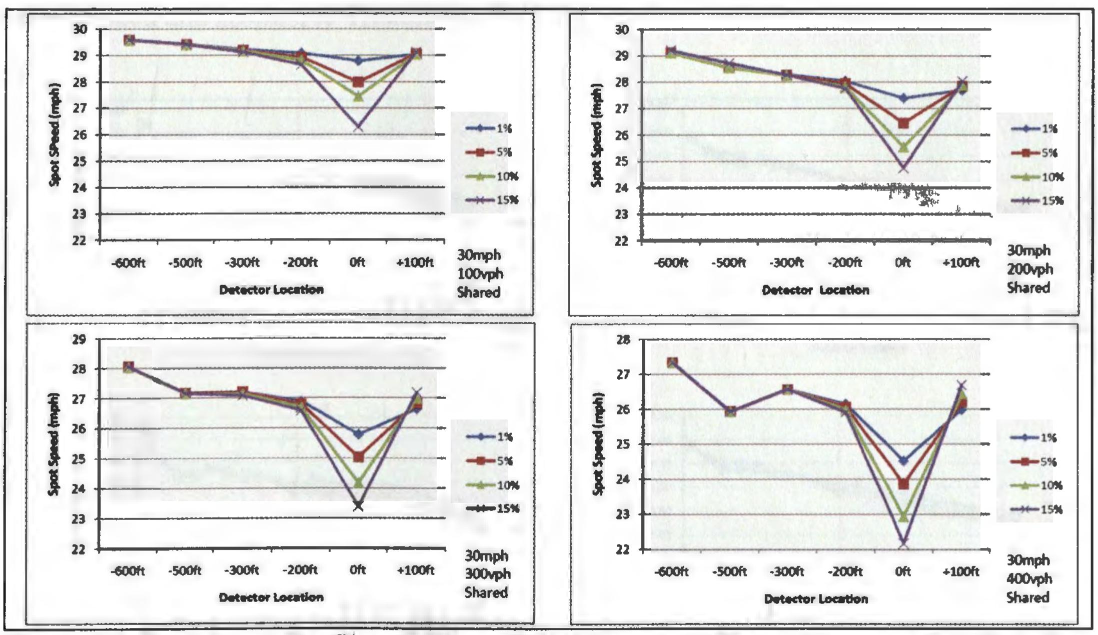

Figure 4.7. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed and Shared Treatment.

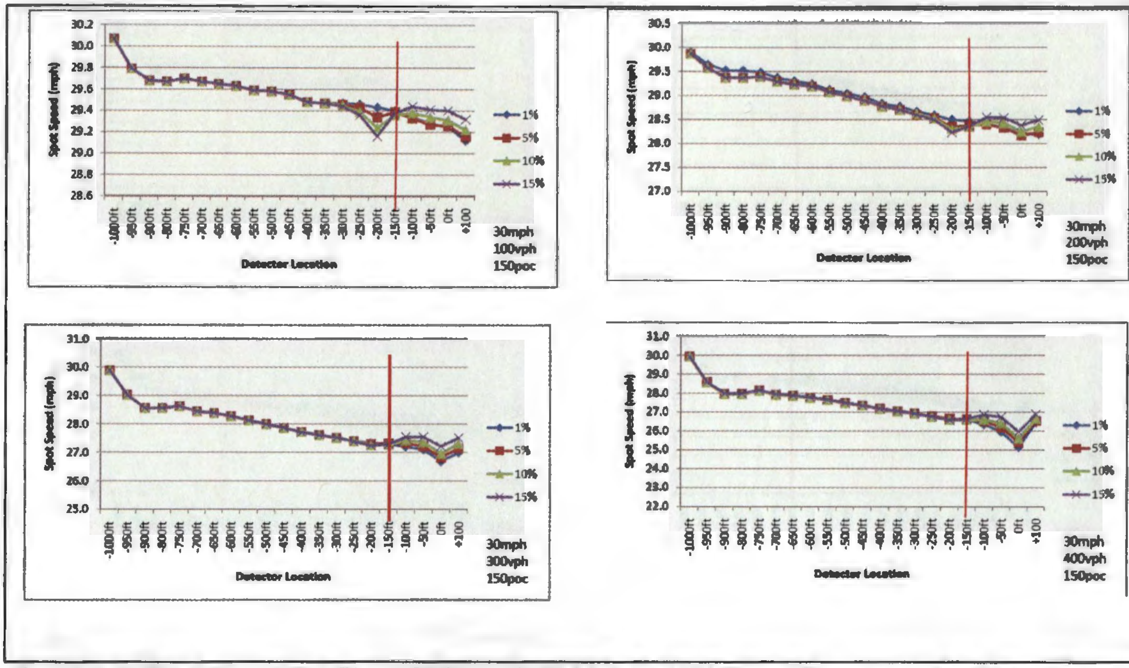

Figure 4.8. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed and Exclusive Treatment (Pocket Length of 150 feet).

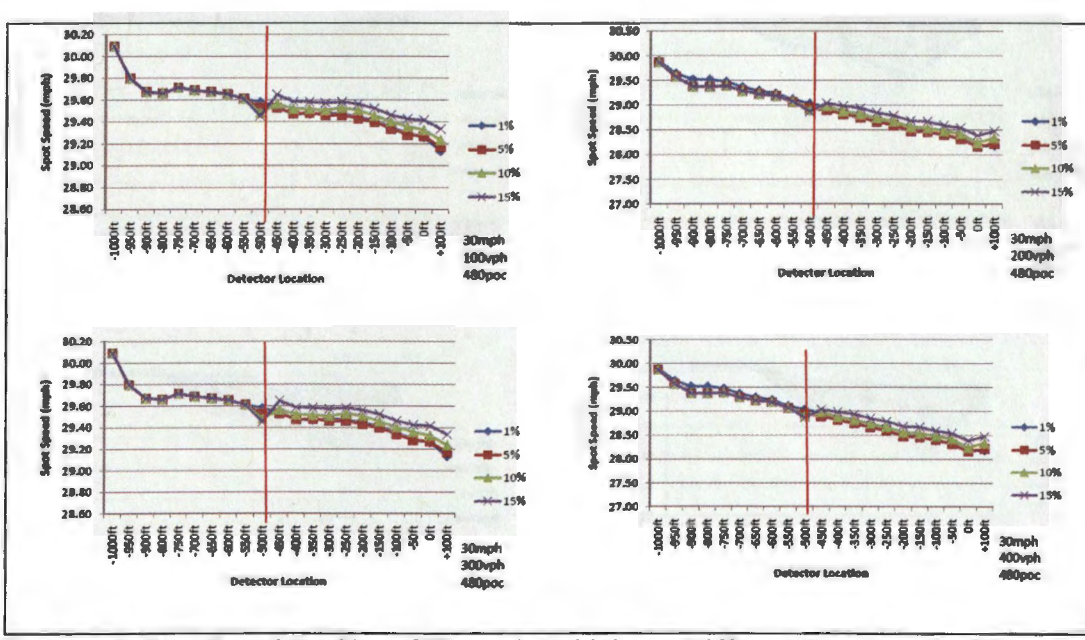

Figure 4.9. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed and Exclusive Treatment (Pocket Length of 480 feet).

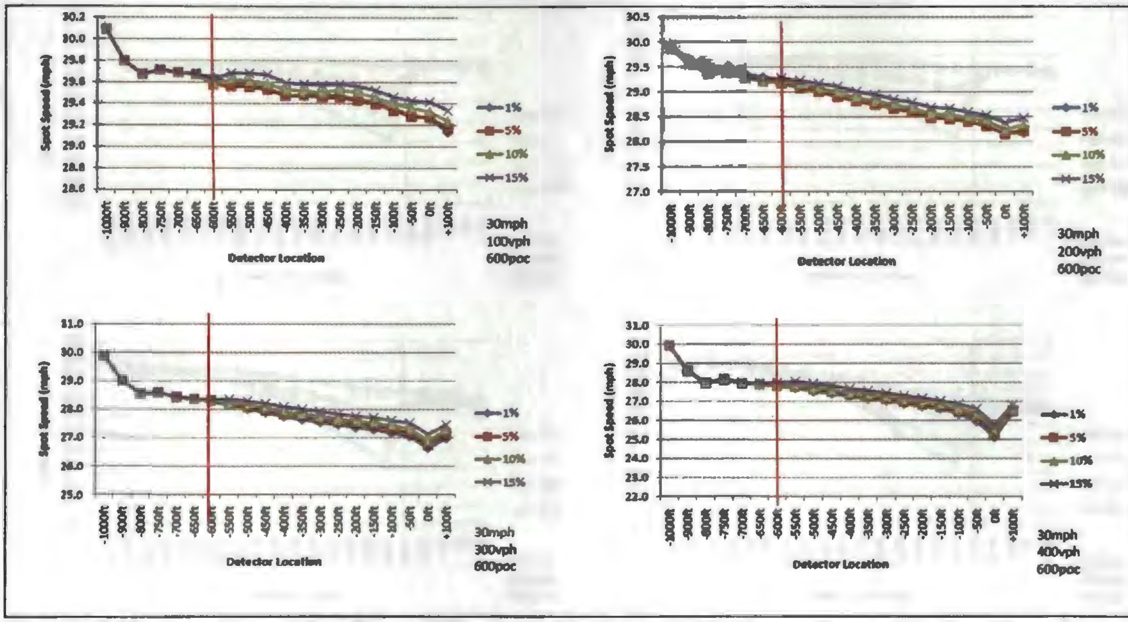

Figure 4.10. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed and Exclusive Treatment (Pocket Length of 600 feet).

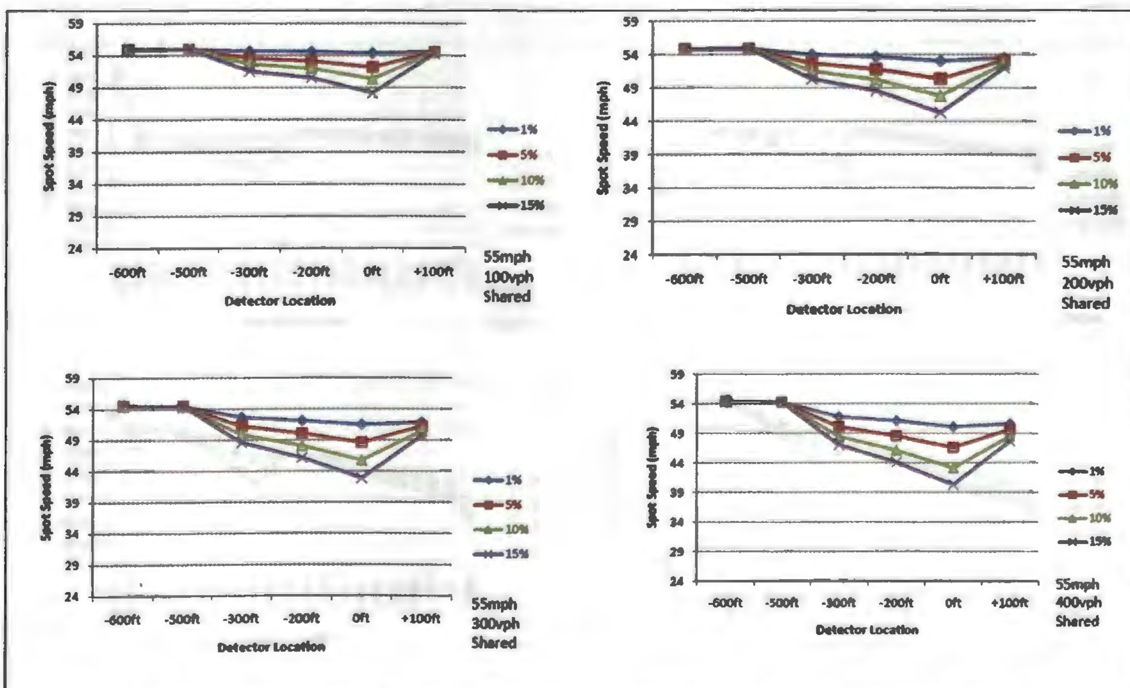

Figure 4.11. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed and Shared Treatment.

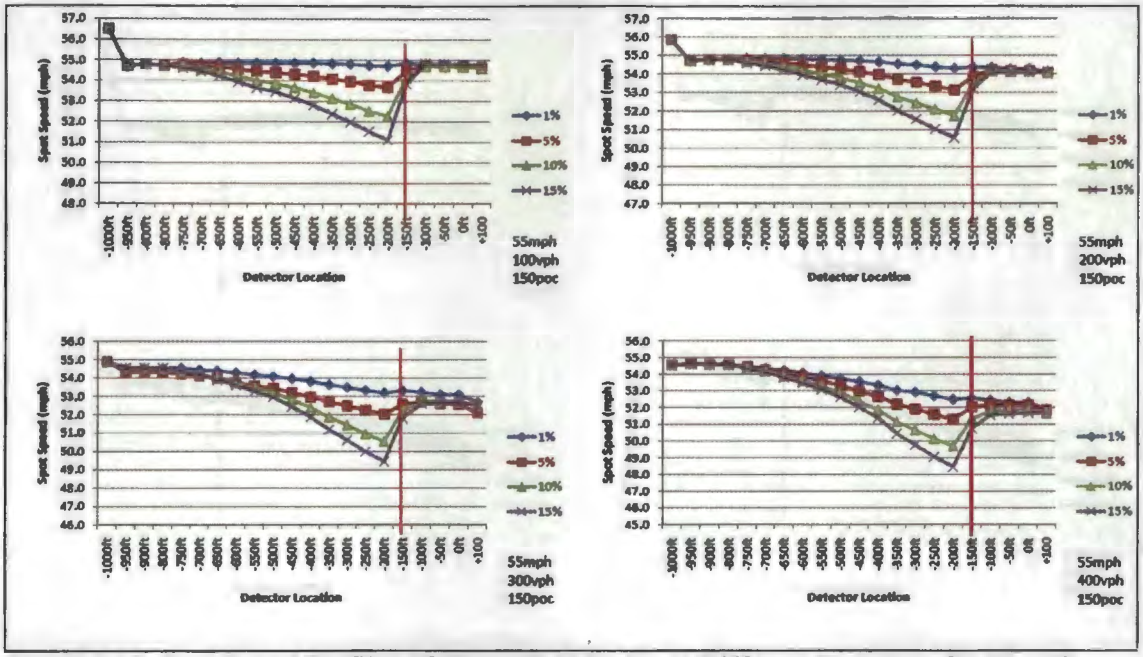

Figure 4.12. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed and Exclusive Treatment (Pocket Length of 150 feet).

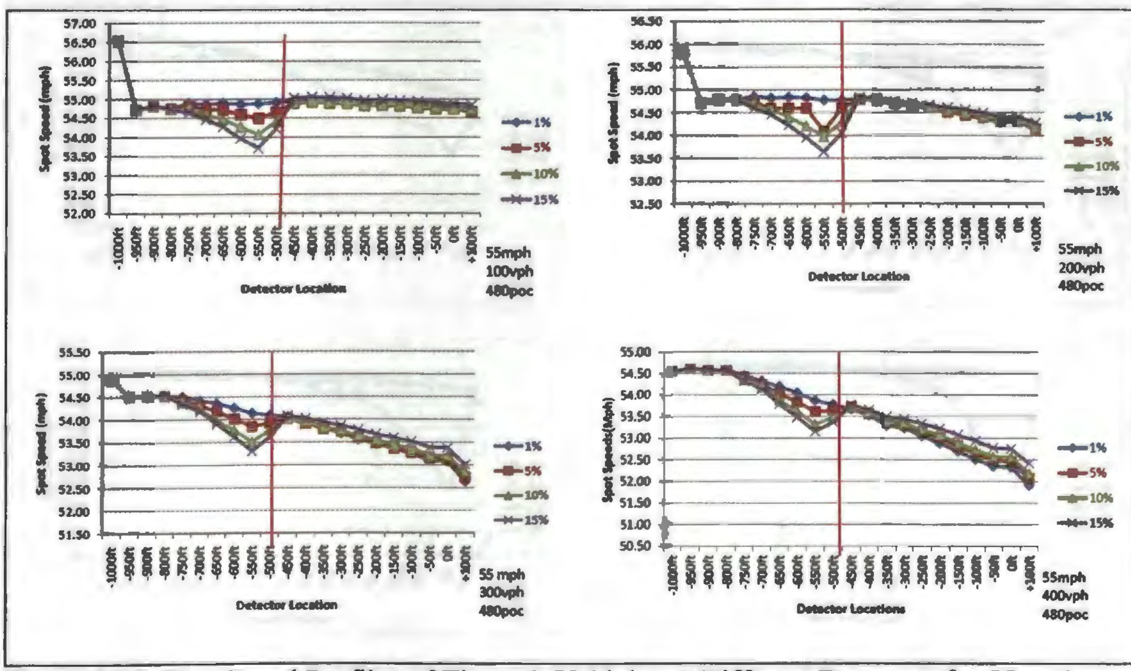

Figure 4.13. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed and Exclusive Treatment (Pocket Length of 480 feet).

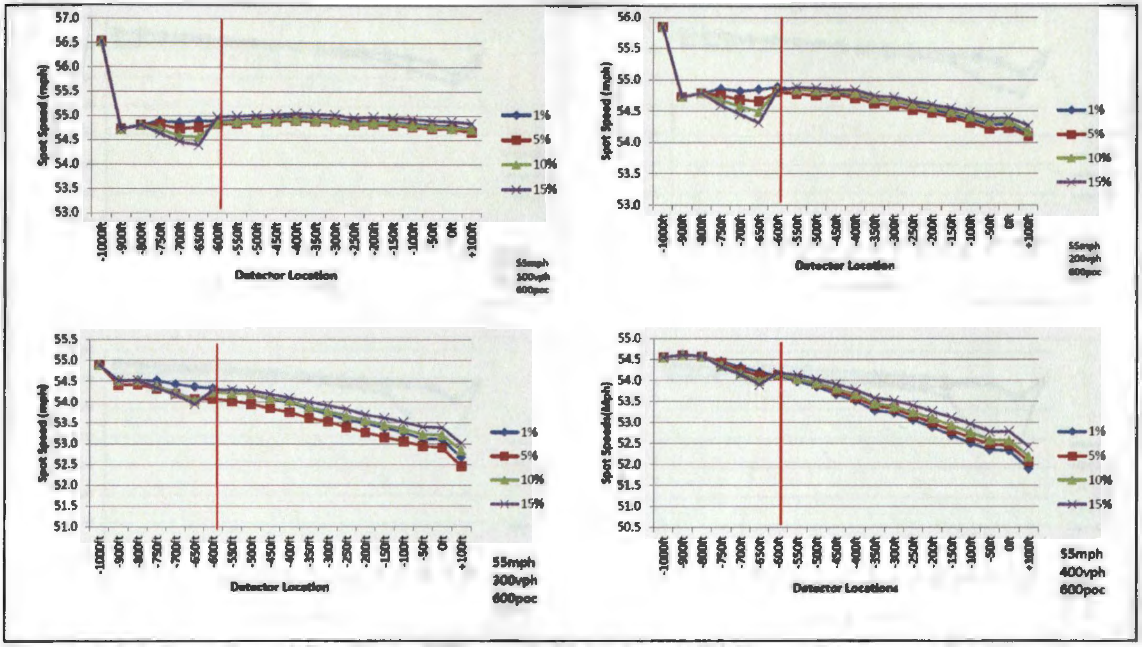

Figure 4.14. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed and Exclusive Treatment (Pocket Length of 600 feet).

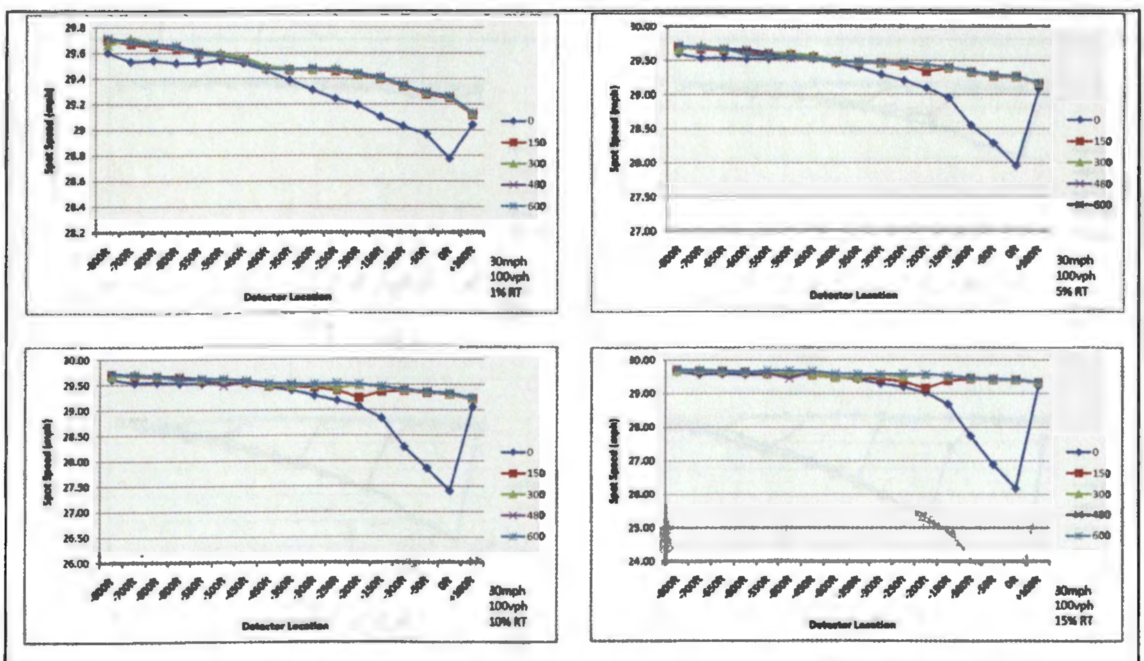

Figure 4.15. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed, 100 vph, and Different Pocket Lengths.

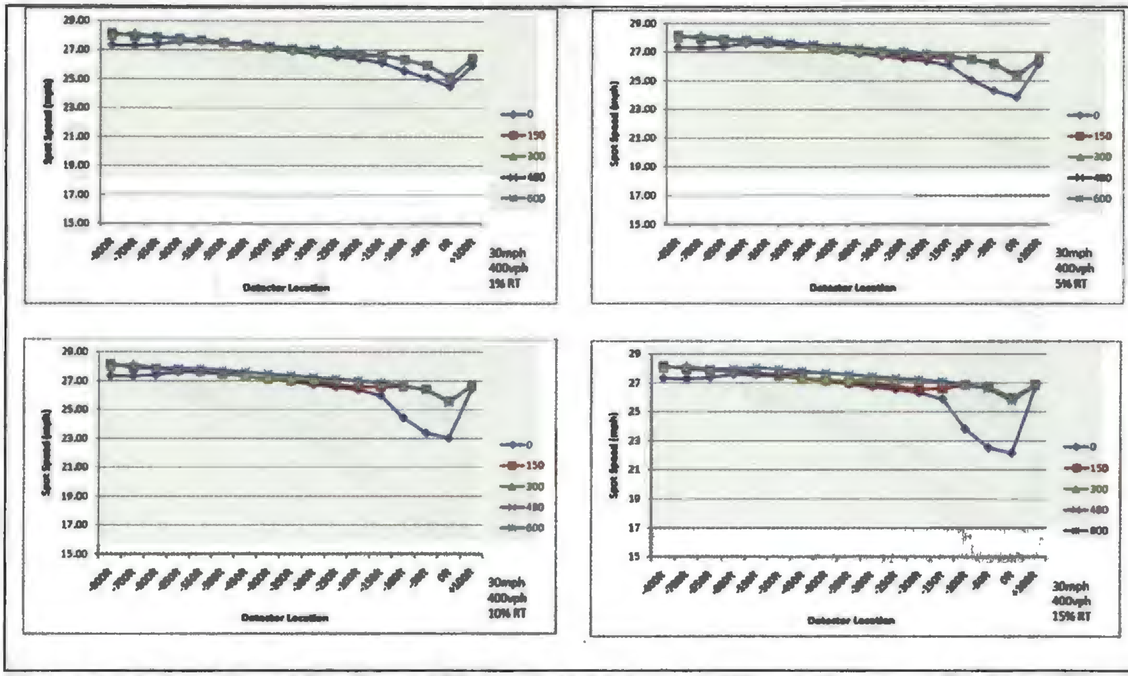

Figure 4.16. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed, 400 vph, and Different Pocket Lengths.

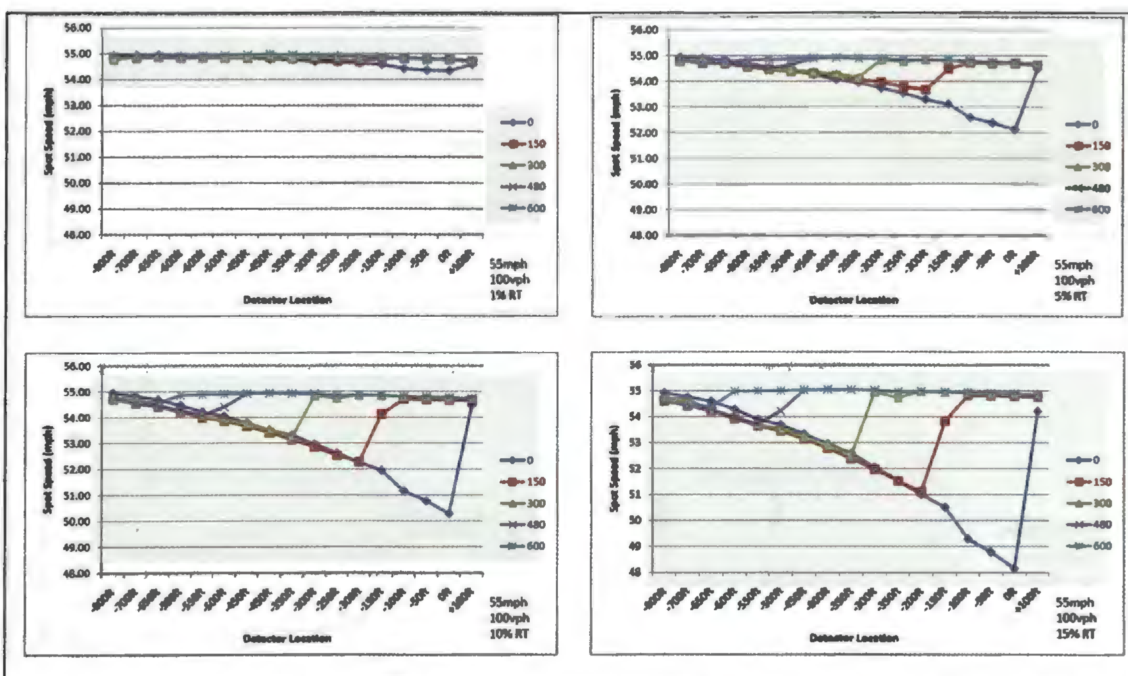

Figure 4.17. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed, 100 vph, and Different Pocket Lengths.

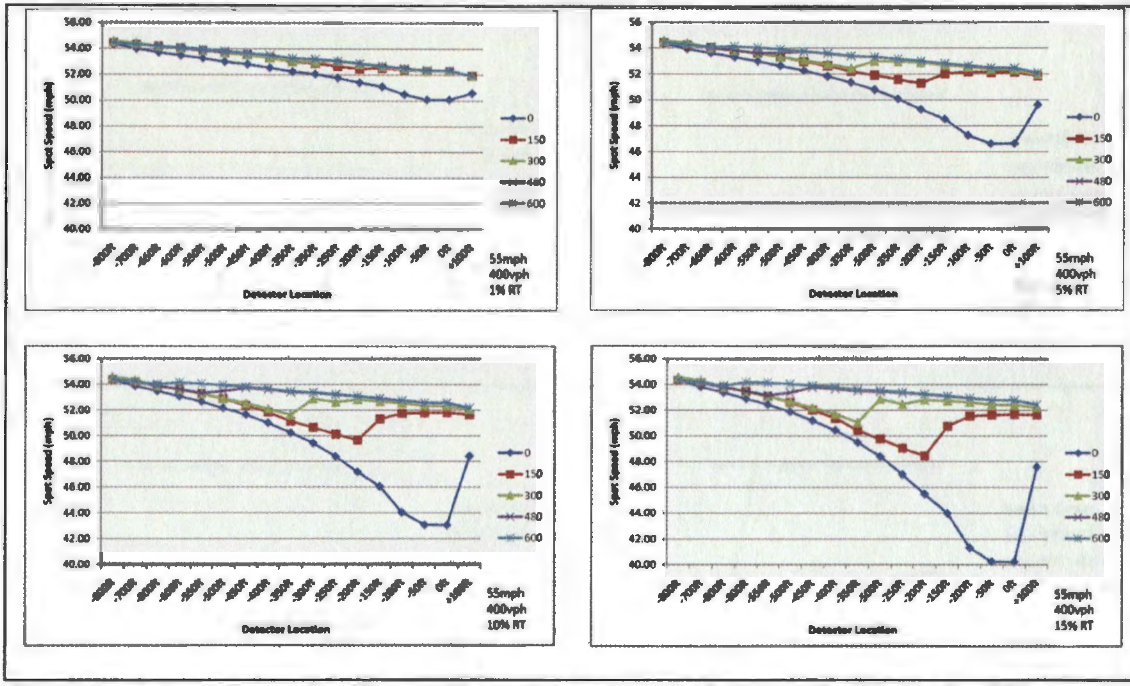

Figure 4.18. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed, 400 vph, and Different Pocket Lengths.

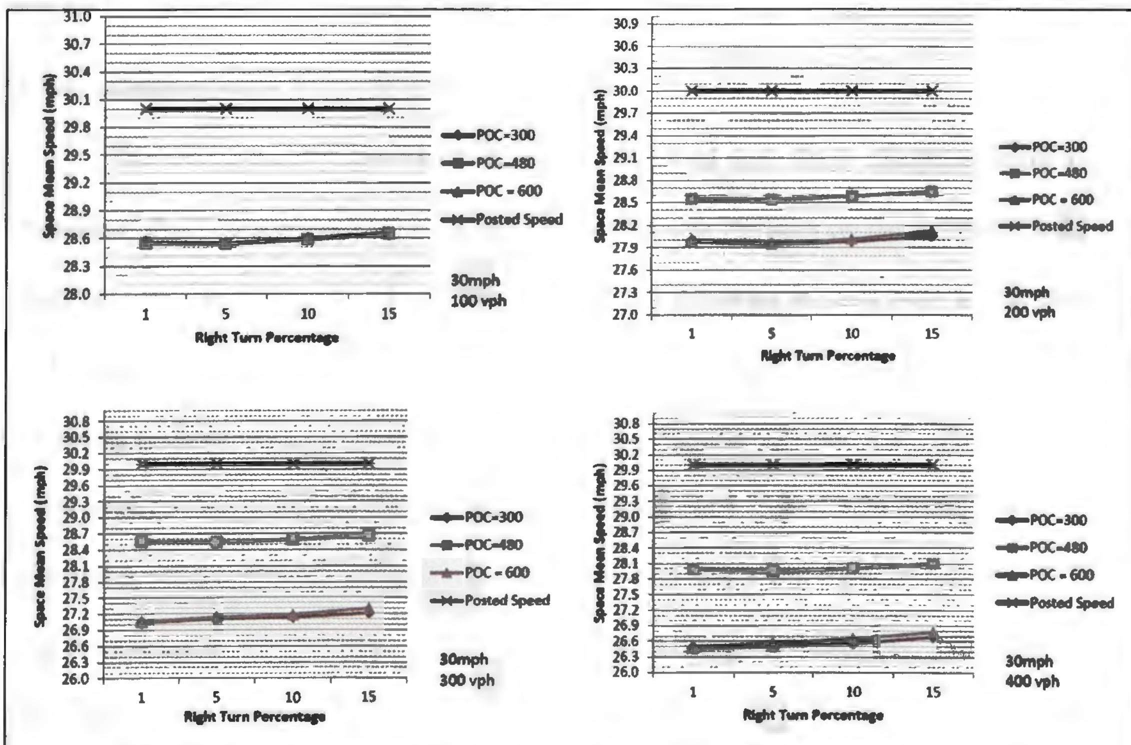

Figure 4.19. Space Mean Speed of Through Vehicles on Approach Link for 30 mph Posted Speed.

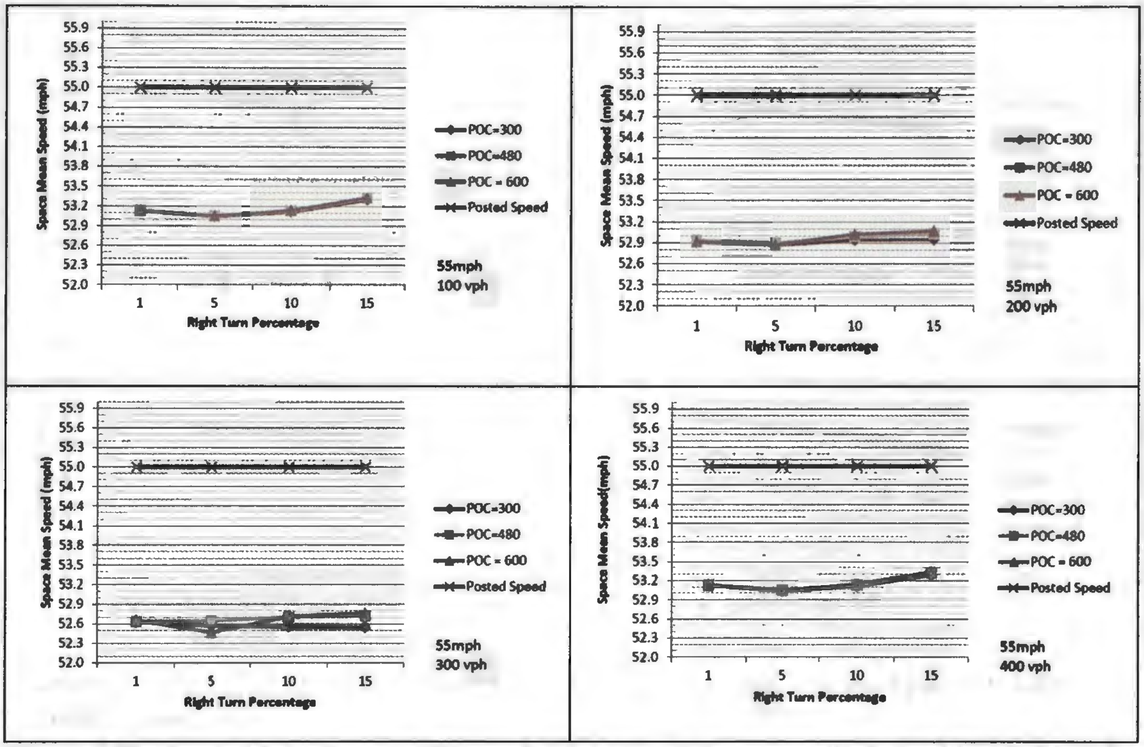

Figure 4.20. Space Mean Speed of Through Vehicles on Approach Link for 55 mph Posted Speed.

4.2.6. Delay Results from Simulations

The two types of delay results that were examined were those related to delay to individual through vehicles and the total delay to through vehicles on the approach link leading to the intersection. In field data based models the delay models were not as robust and using the simulation delay results were improved. The impacts of various factors, including pocket length, on total delay are shown in Figures 4.21 and 4.22. The vehicle delay impacts due to various factors are shown in Figures 4.23 and 4.24. Simulation allowed developing better and more detailed understanding about these influencing factors and their impacts, which in turn can help in improved design and implementation of right-turn lanes.

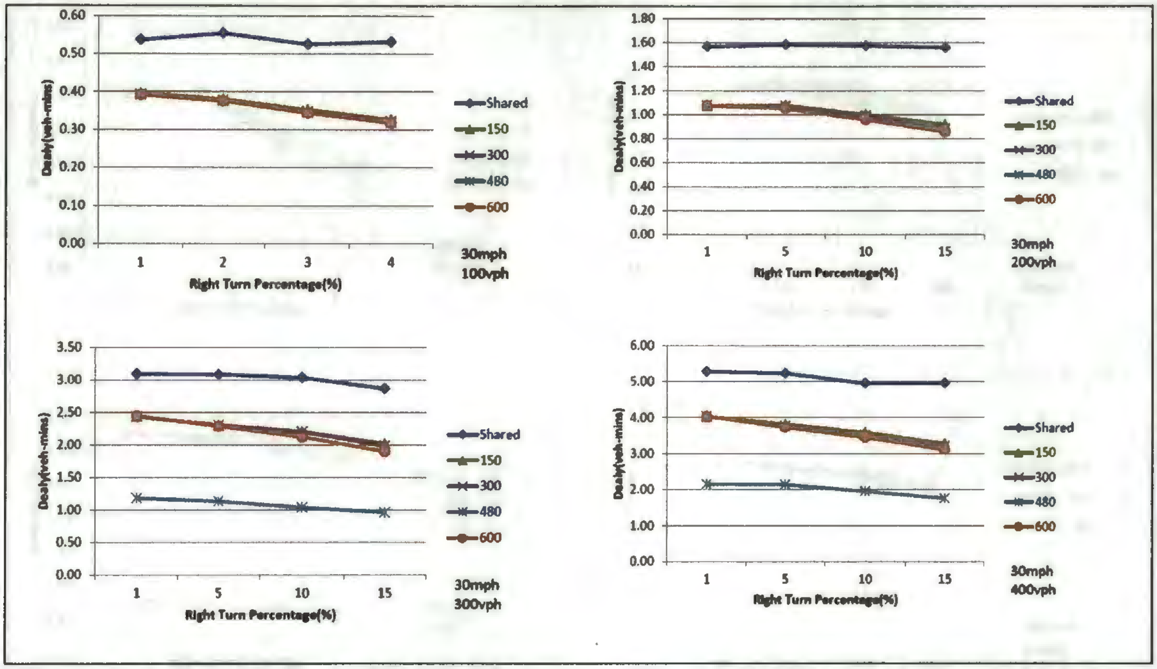

Figure 4.21. Total Delay (in Vehicle-Minutes) of Through Vehicles on Approach Link for 30 mph Posted Speed.

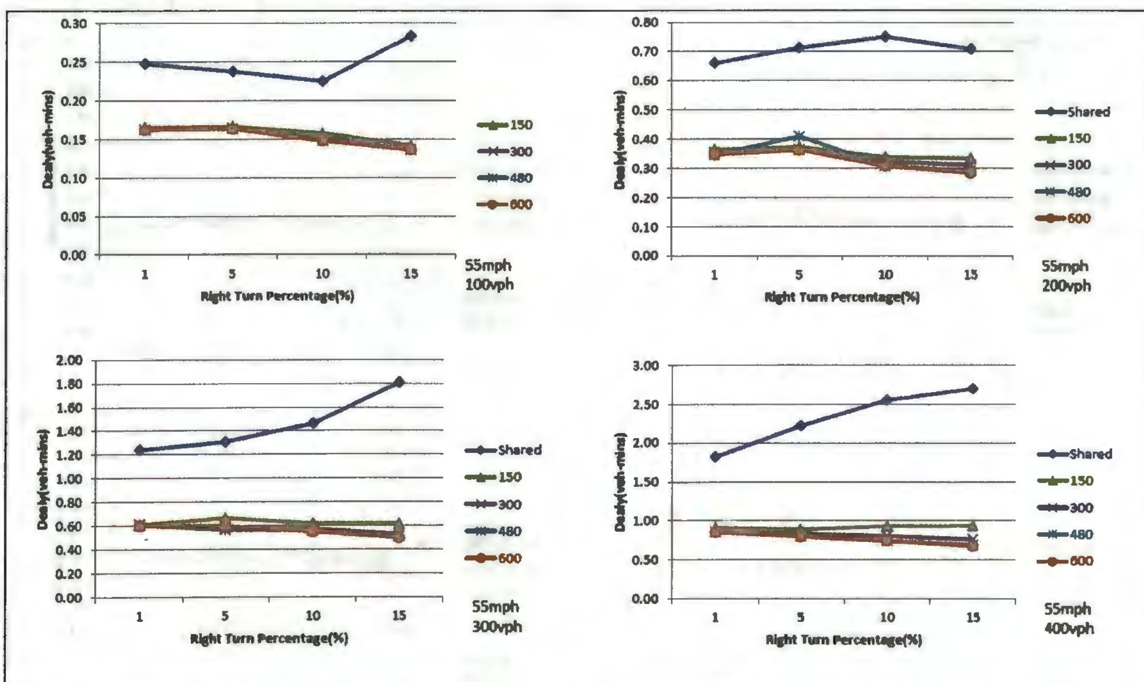

Figure 4.22. Total Delay (in Vehicle-Minutes) of Through Vehicles on Approach Link for 55 mph Posted Speed.

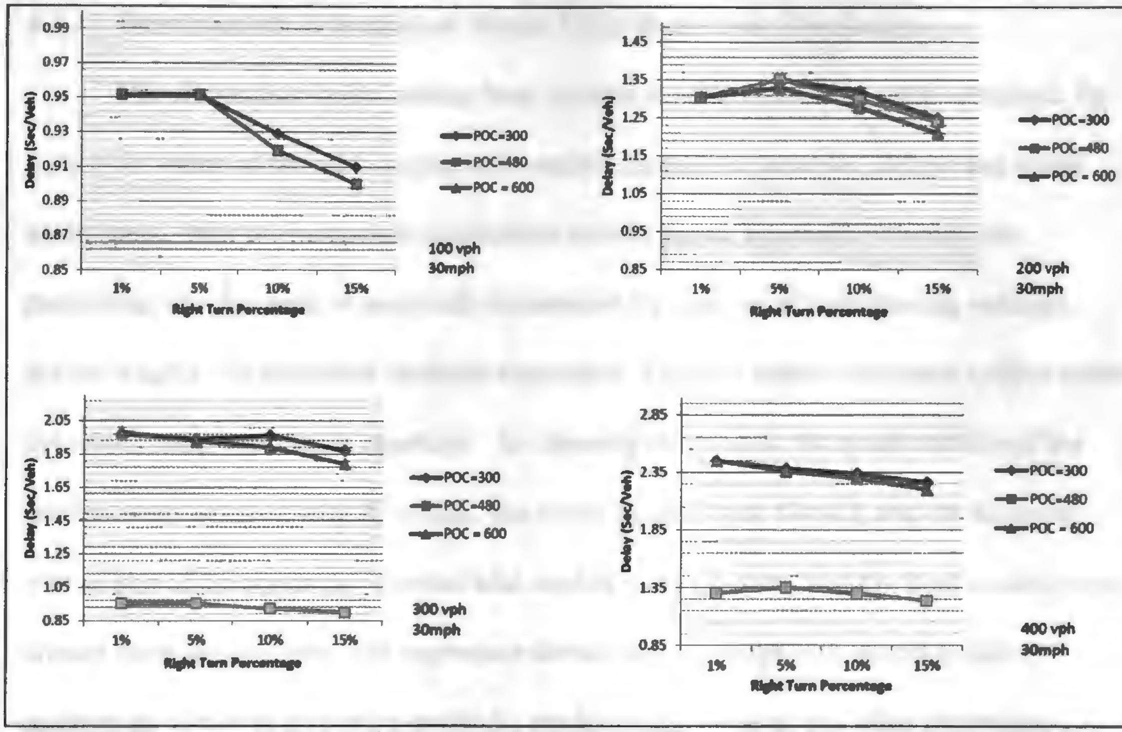

Figure 4.23. Average Delay (in Seconds/Vehicle) of Through Vehicle on Approach Link for 30 mph Posted Speed.

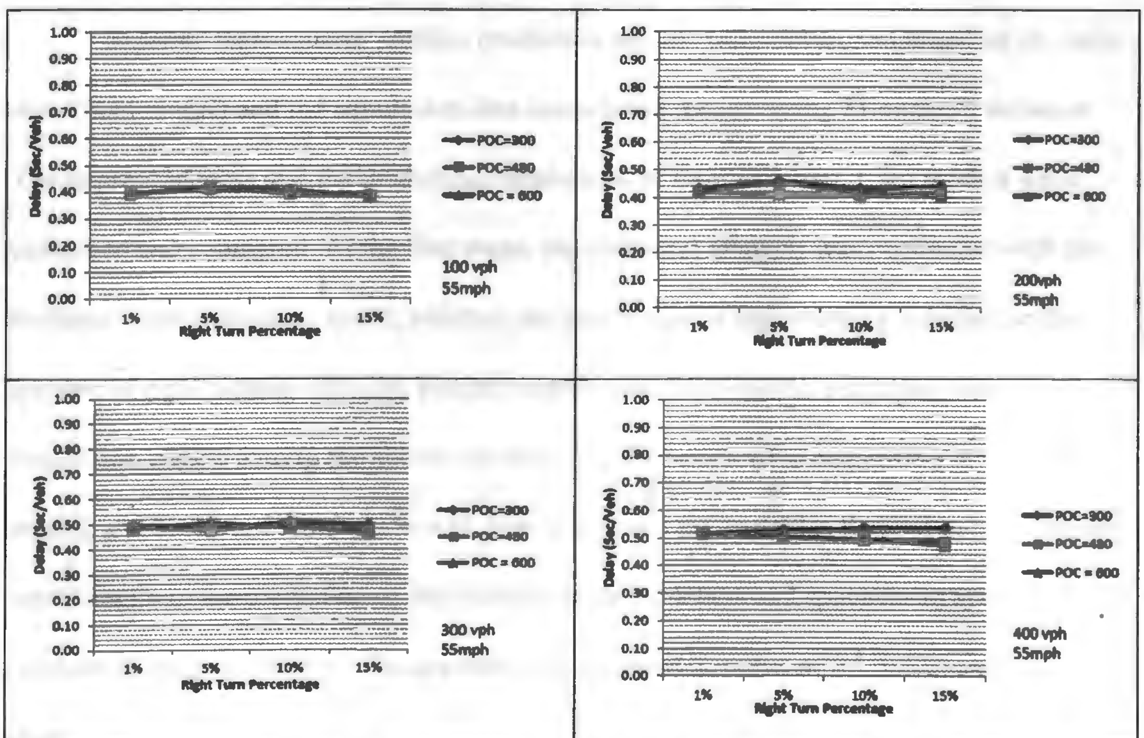

Figure 4.24. Average Delay (in Seconds/Vehicle) of Through Vehicle on Approach Link for 55 mph Posted Speed.

4.3. Development of Statistical Model Using Data from Simulation

The simulation model results from various modeled scenarios were compiled. To assess the nature of the relationship between the dependent variables, delays and space mean speed, with the independent variables such as speed, approach volumes, the percentage of right-turns in approach volumes or the number of right turning vehicles, pocket lengths, the statistical methods were used. Multiple regressions were used to make the relationship into model equations. In choosing the models, the predictability of the models were assessed with R^2 values, the Mean Square Error (MSE), and the nature of scatter plot of the residuals. Several trial models were prepared and the final models were chosen from among them. For regression theories and assumptions, model building techniques, variables screening methods, model fit assessments and other regression-related issues, Mendenhall and Sincich (2003) may be referred.

Separate least squares conflict prediction models were developed based on the field data (field model) and the simulation data (simulation model) using Minitab 15 software. The appropriateness and the predicting capabilities of field and simulation models were examined and compared. At the first stage, the statistical analysis was conducted with the multiple regression using speed, volume, the percentage of right-turning vehicles or the number of right turning vehicles, pocket lengths, and the two-way and three-way interaction effects among the above variables. All the terms were considered in the first model, and backward elimination was done to remove the variables that did not contribute significantly to the prediction of dependent variables, delays and space mean speed, at a confidence interval of 95%. The models were assessed in terms of R^2, MSE, and residual plots.

4.3.1. Model 4: Simulation Based Space Mean Speed Statistical Model

The space mean speed prediction model that finally best fitted the data generated from simulation is provided below as Equation 4.1. The model was for determining the space mean speed of the through vehicles.

$$SMS\text{-}TH = -0.989 - 0.110*(VOL) - 0.0280*(RT\%) + 0.999*(SPEED) + 0.000685*(POC) + 0.000083*(RT\%)*(POC) \qquad 4.1$$

[S = 0.527015, R^2 = 99.7%, Adj. R^2 = 99.7%]

where SMS-TH = space mean speed of through vehicles (in mph);

SPEED = posted speed for the approach (in mph);

VOL = approach volume during 15-minute time interval;

RT% = percentage of vehicles in 15-minute approach volume turning right; and

POC = pocket length (taper length plus full-width lane length).

The parameter estimates and the residual plots of the simulation based space mean speed statistical model are presented in Table 4.4 and Figure 4.25, respectively.

Table 4.4. Parameter Estimates of Simulation Based Space Mean Speed Statistical Model.

Predictor	**β Coefficient**	**Std. Error of Coefficient**	**T-Statistic**	**P-Value**
Intercept	-0.9892	0.1955	-5.06	0.000
(VOL)	-0.109986	0.004908	-22.41	0.000
(RT%)	-0.02797	0.01134	-2.47	0.014
(SPEED)	0.998905	0.003330	299.95	0.000
(POC)	0.0006853	0.0002800	2.45	0.015
(RT%).(POC)	0.00008324	0.00003011	2.76	0.006

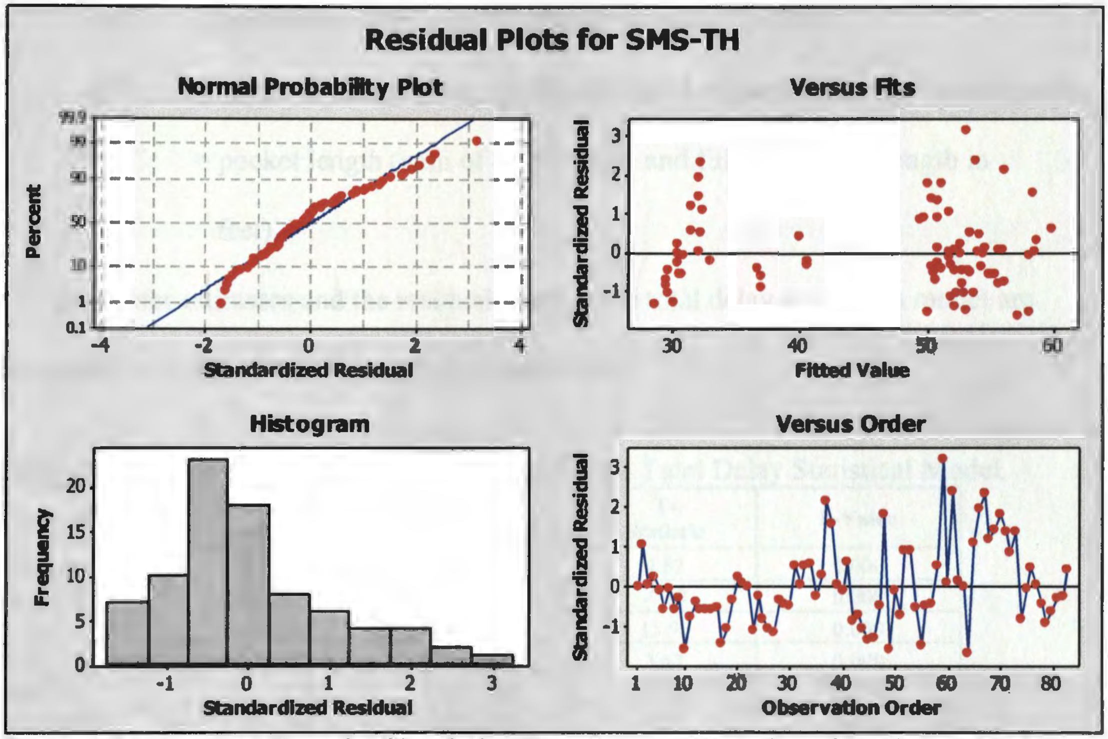

Figure 4.25. Residual Plots for Simulation Based Space Mean Speed Statistical Model.

4.3.2. Model 5: Simulation Based Total Delay Statistical Model

The total vehicle delay (in vehicle-minutes) prediction model that finally fitted the simulation generated data is provided below as Equation 4.2. The model was for determining the cumulative delay (in vehicle-minutes) encountered by through vehicles.

$$TD = 0.975 - 0.0302*(SPEED) + 0.0947*(VOL) + 0.546*(RT) - 0.000031*(POC) + 0.0123*(RT)*(VOL) - 0.0160*(RT)*(SPEED) - 0.000424*(POC)*(SPEED) \quad 4.2$$

[S = 0.403423, R^2 = 83.7%, Adj. R^2 = 83.2%]

where TD = total delay (in vehicle-minutes) by through vehicles in vehicle-minutes during the 15-minute period of analysis;

SPEED = posted speed limit, mph;

VOL = approach volume in 15-minute period;

RT = number of right-turning vehicles in 15-minute approach volume; and

POC = pocket length (sum of taper length and full width lane length in feet).

The parameter estimates and the residual plots of the total delay prediction model are presented in Table 4.5 and Figure 4.26, respectively.

Table 4.5. Parameter Estimates of Simulation Based Total Delay Statistical Model.

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	0.9754	0.2023	4.82	0.000
(SPEED)	-0.030194	0.003953	-7.63	0.000
(VOL)	0.094676	0.005953	15.90	0.000
(RT)	0.5459	0.1505	3.63	0.000
(POC)	-0.0000310	0.0001869	-0.17	0.869
(RT)*(VOL)	0.012269	0.004695	2.61	0.010
(RT)*(SPEED)	-0.016016	0.002436	-6.57	0.000
(RT)*(POC)	-0.0004242	0.0001153	-3.68	0.000

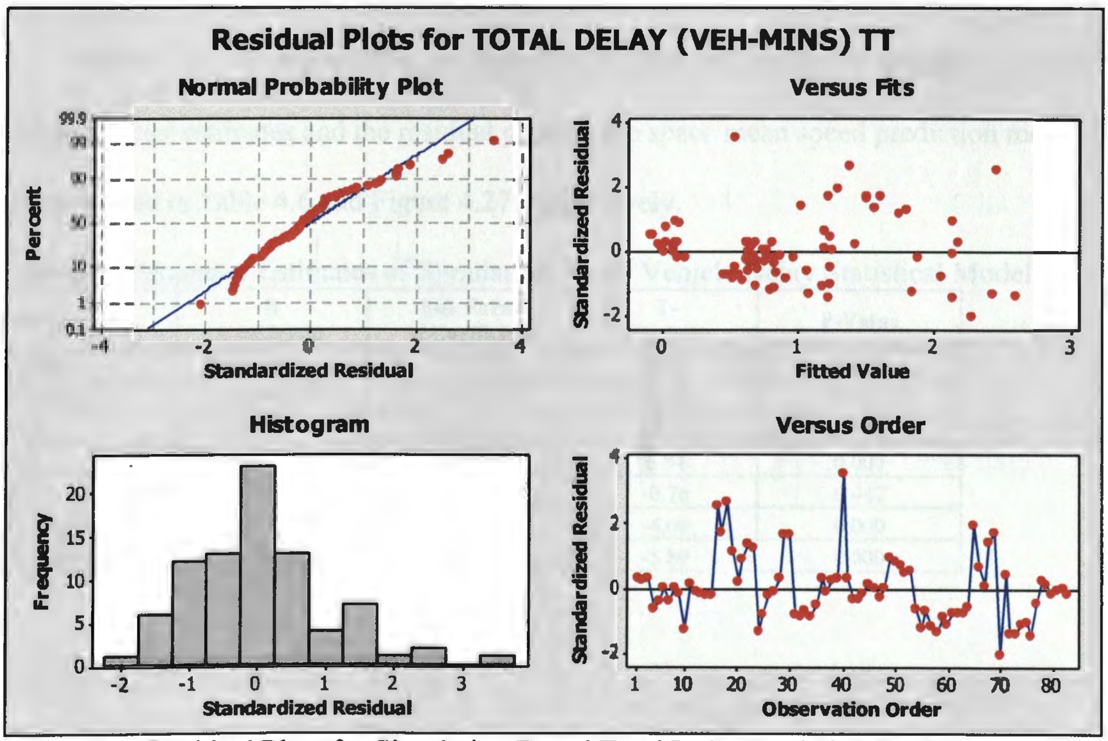

Figure 4.26. Residual Plots for Simulation Based Total Delay Statistical Model.

4.3.3. Model 6: Simulation Based Vehicle Delay Statistical Model

This model determines the delay to individual vehicles on average in seconds per vehicle. The vehicle delay (in seconds per vehicle) prediction model that finally fitted field data is provided below as Equation 4.3. This model predicts the average delay in seconds through vehicle encounter on the approach leading to right turn movement.

$$VD = 1.87 - 0.0364*(SPEED) + 0.0469*(VOL) + 0.463*(RT) - 0.000083*(POC) - 0.00860*(RT)*(SPEED) - 0.000287*(RT)*(POC) \quad 4.3$$

$[S = 0.238720, R^2 = 86.8\%, \text{Adj. } R^2 = 86.5\%]$

where VD = through vehicle delay in seconds;

SPEED = posted speed for the approach;

VOL = 15-minute approach volume;

RT = right turning volume in 15-minute time interval; and

POC = pocket length (taper length plus full-width lane length)

The parameter estimates and the residual plots of the space mean speed prediction model are presented in Table 4.6 and Figure 4.27, respectively.

Table 4.6. Parameter Estimates of Simulation Based Vehicle Delay Statistical Model.

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	1.8690	0.1112	16.80	0.000
(SPEED)	-0.036447	0.002299	-15.86	0.000
(VOL)	0.046851	0.002577	18.18	0.000
(RT)	0.46261	0.06764	6.84	0.000
(POC)	-0.0000831	0.0001093	-0.76	0.447
(RT)*(POC)	-0.00028697	0.00007010	-4.09	0.000
(RT)*(SPEED)	-0.008603	0.001460	-5.89	0.000

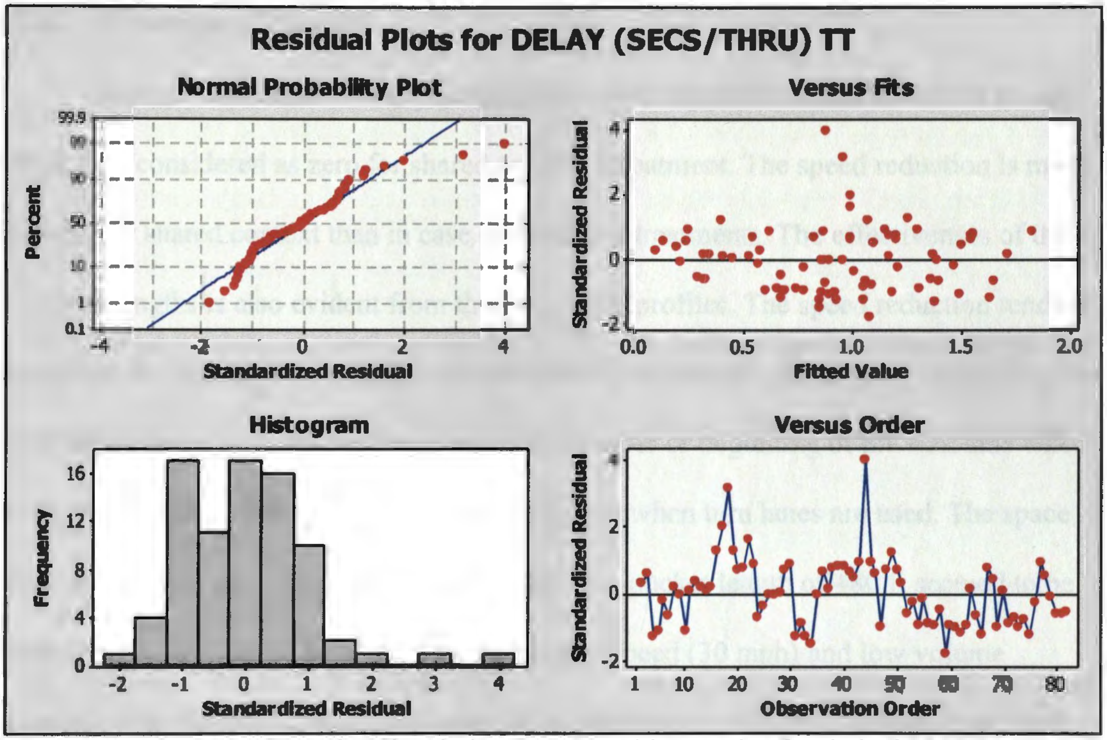

Figure 4.27. Residual Plots for Simulation Based Vehicle Delay Statistical Model.

4.3.4. Validation of Statistical Models Based on Simulation Data

To make sure the calibrated models represented the real situation of each site, field validation was performed. The output from the calibrated models' delay (veh-min), delay (secs/through-veh) and the total time of travel (minutes) were matched with values processed from the field data as shown in Table 4.7 below.

Table 4.7. Validation of Simulation Data Based Models.

Model	Dependent Variable	PRESS	R^2 (fitted model)	$R^2_{jackknife}$	MSE (fitted model)	$MSE_{jackknife}$
Model 4	Space Mean Speed	68.5252	99.75%	99.73%	0.2954	0.3000
Model 5	Total Delay (vehicle-minutes)	40.1745	83.70%	82.38%	0.1630	0.1762
Model 6	Vehicle Delay (seconds/vehicle)	14.0907	86.80%	85.89%	0.0570	0.0610

4.3.5. Discussion of Results

Spot speed profiles results provided how effective pocket lengths were. A pocket length was considered as zero for shared or radius treatment. The speed reduction is much more under shared context than in case of exclusive treatments. The effectiveness of the turn lane lengths is also evident from the spot speed profiles. The speed reduction tends to take place the right before the point where right turn movement takes place, which is at the intersection location for shared case and near the taper or beginning of the turn lane when turn lanes are used. The speed reduction is also less when turn lanes are used. The space mean speed plots provided interesting insights. The pocket length of 480 ft seemed to be most effective among all turn lane lengths for low speed (30 mph) and low volume scenario (100 vph rate of flow). However, at higher speed and higher volume there is no perceptible difference in the impact. The delay is perceptibly less when using turn lane lengths; however, the effectiveness of different turn lane lengths is not that evident.

There are some interesting insights developed from the statistical models developed using data generated from simulation models. All models improved considerably compared to those developed using just field data. The models also provided a better basis for comparing different contexts in a consistent basis. The best improvement was in the vehicle delay model. These models together can provide a very good insight regarding the effectiveness of different turn lane lengths.

The models related to space mean speed, total vehicle delay (in vehicle-minutes), and average vehicle delay (seconds per vehicle) were found to be valid as $R^2_{jacknife}$ was less than R^2 of the fitted model and the $MSE_{jackknife}$ was greater than the MSE of the fitted model (see Table 4.7).

4.4. Summary

There were numerous insights obtained from the development of simulation models and the analysis of results from simulation models. The development of simulation models required caution and care during calibration and validation. Over 2400 simulations were performed for calibration and validation proposes as well as for modeling different scenarios representing the broad range of conditions.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the work of this thesis by presenting its key findings and significant contributions. It is underscored that the conclusions and the recommendations made herein are relevant mostly to right turn activity and the two-lane highway context where major roads have no controls, but many of the lessons are applicable and transferable to several other contexts involving right-turn activity.

5.1. Conclusions

5.1.1. Issues Related to Right-Turn Lanes

The ultimate decision for right turn lanes is based on operational, safety, access, and cost considerations, which makes it a multi-faceted problem. In general, data on approach volume, number of right turns in approach volume or percentage of right turning vehicles in approach volume, approach speed, speed differential, and type of right-turn treatments seem to impact the operational impact of right turning vehicles. Operational impacts due to right turning vehicles have been studied using field data analysis, analytical methods, simulation analysis, or a combination of these methods. The considerations for right turn lane when approach volume is less than 4000 AADT are not well understood or established. It is commonly perceived that at volumes below 4000 AADT, the impact of right-turning traffic does not impact through traffic. The warrants for right turn lane vary by states and bases for developing the warrants also differ. The analyses carried out in this research did find some significant differences in shared treatment and exclusive treatment for AADT less than 4000.

5.1.2. Field Data Collection and Analysis

This research analyzed in detail the impact on space mean speed of through vehicles, total delay of through vehicles, and vehicle delay to through vehicles. Space mean speed of through vehicles on the approach link leading to the intersection is impacted by speed, approach volume, percentage of right-turn vehicles in approach volume, pocket length, as well as interaction terms of pocket length and approach volume, and percentage right turn in approach volume and pocket length. It was interesting to see that percentage right turn and pocket length did not have significant probability values, but the overall model improved when the interaction terms (POC*VOL and POC*RT%) were introduced. The strength of relationship for space mean speed is strong and the signs do make sense. The space mean speed increases as posted speed increases and pocket length increases. The increase in right turn percentage decreases space mean speed.

Total delay to through vehicles on the approach link leading to the intersection is influenced by posted speed limit, approach volume, right turn volume, and pocket length. Total delay decreases with increasing posted speed limit. Total delay increases with increase in approach volume and right turn volume. Total delay decreases with increase in pocket length. The relationship of total delay was not as strong as was observed for space mean speed model.

Vehicle delay in seconds per vehicle is influenced by posted speed limit, approach volume, right turn volume, and pocket length. Vehicle delay decreases with increase in posted speed and increase in pocket length. Vehicle delay model was not as strong, but all variables included in the model were quite significant.

The models related to space mean speed, total vehicle delay (in vehicle-minutes), and average vehicle delay (seconds per vehicle) were found to be valid as $R^2_{jacknifc}$ was less than R^2 of the fitted model and the $MSE_{jackknife}$ was greater than the MSE of the fitted model. Nonetheless, these models needed improvement, which was possible using simulation model and related results.

5.1.3. Use of Simulation in Understanding Impacts

Spot speed profiles results provided how effective pocket lengths were. A pocket length was considered as zero for shared or radius treatment. The speed reduction is much more under shared context than in case of exclusive treatments. The effectiveness of the turn lane lengths is also evident from the spot speed profiles. The speed reduction tends to take place the right before the point where right turn movement takes place, which is at the intersection location for shared case and near the taper or beginning of the turn lane when turn lanes are used. The speed reduction is also less when turn lanes are used. The space mean speed plots provided interesting insights. The pocket length of 480 ft seemed to be most effective among all turn lane lengths for low speed (30 mph) and low volume scenario (100 vph rate of flow). However, at higher speed and higher volume there is no perceptible difference in the impact. The delay is perceptibly less when using turn lane lengths; however, the effectiveness of different turn lane lengths is not that evident.

There are some interesting insights developed from the statistical models developed using data generated from simulation models. All field data based models improved considerably when reanalyzed and developed using simulation generated data. The models also provided a better basis for comparing different contexts in a consistent basis. The best improvement was in the vehicle delay model. These models together can provide a very good insight regarding the effectiveness of different turn lane lengths.

5.2. Recommendations

CORSIM® does not separate taper length and full width turn lane length, which doesn't allow one to model the effects the two lane lengths separately. Some of these concerns were potentially addressed in the calibration process in this research. However, enhancement of the CORSIM® program in this regard can help develop better understanding and potentially better results.

The justification of right-turn lanes shouldn't be solely dependent on the operational cost savings, as there are safety-related issues associated with it. There is also the cost related to construction and maintenance as well. Careful evaluation of all these aspects is recommended when making final decisions regarding the right turn lanes. The operational analyses and models developed in this research when combined with safety and cost analyses and modeling will help develop information for advancing further the knowledge and improving practice.

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APPENDIX A. SAMPLE CORSIM INPUT

```
                              Sample corsim file.trf
Created by TSIS Mon Jun 20 20:07:02 2011 from TNO Version 65
12345678 1 2345678 2 2345678 3 2345678 4 2345678 5 2345678 6 2345678 7 234567
Amiy Varma                              6  192011North Dakota State Univ    0  1
       1   0   0  10      8321 0010   1                   31447       15119     357  2
 900                                                                             3
           1       60                                                            4
   0       0   0   0   0   0   0   0   0   0   1   0                             5
   1   6 402           1     01          8002               20  18  30   0      11
   2   31000           1     01          8001               20  18  30   0      11
   1   4 995           1     01          8004               20  18  30   0      11
   1   5 402           1     01          8003               20  18  30   0      11
   1   2 501           1     01             3               20  18  30   0      11
   4   1 995           1     01         5   2   6       2   20  18  30   0      11
   6   1 402           1     01         4   5   2       5   20  18  30   0      11
   5   1 402           1     01         2   6   4       6   20  18  30   0      11
   2   1 800           1     01         6   4   5       4   20  18  30   0      11
   3   21000           1     01             1               20  18  30   0      11
8001   3               1     01             2               20  18       0      11
8004   4               1     01             1               20  18       0      11
8002   6               1     01             1               20  18       0      11
8003   5               1     01             1               20  18       0      11
   1   6      100                                                               21
   2   3      100                                                               21
   1   4      100                                                               21
   1   5      100                                                               21
   1   2      100                                                               21
   4   1   0   33  33   0                                                       21
   6   1  33   33  33   0                                                       21
   5   1  33   33  33   0                                                       21
   2   1   0   99  01   0                                                       21
   3   2      100                                                               21
8001   3      100                                                               21
8004   4      100                                                               21
8002   6      100                                                               21
8003   5      100                                                               21
   1           4    6   5   2                                                   35
   2           1    3                                                           35
   3           28001                                                            35
   4           18004                                                            35
   5           18003                                                            35
   6           18002                                                            35
   1 1551                                                                       36
   2 11                                                                         36
   3 11                                                                         36
   4 11                                                                         36
   5 11                                                                         36
   6 11                                                                         36
   1   4   9    8950   141     20   0                                           42
   2   1   9    3000   213     20   0                                           42
   2   1   9    2000   212     20   0                                           42
   2   1   9       0   211     20   0                                           42
   3   2   9       0   321     20   0                                           42
   3   2   9    1000   322     20   0                                           42
8002   6   0   0   0  100                                                       50
8001   3       0   0  100                                                       50
8004   4   0   0   0  100                                                       50
8003   5   0   0   0  100                                                       50
8001   3  25   7                                                             0  53
   3  10       5  10   5  10  15  25   2   8  50  20  50 300                    81
                                                             15                140
   0                                                                           170
8002     1689     1005                                                         195
8001        0      516
                                  Page 1

                              Sample corsim file.trf
8004     2979      484                                                         195
8003     1695        0                                                         195
   1     1692      494                                                         195
   2     1191      495                                                         195
   3      191      496                                                         195
   4     2687      496                                                         195
   5     1695       92                                                         195
   6     1683      896                                                         195
   1   0    0                                                                  210
```

APPENDIX B. SAMPLE CORSIM OUTPUT

```
INPUT FILE NAME: C:\TSIS62 Projects\SharedMultiruns\30mph100vph10rtp trf
RUN DATE       : 08/22/11

                              VERSION 6.2
                              RELEASE DATE DECEMBER 2009
                              BUILD NUMBER 510

                              TRAF SIMULATION MODEL

                                 DEVELOPED FOR

                        U. S. DEPARTMENT OF TRANSPORTATION
                          FEDERAL HIGHWAY ADMINISTRATION
               FHWA OFFICE OF OPERATIONS RESEARCH, DEVELOPMENT AND TECHNOLOGY
1
                                  CARD FILE LIST
SEQ.#     +    1    +    2    +    3    +    4    +    5    +    6    +    7    +    8

     1 :Amly Varma                           6  19201North Dakota State univ     0   1
     2          1    0    0   10 97165909 0010  22          31447    679096 8414 58717   2
     3 : 900                                                                           3
     4                   60                                                            4
     5      0         0    0    0    0    0    0    0    0    1    0                   5
```

CARD FILE LIST (CONT)

75

TRAF SIMULATION MODEL
DEVELOPED FOR
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
FHWA OFFICE OF OPERATIONS RESEARCH, DEVELOPMENT AND TECHNOLOGY

1
0

DATE = 6/19/2011
USER = Amiy Varma
AGENCY = North Dakota State Univ

0
0

RUN CONTROL DATA
RUN PARAMETERS AND OPTIONS

VALUE	
0	RUN IDENTIFICATION NUMBER
1	RUN TYPE CODE = (1, 2, 3) TO RUN (SIMULATION, ASSIGNMENT, BOTH) (-1, -2, 3) TO CHECK (SIMULATION, ASSIGNMENT, BOTH) ONLY

NETSIM ENVIRONMENTAL OPTIONS

0	FUEL/EMISSION RATE TABLES ARE NOT PRINTED
0	SIMULATION: PERFORMED — ENVIRONMENTAL MEASURES CALCULATED
	RATE TABLES: EMBEDDED — TRAJECTORY FILE: NOT WRITTEN
2	CODE = (0,1,2) FOR UNIFORM DISTRIBUTION, NORMAL DISTRIBUTION, ERLANG DISTRIBUTION
2	CODE = (1 - 9) USED IN ERLANG DISTRIBUTION
0	INITIALIZATION CODE (0,1) = (DO NOT, DO) FORCE FULL INITIALIZATION PERIOD
0	INPUT UNITS CODE = (0,1) IF INPUT IS IN (ENGLISH, METRIC) UNITS
0	OUTPUT UNITS CODE = (0,1,2,3) IF OUTPUT IS IN (SAME AS INPUT, ENGLISH, METRIC, BOTH) UNITS
1447	CLOCK TIME AT START OF SIMULATION (HHMM)
0	SIGNAL TRANSITION CODE = (0,1,2,3) IF(NO, IMMEDIATE, 2-CYCLE, 3 CYCLE) TRANSITION WAS REQUESTED
41456717	RANDOM NUMBER SEED
67990630	RANDOM NUMBER SEED TO GENERATE TRAFFIC STREAM FOR NETSIM OR LEVEL I SIMULATION
97165909	RANDOM NUMBER SEED TO GENERATE EMISSION HEADWAYS FOR NETSIM SIMULATION
900	DURATION (SEC) OF TIME PERIOD NO. 1
60	LENGTH OF A TIME INTERVAL, SECONDS
10	MAXIMUM INITIALIZATION TIME, NUMBER OF TIME INTERVALS
0	NUMBER OF TIME INTERVALS BETWEEN SUCCESSIVE STANDARD OUTPUTS
0	TIME INTERMEDIATE OUTPUT WILL BEGIN AT INTERVALS OF 0 SECS. FOR 0 SECS. FOR MICROSCOPIC MODELS
1	NETSIM MOVEMENT-SPECIFIC OUTPUT CODE = (0,1) (IF NOT, IF) REQUESTED FOR NETSIM SUBNETWORK

1**

TIME PERIOD 1 - NETSIM DATA

****

1

NETSIM LINKS

0

LINK	LENGTH FT / M	-LANES- FULL	-LANES- L	-LANES- R	PKT GRD PCT	LINK TYPE	-CHANNEL- CODE 8.34567	DESTINATION NODE LEFT	THRU	RGHT	DIAG	OPP. NODE	LOST TIME SEC	Q DIS HDWY. SEC	FREE SPEED MPH/KMPH	RTOR CODE	PED CODE	LANE ALIGN MENT	STREET NAME
(1, 6)	402/ 123	1	0	0	0	1	0000000	0	8002	0	0	0	2.0	1.8	30/ 48	0	0	1-1*	
(2, 3)	1000/ 305	1	0	0	0	1	0000000	0	8001	0	0	0	2.0	1.8	30/ 48	0	0	1-1*	
(1, 4)	995/ 303	1	0	0	0	1	0000000	0	8004	0	0	0	2.0	1.8	30/ 48	0	0	1-1*	
(1, 5)	402/ 123	1	0	0	0	1	0000000	0	8003	0	0	0	2.0	1.8	30/ 48	0	0	1-1*	
(1, 2)	501/ 153	1	0	0	0	1	0000000	0	3	0	0	0	2.0	1.8	30/ 48	0	0	1-1*	
(4, 1)	995/ 303	1	0	0	0	1	0000000	5	2	6	0	2	2.0	1.8	30/ 48	0	0	1-1*	
(6, 1)	402/ 123	1	0	0	0	1	0000000	4	5	2	0	5	2.0	1.8	30/ 48	0	0	1-1*	
(5, 1)	402/ 123	1	0	0	0	1	0000000	2	6	4	0	6	2.0	1.8	30/ 48	0	0	1-1*	
(2, 1)	501/ 153	1	0	0	0	1	0000000	6	4	5	0	4	2.0	1.8	30/ 48	0	0	1-1*	
(3, 2)	1000/ 305	1	0	0	0	1	0000000	0	1	0	0	0	2.0	1.8	30/ 48	0	0	1-1*	
(8001, 3)	0/ 0	1	0	0	0	1	0000000	0	2	0	0	0	2.0	1.8	0/ 0	0	0	1-1*	
(8004, 4)	0/ 0	1	0	0	0	1	0000000	0	1	0	0	0	2.0	1.8	0/ 0	0	0	1-1*	
(8002, 6)	0/ 0	1	0	0	0	1	0000000	0	1	0	0	0	2.0	1.8	0/ 0	0	0	1-1*	
(8003, 5)	0/ 0	1	0	0	0	1	0000000	0	1	0	0	0	2.0	1.8	0/ 0	0	0	1-1*	

* INDICATES DEFAULT VALUES WERE SPECIFIED

LINK TYPE

IDENTIFIES THE DISTRIBUTION USED FOR QUEUE DISCHARGE AND START-UP LOST TIME CHARACTERISTICS.

LANE CHANNELIZATION CODES

0 UNRESTRICTED
1 LEFT TURNS ONLY
2 BUSES ONLY
3 CLOSED
4 RIGHT TURNS ONLY
5 CAR - POOLS
6 CAR - POOLS + BUSES
7 RIGHT TURNS + RIGHT DIAGONAL AND/OR THROUGH
8 LEFT TURNS + LEFT DIAGONAL AND/OR THROUGH
9 ALL PERMITTED MOVEMENTS WITH RESPECT TO THE GEOMETRY AND ADJACENT LANE CHANNELIZATIONS
D DIAGONAL TRAFFIC ONLY
T THROUGH TRAFFIC ONLY

RTOR CODES

0 RTOR PERMITTED
1 RTOR PROHIBITED

PEDESTRIAN CODES

0 NO PEDESTRIANS
1 LIGHT
2 MODERATE
3 HEAVY

TOTAL LINKS: 14
TOTAL NON ENTRY NODES: 6 (ALLOWED: 8999)

NETSIM TURNING MOVEMENT DATA

LINK	TURN MOVEMENT PERCENTAGES LEFT	THROUGH	RIGHT	DIAGONAL	TURN MOVEMENT POSSIBLE LEFT	THROUGH	RIGHT	DIAGONAL	POCKET LENGTH (IN FEET/METERS) LEFT		RIGHT	
(1, 6)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(2, 3)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(1, 4)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(1, 5)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(1, 2)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(4, 1)	0.0	50.0	50.0	0.0	YES	YES	YES	NO	0/	0	0/	0
(6, 1)	33.3	33.3	33.3	0.0	YES	YES	YES	NO	0/	0	0/	0
(5, 1)	33.3	33.3	33.3	0.0	YES	YES	YES	NO	0/	0	0/	0
(2, 1)	0.0	90.0	10.0	0.0	YES	YES	YES	NO	0/	0	0/	0
(3, 2)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(8001, 3)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(8004, 4)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(8002, 6)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0
(8003, 5)	0.0	100.0	0.0	0.0	NO	YES	NO	NO	0/	0	0/	0

SPECIFICATION OF SURVEILLANCE DETECTORS

ID	APPROACH LINK	COVERED LANES A - B	DISTANCE OF TRAILING EDGE FROM NODE 4 FEET / METERS	DETECTOR LENGTH FEET / METERS	TYPE
141	(1, 4)	9 - 0	895.0/ 272.8	2.0/ 0.6	PRESENCE
213	(2, 1)	9 - 0	300.0/ 91.4	2.0/ 0.6	PRESENCE
212	(2, 1)	9 - 0	200.0/ 61.0	2.0/ 0.6	PRESENCE
211	(2, 1)	9 - 0	0.0/ 0.0	2.0/ 0.6	PRESENCE
321	(3, 2)	9 - 0	0.0/ 0.0	2.0/ 0.6	PRESENCE
322	(3, 2)	9 - 0	100.0/ 30.5	2.0/ 0.6	PRESENCE

ENTRY LINK VOLUMES

LINK	FLOW RATE (VEH/HOUR)	TRUCKS (PERCENT)	CAR POOLS (PERCENT)	HOV VIOLATORS (PERCENT)
(8002, 6)	0	0	0	1.00
(8001, 3)	0	0	0	1.00
(8004, 4)	0	0	0	1.00
(8003, 5)	0	0	0	1.00

NETSIM VEHICLE TYPE SPECIFICATIONS

VEHICLE TYPE	LENGTH FEET/METERS	Q DSCHG HDWY FACTOR (PCT)	AVG. OCCUP.	FLEET COMPONENT PERCENTAGES AUTO	TRUCK	CARPOOL	BUS	PERF. INDEX
1**	16.0/ 4.9	100	1.3	75	0	0	0	7
2**	35.0/ 10.7	120	1.2	0	100	0	0	3
3**	16.0/ 4.9	100	2.5	0	0	100	0	2
4**	40.0/ 12.2	120	25.0	0	0	0	100	7
5**	14.0/ 4.3	100	1.3	25	0	0	0	1
6**	53.0/ 16.2	120	1.2	0	0	0	0	4
7**	53.0/ 16.2	120	1.2	0	0	0	0	5
8**	64.0/ 19.5	120	1.2	0	0	0	0	6
9**	14.0/ 4.3	100	2.5	0	0	0	0	1

** INDICATES THAT ALL PARAMETERS FOR VEHICLE TYPE ASSUME DEFAULT VALUES

DEFAULT LINK GEOMETRIC DATA

WIDTH OF LANES	12 FEET
LONGITUDINAL DISTANCE FROM THE STOP LINE TO THE NEAR CURB	4 FEET
FORWARD SIGHT DISTANCE AT STOP LINE	1000 FEET

LANE CHANGE DATA

PARAMETERS	VALUE ENGLISH	/	METRIC	UNITS
DURATION OF LANE CHANGE MANEUVER	3			SECONDS
MEAN DRIVER REACTION TIME	10			TENTHS OF A SECOND
TIME REQUIRED FOR SUCCESSIVE LANE CHANGES	20*			TENTHS OF A SECOND
DECELERATION AT BEGINNING OF LANE CHANGE MANEUVER	5	/	2	FEET [METERS] / SECOND**2
DIFFERENCE IN VEHICLE'S DECELERATION OVER THE DISTANCE BETWEEN ITS POSITION WHEN IT BEGINS TO RESPOND TO AN OBSTRUCTION AND THE POSITION OF THE OBSTRUCTION -				
FOR MANDATORY LANE CHANGE:	10	/	3	FEET [METERS] / SECOND**2
FOR DISCRETIONARY LANE CHANGE:	5	/	2	FEET [METERS] / SECOND**2
PANIC DECELERATION RATE OF LEAD VEHICLE FOR COMPUTATION OF CAR-FOLLOWING LAW	10	/	3	FEET [METERS] / SECOND**2
PANIC DECELERATION RATE OF FOLLOWER VEHICLE FOR COMPUTATION OF CAR-FOLLOWING LAW	15	/	5	FEET [METERS] / SECOND**2
DRIVER TYPE FACTOR USED TO COMPUTE DRIVER AGGRESSIVENESS	25			
URGENCY THRESHOLD	2	/	1	10 * SECONDS**2 / FEET [METERS]
SAFETY FACTOR FOR COMPUTATION OF PERCEIVED RISK OF LANE CHANGE	8			FACTOR * 10
PERCENT OF DRIVERS WHO COOPERATE WITH A LANE CHANGER	50			%
HEADWAY BELOW WHICH ALL DRIVERS WILL ATTEMPT TO CHANGE LANES	20			TENTHS OF A SECOND
HEADWAY ABOVE WHICH NO DRIVERS WILL ATTEMPT TO CHANGE LANES	50			TENTHS OF A SECOND
FORWARD DISTANCE SCANNED BY DRIVER FOR A TURN MOVEMENT / BUS STATION IN ORDER TO ASSESS NEED FOR A LANE CHANGE	300	/	91	FEET / [METERS]

MAXIMUM ACCELERATION TABLE

PERFORMANCE INDEX	0 FT/SEC	10 FT/SEC	20 FT/SEC	30 FT/SEC	40 FT/SEC	50 FT/SEC	60 FT/SEC	70 FT/SEC	80 FT/SEC	90 FT/SEC	100 FT/SEC	110 FT/SEC
1	8.00	9.00	6.00	5.00	5.00	5.00	4.00	3.00	2.00	2.00	1.00	1.00
2	6.00	12.00	10.00	8.00	7.00	6.00	4.00	4.00	4.00	[illegible]	[illegible]	2.00
3	4.69	5.35	4.94	3.42	3.09	2.61	2.14	1.70	1.27	0.86	0.46	0.06
4	2.81	2.42	2.15	2.04	1.74	1.42	1.12	0.83	0.56	0.30	0.04	-0.23
5	2.76	2.37	1.81	1.56	1.25	0.97	0.73	0.52	0.32	0.14	-0.03	0.23
6	2.45	2.14	1.42	1.12	0.85	0.63	0.44	0.29	0.14	0.00	0.14	-0.27
7	7.47	5.33	3.17	2.66	2.29	1.65	1.40	0.95	0.75	0.50	0.35	-0.35

GRADE CORRECTION FACTORS FOR ACCELERATION (USED BY FRESIM ONLY)

PERFORMANCE INDEX	0 FT/SEC	10 FT/SEC	20 FT/SEC	30 FT/SEC	40 FT/SEC	50 FT/SEC	60 FT/SEC	70 FT/SEC	80 FT/SEC	90 FT/SEC	100 FT/SEC	110 FT/SEC
1	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
2	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
3	0.21	0.21	0.21	0.22	0.23	0.25	0.26	0.27	0.28	0.28	0.30	0.31
4	0.16	0.15	0.18	0.22	0.24	0.25	0.27	0.28	0.29	0.31	0.31	0.31
5	0.18	0.17	0.20	0.23	0.25	0.27	0.28	0.30	0.31	0.31	0.31	0.31
6	0.18	0.18	0.22	0.25	0.27	0.29	0.30	0.30	0.31	0.31	0.31	0.31
7	0.27	0.27	0.27	0.27	0.27	0.29	0.29	0.30	0.30	0.30	0.30	0.30

GRADE CORRECTION FACTORS FOR FUEL CONSUMPTION (USED BY FRESIM ONLY)

PERFORMANCE INDEX	0 FT/SEC	10 FT/SEC	20 FT/SEC	30 FT/SEC	40 FT/SEC	50 FT/SEC	60 FT/SEC	70 FT/SEC	80 FT/SEC	90 FT/SEC	100 FT/SEC	110 FT/SEC
1	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
2	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
3	0.26	0.26	0.26	0.28	0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30
4	0.11	0.11	0.23	0.27	0.28	0.29	0.30	0.30	0.30	0.30	0.30	0.30
5	0.16	0.16	0.26	0.28	0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30
6	0.20	0.20	0.28	0.29	0.30	0.30	0.30	0.30	0.31	0.31	0.31	0.31
7	0.27	0.27	0.27	0.27	0.27	0.29	0.29	0.30	0.30	0.30	0.30	0.30

1

TIME VARYING ENTRY VOLUMES

LINK	BEGIN TIME (MINUTES)	FLOW RATE (VEH/HOUR)
(8001, 3)	0	857
(8001, 3)	2	857

1

INITIALIZATION STATISTICS

TIME INTERVAL NUMBER	SUBNETWORK TYPE	PRIOR CONTENT (VEHICLES)	CURRENT CONTENT (VEHICLES)	PERCENT DIFFERENCE	
1	NETSIM	0	15	10000	
2	NETSIM	15	9	40	
3	NETSIM	9	16	77	
4	NETSIM	16	14	12	EQUILIBRIUM ATTAINED

1

ALL EXISTING SUBNETWORKS REACHED EQUILIBRIUM
CUMULATIVE NETSIM STATISTICS AT TIME 15: 2: 0

ELAPSED TIME IS 0:15: 0 (900 SECONDS). TIME PERIOD 1 ELAPSED TIME IS 900 SECONDS

LINK	VEHICLE MILES	TRIPS	VEHICLE MINUTES MOVE TIME	VEHICLE MINUTES DELAY TIME	VEHICLE MINUTES TOTAL TIME	RATIO MOVE/ TOTAL	MINUTES/MILE TOTAL TIME	MINUTES/MILE DELAY TIME	SECONDS / VEHICLE TOTAL TIME	SECONDS / VEHICLE DELAY TIME	SECONDS / VEHICLE CONTROL DELAY	SECONDS / VEHICLE QUEUE DELAY	SECONDS / VEHICLE STOP* TIME	AVERAGE VALUES STOPS (%)	AVERAGE VALUES VOL VPH	AVERAGE VALUES SPEED MPH
(1, 6)	0.00	0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0.0
(2, 3)	0.00	0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0.0
(1, 4)	35.24	187	70.5	12.5	82.9	0.85	2.35	0.35	26.2	3.9	0.0	0.0	0.0	0	748	25.5
(1, 5)	1.60	21	3.2	0.4	3.6	0.88	2.27	0.27	10.4	1.2	0.0	0.0	0.0	0	84	26.4
(1, 2)	0.00	0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0.0
(4, 1)	0.00	0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0.0
(6, 1)	0.00	0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0.0
(5, 1)	0.00	0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0.0
(2, 1)	19.93	210	39.9	8.3	48.1	0.83	2.42	0.42	13.6	2.3	0.1	0.1	0.1	4	840	24.8
(3, 2)	39.20	207	78.4	3.3	81.7	0.96	2.08	0.08	23.4	0.9	0.0	0.0	0.1	4	828	28.8
(8001, 3)		208													832	
(8004, 4)		0													0	
(8002, 6)		0													0	
(8003, 5)		0													0	
0SUBNETWORK=	95.97	208	3.20	0.41	3.61	0.89	2.25	0.25	0.98	0.11	0.00	0.00	0.00		9 1	26.6
			VEHICLE	HOURS --					-- MINUTES	/ VEHICLE TRIP			PER TRIP			

1

CUMULATIVE NETSIM STATISTICS AT TIME 15: 2: 0

ELAPSED TIME IS 0:15: 0 (900 SECONDS). TIME PERIOD 1 ELAPSED TIME IS 900 SECONDS

LINK	VEH-MINS * QUEUE TIME	VEH-MINS * STOP TIME	AVERAGE OCCUPANCY (VEHICLE)	CONGESTION STORAGE (%)	CONGESTION PHASE FAILURE	AVERAGE QUEUE BY LANE ** 1	2	3	4	5	6	7	8	9	MAXIMUM QUEUE BY LANE 1	2	3	4	5	6	7	8	9	NUMBER OF LANE CHANGES
(1, 6)	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(2, 3)	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1, 4)	0.0	0.1	6.1	11.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1, 5)	0.0	0.0	0.4	1.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1, 2)	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(4, 1)	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6, 1)	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(5, 1)	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(2, 1)	0.5	0.4	3.5	13.1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
(3, 2)	0.0	0.2	6.0	11.0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
0SUBNETWORK=	0.5	0.4	16.0	10.2	0																			0

* THESE VALUES INCLUDE THE TIME FOR VEHICLES CURRENTLY ON THE LINK.
** AVERAGE QUEUE CALCULATED BASED ON TIME SINCE BEGINNING OF SIMULATION

1

CUMULATIVE NETSIM STATISTICS AT TIME 15: 2: 0

ELAPSED TIME IS 0:15: 0 (900 SECONDS). TIME PERIOD 1 ELAPSED TIME IS 900 SECONDS

DISCHARGE BY LANE

LINK	LANE 1 VEH	LANE 1 VPH	LANE 2 VEH	LANE 2 VPH	LANE 3 VEH	LANE 3 VPH	LANE 4 VEH	LANE 4 VPH	LANE 5 VEH	LANE 5 VPH	LANE 6 VEH	LANE 6 VPH	LANE 7 VEH	LANE 7 VPH	LANE 8 VEH	LANE 8 VPH	LANE 9 VEH	LANE 9 VPH
(1, 6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(2, 3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1, 4)	187	748	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1, 5)	21	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1, 2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(4, 1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6, 1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(5, 1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(2, 1)	210	840	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(3, 2)	207	828	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1

NETSIM PERSON MEASURES OF EFFECTIVENESS

LINK	PERSON MILE	PERSON TRIPS	DELAY PERSON-MIN	TRAVEL TIME PERSON MIN
(1, 6)	0.0	0.0	0.0	0.0
(2, 3)	0.0	0.0	0.0	0.0
(1, 4)	45.8	243.1	16.2	107.8
(1, 5)	2.1	27.3	0.6	4.7
(1, 2)	0.0	0.0	0.0	0.0
(4, 1)	0.0	0.0	0.0	0.0
(6, 1)	0.0	0.0	0.0	0.0
(5, 1)	0.0	0.0	0.0	0.0
(2, 1)	25.9	273.0	10.8	62.6
(3, 2)	51.0	269.1	4.3	106.2

1 *** NOTE *** TIME PERIOD 1 SPECIFIC NETSIM STATISTICS ARE THE SAME AS CUMULATIVE OUTPUT AT THE END OF TIME PERIOD 1.

1 NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE I

LINK		VEHICLE-MILE			VEHICLE-TRIPS			SPEED (MPH)			STOPS (PCT)		
		LEFT	THRU	RIGHT	LEFT	THRU	RIGHT	LEFT	THRU	RIGHT	LEFT	THRU	RIGHT
(1,	6)	0.00	0.00	0.00	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
(2,	3)	0.00	0.00	0.00	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
(1,	4)	0.00	35.24	0.00	0	187	0	0.0	25.5	0.0	0.0	0.0	0.0
(1,	5)	0.00	1.60	0.00	0	21	0	0.0	26.4	0.0	0.0	0.0	0.0
(1,	2)	0.00	0.00	0.00	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
(4,	1)	0.00	0.00	0.00	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
(6,	1)	0.00	0.00	0.00	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
(5,	1)	0.00	0.00	0.00	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
(2,	1)	0.00	17.93	1.99	0	189	21	0.0	25.2	22.1	0.0	4.8	4.8
(3,	2)	0.00	39.20	0.00	0	207	0	0.0	28.8	0.0	0.0	4.3	0.0
(8001,	3)				0	208	0						
(8004,	4)				0	0	0						
(8002,	6)				0	0	0						
(8003,	5)				0	0	0						

1 NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE II

LINK		MOVING TIME (VEH-MINS)			DELAY TIME (VEH-MINS)			TOTAL TIME (VEH-MINS)			RATIO MOVE/TOTAL (VEH-MINS)		
		LEFT	THRU	RIGHT	LEFT	THRU	RIGHT	LEFT	THRU	RIGHT	LEFT	THRU	RIGHT
(1,	6)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(2,	3)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(1,	4)	0.00	70.48	0.00	0.00	12.47	0.00	0.00	82.95	0.00	0.00	0.85	0.00
(1,	5)	0.00	3.20	0.00	0.00	0.44	0.00	0.00	3.63	0.00	0.00	0.88	0.00
(1,	2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(4,	1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(6,	1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(5,	1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(2,	1)	0.00	35.87	3.99	0.00	6.87	1.41	0.00	42.73	5.40	0.00	0.84	0.74
(3,	2)	0.00	78.41	0.00	0.00	3.27	0.00	0.00	81.68	0.00	0.00	0.96	0.00
(8001,	3)												
(8004,	4)												
(8002,	6)												
(8003,	5)												

1 NETSIM MOVEMENT SPECIFIC STATISTICS TABLE III

LINK		TOTAL TIME (SECS/VEH)			DELAY TIME (SECS/VEH)			QUEUE TIME** (VEH MINS)			STOP TIME** (VEH-MINS)		
		LEFT	THRU	RIGHT	LEFT	THRU	RIGHT	LEFT	THRU	RIGHT	LEFT	THRU	RIGHT
(1,	6)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(2,	3)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(1,	4)	0.0	26.6	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
(1,	5)	0.0	10.4	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(1,	2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(4,	1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(6,	1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(5,	1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(2,	1)	0.0	13.6	15.4	0.0	2.2	4.0	0.0	0.4	0.1	0.0	0.4	0.1
(3,	2)	0.0	23.7	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.2	0.0
(8001,	3)												
(8004,	4)												
(8002,	6)												
(8003,	5)												

** TIME FOR VEHICLES CURRENTLY ON THE LINK ARE INCLUDED IN THESE VALUES.

NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE IV

LINK	TOTAL CONTROL DELAY (VEH-MINS) LEFT	THRU	RIGHT	DIAGONAL	AVERAGE CONTROL DELAY (SECS/VEH) LEFT	THRU	RIGHT	DIAGONAL
(1, 6)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(2, 3)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(1, 4)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(1, 5)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(1, 2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(4, 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(6, 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(5, 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(2, 1)	0.0	0.4	0.0	0.0	0.0	0.1	0.0	0.0
(3, 2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE V

MOES FOR DIAGONAL TURN MOVEMENTS

LINK	VEH MILE	VEH-TRIPS	SPEED (MPH)	STOPS (PCT)	MOVING TIME (VEH-MINS)	DELAY TIME (VEH-MINS)	TOTAL TIME (VEH MINS)	M/T	TOTAL TIME (SECS/VEH)	DELAY TIME (SECS/VEH)	QUEUE TIME (VEH-MINS)	STOP TIME (VEH-MINS)
(1, 6)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(2, 3)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(1, 4)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(1, 5)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(1, 2)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(4, 1)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(6, 1)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(5, 1)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(2, 1)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(3, 2)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(8001, 3)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(8004, 4)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(8002, 6)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
(8003, 5)	0.00	0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0

1

NETSIM CUMULATIVE SURVEILLANCE DETECTOR OUTPUT
AT 15: 2: 0 (900 SECONDS)

DETECTOR ID	TYPE	APPROACH LINK	COVERED LANES A - B	DISTANCE OF TRAILING EDGE FROM DOWNSTREAM NODE FEET / METERS	DETECTOR LENGTH FEET / METERS	VEHICLE COUNT	CUMULATIVE ON-TIME (SEC)	OCCUPANCY** (%)	AVERAGE SPEED (MPH)
141	PRESENCE	(1, 4)	9 - 0	895.0 / 272.8	2.0 / 0.6	189	91.2	10.1	26.2
213	PRESENCE	(2, 3)	9 - 0	300.0 / 91.4	2.0 / 0.6	209	97.2	10.8	26.6
212	PRESENCE	(2, 3)	9 - 0	200.0 / 61.0	2.0 / 0.6	209	101.8	11.3	26.1
211	PRESENCE	(2, 3)	9 - 0	0.0 / 0.0	2.0 / 0.6	210	109.2	12.1	23.1
322	PRESENCE	(3, 2)	9 - 0	100.0 / 30.5	2.0 / 0.6	207	98.3	10.9	26.5
321	PRESENCE	(3, 2)	9 - 0	0.0 / 0.0	2.0 / 0.6	207	95.5	10.6	25.3

** OCCUPANCY IS CALCULATED AS (CUMULATIVE ON-TIME) / (TIME SINCE BEGINNING OF SIMULATION)

THE HIGHEST NUMBER OF VEHICLES ON THE NETWORK WAS 22 VEHICLES.
THIS MAXIMUM OCCURRED AT 131 SECONDS.

NETWORK-WIDE AVERAGE STATISTICS

TOTAL VEHICLE- MILE = 95.97 VEHICLE-HOURS OF: MOVE TIME = 3.20 , DELAY TIME = 0.41 , TOTAL TIME = 3.61
AVERAGE SPEED (MPH)= 26.61 MOVE/TOTAL = 0.89 MINUTES/MILE OF: DELAY TIME = 0.25 , TOTAL TIME = 2.25
NETWORK-WIDE STATISTICS FOR SCRIPT PROCESSING
95.97, 3.20, 0.41, 3.61, 26.61, 0.89, 0.25, 2.25
TOTAL CPU TIME FOR SIMULATION = 1.12 SECONDS
TOTAL CPU TIME FOR THIS RUN = 1.12 SECONDS
0LAST CASE PROCESSED

APPENDIX C. SIMULATION RESULTS

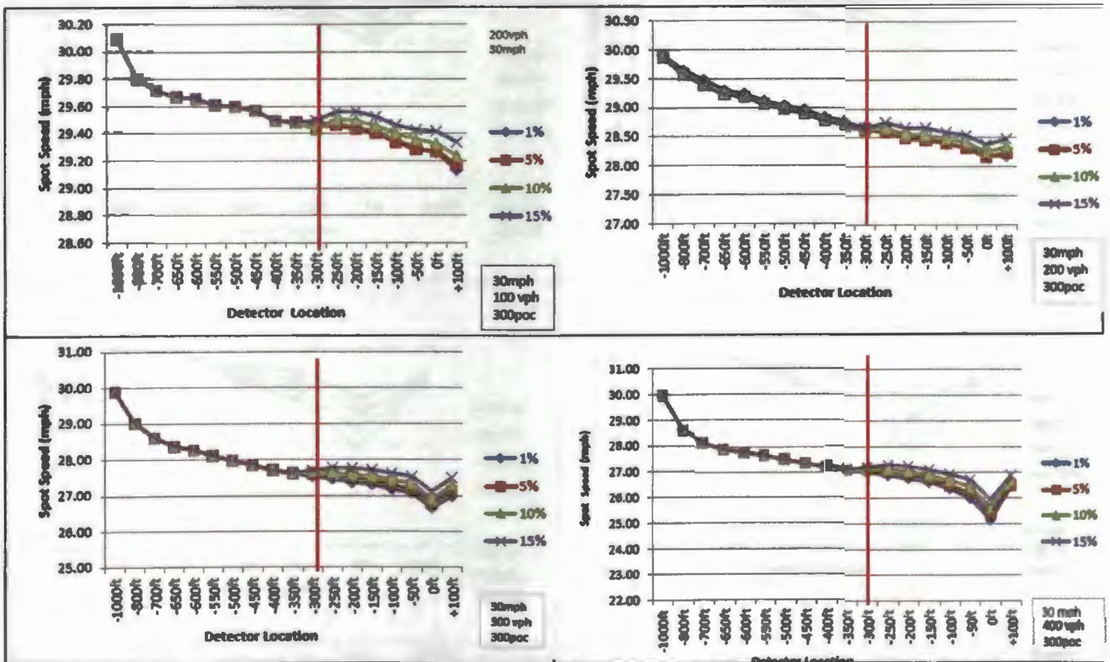

Figure C.1. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed and Exclusive Treatment (Pocket Length of 300 feet).

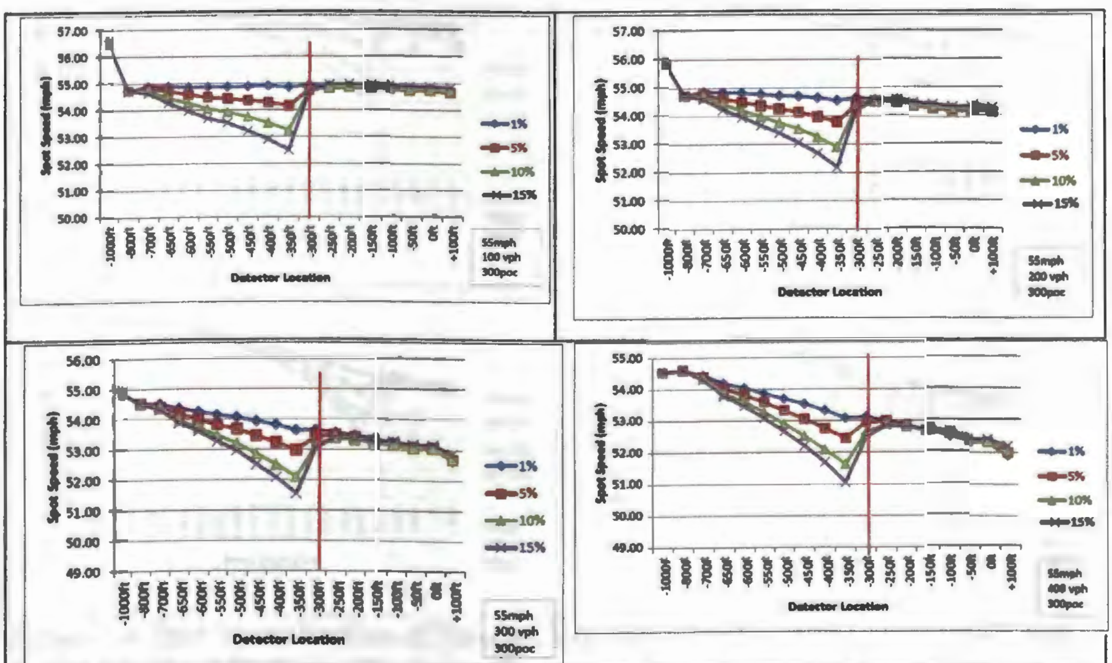

Figure C.2. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed and Exclusive Treatment (Pocket Length of 300 feet).

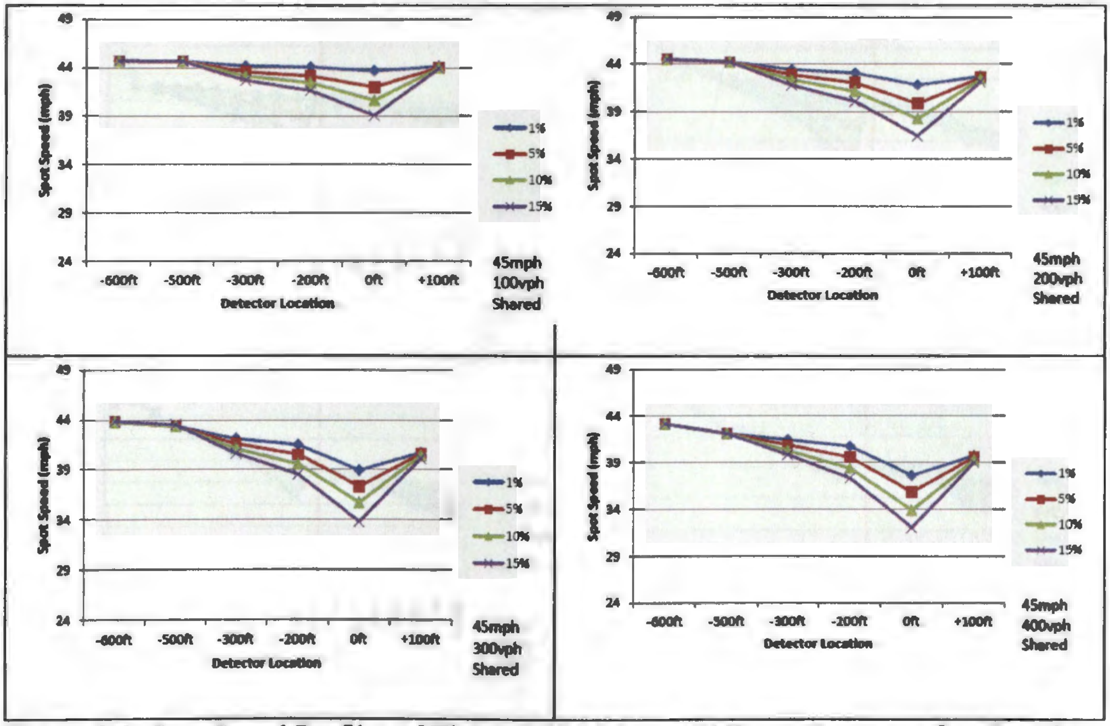

Figure C.3. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed and Shared Treatment.

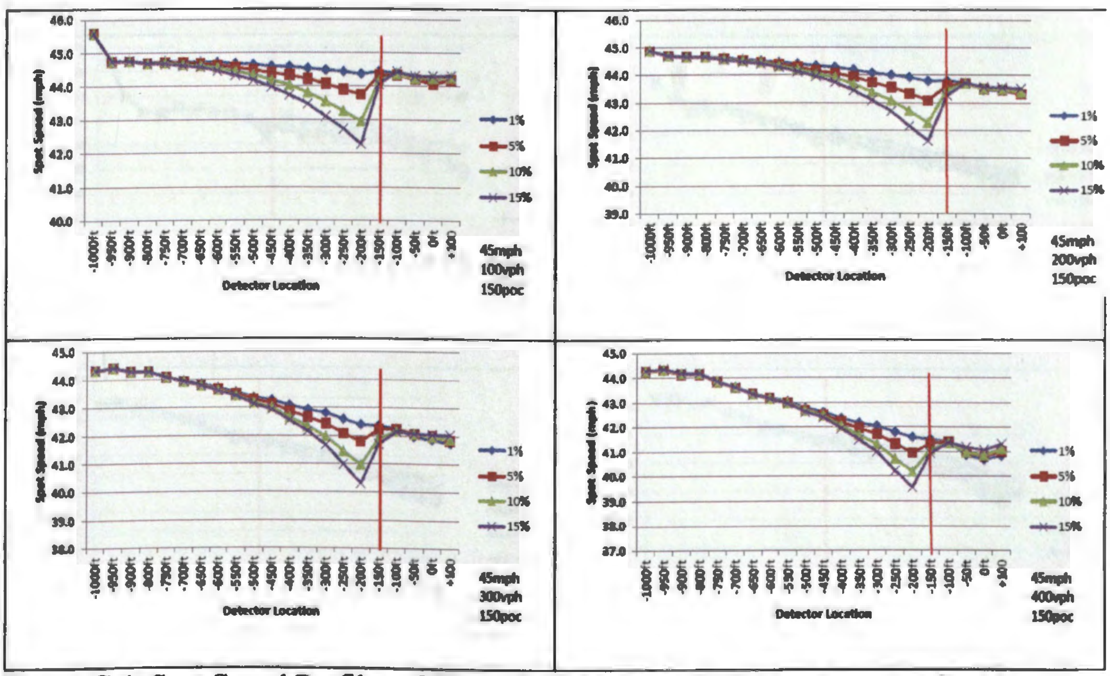

Figure C.4. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed and Exclusive Treatment (Pocket Length of 150 feet).

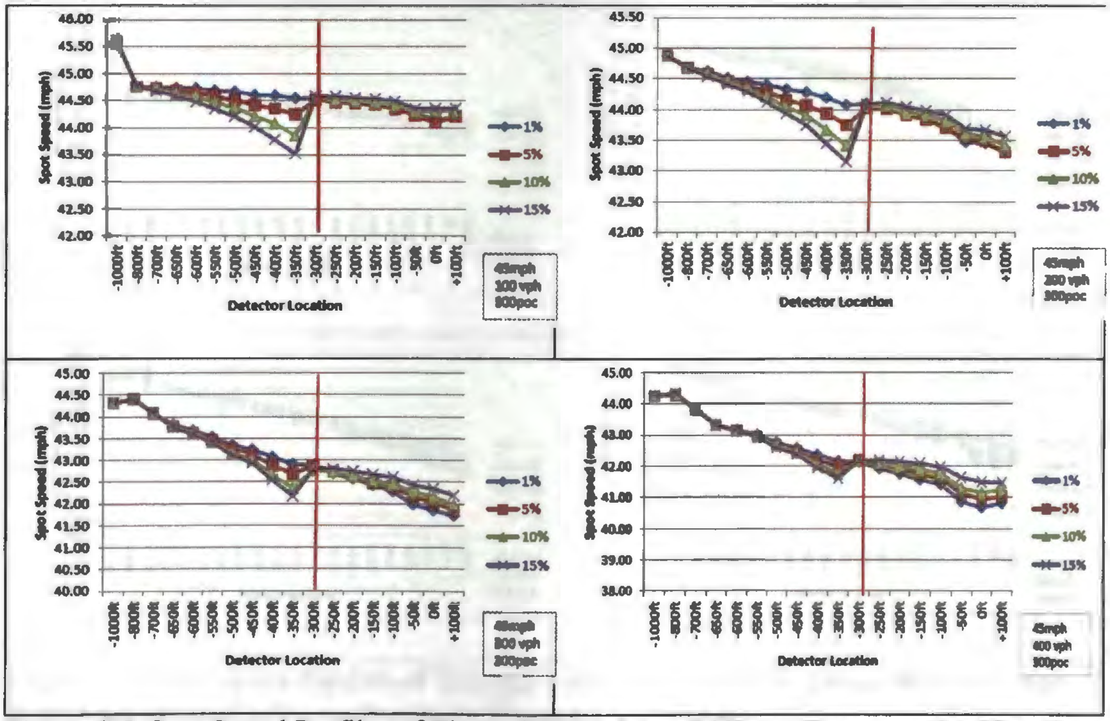

Figure C.5. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed and Exclusive Treatment (Pocket Length of 300 feet).

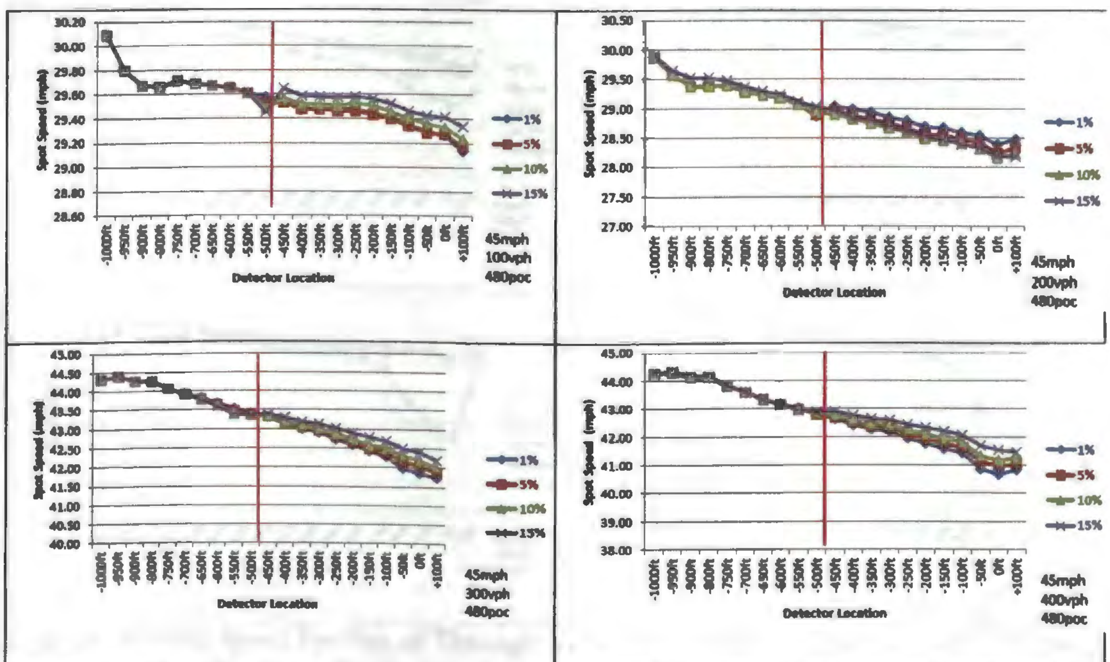

Figure C.6. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed and Exclusive Treatment (Pocket Length of 480 feet).

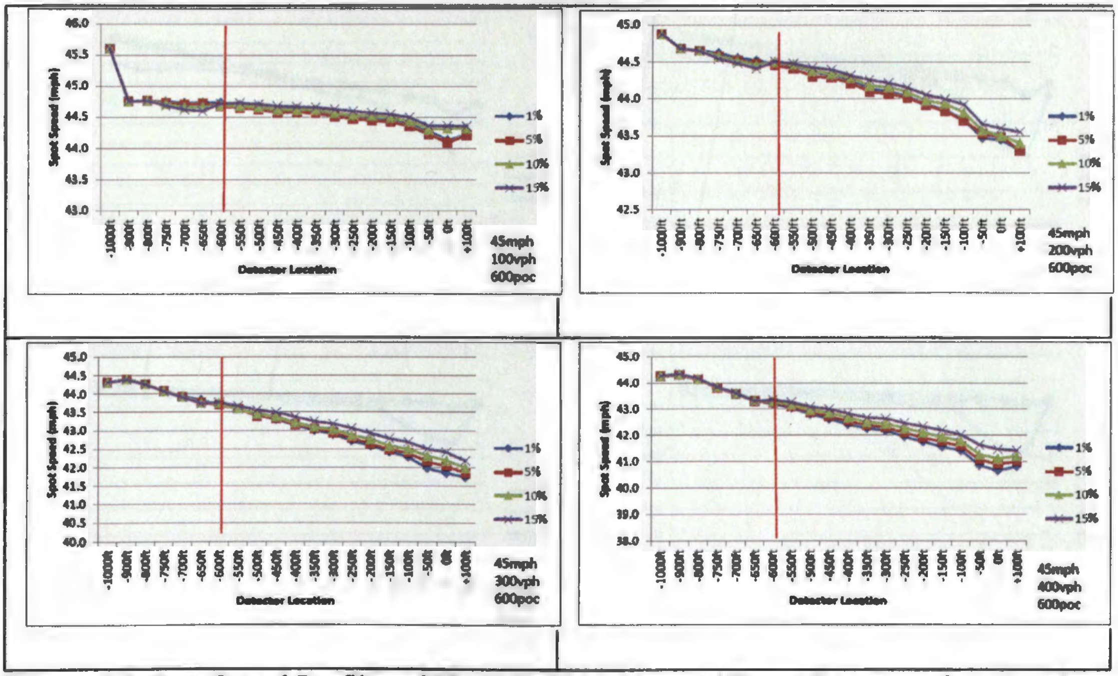

Figure C.7. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed and Exclusive Treatment (Pocket Length of 600 feet).

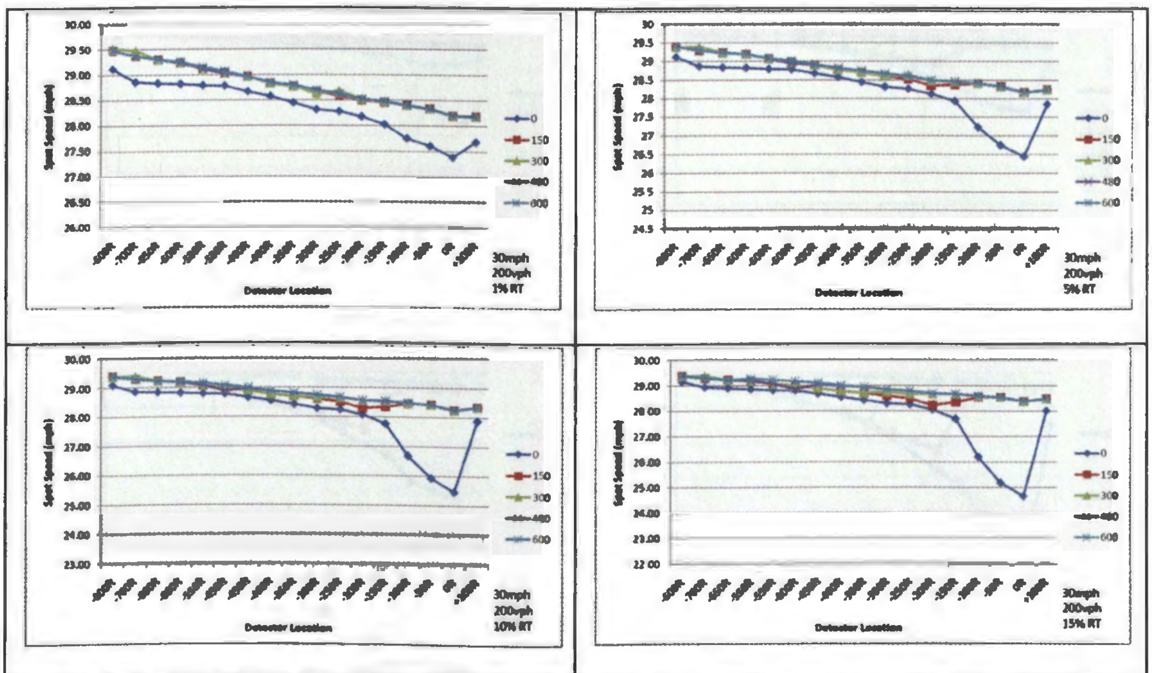

Figure C.8. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed, 200 vph, and Different Pocket Lengths.

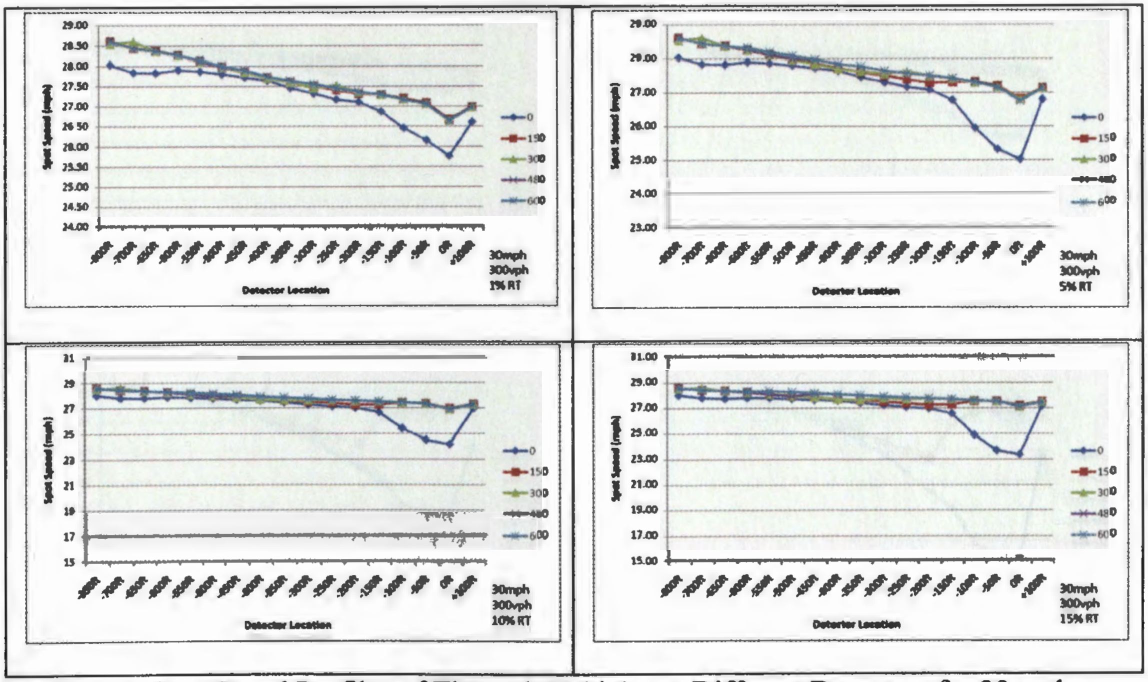

Figure C.9. Spot Speed Profiles of Through Vehicles at Different Detectors for 30 mph Posted Speed, 300 vph, and Different Pocket Lengths.

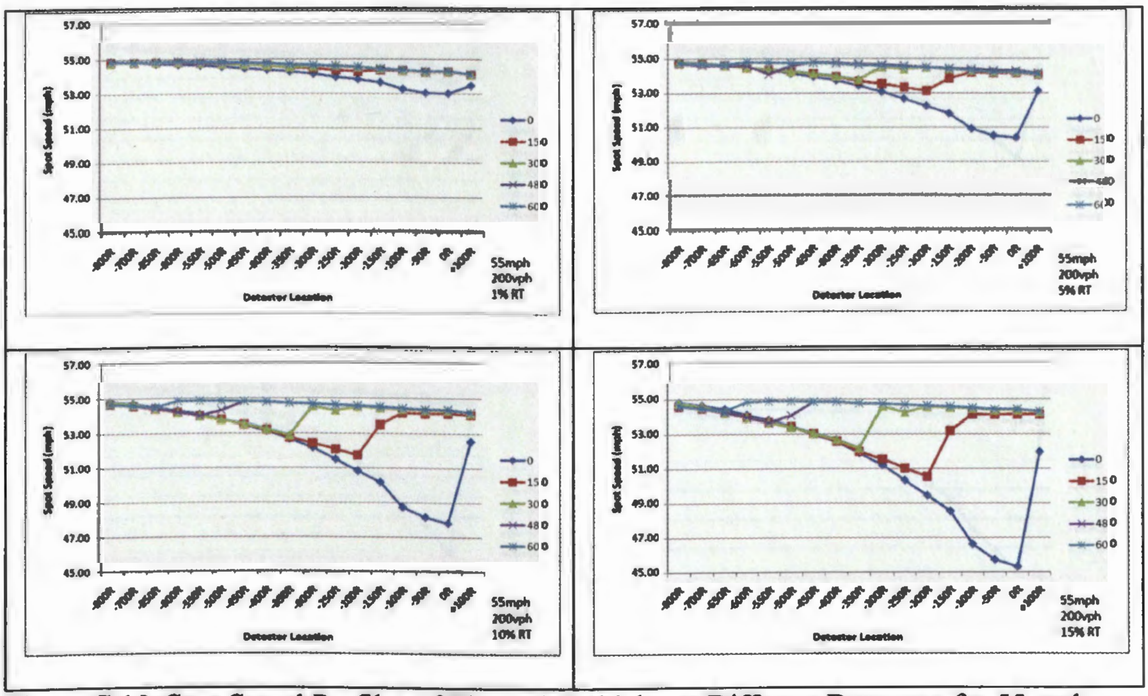

Figure C.10. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed, 200 vph, and Different Pocket Lengths.

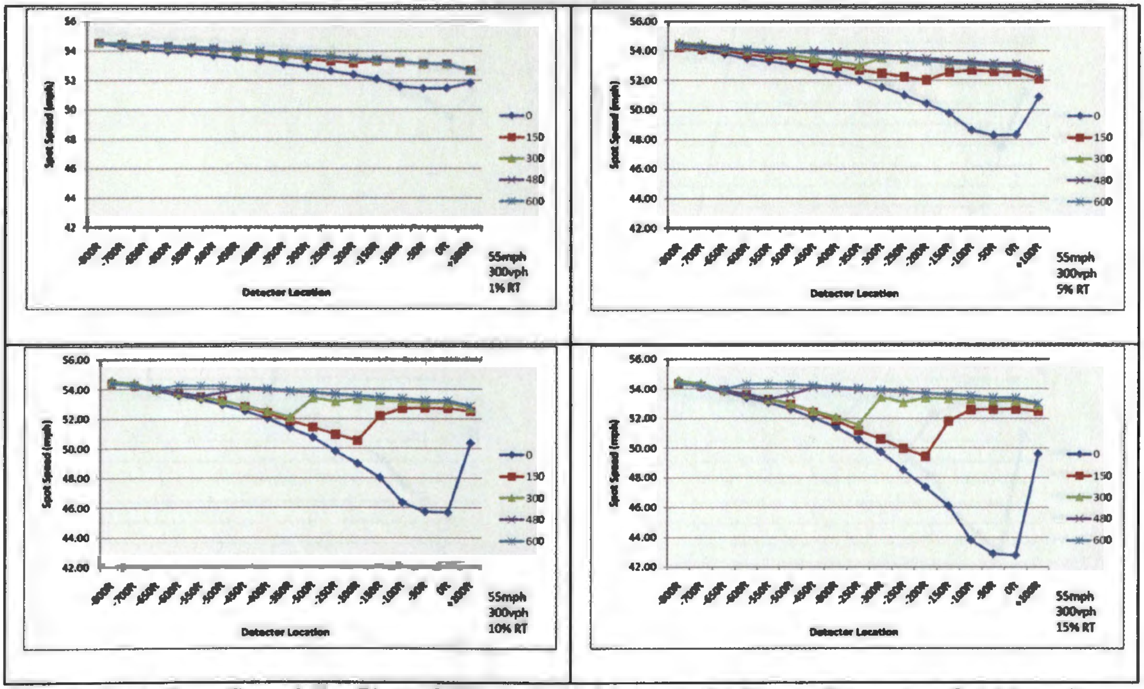

Figure C.11. Spot Speed Profiles of Through Vehicles at Different Detectors for 55 mph Posted Speed, 300 vph, and Different Pocket Lengths.

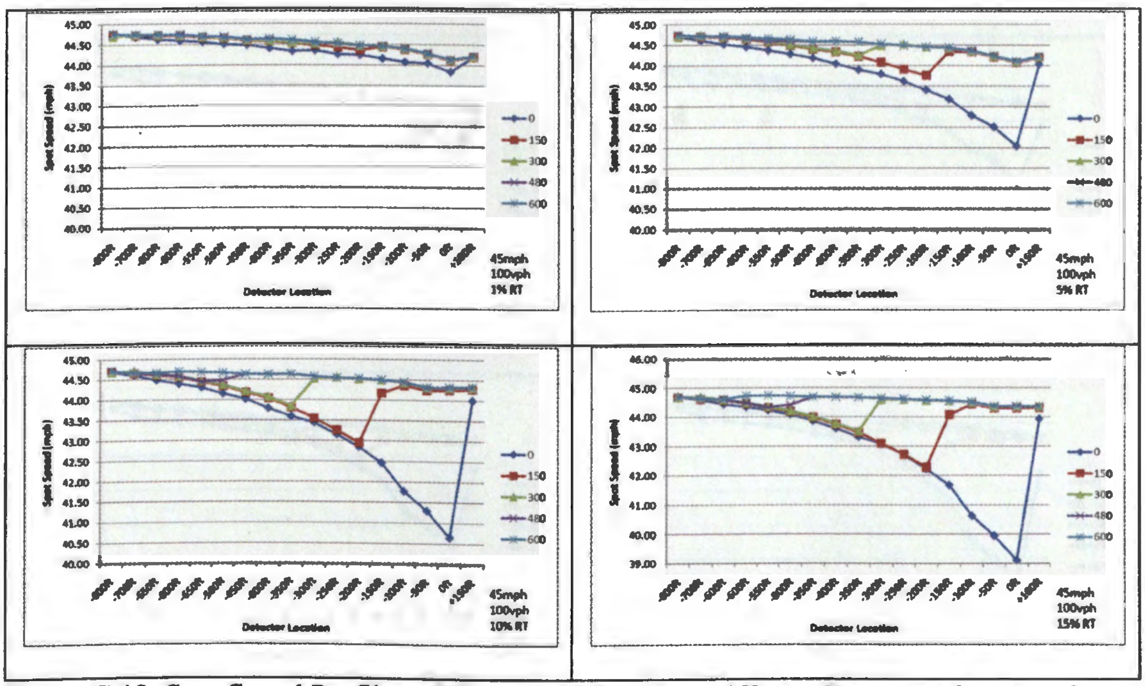

Figure C.12. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed, 100 vph, and Different Pocket Lengths.

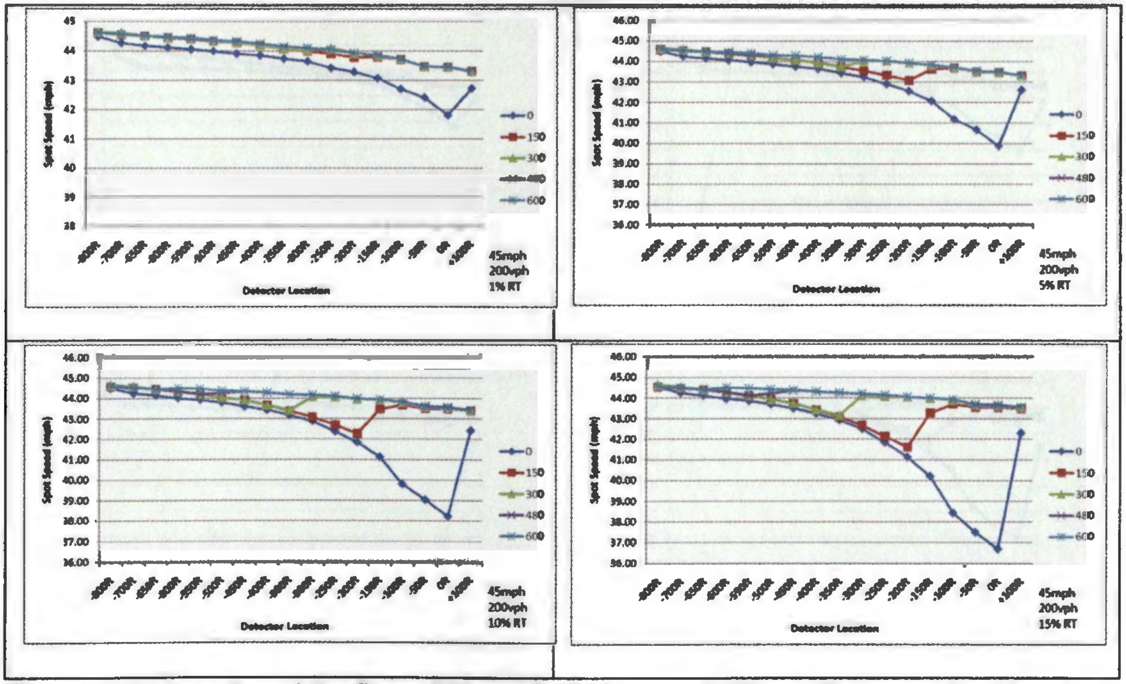

Figure C.13. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed, 200 vph, and Different Pocket Lengths.

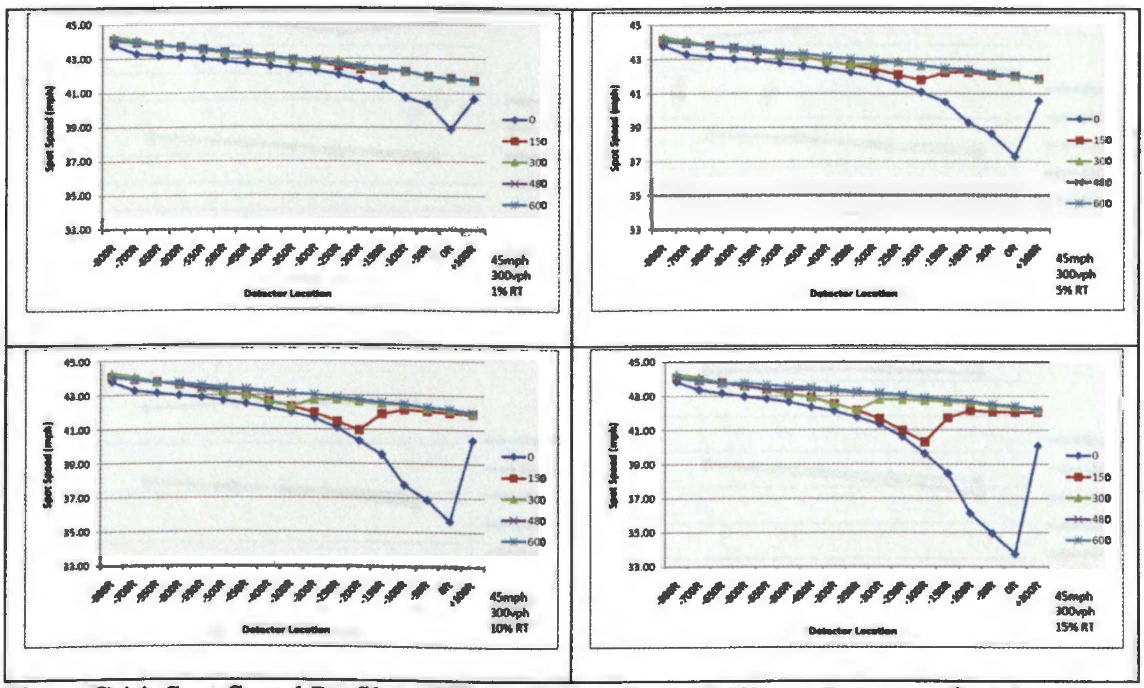

Figure C.14. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed, 300 vph, and Different Pocket Lengths.

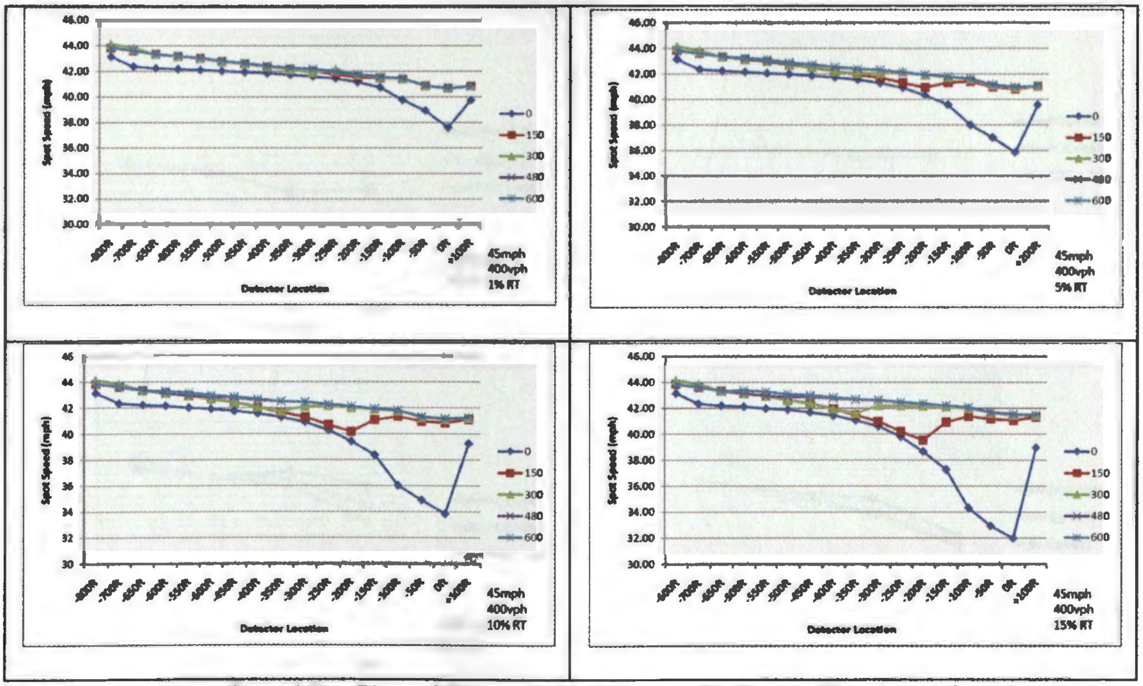

Figure C.15. Spot Speed Profiles of Through Vehicles at Different Detectors for 45 mph Posted Speed, 400 vph, and Different Pocket Lengths.

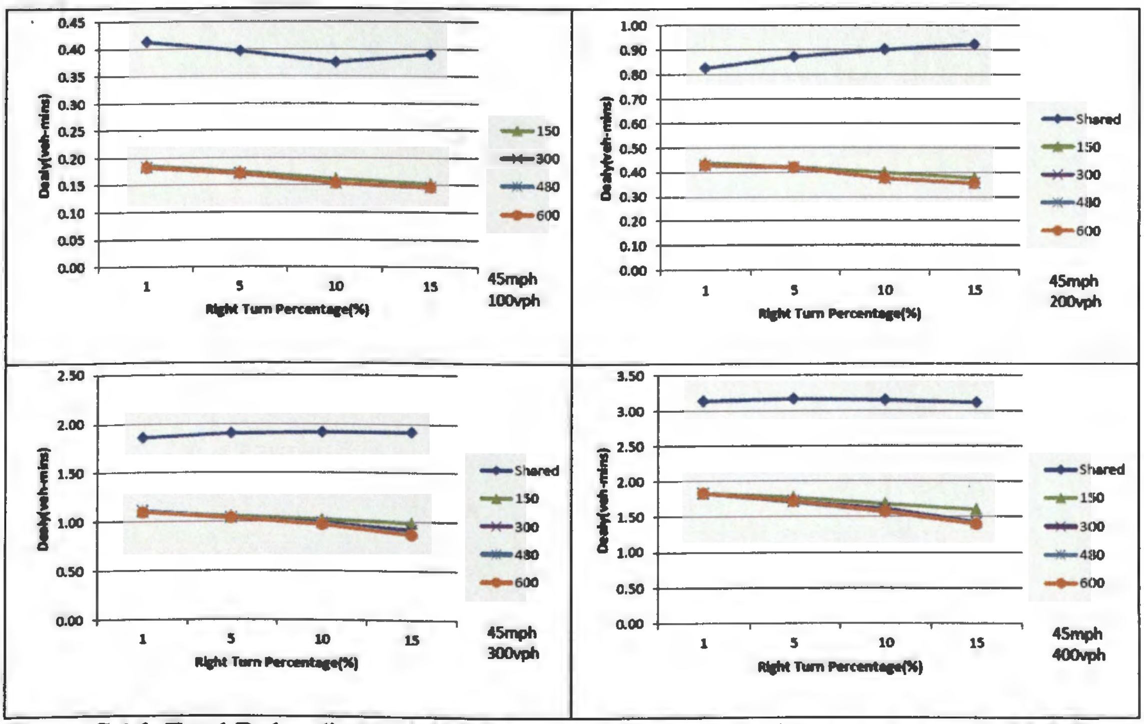

Figure C.16. Total Delay (in Vehicle Minutes) of Through Vehicles on Approach Link for 45 mph Posted Speed.

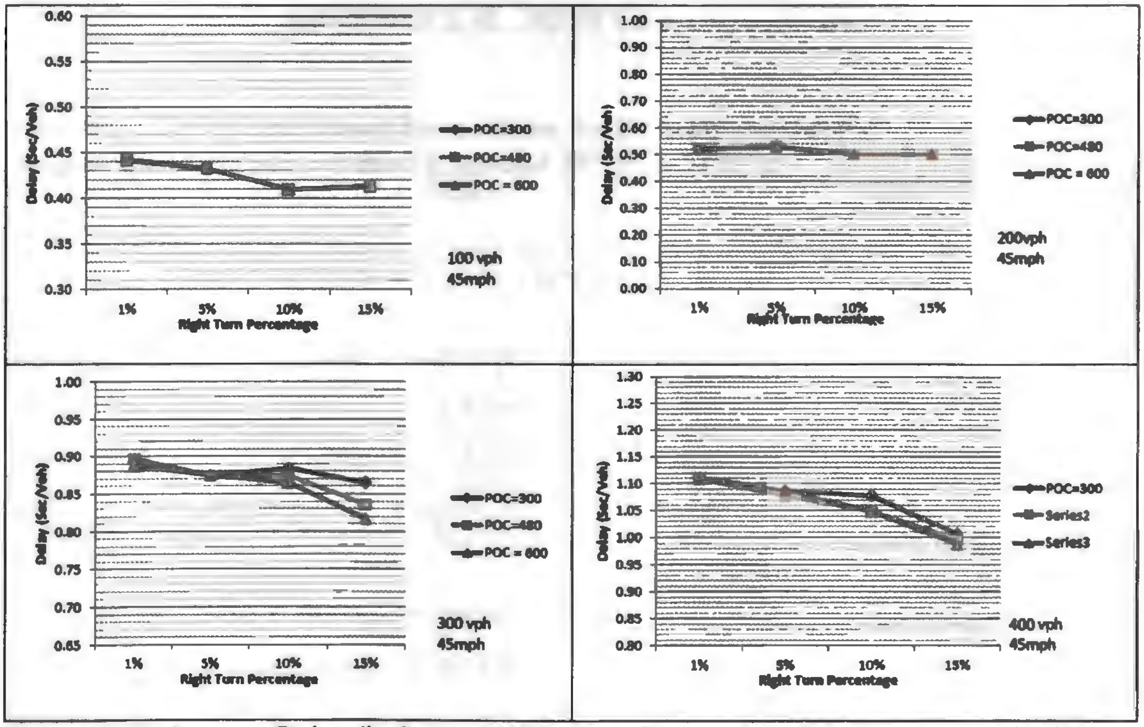

Figure C.17. Average Delay (in Seconds/Vehicle) of Through Vehicle on Approach Link for 45 mph Posted Speed.

APPENDIX D. MINITAB OUTPUTS

MODEL 1-- Field Data Based Space Mean Speed Statistical Model

Regression Analysis: SMS-TH versus SPEED, VOL, ...

```
The regression equation is
SMS-TH = 3.38 + 0.872 SPEED + 0.0346 VOL - 6.18 RT% + 0.00759 POC
         - 0.000167 POC*VOL + 0.0645 RT%*POC
```

Predictor	Coef	SE Coef	T	P
Constant	3.376	2.616	1.29	0.201
SPEED	0.87176	0.06865	12.70	0.000
VOL	0.03462	0.02469	1.40	0.165
RT%	-6.183	5.916	-1.05	0.299
POC	0.007591	0.006747	1.13	0.264
POC*VOL	-0.00016682	0.00006183	-2.70	0.009
RT%*POC	0.06454	0.02463	2.62	0.011

S = 4.66709   R-Sq = 84.1%   R-Sq(adj) = 82.8%

PRESS = 1993.89   R-Sq(pred) = 80.84%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	8751.6	1458.6	66.96	0.000
Residual Error	76	1655.4	21.8		
Total	82	10407.1			

Source	DF	Seq SS
SPEED	1	8313.8
VOL	1	27.4
RT%	1	27.0
POC	1	15.5
POC*VOL	1	218.4
RT%*POC	1	149.6

MODEL 2-- Field Data Based Total Delay Statistical Model

Regression Analysis: TOTAL DELAY (VEH-MINS) versus SPEED, VOL, ...

```
The regression equation is
TOTAL DELAY (VEH-MINS)     = 1.26 - 0.0292 SPEED + 0.0113 VOL + 0.0163 RT
                             - 0.00712 POC - 0.000414 RT*VOL
                             + 0.000023 POC*VOL + 0.000143 POC*SPEED
```

Predictor	Coef	SE Coef	T	P
Constant	1.2555	0.3586	3.50	0.001
SPEED	-0.029184	0.009287	-3.14	0.002
VOL	0.011338	0.002941	3.86	0.000
RT	0.01635	0.02350	0.70	0.489
POC	-0.007116	0.003673	-1.94	0.056
RT*VOL	-0.0004142	0.0001517	-2.73	0.008
POC*VOL	0.00002251	0.00001099	2.05	0.044
POC*SPEED	0.00014267	0.00006968	2.05	0.044

S = 0.607431   R-Sq = 57.3%   R-Sq(adj) = 53.3%

PRESS = 34.1197   R-Sq(pred) = 47.29%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	7	37.0602	5.2943	14.35	0.000
Residual Error	75	27.6730	0.3690		
Total	82	64.7331			

Source	DF	Seq SS
SPEED	1	2.9990
VOL	1	22.2124
RT	1	0.7224
POC	1	4.8828
RT*VOL	1	2.3860
POC*VOL	1	2.3107
POC*SPEED	1	1.5469

MODEL 3-- Field Data Based Vehicle Delay Statistical Model

Regression Analysis: VEHICLE DELAY versus SPEED, VOL, ...

```
The regression equation is
VEHICLE DELAY = 3.17 - 0.0646 SPEED + 0.00662 VOL - 7.73 RT%
                - 0.0122 POC - 0.0583 RT%*VOL + 0.241 RT%*SPEED
                + 0.000258 POC*SPEED


81 cases used, 1 cases contain missing values
```

Predictor	Coef	SE Coef	T	P
Constant	3.1735	0.4144	7.66	0.000
SPEED	-0.06463	0.01115	-5.79	0.000
VOL	0.006622	0.002664	2.49	0.015
RT%	-7.735	2.230	-3.47	0.001
POC	-0.012190	0.003353	-3.64	0.001
RT%*VOL	-0.05830	0.01709	-3.41	0.001
RT%*SPEED	0.24074	0.05561	4.33	0.000
POC*SPEED	0.00025765	0.00006235	4.13	0.000

```
S = 0.558960   R-Sq = 38.6%   R-Sq(adj) = 32.7%

PRESS = 28.1337   R-Sq(pred) = 24.22%


Analysis of Variance
```

Source	DF	SS	MS	F	P
Regression	7	14.3157	2.0451	6.55	0.000
Residual Error	73	22.8079	0.3124		
Total	80	37.1236			

Source	DF	Seq SS
SPEED	1	1.1751
VOL	1	0.0261
RT%	1	0.0593
POC	1	0.8985
RT%*VOL	1	0.6418
RT%*SPEED	1	6.1802
POC*SPEED	1	5.3348

MODEL 4 – Simulation Based Space Mean Speed Statistical Model
Regression Analysis: SMS-TH versus VOL,RT%, ...

```
The regression equation is
SMS-TH = - 0.989 - 0.110 VOL - 0.0280 RT% + 0.999 SPEED
          + 0.000685 POC + 0.000083 RT%*POC
```

Predictor	Coef	SE Coef	T	P
Constant	-0.9892	0.1955	-5.06	0.000
VOL	-0.109986	0.004908	-22.41	0.000
RT%	-0.02797	0.01134	-2.47	0.014
SPEED	0.998905	0.003330	299.95	0.000
POC	0.0006853	0.0002800	2.45	0.015
RT%*POC	0.00008324	0.00003011	2.76	0.006

S = 0.527015   R-Sq = 99.7%   R-Sq(adj) = 99.7%

PRESS = 68.5252   R-Sq(pred) = 99.73%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	5	25236.8	5047.4	18172.63	0.000
Residual Error	232	64.4	0.3		
Total	237	25301.2			

Source	DF	Seq SS
VOL	1	189.7
RT%	1	2.3
SPEED	1	25023.2
POC	1	19.4
RT%*POC	1	2.1

MODEL 5 -- Simulation Based Total Delay Statistical Model

Regression Analysis: TD versus VOL, RT, ...

```
The regression equation is
TD = 0.975 + 0.0947 VOL + 0.546 RT - 0.0302 SPEED
                          - 0.000031 POC + 0.0123 RT*VOL - 0.0160 RT*SPEED
                          - 0.000424 RT*POC


Predictor         Coef    SE Coef      T      P
Constant        0.9754     0.2023   4.82  0.000
VOL           0.094676   0.005953  15.90  0.000
RT              0.5459     0.1505   3.63  0.000
SPEED        -0.030194   0.003958  -7.63  0.000
POC         -0.0000310  0.0001869  -0.17  0.869
RT*VOL        0.012269   0.004695   2.61  0.010
RT*SPEED     -0.016016   0.002436  -6.57  0.000
RT*POC      -0.0004242  0.0001153  -3.68  0.000


S = 0.403423   R-Sq = 83.7%   R-Sq(adj) = 83.2%

PRESS = 40.1745   R-Sq(pred) = 82.38%


Analysis of Variance

Source           DF       SS      MS       F      P
Regression        7  190.867  27.267  167.54  0.000
Residual Error  228   37.107   0.163
Total           235  227.974


Source    DF   Seq SS
15minVol   1  115.971
RT         1    0.010
MPH        1   61.266
POC        1    3.297
RT*VOL     1    1.053
RT*SP      1    7.066
RT*POC     1    2.203
```

MODEL 6 -- Simulation Based Vehicle Delay Statistical Model

Regression Analysis: VD versus VOL, RT, ...

```
The regression equation is
VD = 1.87 + 0.0469 VOL + 0.463 RT - 0.0364 SPEED
                     - 0.000083 POC - 0.000287 RT*POC - 0.00860 RT*SPEED
```

Predictor	Coef	SE Coef	T	P
Constant	1.8690	0.1112	16.80	0.000
VOL	0.046851	0.002577	18.18	0.000
RT	0.46261	0.06764	6.84	0.000
SPEED	-0.036447	0.002299	-15.86	0.000
POC	-0.0000831	0.0001093	-0.76	0.447
RT*POC	-0.00028697	0.00007010	-4.09	0.000
RT*SPEED	-0.008603	0.001460	-5.89	0.000

S = 0.238720   R-Sq = 86.8%   R-Sq(adj) = 86.5%

PRESS = 14.0907   R-Sq(pred) = 85.89%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	86.719	14.453	253.62	0.000
Residual Error	231	13.164	0.057		
Total	237	99.883			

Source	DF	Seq SS
VOL	1	26.284
RT	1	0.011
SPEED	1	55.263
POC	1	2.066
RT*POC	1	1.117
RT*SPEED	1	1.977