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Warrants for Right-turn Lanes/Treatments on Two-lane Roads

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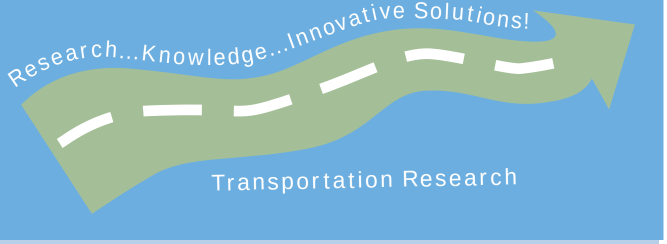

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16. Abstract (Limit: 200 words)

The goal of this project was to analyze geometric, speed, volume, and crash data for a broad range of conditions with the ultimate objective of establishing bases for warrants for right-turn lanes on two-lane roads where major approach did not have any controls. Right-turn lane guidelines for this contest is not clear and convincing. Safety effectiveness and savings were estimated using extensive data examination and analysis of crash data, several statistical models that were developed using crash data, and a conflict model, which was developed using field data. It was found that not all accidents are eliminated with use of right-turn lane. However, right-turn lanes were effective in improving safety. More interesting was the finding that safety effectiveness of right-turn lanes was more at driveways than at intersections. Operational effectiveness was estimated using a delay model and a fuel consumption model, which were developed using field data, simulation software (CORSIM®), and statistical software, Minitab®. The volume thresholds that varied with changes in right-turn lane cost and fuel cost were provided as alternative scenarios for warrants. The warrants established here will be helpful in decision-making regarding whether to implement a right-turn lane or not on two-lane roads.

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Final Report

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Executive Summary

Background and motivation

Minnesota Department of Transportation (Mn/DOT) Road Design Manual identifies nine warrants for considering a turn lane on reconstruction and new construction projects; eight of these warrants apply to preservation projects. Mn/DOT's policy for right-turn lanes/treatments on two-lane roads is being discussed and reevaluated. Recently, some updates in turn-lane policies have been prompted by the need to incorporate new Access Management Policy into highway design. Thus, this research was needed to analyze speed, traffic volume, crash and geometric data for the broad range of conditions, with the ultimate goal of establishing bases for warrants for right turn lanes on two-lane roads that do not have any control on main highway.

Objectives

The research objectives were to:
- To analyze geometric, speed, volume and crash data for a broad range of conditions related to right-turn lanes/treatments on two-lane roads in Minnesota; and
- To develop procedures for establishing and applying volume and other warrants for right-turn lanes/treatments by State on two-lane roads.

Scope of research

This research was focused on need for right turn lanes on on two-lane roads where main highway did not have any controls. For safety assessment, crash and related data for years 2000-2002 and 2004-2005 were used. Field data collection from various intersections spread throughout Minnesota during summers of 2007 and 2008 provided additional data and insights and formed the bases for statistical and simulation models developed to understand operational and safety impacts of right turn lanes.

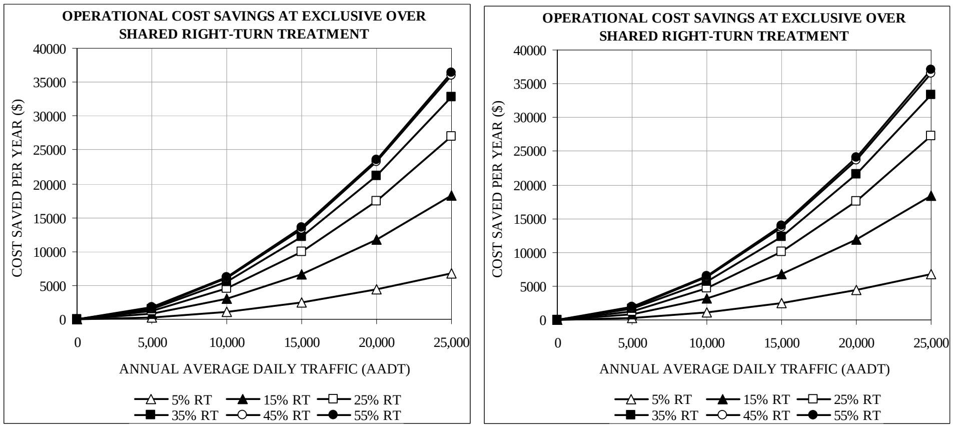
Research approach

The research approach included seven tasks. Task 1 was to conduct literature review and identify relevant factors. Task 2 was to develop a systematic methodology for right-turn lane/treatment need assessment. Task 3 was to collect data from existing datasets/databases (traffic volume, speed, video logs, accident records and others). Task 4 was to perform statistical analyses and simulations. Task 5 was to develop examples for the application of the proposed process of determining the need for right-turn lanes/treatments on two-lane roads, make recommendations and develop charts. Tasks 6 and 7 were developing reports and making presentations to TAP.

Data Sources and reduction

Various data sources were used in this study. Data were obtained from Mn/DOT (Videologs and operational and cost data), Minnesota Department of Public Safety (accident data), Google Earth, and field data collection from various intersections spread throughout Minnesota.

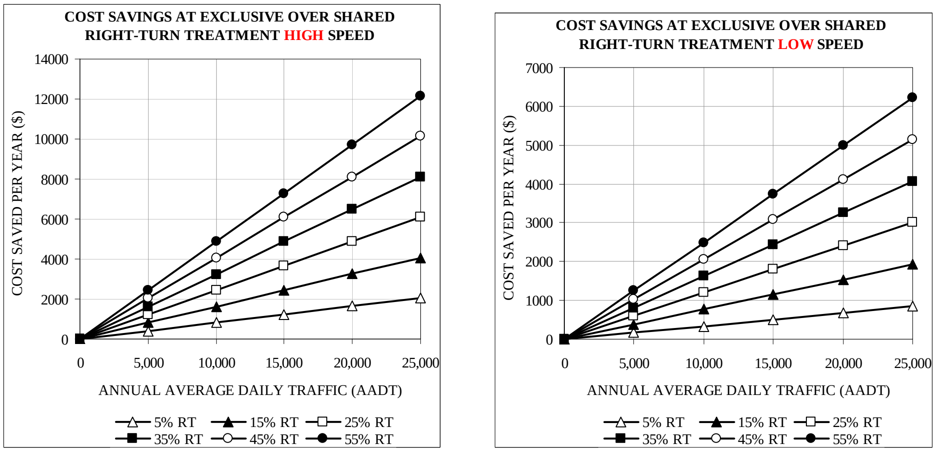
Operational effects--Operational cost savings resulting from right turn lanes are shown in figure below:



(a) Fuel cost $3/gallon (b) Fuel cost $ 4/gallon

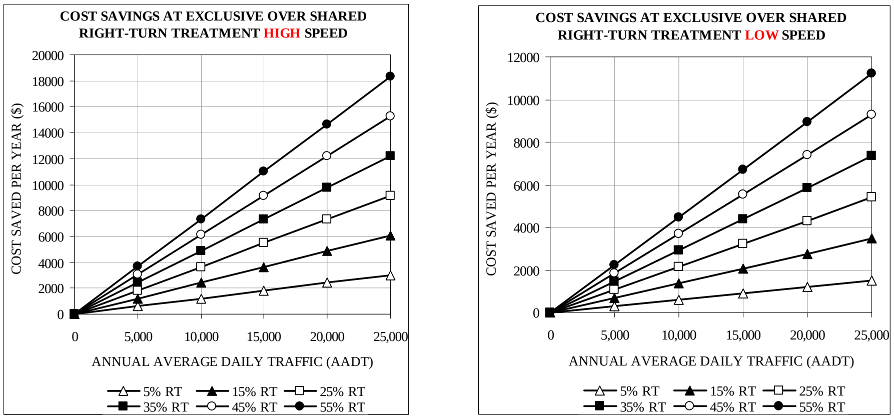
Figure 1. Annual operational cost savings

Safety effects-- The annual safety savings resulting from right turn lanes at intersections and driveways are shown in figures below:



(a) High-speed intersections (b) Low-speed intersections

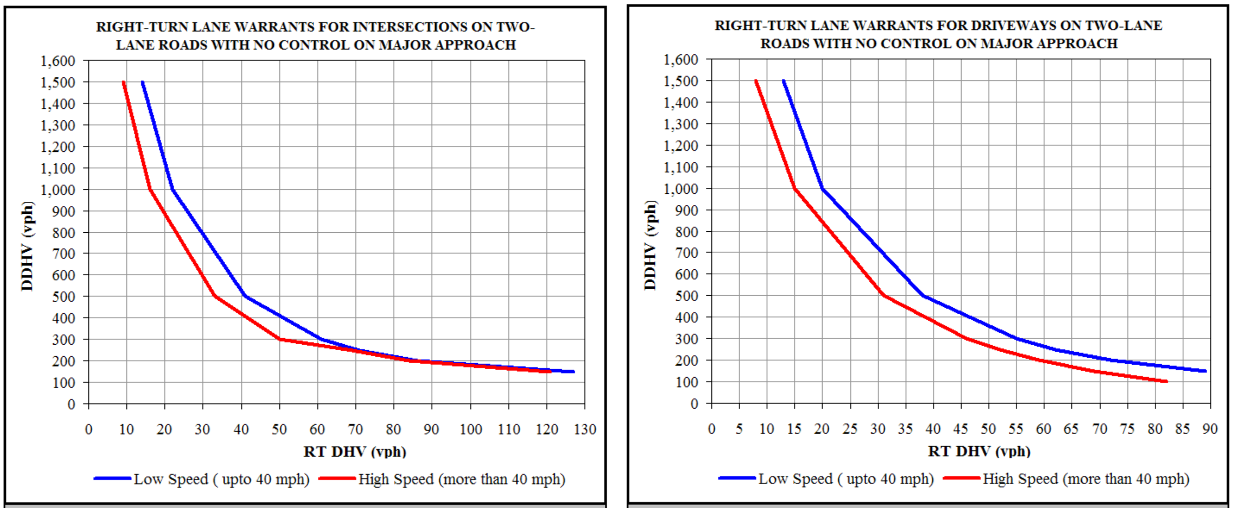
Figure 2. Annual safety cost savings at intersections.



(a) High-speed driveways (b) Low-speed driveways

Figure 3. Annual safety cost savings at driveways.

Warrants



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $30,000 / Cost of Fuel = $3)

Speed (mph)	DDHV (vph)							
	100	150	200	250	300	500	1,000	1,500
≤ 40	NA	127	86	71	61	41	22	14
> 40	NA	121	84	69	50	33	16	9

Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $30,000 / Cost of Fuel = $3)

Speed (mph)	DDHV (vph)							
	100	150	200	250	300	500	1,000	1,500
≤ 40	NA	89	72	62	55	38	20	13
> 40	82	69	59	52	46	31	15	8

(a) Intersections (b) Driveways

Figure 4. Example warrant for right-turn lanes (Cost of fuel $3/gallon; right turn lane cost $ 30,000)

Conclusions and recommendations

Right turn lane guidelines exist, but they are not clear and convincing for contexts dealing with two-lane roads where main highways do not have any control. From safety analysis it was found that not all accidents are eliminated with use of right-turn lane. The probabilities of right-turn related crashes on two-lane road and the probabilities of rear-end and side-swipe same direction crashes among these crashes differ based on speed and right-turn treatment. However, right-turn lanes were effective in improving safety. More interesting was the finding that safety effectiveness of right-turn lanes was more at driveways than at intersections. The volume thresholds that varied with changes in right turn lane cost and fuel cost were provided as alternative scenarios for warrants. The warrants established here will be helpful in decision-making regarding whether to implement a right-turn lane or not on two-lane roads.

Among the immediate application of the findings is providing additional details in the road design manual with regard to the warrant for right turn lanes on two-lane roads where there are no controls on main highways. A good discussion with design and traffic engineers will be very productive. For some actual sites this warrant should be applied to see if it makes sense. Another good implementation would be development of a spreadsheet based model to allow the design and traffic engineers to do “what if” scenario or sensitivity analyses for different contexts in much flexible and efficient manner. Intersection inventory database should be updated to include the right turn geometry information for all approaches at intersections and possibly right turn percentages. Accident location information can be improved also. Right turn lane cost data is not well established and more effort in this direction is needed to help improve decision regarding which right-turn lane warrants to choose. A simulation based conflict model can enhance the safety assessment further.

Chapter 1 Introduction

1.1 Background and motivation

Reevaluation of policies regarding the need for right-turn lanes/treatments on two-lane roads has been motivated from the fact that funding is limited, states (including Minnesota) desire the move towards “zero deaths” and the need for cost-effective decisions.

Harmelink (1967) did a pioneering Canadian study on volume warrants for left-turn based queuing principles and some field studies for two and four-lane rural highways for three different speed conditions. Gauz et al. (1980) reported traffic conflict analysis at intersections work in the National Cooperative Highway Research Program (NCHRP) 219. Cottrell’s study for Virginia, based on Harmelink’s study, in 1982, has been the basis for most common volume based warranting concept for right-turn lanes in practice today. Newman’s work on intersection chanelization, reported in NCHRP 279, also contains right-turn lane warrants based on Cottrell’s work. McCot et al. (1994) provided guidelines for right-turn lanes on urban roadways in Nebraska and used simulation analyses. Stover (1996) developed a discussion paper on right-turn lanes for the Oregon Department of Transportation and in his paper also discussed the warrants in the American Association of State and Highway Transportation Officials (AASHTO) policy and those in use in the Colorado Department of Transportation. 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 Thallar (2003) evaluated the need for right-turn deceleration lanes in Florida using speed differential as a measure.

Minnesota Department of Transportation (Mn/DOT) Road Design Manual identifies nine warrants for considering a turn lane on reconstruction and new construction projects; eight of these warrants apply to preservation projects. Mn/DOT’s policy for right-turn lanes/treatments on two-lane roads is being discussed and reevaluated. Recently, some updates in turn-lane policies have taken place to incorporate new Access Management Policy into highway design. Thus, this research was needed to look into the background information before developing new process, procedure and bases, which will enable Mn/DOT to make cost-effective decisions regarding right-turn lanes/treatment on two-lane roads.

There was need to collect data on a broad range of conditions and research the need for right-turn lanes in a comprehensive manner. The range of conditions included rural and urban areas, two-lane highways, land use associated with the cross street or entrance and contexts with turn lanes, with just right-turn lanes or with neither. Speed, traffic volume, crash and geometric data for the broad range of conditions had to be studied and analyzed for various scenarios. The ultimate goal was to establish bases for warrants for right-turn lanes.

1.2 Objectives

The research objectives were to:

(1) To analyze geometric, speed, volume and crash data for a broad range of conditions related to right-turn lanes/treatments on two-lane roads in Minnesota; and

(2) To develop procedures for establishing and applying volume and other warrants for right-turn lanes/treatments by State on two-lane roads.

1.3 Scope

This research was focused on need for right turn lanes on on two-lane roads where main highway did not have any controls. For safety assessment, crash and related data for years 2000-2002 and 2004-2005 were used. Field data collection from various intersections spread throughout Minnesota during summer of 2007 provided additional data and insights and formed the bases for statistical and simulation models developed to understand operational and safety impacts of right turn lanes. All the possible contexts statewide in Minnesota were thus studied in establishing bases for the warrants. This is unique and significant aspect of this study. It is very difficult to find any source or to collect data on right turn percentages for each hour of the day. Hence, the scope of assessment assumed right turn percentages to be same for all hours. In addition, it is rare to find a project specifically for building right turn lanes; they are usually part of larger improvement or expansion project. Thus, the right turn lane cost numbers were based on some assumptions regarding fixed and variable costs related to right turn lanes. Right of way costs were not included as most of these decisions regarding right turn lanes are within the existing right of way in Minnesota.

1.4 Research Approach

The research approach included seven tasks. Task 1 was to conduct literature review and identify relevant factors. Task 2 was to develop a systematic methodology for right-turn lane/treatment need assessment. Task 3 was to collect data from existing datasets/databases (traffic volume, speed, video logs, accident records and others). Task 3 was very time consuming and data intensive as it required conflating data from numerous data sources and extensive use of GIS. Task 4 was to perform statistical analyses and simulations. A special kind of statistical technique, logistic regression, was critical in developing appropriate and useful models for safety assessment. Similarly, CORSIM served an important tool to develop simulation model and results for understanding operational impacts. The simulation results were then statistically analyzed to come up with predictive models for delays. Task 5 was to develop bases for warrants for right turn lanes and some examples for the application of the warrants. Tasks 6 and 7 were developing reports and making presentations.

1.5 Report organization

This report is organized in six chapters. Chapter 2 provides literature review and identifies relevant factors. Chapter 3 discusses some definitions and generic methodology used in this study. Chapter 4 provides a comprehensive data examination and modeling and analysis related to safety impacts of right-turn lanes. Chapter 5 provides details of the operational impacts related to right-turn lanes. Chapter 6 provides results for operational impact savings, safety impact savings, threshold charts, and warrants. Chapter 7 provides significant conclusions and recommendations.

Chapter 2 Literature Review

2.1 Right-turn related studies

Several studies have been carried out in past related to right-turn movement and related need for right-turn lane. One of the key needs is to identify and study conflicts. Conflicts in turn affect both safety and traffic flow near intersections. Typically, there are three types of conflicts – crossing, merging, and diverging conflicts. As far as right-turn movements are considered, the conflicts to deal with are merging and diverging conflicts. Both merging and diverging conflicts can potentially result into rear-end or side-swipe conflicts.

Glauz and Migletz (1980) reported the work carried out for a comprehensive study of traffic conflict analysis as part of National Cooperative Highway Research Program (NCHRP) 219. In their study, signalized and unsignalized intersections on two-lane and four-lane roads and operating under both high and low speeds were considered. The report provides discussion of both theoretical concepts and field studies.

Cottrell (1981) was the first reporting of right-turn related study, carried out in Virginia, which tried to establish volume thresholds for determining the need for right-turn lanes. The study was based on collection of conflict data along with data on approach volume and right-turn volume. Their study has been the basis for guidelines used by many DOTs for the need of the right-turn lanes.

Neuman (1985) reported the work carried out for a comprehensive study of intersection channelization, as part of NCHRP 279, and contained guidelines for determining need for right-turn lane, which was essentially adapted from Cottrell (1982). One of the key assertions made in this report was that, in terms of safety, special treatments for right-turning vehicles are less critical than for left-turns. This was based on the premise that right turns involve fewer and less severe conflicts, and tend to have lesser influence on through traffic. However, the study reported that there are conditions for which an added cost of providing exclusive right-turn lanes is fully justified by improvements to traffic flow.

McCoy et al. (1984) looked into cost effectiveness evaluation of turning lanes on uncontrolled approaches of rural intersections. An analysis of intersection crashes on rural two-lane highways in Nebraska was conducted to determine the safety effects of the turning lanes and a computer simulation study was conducted to determine the operational effects. The results were incorporated into the cost-effectiveness methodology. McCoy et al. (1993) studied and developed guidelines for right-turn lanes at intersections on both two- and four-lane roads using computer simulation. The safety effects were established using the “speed differentials” obtained with contexts where there were no right-turn lanes versus conditions where right-turn lanes existed.

Hasan and Stokes (1996) developed guidelines for right-turn treatments (full-width lane and taper were considered over do-nothing radius treatment) at unsignalized intersections and driveways on the state highway system of Kansas. A model was developed to determine the operational effects in terms of delay and excess fuel consumption experienced by through vehicles due to right turns. The relationship between speed differential and crashes was used to estimate the reduction in right-turn same direction rear-end crashes that would be expected to result from the provision of a right-turn treatment.

Gluck et al. (1999), as part of NCHRP 420 study, reported on impact of access management techniques. The research looked into the role and use of right-turn lanes as part of the broader strategy for access management for a corridor. Dixon et al. (1999) analyzed right-turn treatments for signalized intersections based on two-year crash history for Cobb County in Atlanta metro area in Georgia.

The discussion on right-turn lanes and the need for it have been documented in Policy on Geometric Design of Highways and Streets (AASHTO, 2001), Highway Capacity Manual (TRB, 2001), and Harwood et al. (2002). Hadi and Thakkar (2003) used speed differential as a measure to evaluate the need for right-turn deceleration lanes at unsignalized intersections in Florida and used simulation and data from two intersections.

2.2 Safety-related studies

In this section, some of the safety-related findings from past studies will be summarized. Cottrell (1981) while developing criteria for the treatment of right-turn movements on rural roads found 40-70% reduction in peak hour same direction rear-end conflict on two-lane highways with full-width lane treatment based on statistical modeling. The study considered 21 rural, non-signalized intersections, in Virginia and involved two- and four-lane roadways.

McCoy et al. (1984), using comparative study of 32 intersection approaches in Nebraska on rural two-lane roadways, found 30% reduction in average right-turn crash rate. Harwood et al. (2000), using negative binomial distribution and accident modification factors developed by an expert panel, concluded that right-turn lane along major approach to a STOP-controlled intersection reduces intersection-related crashes by 5%. The study used only rural two-lane roadways.

Harwood et al. (2002) studied 280 improved and 300 similar unimproved unsignalized and signalized intersections (on rural two- and four-lane roads) in Illinois, Iowa, Louisiana, Minnesota, Nebraska, North Carolina, Oregon, and Virginia. The study used observational “before-and-after” safety evaluations and concluded that right-turn lane along major-road approach reduces total intersection crashes at rural unsignalized intersections by 14% and at urban signalized intersections by 4%.

Not all studies concluded that there were always safety enhancements due to right-turn lane implementation. Bauer and Harwood (1996), using statistical modeling with negative binomial regression of 14,432 signalized and unsignalized intersections (on rural and urban roads) in California, found that right-turn channelization resulted in an increase in total multiple-vehicle crashes and fatal injury crashes. Similarly, Vogt and Bared

(1998), using Poisson and negative binomial modeling of 389 three-legged unsignalized intersections (on rural roads) in Minnesota, found that there was 27% increase in the total number of crashes at three-leg rural unsignalized intersections when a right-turn lane existed. Fitzpatrick and Schneider (2005), using analytical evaluation of crash records for 9 urban/suburban intersections in Texas (with 16 crashes involving right-turning vehicles), found that a right-turn crash is expected every 9 years at a right-turn lane separated only by a lane line and every 25 years at a shared lane.

2.3 Conflict-related studies

Traffic conflicts technique (TCT) is one of the widely used surrogate safety measures. It was developed in order to objectively and quickly measure the crash potential of a highway location in the absence of reliable and adequate crash history data. The TCT was employed in this study for its relevance as well as its simplicity to apply in the field. The overall goal of the conflict analysis is to develop a conflict prediction model to determine a relationship between conflict and crash.

The validity of TCT in traffic safety study has been adequately established in the past through several studies. Glauz and Migletz (1980) reported the work carried out for a comprehensive study of traffic conflict analysis at intersections as a part of National Cooperative Highway Research Program (NCHRP) 219. The report provides discussion of both theoretical concepts and field studies in their attempt to formalize and standardize TCT procedures. In the study, a traffic conflict was defined as “a traffic event involving two or more road users, in which one user performs some atypical or unusual action, such as a change in direction or speed, that places another user in jeopardy of a collision unless an evasive maneuver is undertaken”. In addition, a traffic event called secondary conflict was also defined as involving “an additional vehicle that is conflicted with by an instigating vehicle that slowed or swerved in response to some other conflict situation”. Parker and Zegeer (1989) developed step-by-step procedures on how to observe and collect traffic conflicts at signalized and unsignalized intersections. They also developed procedures for analyzing and interpreting the results of conflict surveys (Parker and Zegeer, 1988).

In this study, the traffic conflict of interest is the conflict due to right turns, known as right-turn, same-direction conflict. This type of conflict occurs when the first (lead) vehicle slows to make a right turn, thus endangering the second (following) vehicle with a rear-end crash. In addition, the secondary conflict due to right turns will also be interest.

Researchers in the past have tried to identify intersections with high risk of potential crash by developing conflict value tables at different road geometric conditions. Crowe (1990) developed conflict value tables for three-legged unsignalized intersections by observing conflict at 10 three-legged unsignalized intersections in Houston area. The intersections surveyed included both two- and four-lane major roads. The mean number of right-turn, same-direction conflict was found to be 51 (65 including secondary conflicts) for an 11-hour day (7:00 AM to 6:00 PM) observed during weekdays (Monday through Friday) with dry pavement conditions. Weerasuriya and Pietrzyk (1998) also developed expected conflict value tables for unsignalized three-legged intersections by surveying 38 intersections in west-central Florida. The intersections surveyed included unsignalized three-legged intersections with various lane combinations. Conflicts were observed during a 4-hour observation period on a weekday (Monday through Thursday) between 7:00 AM to 6:00 PM under dry pavement conditions. They found that the mean right-turn, same-direction conflict counts observed was 3.92 for 3-legged 2x2 intersections, 2.83 for 3-legged 2x4 intersections and 16 for 3-legged 2x6 intersections. Cottrell (1981) while developing criteria for the treatment of right-turn movements on rural roads found 40-70% reduction in the peak hour same direction rear-end conflicts due to right turns on two-lane highways with full-width lane treatment. The study considered 21 rural non-signalized intersections in Virginia and involved two- and four-lane roadways.

2.4 Logistic regressions in traffic safety studies

Logistic regression models have been successfully used to identify risk factors in traffic safety studies. Walker (1996) developed methodology application for National Highway Traffic Safety Administration on how logistic regression techniques could be used in safety studies.

Christian (2000) used logistic regressions to investigate the factors associated with motorcycle crashes reported in Kentucky and traumatic brain injury. Aultman-Hall and Padlo (2004) used binary logistic regressions, in combination with quasi-induced exposure crash analysis technique, to test the statistical significance of factors affecting young driver safety.

Yan et al. (2005) studied characteristics of rear-end crashes at signalized intersections. Using quasi-induced exposure concept and multiple logistic regression models, several significant risk factors for rear-end crashes related to the traffic environment, driver, and vehicle types were identified.

2.5 Guidelines for right turn treatment

Several studies have been done in the past regarding the guidelines for right turn treatment. Most of the guidelines were based upon the economic analysis of the benefit that the treatment provided over the cost of construction. Different treatment types like full width lane, taper or radius were considered depending upon the context and objective of the analysis. Some of the guidelines that were developed for a particular state have been adopted by others states as well. This section summarizes the past study related to the right-turn lane guidelines.

Alexander (1970) developed the economic warrants for the construction of right turn deceleration lane based upon economic benefits due to delay savings versus cost of construction, operation and maintenance. Cottrell (1981) developed guidelines for right turn treatment for rural two lane and four lane roads on the basis of volume threshold for right turning traffics and the through traffics on the approach with right turn treatments. He considered three types of treatments as radius, taper and full width lane.

McCoy et al. (1993) developed guidelines for the use of right turn lane based upon benefit-cost analysis. The benefits were related to the operational and accident cost saving to the road users by the application of right turn lane and the cost was related to the cost of construction. This study concluded that the right turn design hour volume that warrants the right turn lane is lower on high speed and high volume roads because of higher road user's cost related to safety and operation.

Hassan and Stokes (1996) developed guidelines for right turn treatments (such as full width lane and taper) based upon the economic analysis conducted over wide range of traffic volumes and speeds. The basis for the guidelines was economic analysis benefit-cost related to the operational and accident cost savings and the cost of construction. He found that the right turn treatments were effective on high speed and high volume roads because of higher cost savings that could be achieved with the application of right turn treatments.

Hadi and Thakkar (2003) used speed differential as a measure to evaluate the need for right turn lanes for unsignalized intersections and produced a table with critical right turn volumes for two scenarios with benefit–cost ratio of 1.5 and 2 related to the accident savings and right turn lane cost . According to the National Cooperative Highway Research Program (NCHRP) Report 279 (Neuman, 1985), the provision of right turn lanes were justified in urban areas based on volume of right turns, right turning rear end accidents, and/or pedestrian crossing volumes. Similarly in rural areas, speed, volume of right turns and the landuse types are the governing factors.

AASHTO (2001) provides the general design consideration for auxiliary lane applicable to both left and right turn treatments. Road design manual published by Minnesota Department of Transportation (Mn/DOT, 2000) states that, in urban areas, right turn lanes were considered favorable if the construction is economically feasible in view points of amount of right of way needed, type of terrain, and environmentally and culturally sensitive areas. In case of rural intersections, right turn lanes were considered favorable in all the roads with ADT 1500 and the design speed over 45 mph or in all public road access points serving substantial trip generation or serving more than 10 residential units.

The road design manual of South Dakota (SDDOT, 2007) states that it considers the right turn treatments according to the policy described in Oregon DOT Policy manual 1999. There is also a provision to apply right turn lane in the locations with five or more accidents per year of the type that could be remedied with right turn treatments. Similarly Road Design Manual of North Dakota (NDDOT, 2004) states that the application of turn lanes is determined by traffic operation analysis. Such analysis could be conducted by Planning Division of NDDOT or a Consultant. According to the Iowa Road Design Manual (IADOT, 1995), right turn lanes for rural two-lane roads are warranted based upon the present ADT and are different for major and minor approaches.

2.6 Significant Factors Affecting Operational Impacts

The past studies have shown that the right turning vehicles in a shared lane cause through vehicles to reduce their speed so that they can maintain the safe headway from the right turning vehicle. This phenomenon impeded through traffic and leads to the operational effects such as delay and excess fuel consumption. Delay could be defined as the difference in travel time of a vehicle under conditions of impedance and non-impedance. Excess fuel consumption results due the acceleration and deceleration that vehicle undergoes during speed change cycles. Several studies have tried to quantify these effects using analytical or mathematical models, simulation, or statistical analysis of field data. Simulation allows one to study the stochastic behavior of vehicles observed during impedances and differing driver behaviors. This section reviews past studies related to assessment of operational impacts.

2.6.1 Operational Delay

Alexander (1970) developed the economic warrant for the construction of right turn deceleration lanes based upon the data recorded from ten field sites including three field sites with right turn lane and seven field sites without right turn lane. This study found that delay to through vehicle by right turning vehicles in the locations having right turn lanes was very low. In addition, the study concluded that the provision of right turn lane almost eliminated all delay to through vehicles. The study developed a regression equation of the delay to through vehicles (seconds/hour) as a function of number of right turns in approach traffic , approach traffic volume and mean speed of non-delayed through vehicles.

Stover et al. (1970) used simulation to compute the delay due to the right turning vehicles. This study calibrated the simulation model with the use of deceleration rate and right turn speed data from model using time-lapse photography of one field location. The study, using graphical plot, showed that the delay by right turning vehicles increases exponentially as the volumes in the driveway increases and the difference in speed in through traffic and driveway entrance increases.

McCoy et al. (1984) developed the warrants for the construction of turning lanes on the uncontrolled approaches of the intersection on rural two lane highways. This study used micro simulation software, NETSIM, for computation of operational effects as delay, fuel consumption and stops. Due to the errors in series of NETSIM runs used for simulation of right turn lanes, the study adopted the same equation that was developed to estimate the delay savings due to left turn lanes for right turn lanes too. The developed exponential equation expressed delay savings in seconds per vehicle for left turn lanes as a function of opposing volume, approach volume and free flow approach speed. 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.

Later in 1993, McCoy et al. (1993) were successful in simulating the uncontrolled approach with “shared” and “exclusive right turn lane” using NETSIM software. This study established the delay equation for uncontrolled approach for the cases with and without right turn lane for two-lane and four-lane roads. The developed equation explains that the delay due to right turning vehicles to the through vehicles is affected significantly with approach speed of the roadway, volumes at the approach, volumes of right turning vehicles and the interactive term expressed as the product of volumes of right turning vehicles and presence/absence of right turn lane. Hassan and Stokes (1996) developed equation for delay to through vehicle due to the effect of right turning vehicles during his work for the development of guidelines for right turn treatments at unsignalized intersections and driveways on state highway system of Kansas. 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).

Bonneson (1998) developed a deterministic/analytical model to predict the delay due to right turning vehicles from the outside of through lane of Major Street to through vehicles. For the verification of the model developed in this study, the study compared computed delay with the delay obtained from the model developed by other researchers in the past that had used 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 about geometric delays due to the right turning vehicles at the intersection taking into account of radius of curvature of turns. The study concluded that with the decrease of radius of curvature of travel way, the delay by right turning vehicle to the through vehicle increases. The study put forward an analytical equation of the total time impacted by right turning vehicles taking into consideration of deceleration time, clearance time, acceleration time of the through vehicle, the headway between adjacent vehicles, and a minimum headway of 1.9 seconds. Wolfe and Piro (2003) developed the model for delay to through vehicles by right turning vehicles based on difference in through and right turning vehicle's speed, total volume and right lane volume. The study was based on data collected from twelve intersections.

2.6.2 Excess Fuel Consumption

Dale (1980) produced the graphs to compute additional fuel consumption attributed to corresponding speed change cycles. The graph gives the value of additional fuel consumption in terms of gallons per 1,000 speed changes. Mounce (1983) did simplistic model analysis for the difference in fuel consumption for arterial through vehicles which are forced to accelerate or decelerate by right turning vehicles into a driveway. The study found that at the arterial-driveway hourly volume product level above 50,000, the provision of right turn lane can save up to 30,000 gallons of fuel annually.

Lima (1984) put forwarded a microcomputer approach for Federal Highway Agency (FHWA) procedure estimating highway user costs fuel consumption, and air pollution. He explained that there was an additive functional relationship between the fuel consumption and four measure of effectiveness such as uniform speed, stops, idling, and speed changes.

McCoy et al. (1984) used the same equation developed for the fuel savings due to left turn lanes for right turn lanes due to the errors in series of NETSIM runs used for simulation of right turn lanes. The equation shows the exponential relationship between fuel savings with opposing volumes, approach volumes and left turn percentage. The equation was adopted for right turn lane replacing the opposing volume with zero and left turn percentage with right turn percentage.

Mc Coy et al. (1993) developed the fuel consumption model for a two lane unsignalized approach which showed a linear relationship between fuel consumption and approach speed , volumes of right turning vehicles , total approach volume and the presence/absence of right turn lane.

Hassan and Stokes (1996) used the relationship between excess fuel consumption and speed change cycle developed by Dale in 1980. He developed the excess fuel consumption model for impacted vehicle due to right turning vehicles in which excess fuel consumption was the function of directional design hour volume and roadway operating speed.

According to the" Revised Monograph on Traffic Flow Theory" (Ardekani et al., 2005), fuel consumption on the broad basis is affected by the factors such as vehicle, environment, driver and traffic conditions.

2.7 Simulation of operational impacts

2.7.1 Right turn related

Mc Coy et al (1984) attempted unsuccessfully to simulate the operational effect of right turn lanes using NETSIM software. However, McCoy et al. (1993) successfully simulated 3-legged intersection using NETSIM software. A total of 4320 combinations of input variables for two-lane roads were used to compute delay and fuel consumption for shared and exclusive cases and in turn to develop predictive relationships using multiple regression method. The study conducted simulation for 15-minutes period and considered the model calibrated when the speed data from simulations (using default parameters) matched the field obtained speed data. Bonneson (1998) used NETSIM software to calculate delay to through vehicles due to right turning vehicles to verify his analytical approach. He deduced the delay due to density of traffic stream from through delays reported by NETSIM output to get delay due to right turn activity.

2.7.2 Other studies

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 of comparison among other analyzed 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 delay for each vehicle by subtracting travel time at desired free flow speed from actual travel time. Gafarian and Halati (1986) defined NETSIM as a stochastic microscopic traffic simulation model with sampling interval of 1 second.

Dowling et al. (2004) defined microscopic model as the models 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 such that in each time step (of 1 second) advancement of lead vehicle, the follower vehicle was moved to the location such that the follower vehicle should be able to stop without collision if the lead vehicle decelerated with maximum deceleration rate. Siddiqui (2003) used NETSIM software for urban network as a basis to provide logical and sequential calibration and validation result of micro- simulation traffic models. In terms of validation, Sacks et al (2002) summarized that CORSIM output may match with field observations if carefully tuned and calibrated.

Chapter 3 Definitions and Safety Methodology

This chapter provides different definitions and contexts relevant to this research and describes the methodology used in the study.

3.1 Right-turn types

Right-turn treatment at a road intersection may be defined as a geometric treatment provided with an intention to facilitate right-turn movements of traffic, and to improve safety and operational efficiency. Three basic types of right-turn treatments are provided at intersections depending on road environment and traffic conditions: (1) no special treatment other than the radius, (2) a taper, and (3) a full-width lane. For the purpose of this report, radius right-turn treatment will also be referred as shared right-turn treatment. Similarly, a treatment with right-turn lane will also be referred as exclusive right-turn treatment.

Figure 3.1 shows a radius/shared right-turn treatment. As the name suggests, no special treatment other than the radius is provided. The radius treatment may, sometimes, take the form of a turning roadway as shown in Figure 3.2.

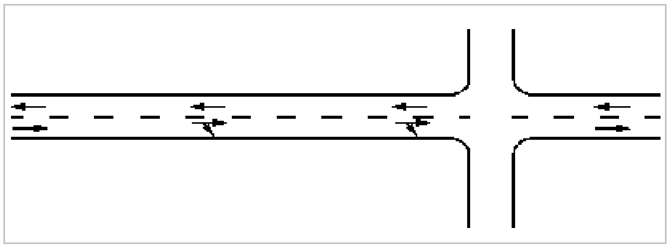


Figure 3.1. Shared/radius right-turn treatment.

Figure 3.3 shows a taper right-turn treatment. In this type, the treatment is taken one step further over the shared type in the form of a taper. Literature suggests that a taper treatment is not a common type of right-turn treatment.

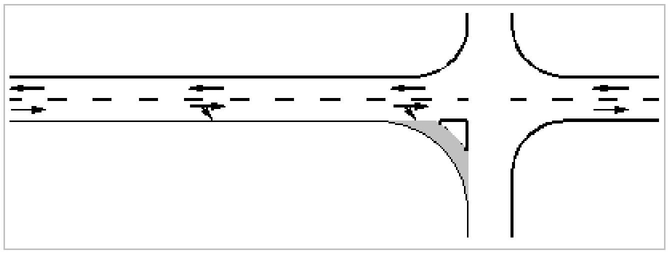


Figure 3.2. Shared/radius right-turn treatment with turning roadway.

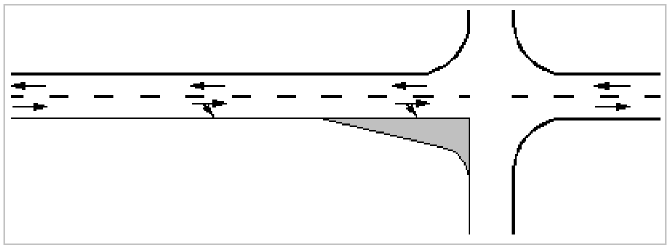


Figure 3.3. Taper right-turn treatment.

Exclusive right-turn treatment in the form of a full-width lane is shown in Figure 3.4. The full-width lane in this type of treatment separates right-turning traffic from the through traffic. A turning roadway is also provided, sometimes, together with the exclusive lane as shown in Figure 3.5.

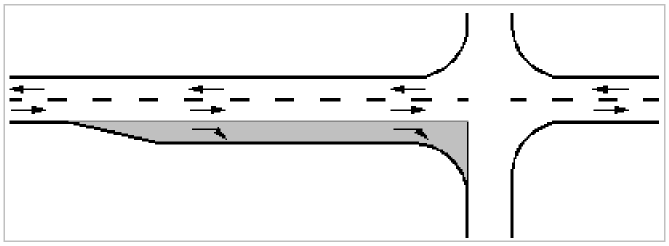


Figure 3.4. Exclusive right-turn treatment.

Among the three basic types of right-turn treatments discussed above, full-width lane treatment is considered the superior type. However, it was found that a right-turning vehicle that had moved to the exclusive lane would, sometimes, obstruct the line of sight of the vehicle yielding at the minor cross road. This created safety problems. In order to address this safety issue, transportation professionals have come up with a new configuration of exclusive treatment called offset right-turn treatment as shown in Figure 3.6. The full-width lane is offset further from the traveled lane so that the configuration allows unobstructed line of sight to yielding vehicle at the cross road.

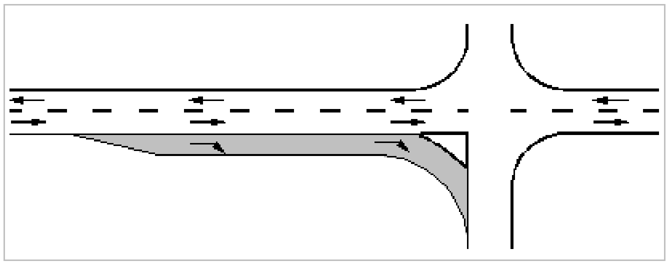


Figure 3.5. Exclusive right-turn treatment with turning roadway.

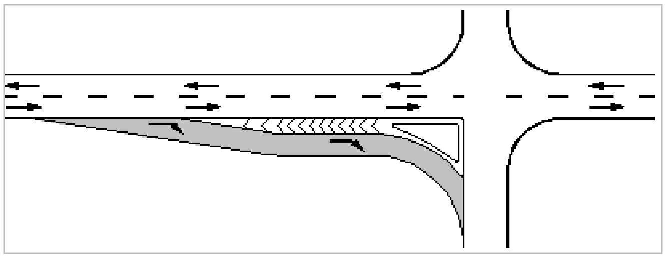


Figure 3.6. Offset right-turn treatment.

3.2 Crash types

Road crashes involving two or more vehicles belong to one of the six basic crash types as shown in Figure 3.7.

Left-turn crash involves left-turning vehicles and usually occurs when left-turning vehicle fails to yield to the through traffic. A rear-end crash occurs when the front of a vehicle hits the rear of a leading vehicle. This is one of the most common types of crashes. According to National Highway Traffic Safety Administration (2006), there were approximately 1.9 million rear-end crashes in 2004 in the U.S., constituting about 30.5% of all police reported crashes. Sideswipe crash occurs when the sides of vehicles strike each other. Two configurations are possible – same direction sideswipe crash and opposite direction sideswipe crash. Right-angle crash is another most common type. The collision angle in this case is about a right angle. Right-turn crash occurs when one of the vehicles was making a right turn. Type 5(a) and 5(b), as shown in Figure 3.7, are the two types of right-turn crash possible. The type 5(a) occurs when the right-turning vehicle encroaches into the opposing lane. The type 5(b) results due to merge conflict between right-turning vehicle and through vehicle from cross road. Head-on crash typically occurs when a vehicle crosses a centerline or a median and crashes into an approaching vehicle.

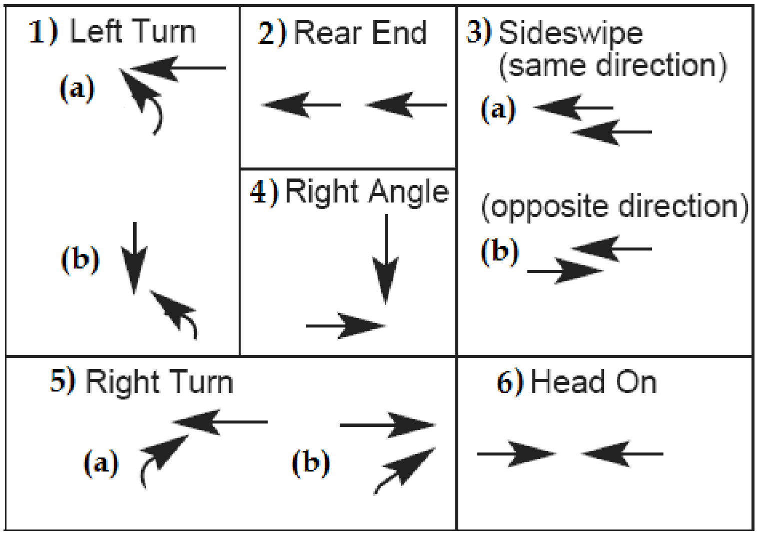


Figure 3.7. Crash types.

3.3 Overall methodology for analyzing crash data

The overall methodology to analyze crash data is presented in Figure 3.8. The methodology broadly consisted of the following three stages:

- Data collection,
- Data reduction, and
- Analysis.

The data collected for this study included the crash history data, traffic volume data, intersection inventory data, crash reports, videolog data, and the GIS shapefiles. Road intersection images were also retrieved using Google Earth software. The collected data were then conflated with crash history data.

Statewide crash history data for the study were collected for the State of Minnesota. The dataset included all reported crashes that involved 2 or more vehicles and occurred on two-lane roadways in the State of Minnesota over a period of 5 years from 2000 to 2002, and 2004 to 2005. Traffic volume data for the relevant roadways were collected for the corresponding periods. Right-turn treatment information at an intersection was obtained by making use of videolog data regarding physical features of the Minnesota Trunk Highway System, crash reports prepared by the Minnesota Department of Public Safety, and input from Mn/DOT officials; and also by retrieving crash locations using Google Earth software. Types of crashes basically associated with right-turning vehicles were identified through exploratory analyses. Binary logistic regression models were then developed to determine the nature of relationships between the various explanatory factors and crashes that involved at least one vehicle making a right turn, and also to assess the impacts of shared/exclusive right-turn movements on such crashes.

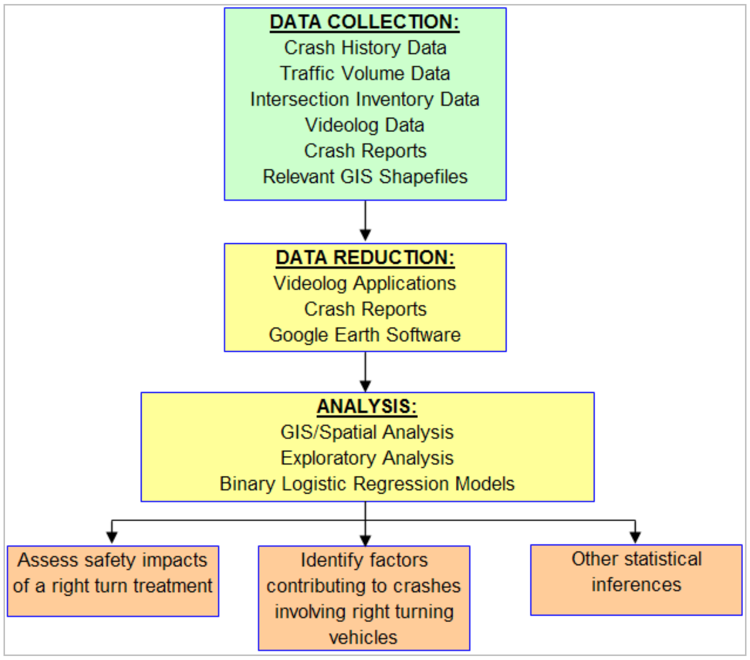


Figure 3.8. Overall methodology.

Chapter 4 discusses, in detail, the multiple sources from where data were obtained, the nature of data, and the data collection efforts. Any crash history data point that did not meet the data requirements was eliminated from the dataset. The main focus of data reduction was to ensure that data requirements were met. Chapter 4 also provides a discussion regarding different data reduction techniques used. The data requirements were specified to include the following criteria:

- The crash involved 2 or more vehicles,
- The crash involved two-lane roadways,
- The crash was classified as intersection/driveway/alley crash, and
- The crash data point included location information.

Analysis included exploratory analyses and binary logistic regression analyses. Exploratory analyses were carried out to objectively assess the nature, extent and pattern of crashes. Binary logistic regression models were developed to determine the significant explanatory factors associated with crashes. The subsequent sections provide brief descriptions on each type of analysis. A detailed discussion of design of experiments used in selection and categorization of variables as well as the exploratory analyses and binary regression analyses are discussed in detail in Chapter 4.

3.4 Analysis using GIS

GIS software, ArcGIS 9, was used at the initial stage of data processing and investigation by importing crash history, traffic volume and intersection inventory data into GIS environment. Several maps were drawn highlighting crash locations and traffic volumes. Proximity analysis provided useful information regarding crash locations in relation to intersection locations. Maps and results from the analyses provided a starting point to proceed further into the study. Chapter 4 presents some sample maps developed based on proximity analysis.

3.5 Exploratory analysis

With thousands of data points available, it was found beneficial to use exploratory analysis to determine the nature, extent and pattern of crashes so that further analysis could be based on the results obtained from such analyses. The exploratory analysis considered all crash types.

Exploratory analysis was carried out using MICROSOFT EXCEL® spreadsheets. Two sets of data were used for exploratory analysis. One set of data included all the crash history data points, whereas the other set of data included only crashes that involved at least one vehicle making a right turn. As mentioned earlier, the main objectives of the exploratory analysis were to determine the nature, extent and pattern of crashes. The information provided important basis for choice of independent and dependent variables to be used in developing binary logistic regression models.

3.6 Logistic regression models

Two types of logistic regression models may be used: binary logistic regressions or multinomial (polytomous) regression models. Binary logistic regression models use the dependent variables two levels or classes. A binary logistic regression model describes a linear relationship between the logit, which is the logarithm of odds, and a set of predictors. It has the form as shown below:

$$\ln [\pi/(1-\pi)] = \pi^* = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n, \qquad \ldots (3.1)$$

where

π = P(Y=1) = Probability that Y=1, where 1 indicates the desired event;
x_n = Explanatory factors (one dimensional factors or the interaction of factors); and
β_n = Model Coefficients.

Multivariable multinomial logistic regression models were used to estimate and identify the significant factors affecting severity of a multiple vehicle crash involving vehicles making right turns. These models require outcome variables with more than two levels on ordinal or nominal scales; for outcome variables with two levels, binary logistic regression methods can be used.

The ordinal-response logistic regression model has the response variable (Y) with k+1 ($k \geq 1$) levels of ordinal values, denoted for convenience by 1, 2, ..., k, k+1. Based on the cumulative probabilities of the response categories, the model is fitted as a common-slopes cumulative model, which is a parallel lines regression model. The model with a logit link function, often referred to as the proportional odds model, has the form shown below (SAS, 2003):

$$\text{Logit}(\gamma_i) = \ln [\gamma_i/(1-\gamma_i)] = \alpha_i + \beta'\mathbf{x}, \quad i = 1, 2, \ldots, k \qquad \ldots (3.2)$$

where
$\gamma_i = P(Y \leq i \mid \mathbf{x})$, the cumulative probability that the response falls in the i^{th} category or below;
$\alpha_1, \alpha_2, \ldots, \alpha_k$, are k intercept parameters;
β is the vector of parameters; and
x is the vector of explanatory factors (one dimensional factors or the interaction of factors).

The nominal-response logistic regression model uses generalized logits approach to model the relationship between the response and the explanatory factors. For a categorical variable, the generalized logits are defined as natural logarithm of the probability of each category over the probability of the baseline (or reference) category.

Since the k+1 possible responses have no natural ordering, these generalized logits are modeled as linear functions of explanatory factors with different regression parameters for each logit, and have the forms shown below (SAS, 2003):

$$\ln\left[\frac{\mathrm{P(Y = i} \mid x)}{\mathrm{P(Y = k + 1} \mid \mathrm{x)}}\right] = \alpha_i + \beta'_i\mathbf{x},\ \mathrm{i} = 1, 2, \ldots, \mathrm{k} \qquad \ldots (3.3)$$

where

$\alpha_1, \alpha_2, \ldots, \alpha_{k,}$ are k intercept parameters;

$\beta_1, \beta_2, \ldots, \beta_{k,}$ are k vector of parameters; and

x is the vector of explanatory factors (one dimensional factors or the interaction of factors).

3.6.1 Model assessments

The appropriateness of the regression models developed in this study was assessed using goodness-of-fit tests. The following two methods were used:

Hosmer-Lemeshow test: The null hypothesis for this test was: the model fitted the data. The alternative hypothesis was: the model did not fit the data.

The test statistic for this test is given by

$$\hat{C} = \sum_{k=1}^{g} \frac{(O_k - E_k)^2}{v_k}, \qquad \ldots (3.4)$$

where

g is the number of partitions created in the dataset,

O_k is the observed number of events in the kth group,

E_k is the expected number of events in the kth group, and

v_k is a variance correction factor for the kth group.

If the observed number of events differs from what is predicted by the model, the statistic $\hat{C}$ will be large and there will be evidence against the null hypothesis. This statistic may be obtained in SAS with lackfit option in the model statement. It has an approximate chi-squared distribution with (g-2) degrees of freedom.

Pearson test: As with Hosmer-Lemeshow test, the null hypothesis for this test was: the model fitted the data. The alternative hypothesis was: the model did not fit the data.

The test statistic for this test is given by

$$X^2 = \sum_{i=1}^{n} \frac{(y_i - \hat{y}_i)^2}{\mathrm{var}_i}, \qquad \ldots (3.5)$$

where

y_i is the observed response,
$\hat{y}_i$ is the predicted response or predicted probability for the i^{th} subject, and
var_i is the estimated variance of the response.

This statistic has an approximate chi-squared distribution with degrees of freedom equal to the number of covariate patterns (the number of unique profiles in SAS®) minus the number of parameters estimated. This test can be obtained in SAS® with scale=none option in the model statement.

3.6.2 Odds ratio and relative risk

Odds are the probability of an event occurring divided by the probability of the event not occurring. An odds ratio is the ratio of two odds, whereas relative risk is the ratio of two probabilities.

The odds ratio is one of the most common measures to assess the relationship between the outcome variable and explanatory factors because odds ratios are easily obtained from logistic regression models. However, when the occurrence of the desired outcome event is more than 10% (the desired event is a common event), the odds ratio usually overestimates or underestimates the relative risk depending on whether the odds ratio is more than 1 or less than 1, respectively (McNutt et al., 2000). Therefore, odds ratio in this study was used to estimate relative risk only in cases when the desired outcome event was a rare event.

Chapter 4   Safety Analyses

4.1   Background data analysis

Right turn related accidents were spread all over Minnesota. Rear-end, sideswipe – same direction, right-angle, and right-turn accidents comprised 93% of all accidents that were related to vehicle turning right.

4.1.1 Definition of context

The following terms are used throughout this document to define a specific context. This terminology and classification was necessary to identify right-turn treatment types using videolog and Google Earth software.

System road: The roadway, which is used as the reference road to record crash-related information in the crash history dataset. For example, if a crash occurred at the middle of an intersection involving two different vehicles that had been traveling on different roadways, the crash record in the crash history database would still be referenced to any one of these roads.

Cross road: Any roadway that intersects a System road. The crash history dataset obtained for the study did not include information related to Cross roads.

TO-case: A case of a right-turn movement by a vehicle when the vehicle making a right turn was passing onto a System road from a Cross road.

FROM-case: A case of a right-turn movement by a vehicle when the vehicle making a right turn was passing onto a Cross road from a System road.

Private driveway: A driveway to an independent residential house, including private field approaches, where the volume of right-turning vehicles would be significantly low.

Commercial driveway: A driveway leading to business units, including public driveway leading to churches, cemetraries, recreational places, etc. where the volume of right-turning vehicles would be significantly higher as compared to a private driveway.

Whereas the study considered the entire crash history dataset (reduced) in order to determine the significant factors leading to a crash that involved at least one vehicle making a right turn, it considered only the FROM-case dataset in the analysis to determine safety effectiveness of right-turn treatments. The exploratory analysis was carried out using the entire crash history dataset as well as the FROM-case dataset.

4.1.2 Crash history data

The crash history dataset was obtained from the Minnesota Department of Transportation (Mn/DOT). The dataset included all reported crashes in the State of Minnesota over a period of five years from 2000 to 2002, and 2004 to 2005 that occurred on two-lane roadways and involved at least 2 vehicles. The dataset included the following information: (1) route ID (for the System road), (2) crash location in terms of reference post/true miles, (3) reliability of crash location information, (4) investigating officer, (5) district (Mn/DOT construction district), (6) county number, (7) city or township number, (8) date crash occurred, (9) time of day crash occurred, (10) severity of crash, (11) number of vehicles involved in crash, (12) relationship to junction, (13) posted speed limit of roadway, (14) type of crash, (15) diagram of crash, (16) location of first harmful event, (17) traffic control devices, (18) light conditions, (19) weather conditions, (20) road surface conditions, (21) road character, (22) road design, (23) vehicle type, (24) direction vehicle was traveling, (25) action by vehicle, (26) contributing factors (2 possible), and (27) crash/accident number.

The crash history dataset included alley/driveway crashes and intersection crashes. According to Mn/DOT's Transportation Information System (TIS) User's Manual 2006, intersection crashes are those with the following codes in the relationship to junction data element: (1) '02' T-intersection, (2) '03' Y-intersection, (3) '04' 4-legged intersection, (4) '05' 5 or more leg intersect, (5) '06' TRF circle or roundabout, (6) '07' intersection-related, (7) '20' interchange on ramp, (8) '21' interchange off ramp, and (9) '22' interchange other area.

The total number of crash history data points obtained from Mn/DOT was 22,211. This dataset was obviously the most important dataset because it provided crash-related information on which safety analysis is based. A subset of this dataset was also created to include only those crashes that involved at least one vehicle making a right turn.

A crash that involved at least one vehicle making a right turn was identified by using the information provided in 'DIAG' Diagram of crash and 'ACT' Action by vehicle columns in the dataset. A crash with the DIAG column coded with the value '6' (right-turn) was identified as involving right-turn maneuver by at least one of the vehicles involved in the crash. Similarly, a crash record with its ACT column for a vehicle coded with the value '5' (vehicle making a right turn) was identified as involving right-turning maneuver by that vehicle. Therefore, the subset of crashes involving at least one vehicle making a right turn included crash records that had DIAG column coded with '6' or ACT column coded with '5'. The total data points in this subset turned out to be 1,791.

4.1.3 Traffic volume data

The traffic volume data were obtained from Mn/DOT for the same time period as crash history data, i.e., for five years from 2000 to 2002, and 2004 to 2005. The dataset included the following information: (1) route ID, (2) beginning and end points of road sections in terms of true miles for which the traffic volume data are applicable, (3) data year, (4) annual average daily traffic (AADT), and (5) heavy commercial vehicle (HCV) traffic.

4.1.4 Intersection inventory data

Intersection inventory data were obtained from Mn/DOT. The dataset provided intersection inventory information, including location information of every intersection in terms route ID and reference post/true miles. The dataset contained information on 7,893 intersections. The dataset was used to investigate the proximity of a crash location to an intersection. It was also helpful in determining the type of land use at an intersection. However, land-use data were not used in the analysis.

4.1.5 Crash locations and GIS

GIS shapefiles for Minnesota's state boundary, district boundary, county boundary, and road network were obtained from Mn/DOT. Crash history, traffic volume, and intersection inventory data could be imported as shapefiles in the GIS environment. This could be done through ArcGIS 9's 'Add Route Events' command by using road network shapefile as route reference, route IDs as route identifier, and true miles as location measures.

Various maps were created using these shapefiles. Proximity analysis was carried out to determine the closeness of a crash location and an intersection location, and to determine multiple crash locations. Such analyses and maps in the initial stage of the study proved to be useful and provided a starting point to carry forward into the study.

Minnesota's road network is shown in Figure 4.1. Locations of all crashes from year 2000 to 2002, and 2004 to 2005, at intersections where at least one road was a two-lane road, with no control on the major road are shown in Figure 4.2. Of these crashes, locations for crashes that involved at least one vehicle making a right turn are shown in Figure 4.3. Intersection locations included in the intersection inventory dataset are shown in Figure 4.4.

4.1.6 Videolog data and contexts

One of the objectives of the study was to identify the roles that a specific type of right-turn treatment plays in a crash involving right-turning vehicles. Unfortunately, crash history data did not include right-turn treatment information. Attempts to locate other data sources in electronic formats that provide right-turn treatment information at an intersection so that speedy conflation with crash history data could be achieved were unsuccessful. Therefore, it was decided to access the videolog database maintained by Mn/DOT to determine right-turn treatment type at crash locations. The videolog database maintained by Mn/DOT provides high-quality road images that could be used to investigate road intersection geometry.

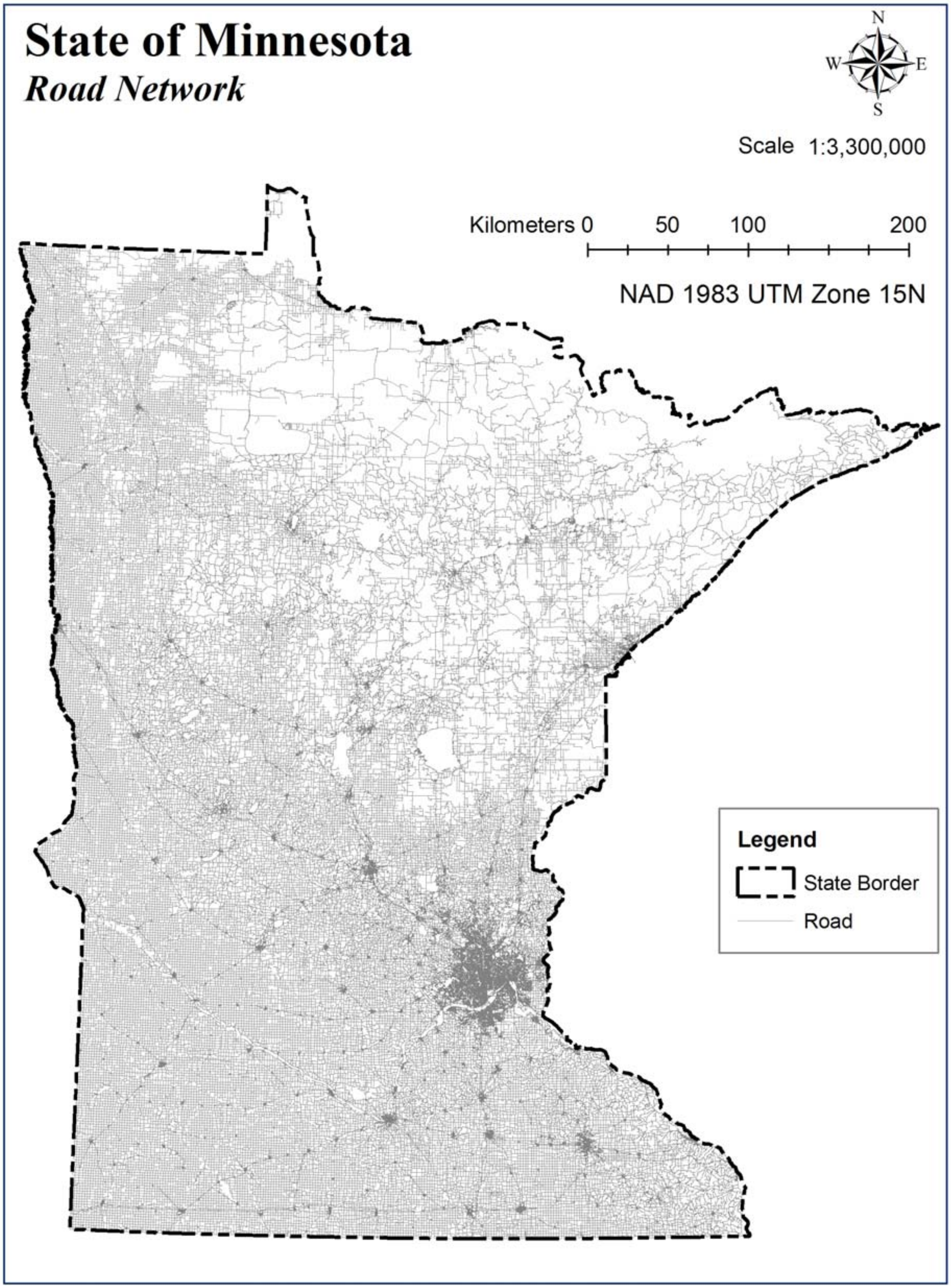


Figure 4.1. Road network in the state of Minnesota.

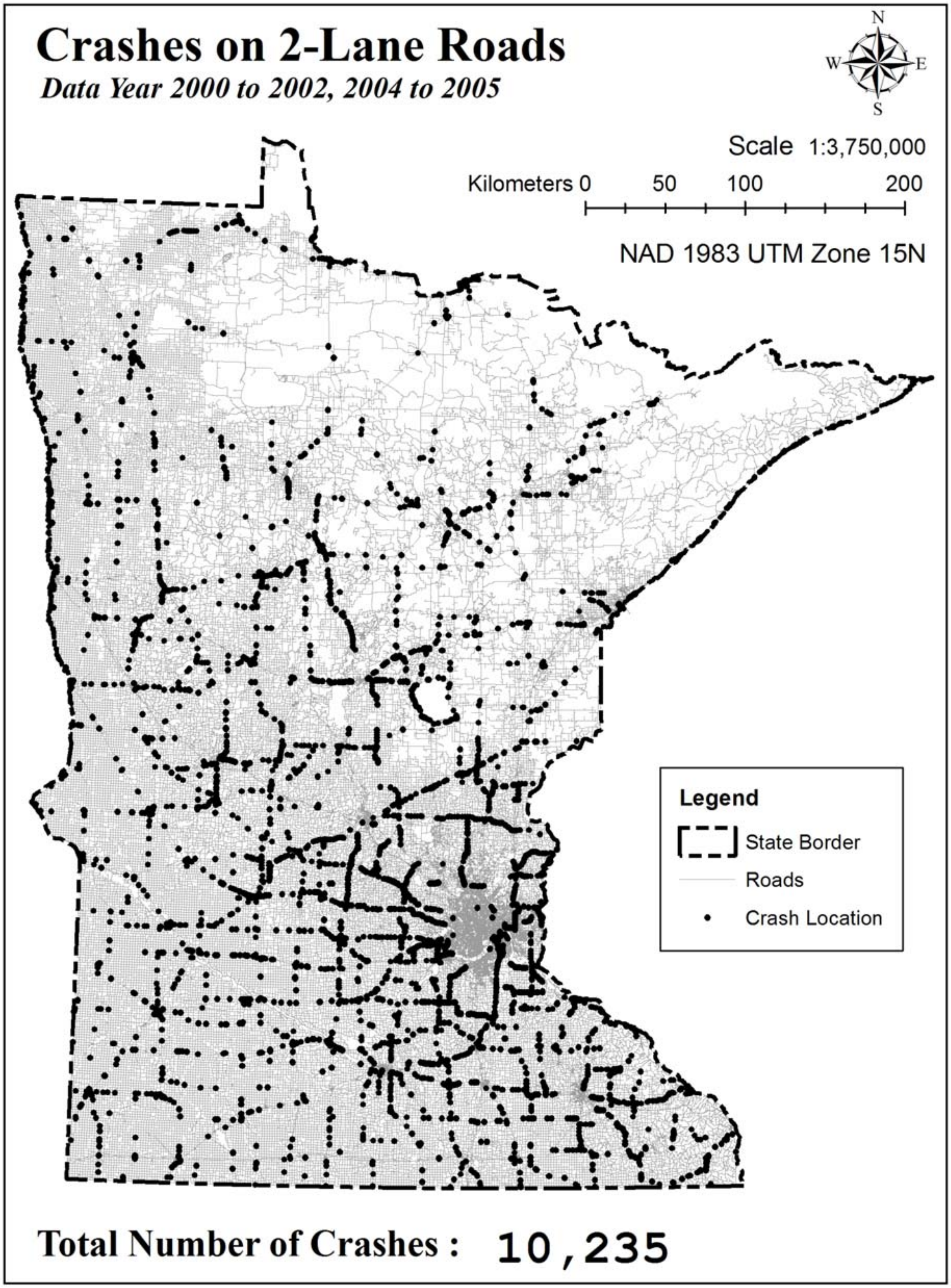


Figure 4.2. Locations of crashes in 2000-2002 and 2004-2005.

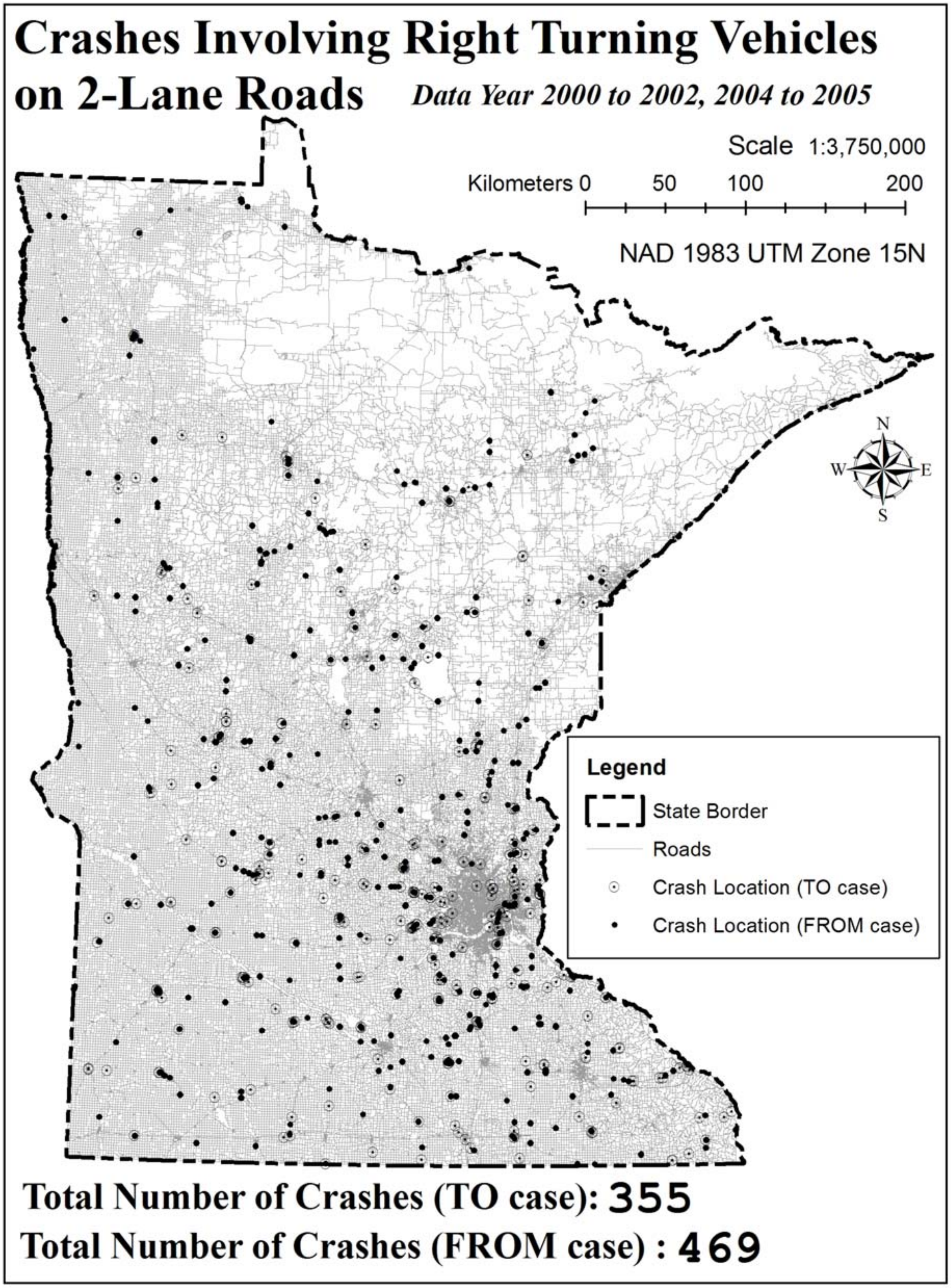


Figure 4.3. Locations of crashes that involved at least one right-turning vehicle.

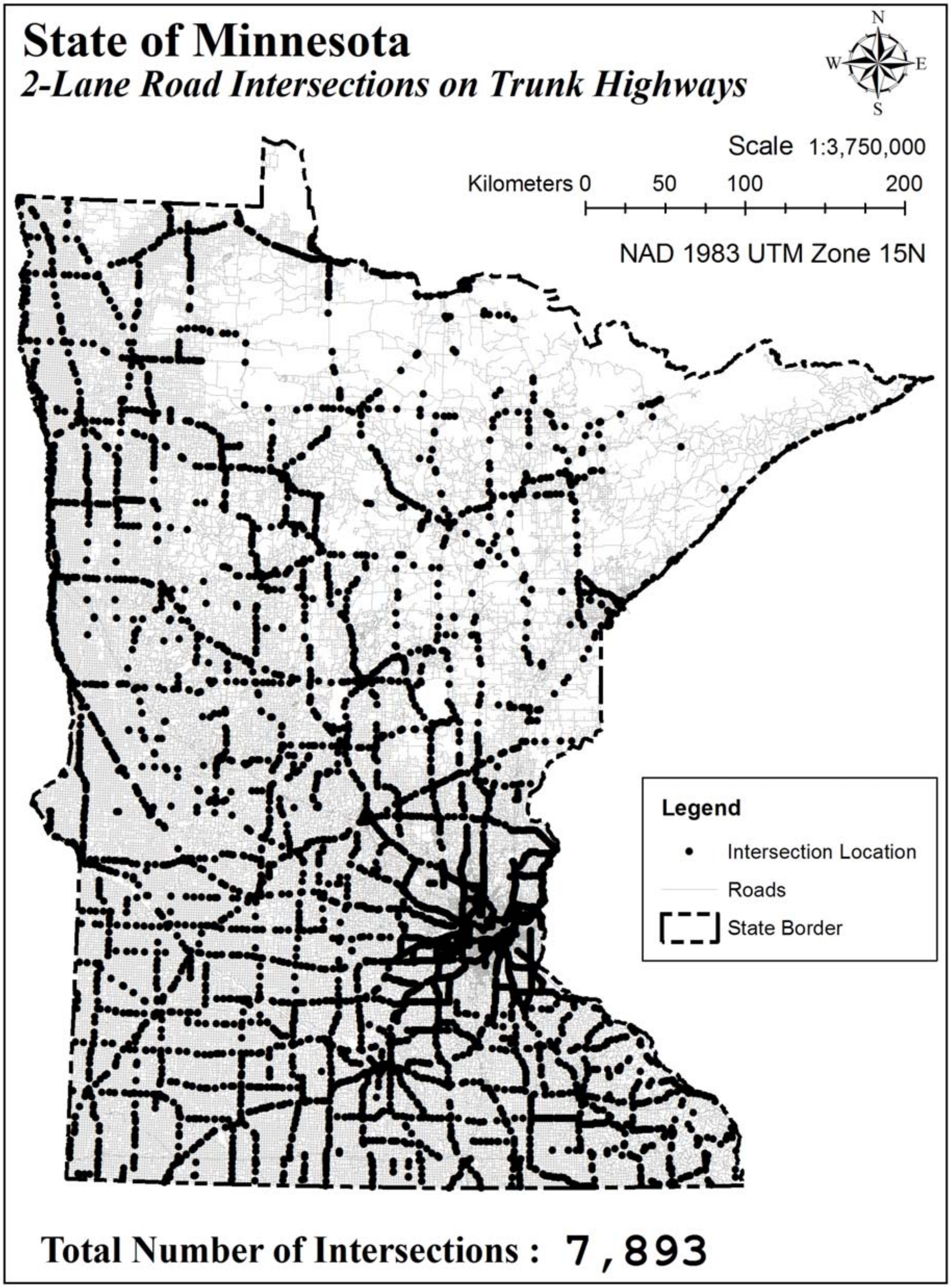
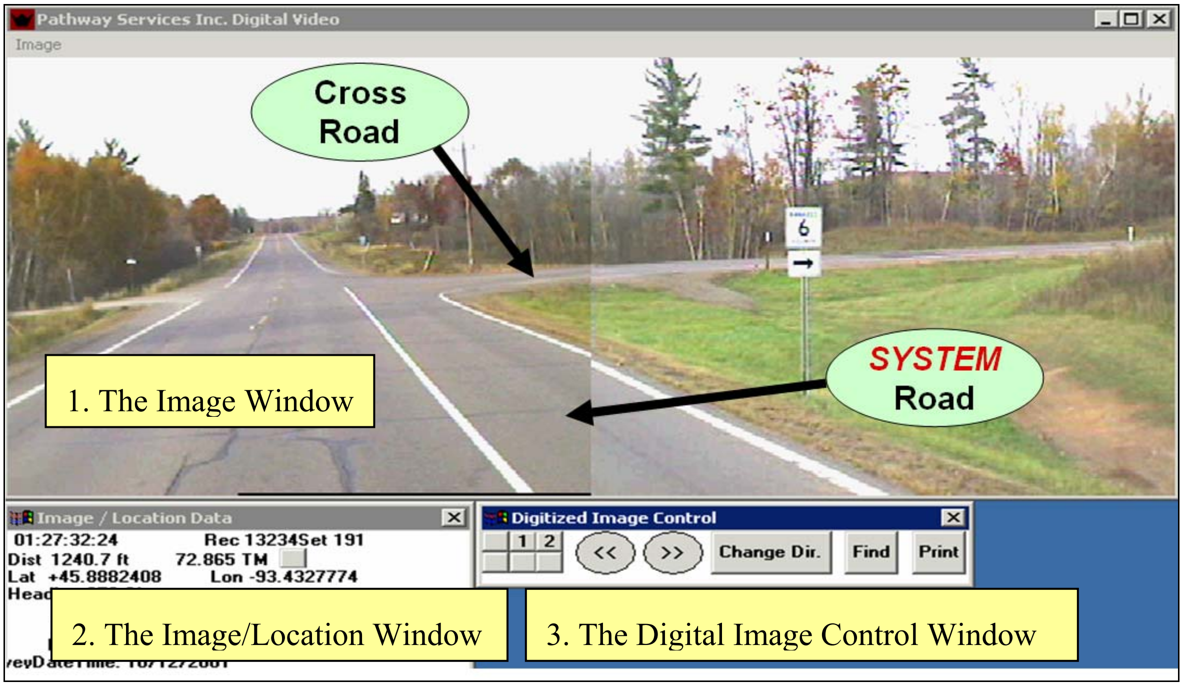


Figure 4.4. Locations of intersections in intersection inventory.

The videolog application of Mn/DOT consists of three windows–the Image window, the Image/Location window, and the Digital Image Control window–as shown in Figure 4.5 (random location, not analyzed in this thesis). Using these videolog application windows, route IDs, and true mile/reference post information for a crash in the crash history dataset, the image of a crash location could be displayed. The videolog application also provides latitude and longitude information of the camera position.



01:27:32:24 Rec 13234Set 191
Dist 1240.7 ft 72.865 TM
Lat +45.8882408 Lon -93.4327774

Figure 4.5. Typical videolog application windows.

Videolog images are recorded and maintained on a yearly basis. Therefore, a videolog image of a crash location for the year when crash occurred could be accessed to determine right-turn treatment type as it was in that year.

However, due to the manual process involved in identifying right-turn treatment through videolog images, it was not considered feasible to investigate all available crash history data points to identify right-turn treatment type. Therefore, identification of right-turn treatment type through videolog was considered only for the crashes that involved at least one right-turning vehicle.

One important limitation in the use of videolog database was found with respect to a distance, referred to as ‘skip length’. ‘Skip length’ is the distance by which a videolog image would advance along the System road on a single click on the videolog application window button that advanced images. The minimum skip length was 25 feet in Metro area and 50 feet in outstate (Videolog User Manual, 2004). This limited clear and closer observations of a Cross road when it fell within this skip length. Directional control in terms of advancing videolog images along a Cross road is not available with Mn/DOT’s videolog applications. It follows that right-turn treatment type on Cross roads could not always be identified. The identification of right-turn treatment type on a Cross road was important when a vehicle made a right turn onto a System road from a Cross road. In the subset of crash history data that involved at least one vehicle making a right turn, it was now important to identify whether the right-turning vehicle was passing onto a System road from a Cross road (TO-case) or it was passing onto a Cross road from a System road (FROM-case). However, categorizing a crash history record as belonging to either the TO-case or FROM-case required another data source that described a crash event in more detail. This data source was found in the form of crash reports maintained by the Minnesota State Department of Public Safety. According to the Minnesota State law (Minnesota Office of the Revisor of Statutes, 2006), every crash that results in injury or death, or total property damage of $1000 or more, must be reported.

4.1.7 Crash reports and contexts

Crash reports maintained by the Minnesota Department of Public Safety were obtained through Mn/DOT for crashes that involved at least one vehicle making a right turn. The main purpose of collecting crash reports was to identify whether the right-turning vehicle was passing onto a System road from a Cross road (TO-case) or vice versa (FROM-case). A crash report would generally include a sketch of crash diagrams with vehicle positions, followed by a description of the events that led to crash. So, in most of the cases, it was possible to identify the TO-case or FROM-case. In order to identify the correct crash report related to a crash record in the crash history dataset, the crash/accident number in a crash record was matched with the crash/accident number on a crash report.

4.1.8 Google Earth data and contexts

While examining the crash reports, it was found that the reporting officer would, sometimes, refer the roads involved in a crash by street names. The crash records in the crash history dataset, on the other hand, did not include street names. It would use Route IDs as route identifiers. In such cases, it became difficult to identify the System road among the roads that were mentioned in the crash report. The intersection inventory dataset was helpful to resolve such problems because intersection inventory data included names of Cross roads. However, the crash history data also included crashes at locations that were not found in the intersection inventory dataset. As such, the need for other data sources that could be used to identify a road by both street name as well as road number was felt necessary. It was found that Google Earth software was most suitable for this purpose and could also be used to retrieve the images of crash locations.

The image/location window of videolog applications provides the location of the camera in terms of latitude and longitude (Lat-Lon). The “Lat-Lon” information at a crash location could, therefore, be obtained and could be fed into the Google Earth software to retrieve the image of that location.

4.2 Data reduction of background data

Data reduction is needed to develop a consistent set of data and more importantly to format the data so that it is amenable for statistical analysis. Consistent set of data required that the crash data, traffic data, intersection inventory data, videolog data, and the Google Earth data be tied to a common location and thus the need for conflating different datasets. The formatting of the consistent data to make it amenable for statistical analysis required categorizing the data.

4.2.1 Conflating crash history data with traffic volume data

Traffic volume on a roadway is considered to be one of the important factors contributing to road crashes. In order to determine the nature of relationship of traffic volume on crash occurrence, it was, therefore, necessary to conflate the traffic volume dataset with the crash history dataset.

The GIS software and EXCEL VBA program were two of the tools that were used to conflate the traffic volume dataset with the crash history dataset. Simple EXCEL VBA programs were written and were found to be suitable for the purpose.

The traffic volume data in terms of AADT and daily HCV traffic were available in five separate files for five different years corresponding to data years in crash history dataset. Six additional columns were created in crash history data table to include the AADT and daily HCV information for three different years. The AADT and daily HCV traffic were then averaged over five years. Both average AADT and average daily HCV traffic were then reclassified as qualitative values, each having two levels – low and high.

It was found that 84 records in the crash history dataset had true mile/reference post values missing. As a result, traffic volume data for these records could not be found. Similarly, for 187 crash records, traffic volume data in the traffic volume dataset could not be found.

4.2.2 Conflating crash history data with videolog data

As mentioned earlier in this document, the main purpose of videolog data was to identify the right-turn treatment information at an intersection. It was also mentioned that in view of the manual process involved with videolog applications, it was considered not feasible to examine all available crash history data points. Therefore, the subset of total crashes that involved at least one vehicle making a right turn was considered for videolog observations. This subset contained 1,791 data points and still required months of observations.

Whenever the videolog image for a crash location was found, and the movement of the vehicle making a right turn was ascertained using crash records, the right-turn treatment information for the relevant intersection approach would be obtained and entered in the column in the crash history dataset that contained right-turn treatment information. In addition, information related to land use in the vicinity of the crash location was also recorded for possible use in the later stage of the ongoing research.

Another important use of the videolog data was found in verifying the number of lanes of a roadway. If a System road for a crash record was found to have more than two traveled lanes, one each way, the record was eliminated from the dataset.

4.2.3 Conflating crash history data with crash reports

The crash reports provided the only means available to identify the TO-case and FROM-case. It involved manual examination of every relevant crash report. An additional column was created in the crash history dataset to incorporate special comments as provided in the crash reports for quick reference for future use. Of 1,791 crash history data points that involved at least one vehicle making a right turn, 469 records were identified as belonging to the FROM-case and 355 records to the TO-case. 807 records were classified as ‘not relevant’ for a variety of reasons such as signalized intersections, multi-lane/divided roads, crash involving pedestrians, motor cycles, parked vehicles, etc. The TO-/FROM-case for the remaining records could not be identified.

4.2.4 Conflating crash history data with Google Earth data

The role of the Google Earth software was found to be useful when a System road could not be identified using crash reports. Using latitude and longitude information provided in the image/location window of the videolog applications, it was possible to retrieve the image of a crash location using the software. The image would identify a road with both local street name and road number.

Another use of Google Earth was found in the identification of right-turn treatment itself. The software provided the date the image of a location was last updated. So, it was also possible to find out whether the image was taken in the same year when the crash occurred. If that was the case, then the right-turn treatment information would also be obtained whenever the resolution of the image permitted the use of this information at high reliability.

4.2.5 Conflating crash history data with intersection inventory data

The intersection inventory dataset was used to gather information regarding general road environment at the crash locations. It was also used to identify Cross roads whenever a match was found between a crash location in the crash history dataset and an intersection location in the intersection inventory dataset. Not all crashes could, however, be related to intersections in the intersection inventory dataset. This was because the crash history dataset also included the crashes that were identified as alley/driveway crashes or intersection-related crashes.

4.2.6 Consistency issues

As data for the study came from various sources, it was very important that a consistent set of data was maintained. It was also important to realize that the road environment information in the crash history dataset related to the System roads.

It was noted that, sometimes, the image of a crash location retrieved using the information provided in the crash history record would not match with the one retrieved using the information provided in the crash report. In such cases, it became important to look into the comparative degree of reliability of different data sources. The crash report was considered to be having the highest reliability because it included much detailed information regarding the location and nature of crash. Any crash record that could not be considered in the analysis because of missing information or because of not meeting the data requirements was eliminated from the final dataset.

4.2.7 Data categorization

It was felt that classifying crash data that involved at least one right-turning vehicle in terms of TO-case and FROM-case was not sufficient. For example, among FROM-case crashes, some crashes involved collisions between vehicles travelling on the System road, whereas some other involved collisions between vehicles that were travelling on different roads. Similarly, in case of TO-case crashes, some crashes occurred as a result of failure to yield by the vehicles at Cross-road to the System-road vehicle, whereas some other crashes were rear-end crashes at Cross-road that primarily occurred as a result of the inattention of the drivers of following vehicles. Therefore, it was considered that classifying crash as either belonging to TO-case or FROM-case was not sufficient. Instead, it was required to classify crash according to the set of conditions or nature of events when crash occurred. Accordingly, it was decided to classify crash in 13 stacks as shown in Table 4.1.

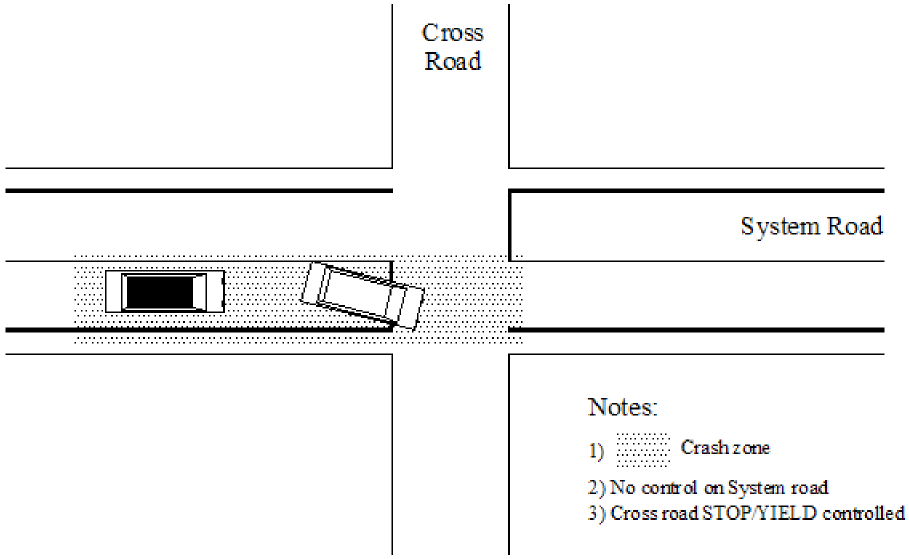
Table 4.1. Classification of crash involving at least one vehicle making a right turn.

Stack	Event/Conditions	Case
1*	Crash involving right-turning vehicles occurred between vehicles travelling on the System-road	FROM
2*	Crash involving right-turning vehicles occurred between vehicles travelling on the System-road and Cross-road	FROM
3*	Crash involving right-turning vehicles resulting from initial left turn indications	FROM
4**	Early/false turn indications by right turning vehicle, failure to yield by the vehicle at Cross-road	-
5	Failure to yield by the right-turning vehicle at Cross-road	TO
6	Opposing hit, failure to yield by the right-turning vehicle at Cross-road	TO
7	Parallel stopping by right-turning vehicles at Cross-road	TO
8	Rear-end crash at Cross-road	TO
9	Vision obstructions by the right-turning vehicle, failure to yield by the vehicle at Cross-road	-
10	Crash due to obscured visibility (as specifically stated in crash reports), failure to yield by the right-turning vehicle at Cross-road	TO
11	Control on the System road	FROM
12	Not relevant (signalized intersection, divided/multi-lane road, parked vehicle, etc.)	-
13	Crash report not available	-

* Further divided into: (a) Crash at intersection, (b) Crash at commercial/public driveway, and (c) Crash at private driveway/field approach

** Further divided into: (i) Early RT signaling, (ii) Early LT signaling, (iii) False RT signaling, and (iv) False LT signaling

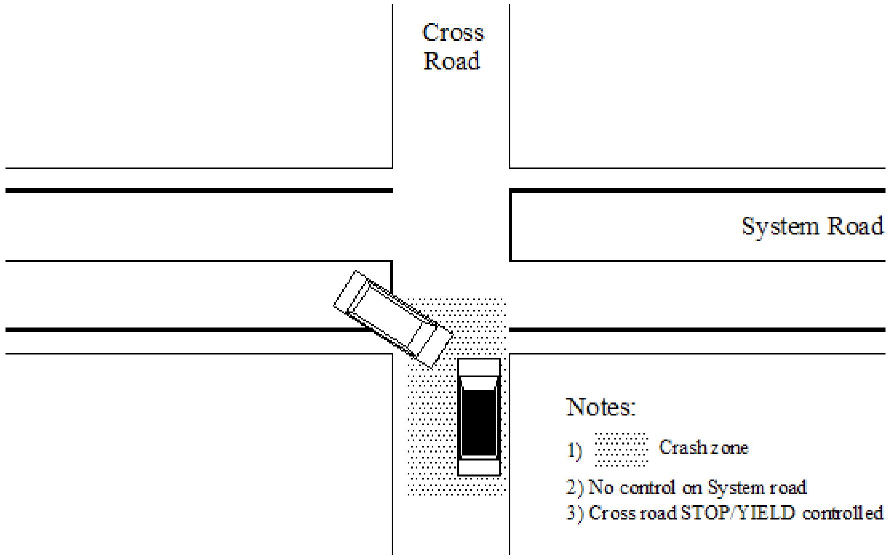
Out of these 13 stacks crash classification considered in this study, following eight stacks were considered relevant for further examinations: stacks 1, 2, 3, 5, 6, 7, 8, and 9. Schematic diagrams for these eight stack crash classifications are shown in Figures 4.6 through 4.13.



Stack 1 classified crash

Crash involving right-turning vehicles occurred between vehicles travelling on the System-road (FROM Case)

Figure 4.6. Stack 1 classified crash.



Stack 2 classified crash

Crash involving right-turning vehicles occurred between vehicles travelling on the System-road and Cross-road (FROM Case)

Figure 4.7. Stack 2 classified crash.

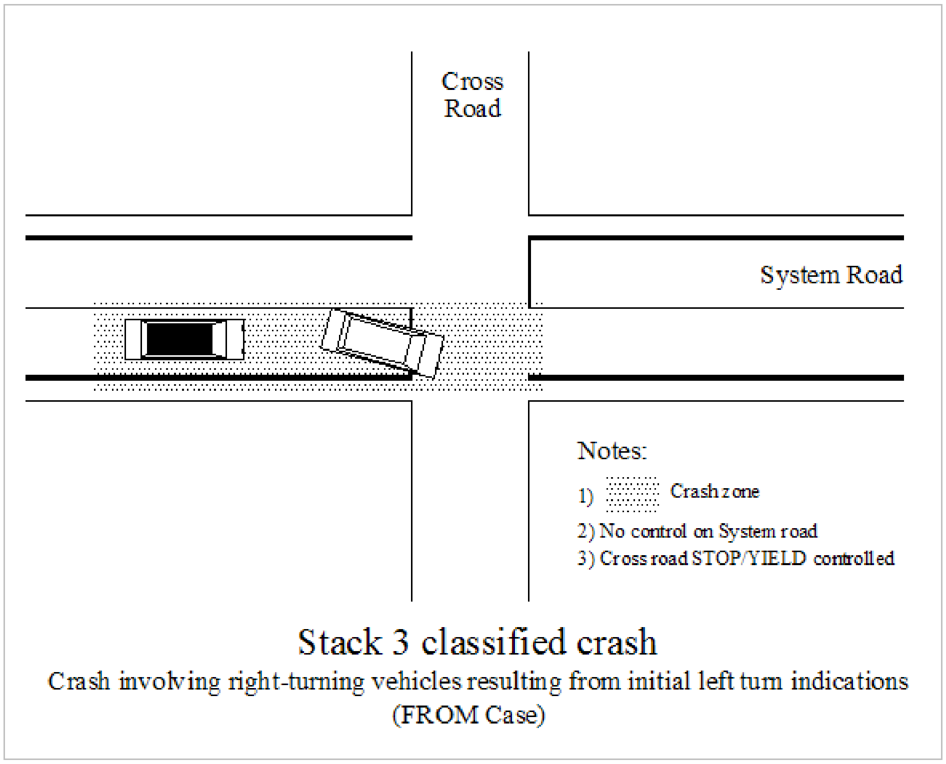


Figure 4.8. Stack 3 classified crash.

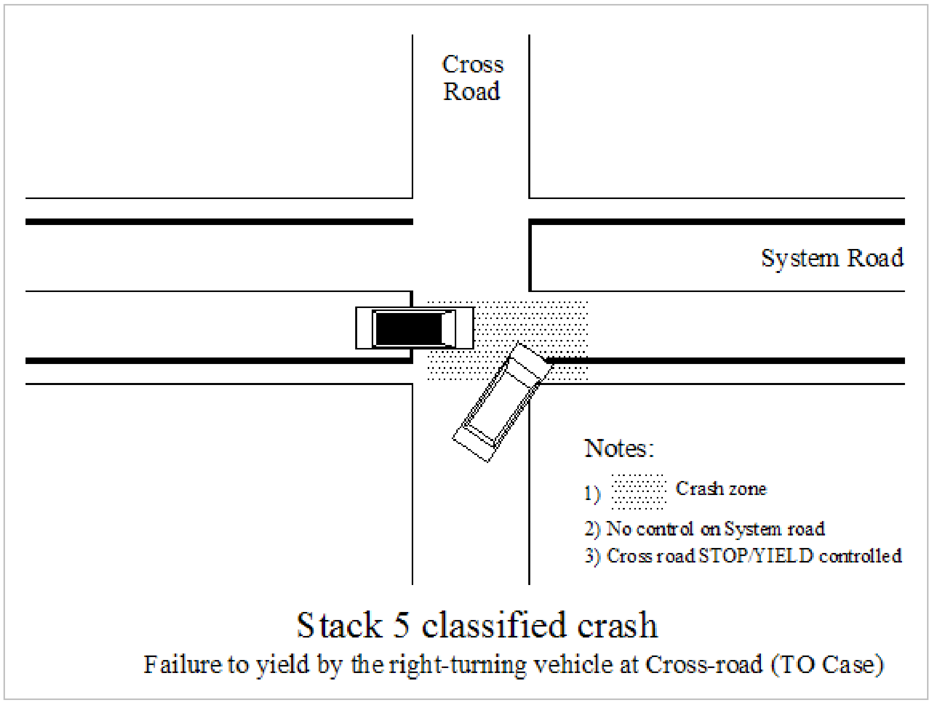


Figure 4.9. Stack 5 classified crash.

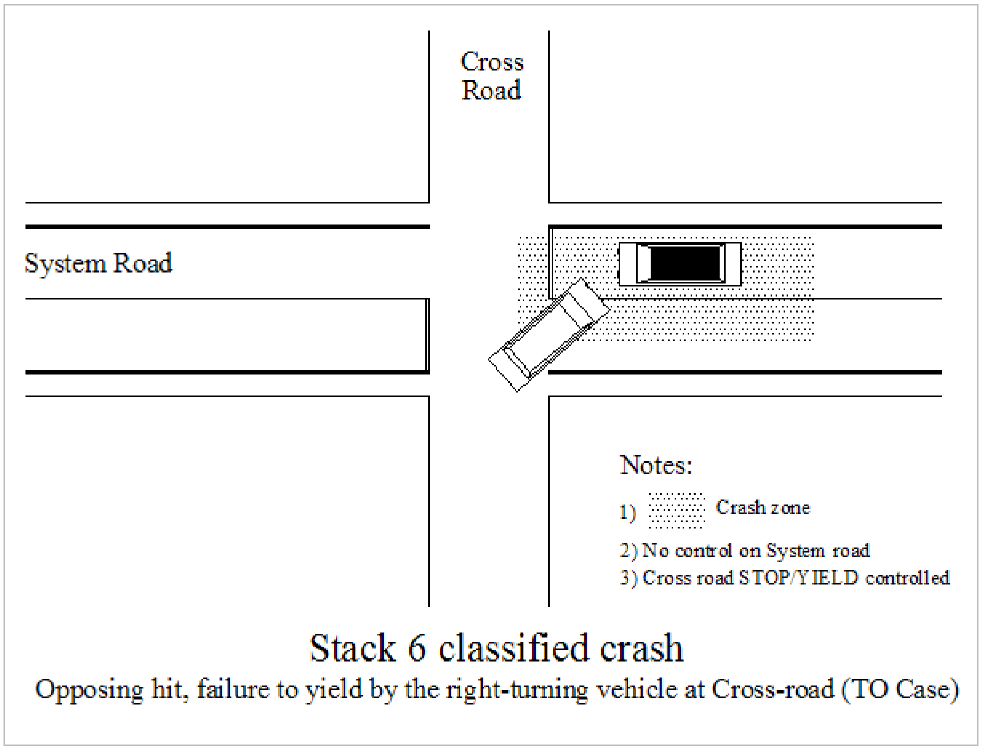


Figure 4.10. Stack 6 classified crash.

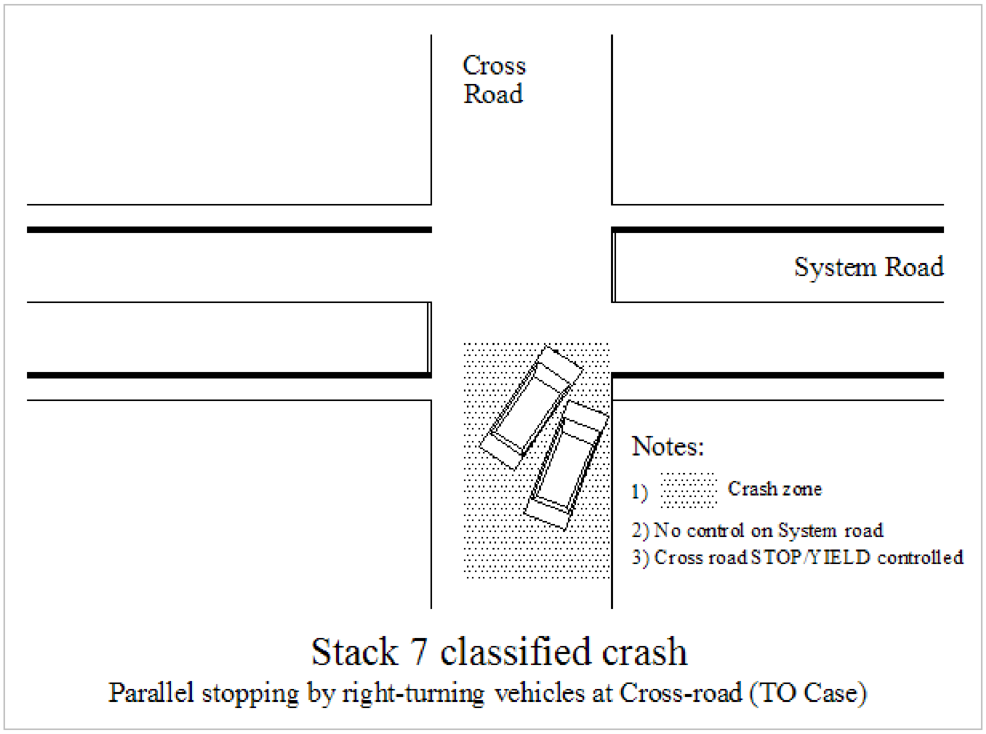
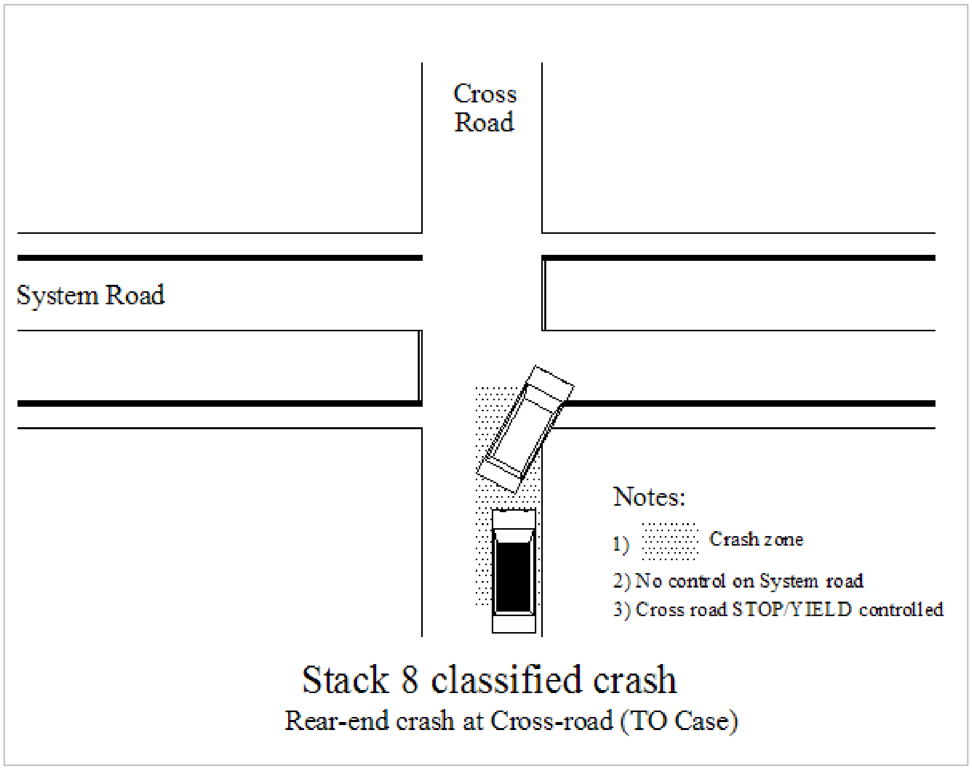


Figure 4.11. Stack 7 classified crash.



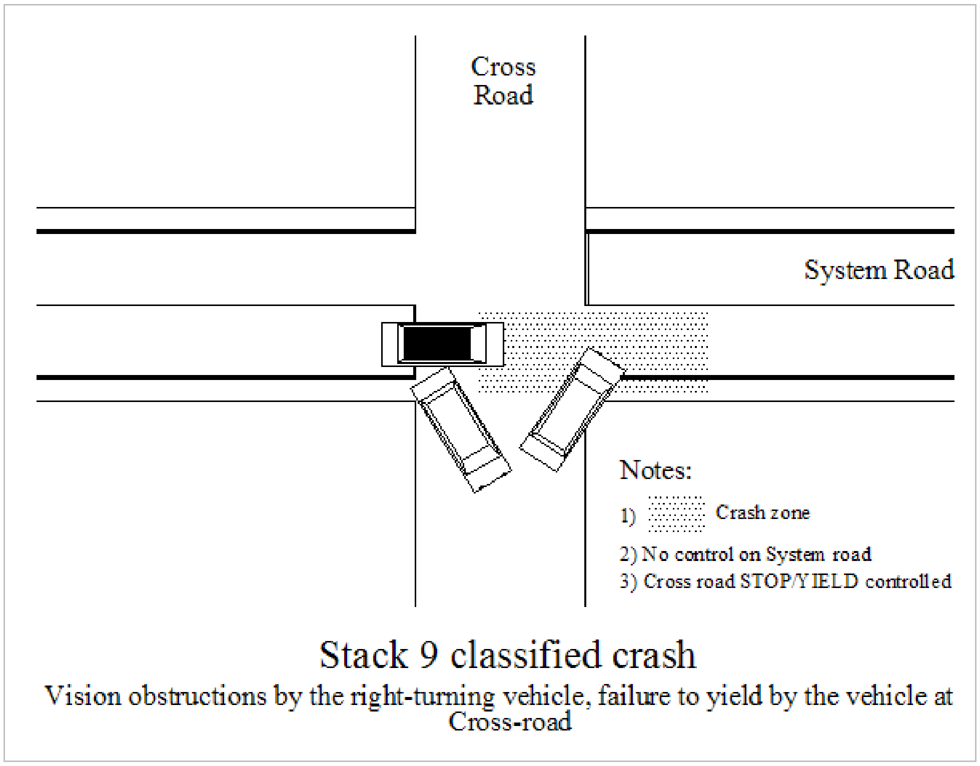
Notes:

1) ▨ Crash zone
2) No control on System road
3) Cross road STOP/YIELD controlled

Stack 8 classified crash

Rear-end crash at Cross-road (TO Case)

Figure 4.12. Stack 8 classified crash.



Notes:

1) ▨ Crash zone
2) No control on System road
3) Cross road STOP/YIELD controlled

Stack 9 classified crash

Vision obstructions by the right-turning vehicle, failure to yield by the vehicle at Cross-road

Figure 4.13. Stack 9 classified crash.

4.2.8 Final dataset

The final dataset was created by conflating the data from different sources with the crash history dataset as mentioned and discussed in the preceding sections. The different data sources included the videolog data, crash reports, intersection inventory data, and the images retrieved through the Google Earth software. Officials from Mn/DOT also helped in reviewing the reduced data. Their observations were especially crucial with regard to the right-turn treatment information and the number of lane on the roadways.

In summary, the finally reduced datasets included the following four separate datasets:

- Total crash history dataset including 10,235 data points;
- Crash dataset consisting of 824 data points that included crashes involving at least one vehicle making a right turn (subset of total crashes);
- Crash dataset consisting of 469 data points that were identified as belonging to the FROM-case (subset of crashes that involved at least one vehicle making a right turn); and
- Crash dataset consisting of 355 data points that were identified as belonging to TO-case category (subset of crashes that involved at least one vehicle making a right turn).

It is to be noted that the right-turn treatment information could be obtained only for those crashes that were identified as belonging to the FROM-case. Therefore, whenever an analysis considered right-turn treatment as one of the variables in the study, it follows that the data for the analysis were drawn from the FROM-case subset. Moreover, it was also found that all identified right-turn treatments belonged to either the shared type or exclusive type. Therefore, as far as right-turn treatments are concerned, the study made distinctions only in terms of the shared and exclusive right-turn treatment types. A summary of crash involving at least one vehicle making a right turn is presented in Table 4.2.

Table 4.2. Summary of crash involving at least one vehicle making a right turn.

Stack		Case	Year					Sub Total	Total
			2000	2001	2002	2004	2005		
1	a*	From	40	57	23	32	34	186	344
	b		16	9	20	13	21	79	
	c		13	18	11	20	17	79	
2	a	From	22	18	15	12	18	85	91
	b		0	2	1	1	1	5	
	c		0	1	0	0	0	1	
3	a	From	7	6	2	7	3	25	34
	b		1	0	0	0	1	2	
	c		2	1	3	0	1	7	
4	(i)**	-	1	5	5	4	1	16	355
	(ii)		1	0	0	0	0	1	
	(iii)		1	1	1	2	1	6	
	(iv)		0	0	0	0	0	0	
5		To	25	33	29	17	23	127	
6		To	9	10	2	7	4	32	
7		To	21	27	15	16	10	89	
8		To	10	14	8	14	3	49	
9		-	1	1	8	2	1	13	
10		To	4	7	0	5	6	22	
11		From	7	7	3	4	2	23	23
12		Not relevant	137	132	119	198	198	784	784
13		No CR	67	28	61	3	1	160	160
Total			**385**	**377**	**326**	**357**	**346**	**1791**	**1791**

* (a) Crash at intersection, (b) Crash at commercial/public driveway, and (c) Crash at private driveway/field approach

** (i) Early RT signaling, (ii) Early LT signaling, (iii) False RT signaling, and (iv) False LT signaling

Next several sections describe design of experiment for analysis of crash data.

4.3 Explanatory factors

Fifteen explanatory factors from the available dataset were determined to be relevant for crash analysis for potential association with crash occurrence as contributing factors. These factors were provided with categorical values. If any factor had quantitative values, the values were converted into categorical values. The levels of values for each of these factors were kept at a minimum as far as possible. A brief description on each of these factors is presented in the sections that follow.

4.3.1 Day of week

Traffic volume varies significantly over the days of a week, especially between weekdays and weekends. Therefore, in order to determine the potential relationship with crash occurrence, days of a week were included in the analysis as explanatory factors with two levels of values as follows: (1) weekdays and (2) weekends. Monday through Thursday were categorized as weekdays while the remaining days were considered as weekends.

4.3.2 Time of day

As with days of a week, traffic volume also varies considerably over the time of a day. Accordingly, the time of a day was also considered to be one of the explanatory factors for further analysis with the following two levels of values: (1) day and (2) night. For the purpose of this study, the time period from 7:00 AM to 6:00 PM was considered daytime. Any time beyond this range was considered nighttime.

4.3.3 Posted speed limit

The posted speed limits of roadways were available as quantitative values in the crash history dataset. Therefore, the speed limit values were reclassified as the categorical values with two levels as shown in Table 4.3.

Table 4.3. Posted speed limit of a roadway.

Posted Speed Limit of a Roadway	Category
Less than or equal to 40 mph	Low
More than 40 mph	High

mph = mile per hour.

4.3.4 Light conditions

The crash history dataset included the information on the light conditions on a roadway at the time of the crash. The light conditions were divided into three levels of values as shown in Table 4.4.

Table 4.4. Light conditions on roadways.

Light conditions at the time of crash	Category
Daylight	Daylight
Sunrise	Some light
Sunset	Some light
Dark - street lights on	Some light
Dark - street lights off	No light
Dark - no street lights	No light
Dark - unknown lighting	No light

4.3.5 Weather conditions

Weather conditions at the time of crash were considered as explanatory factors. The three levels of values considered for weather conditions are shown in Table 4.5.

Table 4.5. Weather conditions at the time of a crash.

Weather conditions at the time of crash	**Category**
Clear	Clear
Cloudy	Somewhat clear
Rain	Not clear
Snow	Not clear
Sleet, hail, or freezing rain	Not clear
Fog, smog, or smoke	Not clear
Blowing sand, dust or snow	Not clear
Severe cross winds	Not clear

4.3.6 Road surface conditions

Road surface conditions are considered to be important factors affecting crash occurrences. The road surface conditions at the time of crash were classified into two levels of values as shown in Table 4.6.

Table 4.6. Road surface conditions at the time of a crash.

Surface conditions at the time of crash	**Category**
Dry	Dry
Wet	Wet & Slippery
Slush	Wet & Slippery
Water (standing, moving)	Wet & Slippery
Muddy	Wet & Slippery
Snow	Wet & Slippery
Ice / packed snow	Wet & Slippery
Debris	Wet & Slippery
Oily	Wet & Slippery

4.3.7 Road character

The type of road geometry at a crash location was included in the analysis as an explanatory factor to determine its association with a crash. The variable has four levels of values as shown in Table 4.7.

Table 4.7. Road character at a crash location.

Road character at crash location	Category
Straight and level	Straight & level
Straight and grade	Straight & grade
Straight at hillcrest	Straight & grade
Straight in sag	Straight & grade
Curve and level	Curve & level
Curve and grade	Curve & grade
Curve at hillcrest	Curve & grade
Curve in sag	Curve & grade

4.3.8 Traffic volume

The numerical values of traffic volume were reclassified with three levels of the categorical values as presented in Table 4.8. The traffic volume obtained for the study included the total volume for both directions of a roadway. The traffic volume used in the analysis was the average of five years from 2000 to 2002, and 2004-2005.

Table 4.8. Traffic volume.

Traffic Volume (AADT)	Category
Less than or equal to 10,000 vpd	Low
More than 10,000 vpd	High

vph = vehicle per day.

4.3.9 Heavy commercial vehicle traffic

The daily heavy commercial vehicle (HCV) expressed as the percentage of AADT was considered an explanatory factor. The average of daily heavy commercial vehicle traffic for five years from 2000 to 2002, and 2004 to 2005 was considered for analysis. The numerical values of the variable were then categorized into two levels of values as shown in the Table 4.9.

Table 4.9. Percentage of heavy commercial vehicles.

Percentage of Heavy Commercial Vehicle	Category
Less than or equal to 10%	Low
More than 10%	High

4.3.10 Driver error

The crash history data included up to two probable causes leading to the crash for each vehicle involved in a crash. The causes listed for the first two vehicles in the crash history data were considered for analysis. So, for one crash, up to four causes could be identified. Each of these causes was classified as belonging to one of the following category of explanatory factors: (1) driver error, (2) driver inattention, (3) vehicular defects, and (4) obscured visibility.

Each of these explanatory factors was considered with two levels of values – YES and NO. If a cause categorized as driver error was indicated for a crash in the crash history data, then the categorical value YES would be entered as the value for the explanatory factor 'driver error', otherwise the value NO would be entered.

The following were considered driver error: (1) failure to yield right of way; (2) illegal or unsafe speed; (3) following too closely; (4) disregard of traffic control device; (5) driving left of roadway center – not passing; (6) improper passing or overtaking; (7) improper or unsafe lane use; (8) improper parking, starting, or stopping; (9) improper turn; (10) unsafe backing; (11) no signal or improper signal; (12) over-correcting; (13) driver inexperience; (14) chemical impairment; and (15) failure to use lights.

4.3.11 Driver inattention

In addition to the driver error, the driver inattention was also included in the analysis as an explanatory factor. The following causes indicated for a crash in the crash history dataset were classified as driver inattention: (1) driver inattention or distraction and (2) driver on car phone, cb, or two-way radio.

4.3.12 Vehicular defects

The vehicular defects included the following causes associated with a crash in crash history data: (1) defective brakes, (2) defective tire or tire failure, (3) defective lights, (4) inadequate windshield glass, (5) oversize or overweight vehicle, and (6) other vehicle defects or factors.

4.3.13 Obscured visibility

The visibility is one of the important factors in any road crash analysis. The following causes indicated for a crash in the crash history dataset were considered as obscured visibility: (1) vision obscured – windshield glass, (2) vision obscured – sun or headlights, and (3) vision obscured – other.

4.3.14 Driver error or driver inattention

An additional explanatory factor–driver error or driver inattention–was created by combining driver error and driver inattention variables discussed in the preceding sections. Though driver inattention could be thought of as arising out of carelessness rather than error in judgment, and may form a special class of variable in itself, it basically constitutes an instance of driver error.

4.3.15 Right-turn treatments

It was found that a right-turn treatment at a crash location would either be a shared type or an exclusive type. No crash event was found in crash history dataset that occurred at an intersection approach with taper or offset right-turn treatments. Therefore, the explanatory factor, right-turn treatment type, included the flowing two levels of values: (1) shared right-turn treatment and (2) exclusive right-turn treatment.

4.3.16 Type of intersecting road

This explanatory factor was used only in case of models that used crash history data from FROM-case. The type of intersecting road was indentified in terms of roadway, private driveway or commercial driveway.

4.3.17 Intersection type

The intersection type explanatory factor was used as a broad classification of intersection in terms of roadway intersection or driveway intersection. The reason for this classification was whereas the type of driveway as private or commercial driveway could be identified for FROM-case crash using crash reports, the identification of the same was not possible for the entire crash history data.

4.3.18 Involvement of tractor-trailer combination in crash

The involvement of a tractor-trailer combination in a crash was also used as an explanatory factor. The involvement of a tractor-trailer in a crash event was dentified with ‘Yes’ or ‘No’ values.

4.3.19 Crash type

The crash type was used as an explanatory factor for the severity model. The levels of values used were rear-end, sideswipe (same direction), right-angle, right-turn, and other crash type. The reason for using only four distinct crash types, and grouping all other crashes into other category was that these four types of crash constituted more than 90% of all crashes that involved vehicles turning right as presented in exploratory analysis section of this report.

4.4 Generalized/basic models

A total of eleven logistic regression models were fitted using the crash history data. Ten models were fitted using binary logistic regression methods; five models for FROM-case and five for TO-case crash history data. The crash severity model was developed using multivariable multimonial logistic regression method. Two sets of data were used to fit the models. The two datasets included the following:

- Total crash history data points,
- The subset of crashes that included only the FROM-cases, and
- The subset of crashes that included only the TO-cases.

In general, the models were of the forms as presented in Chapter 3 where the desired outcome event Y = 1 was the crash/crash-type that was of interest. Explanatory factors included factors described in the preceding sections including up to three-way interaction terms.

In this study, crash history dataset consisted of several variables that were mostly provided with categorical values. The dependent variables were designed in terms of two events: crash meeting certain criteria occurred (Y=1) or it did not occur (Y=0). In such cases, binary logistic regression model is an appropriate approach to determine the influence of different explanatory factors on the occurrence of crashes. On the other hand, in order to estimate and identify the significant factors contributing to different levels of severity, multinomial logistic regression models are appropriate as the dependent variable (severity) had more than two classes.

The models, in this study, were developed and analyzed using SAS 9.1 software. Most of the binary regression models were related to those types of crashes where at least one right-turning vehicle was involved. Since the model included many predictors, the stepwise selection procedure was used to include significant factors in the model. This selection procedure starts with no predictors in the model. It examines each predictor that could possibly be added in the model and then adds the most significant predictor. In the next stage, the procedure adds the next most significant predictor. It then checks to see if any of the previously included predictors have now become insignificant. If that is case, then it removes that predictor. The procedure continues until there are no further significant predictors to add into the model.

4.5 Design variables

Design variables (or dummy variables) are used to represent the various levels of nominal scale variables. These variables are merely identifiers and have no numeric significance. There are two methods to code design variables: reference cell coding (reference coding in SAS) and deviation from means coding (effect coding in SAS). In reference cell coding, the design variables take the value of 0 or 1. The reference group has all the design variables set to 0, whereas the other groups have a single design variable equal to 1. In deviation from means coding, design variables are set equal to -1 for one of the categories, whereas the remainder of the categories take the value of 0 or 1.

In this study, reference cell coding was used because it was easier to interpret than deviation from means coding. The reference coding scheme used for explanatory factors in model development is shown in Table 4.10. The levels of values for explanatory

Table 4.10. Explanatory factors and design variables used in model development.

Sl.	Explanatory Factors	Levels	Design Variables		
1)	DTYPE	Weekend	1		
	(Day of week)	Weekday	0		
2)	DTIME	Night	1		
	(Time of day)	Day	0		
3)	SPEED	High	1		
	(Posted speed limit)	Low	0		
4)	LIGHT	No light	1	0	
	(Light conditions)	Some light	0	1	
		Daylight	0	0	
5)	WETHR	Not clear	1	0	
	(Weather conditions)	Somewhat clear	0	1	
		Clear	0	0	
6)	SURFC	Wet & slippery	1		
	(Road surface conditions)	Dry	0		
7)	RDCHR	Curve & grade	1	0	0
	(Road character)	Curve & level	0	1	0
		Straight & grade	0	0	1
		Straight & level	0	0	0
8)	AADTC	High	1		
	(Traffic volume as AADT)	Low	0		
9)	HCVPR	High	1		
	(Volume of heavy commercial vehicle)	Low	0		
10)	DRERR	Yes	1		
	(Driver error)	No	0		
11)	INATT	Yes	1		
	(Driver inattention)	No	0		
12)	VHDEF	Yes	1		
	(Vehicular defects)	No	0		
13)	VISON	Yes	1		
	(Obstructed visibility)	No	0		
14)	DRENI	Yes	1		
	(Driver error, or driver inattention)	No	0		

Table 4.10. (Continued)

15)	RTTRT (Right turn treatment)	Shared	1			
		Exclusive	0			
16)	DRWAY (Intersection type, From-case only)	Commercial driveway	1	0		
		Private driveway	0	1		
		Roadway*	0	0		
17)	JUNCT (Intersection type)	Driveways	1			
		Intersection*	0			
18)	TTCMB (Involved truck-trailer combination)	Yes	1			
		No	0			
19)	CRASHTYPE (Type of crash)	Rear-end	1	0	0	0
		Sideswipe (same dir.)	0	1	0	0
		Right-angle	0	0	1	0
		Right-turn	0	0	0	1
		Other	0	0	0	0

factors were kept as small, within the range of meaningful interpretation, as possible to avoid convergence problems in the regression models.

4.6 Model assessment

The appropriateness of the fitted models was checked using two widely used goodness-of-fit tests: Hosmer-Lemeshow test and Pearson test. The null hypothesis in these tests was: model fitted the data. The alternative hypothesis was: model did not fit the data. The significance level used for hypothesis testing was 0.05. In addition, three different logistic regression diagnostics were also considered to visually assess the fitted models.

Next several sections discuss analysis of crash data and results.

4.7 Exploratory analysis

Exploratory analysis provides a basis for objective analysis to find patterns in the data that are not predicted by the researcher's current knowledge or pre-conceptions. To get an idea of the nature, patterns and extents of crashes, exploratory analyses were carried out using different variables. Two sets of crash data were used for the exploratory analysis:

- Total crash set and
- Subset of crashes that involved at least one vehicle making a right turn from a System road.

The sub-sections that follow discuss briefly the results of the exploratory analysis.

4.7.1 Total crash set

The total crash set containing all 10,235 crash history data points was used in order to understand the general crash patterns. Figure 4.14 shows the crash share by daytime and nighttime. It is observed that about 85% of the total crashes took place during daytime, which is understandable as traffic volume would be significantly high during daytime as compared to nighttime.

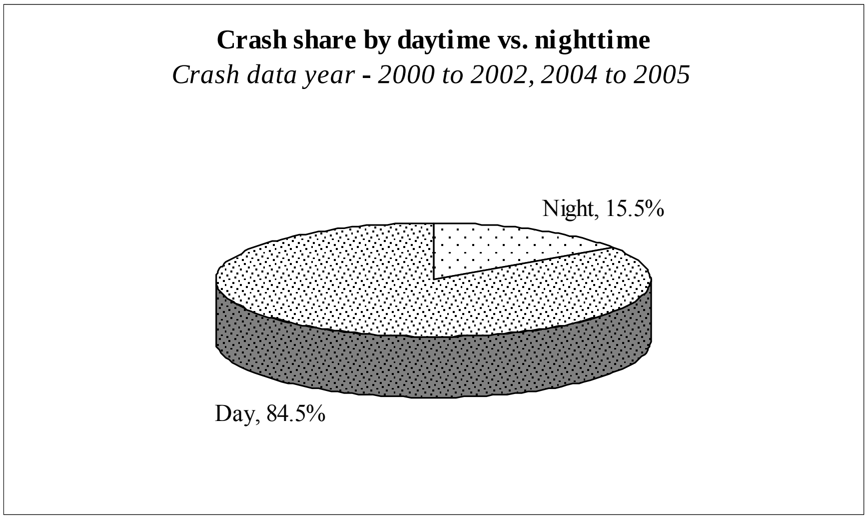


Figure 4.14. Crash share by daytime/nighttime.

However, if we look at the pattern of crashes by time over a day, it is observed from Figure 4.15 that most of the crashes took place during afternoon peaks when roadways would be the busiest. This indicates traffic volume, in fact, influenced crash occurrences.

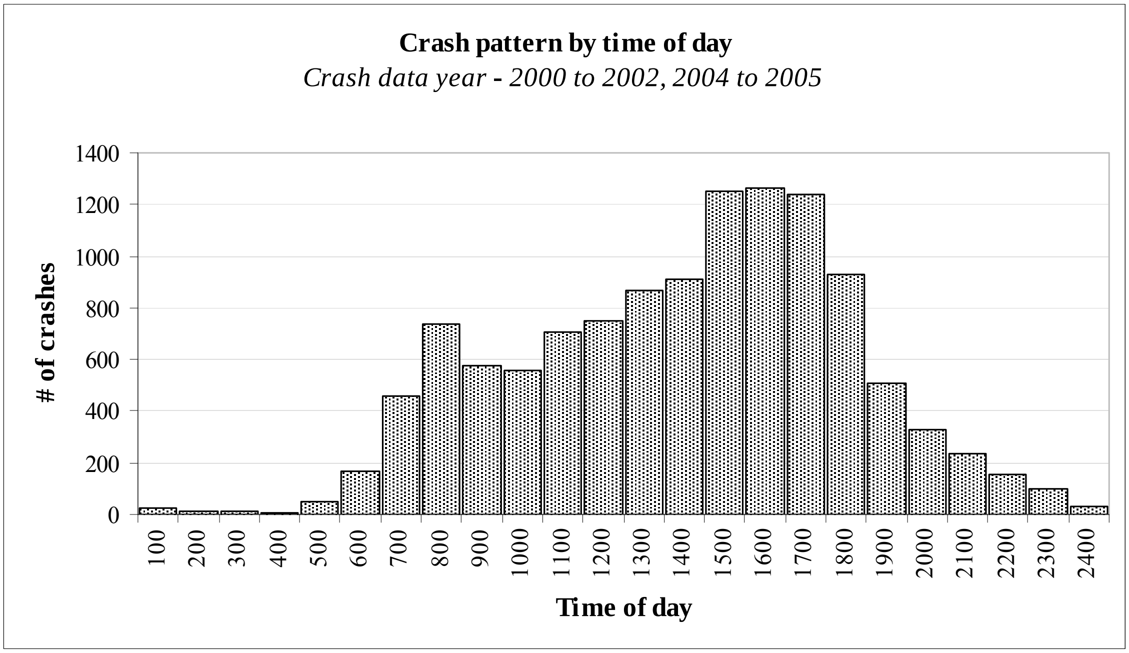


Figure 4.15. Crash pattern by time of day.

Crash share by days of week are shown in Figures 4.16 and 4.17. In Figure 4.16, it is observed that about 60% of the crashes took place during weekdays. When the frequencies of crashes were plotted against the days of a week as shown in Figure 4.17, it was observed that Fridays are relatively more dangerous than other days.

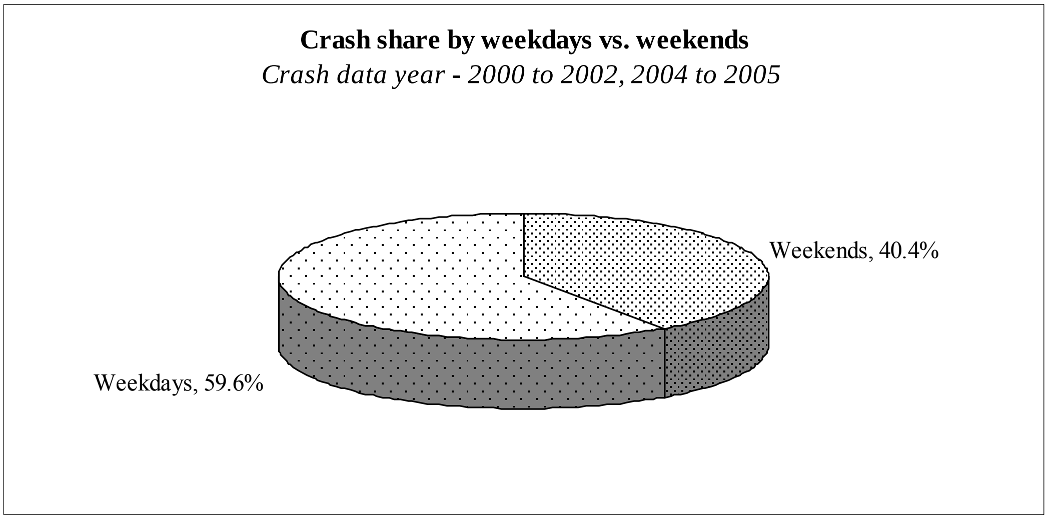


Figure 4.16. Crash share by weekdays/weekends.

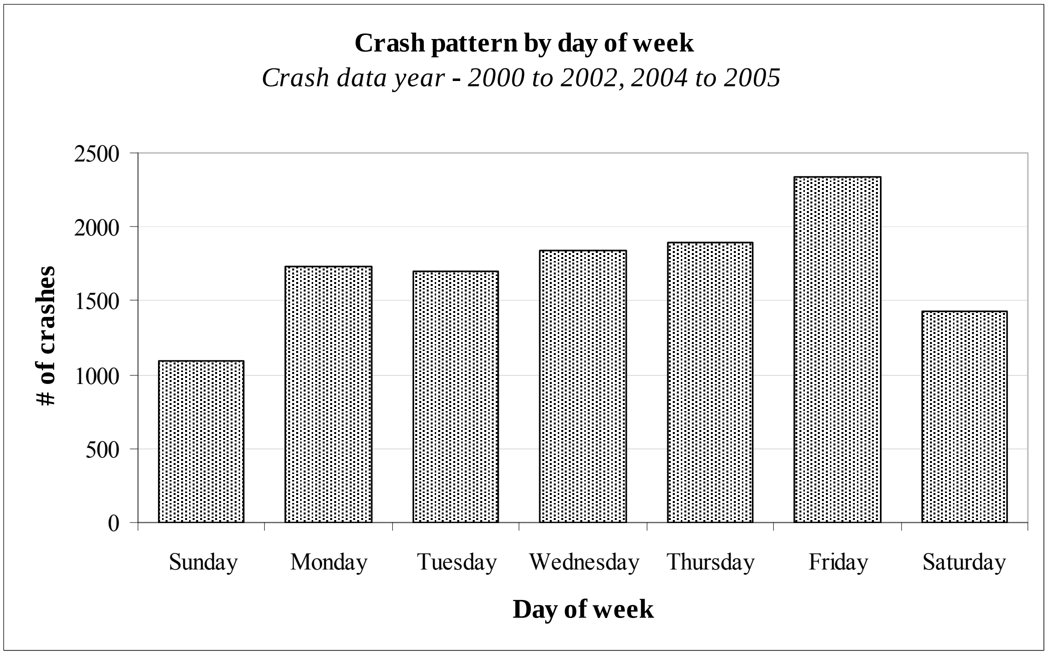


Figure 4.17. Crash pattern by day of week.

Crash pattern by date of a month is shown in Figure 4.18. The plot clearly reveals four peaks, which may seem to indicate some kind of associations of crash occurrence with four weeks in a month. However, it should be noted that a particular date of a month does not necessarily fall on the same day of a week. Figure 4.19 shows the crash frequency during different months in a year. It is observed from the figure that February to March are relatively safer months compared to others.

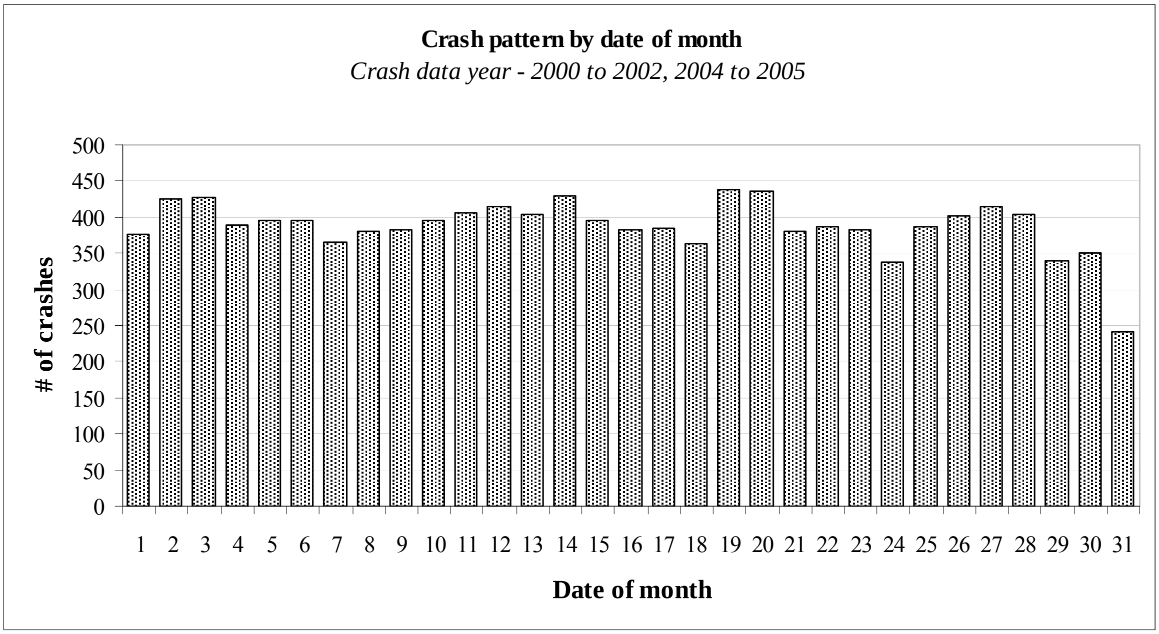


Figure 4.18. Crash pattern by date of month.

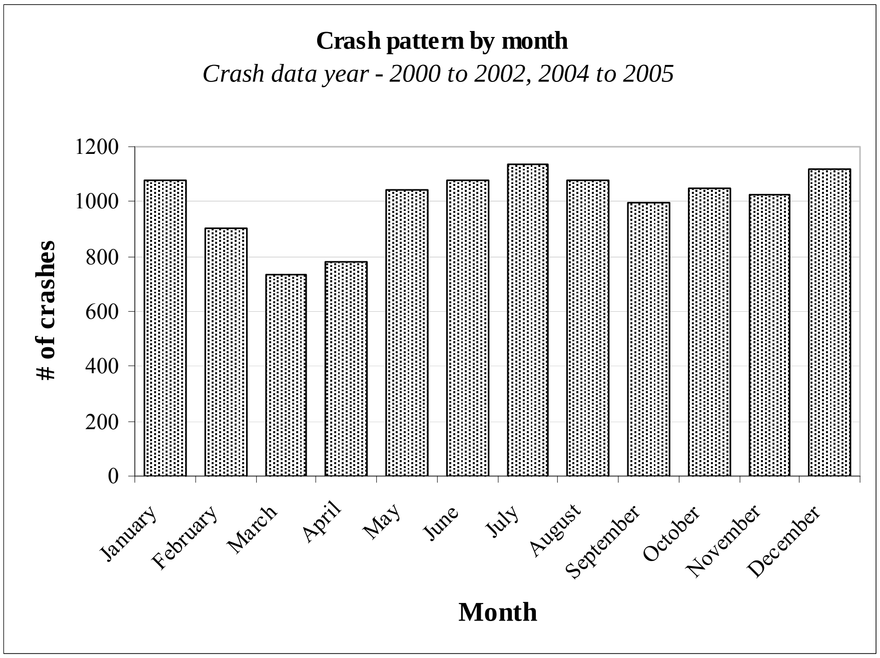


Figure 4.19. Crash pattern by month.

In terms of crash severity, Figures 4.20 and 4.21 show that 60% of crashes resulted in property damage with no apparent injury. The crashes that resulted in injury (incapacitating and non-incapacitating) and possible injury were about 16% and 23%, respectively, whereas about 1.5% of the crashes resulted in fatalities.

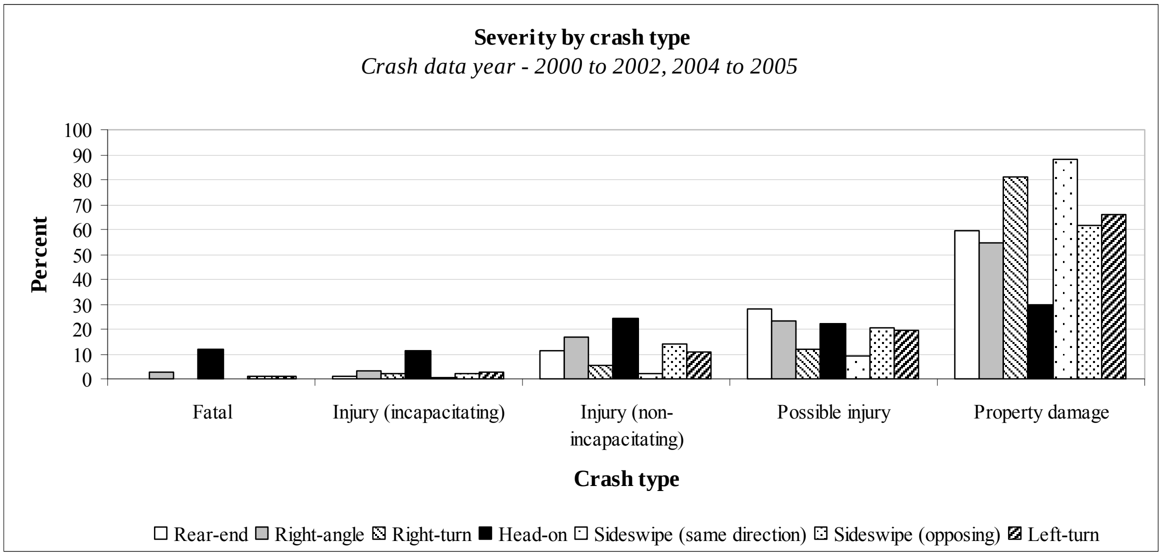


Figure 4.20. Severity by crash type.

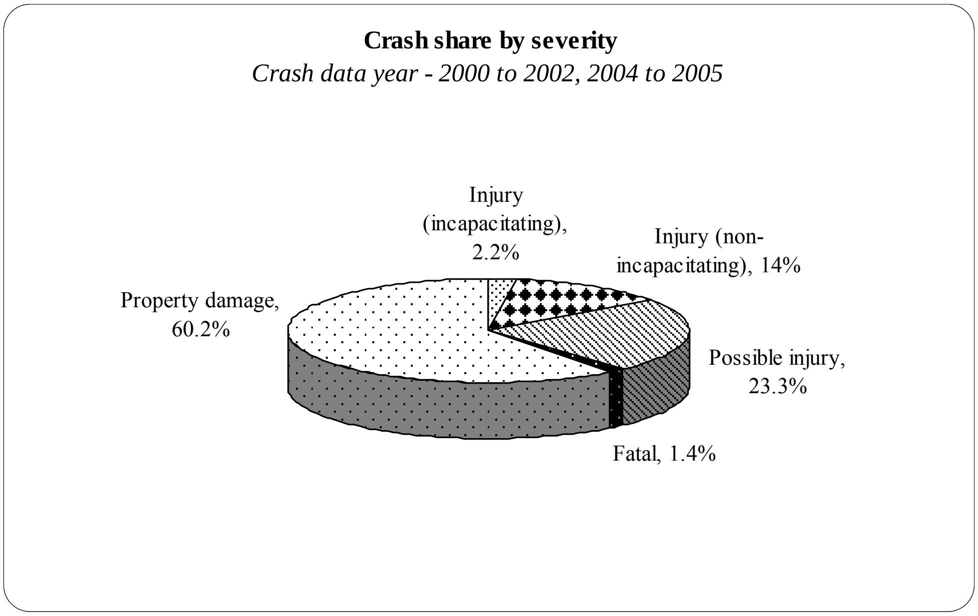


Figure 4.21. Crash share by severity.

As far as crash pattern by crash type is concerned, Figure 4.22 shows that the most common type of crash was the rear-end type, accounting for about 39% of the total crashes. Closely following rear-end crashes in terms of frequency was the right-angle crashes with 34% share in the total crashes. It is also seen from the figure that four crash types, namely, rear-end, right-angle, left-turn, and the sideswipe (same-direction) accounted for about 85% of the total crashes. These crash types also peaked around the same time period during afternoon peaks as shown in Figure 4.23.

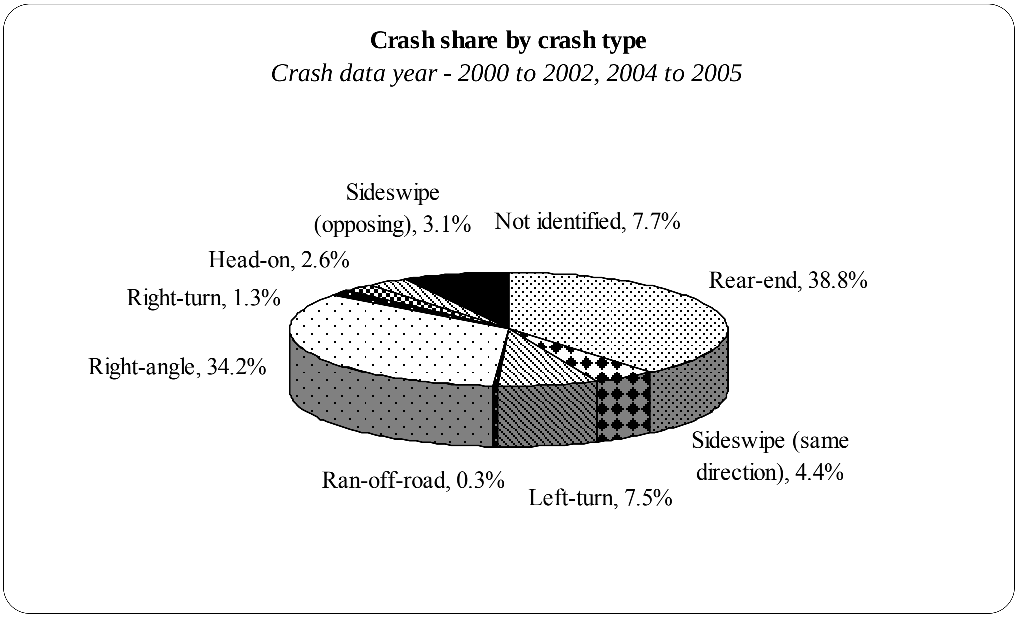


Figure 4.22. Crash share by crash type.

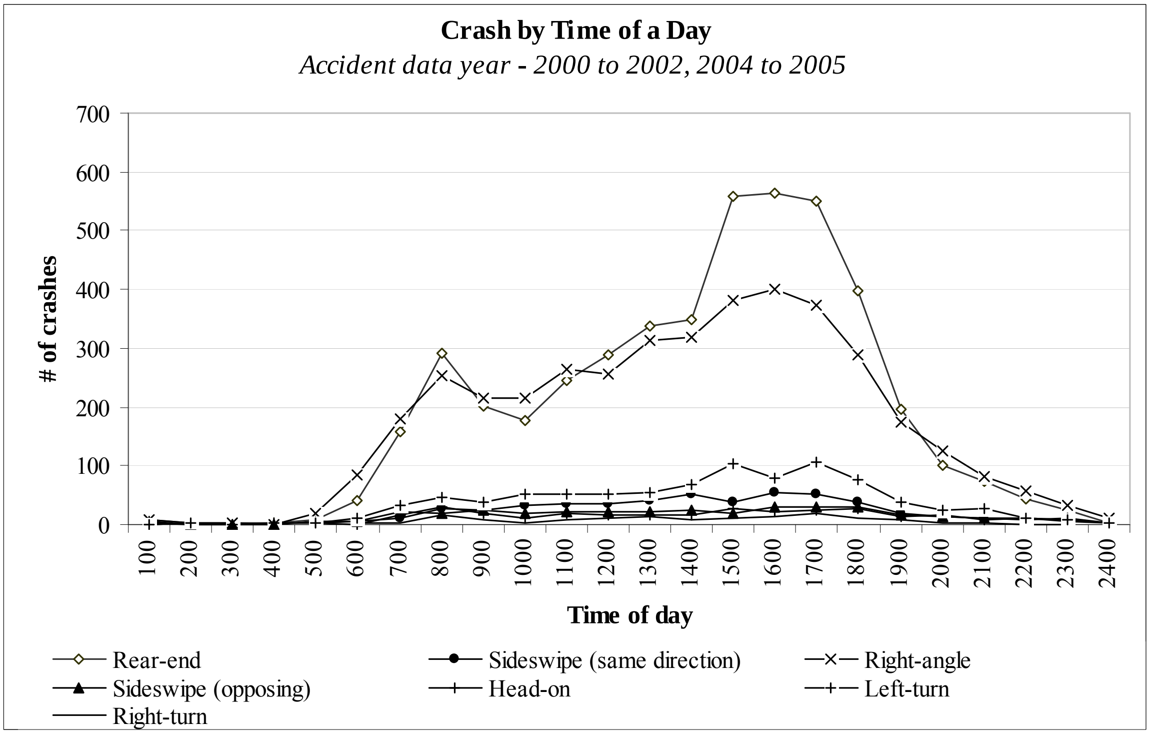


Figure 4.23. Crash pattern of various crash types by time of day.

Crash share by posted speed limits of roadways is shown in Figure 4.24. It is observed in the figure that most crashes took place when the posted speed limit of the roadways was either 30 mph (30%) or 55 mph (48%). This is possibly due to the facts that roadways usually have posted speed limits of 30 mph or 55 mph. If we divide the speed regime into two parts–low (40 mph or less, typical in urban areas) and high (more than 40 mph, typical in rural areas)–we observe from the figure that about an equal number of crashes occurred in low and high speed regimes, or urban and rural environments.

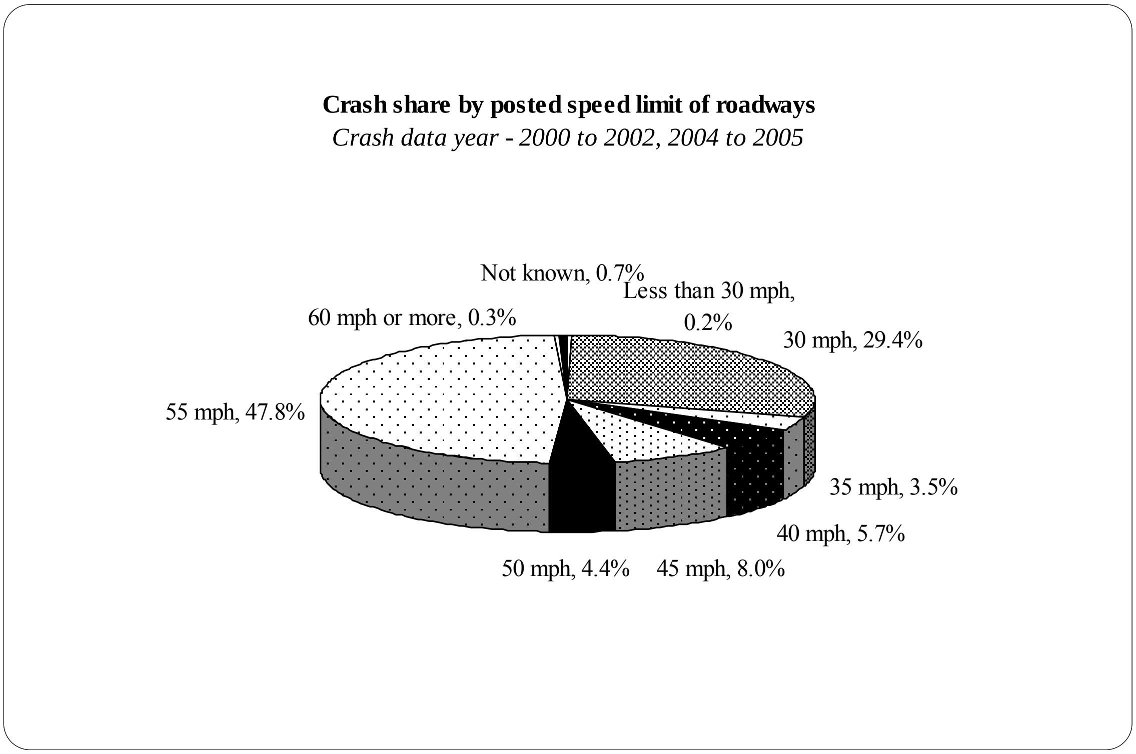


Figure 4.24. Crash share by posted speed limit of roadways.

4.7.2 Subset of crashes involving at least one vehicle making a right turn from a system road

Exploratory analyses were also carried out to determine the crash patterns when a crash at least involved one vehicle making a right turn from a System road. The relevant crash dataset included 469 crash data points out of the total crashes of 10,235. This meant that the prevalence of crashes that involved at least one vehicle making a right turn from a System road was about 5% of total crashes.

Figure 4.25 presents the crash share by different crash types. It is observed in the figure that four crash types, namely, the rear-end, sideswipe (same-direction), right-angle, and the right-turn, constituted about 81% of the total crashes. However, when the crashes labeled ‘not identified’ was not included in the estimates, it was found that these four types of crashes constituted more than 93% of the total crashes as shown in Figure 4.26. From these observations, it may be concluded that the crashes involving at least one vehicle making a right turn from a System road (major road) may be analyzed in terms of rear-end, sideswipe (same-direction), right-angle, and the right-turn crashes.

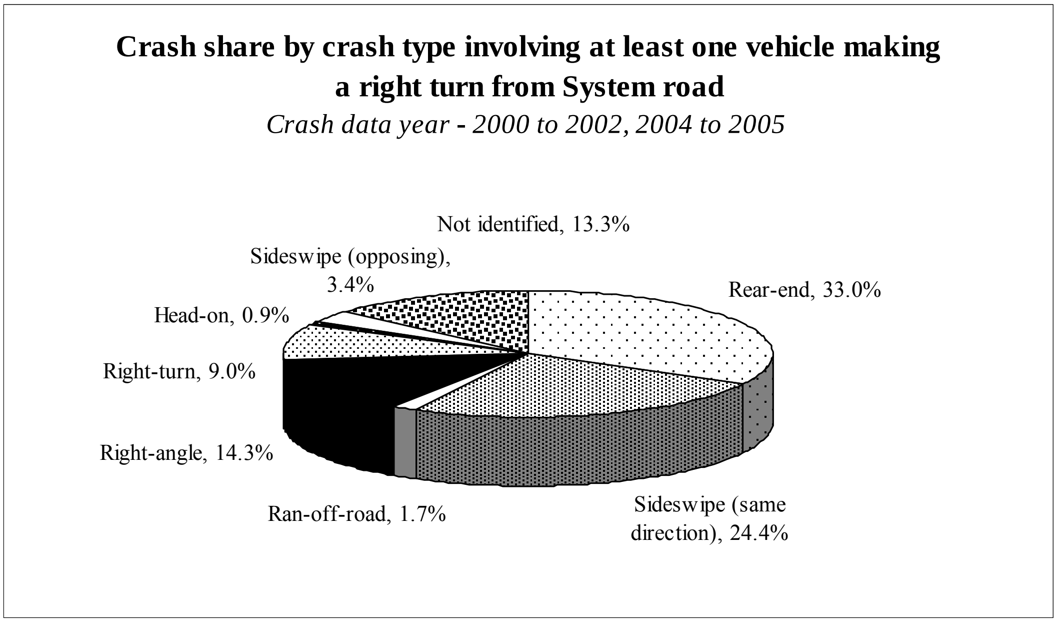


Figure 4.25. Crash share by crash type, given that the crash involved at least one vehicle making a right turn.

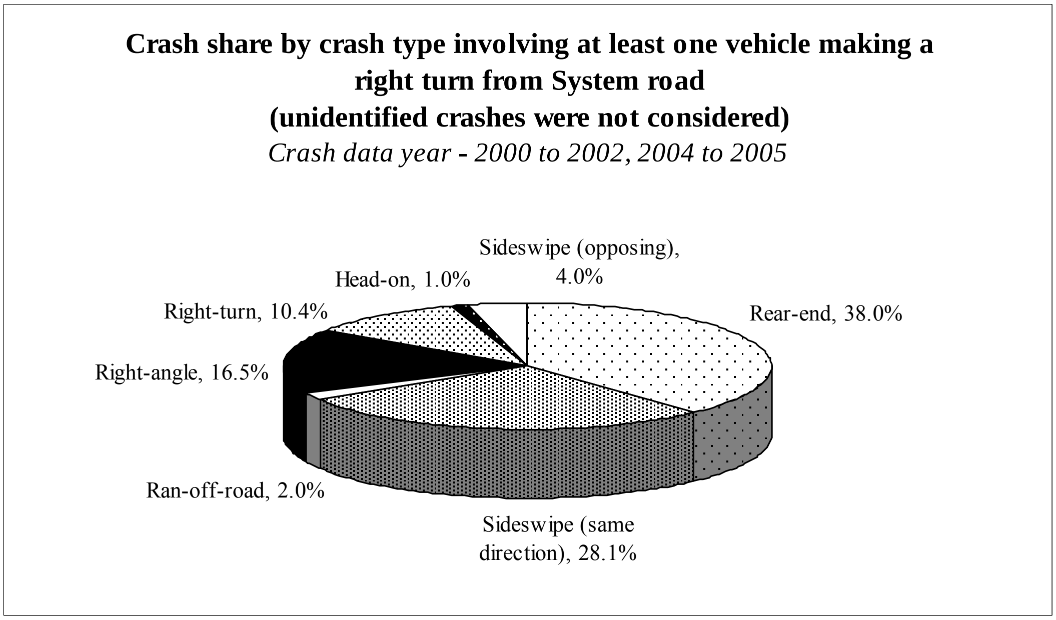


Figure 4.26. Crash share by crash type, considering only crashes with identified crash types, given that the crash involved at least one vehicle making a right turn.

In the course of right-turn treatment identification process, it was found from the information in the crash reports that when a crash involved a truck-trailer combination, about 60% of the crashes were of the type sideswipe (same-direction). Generally, in such crashes, semi trailer would move to the leftmost portion of the traveled lane to acquire a larger turn radius required for the right-turn movement. This maneuver of the semi trailer would lead the driver of a following vehicle to think that the semi trailer wanted to make a left-turn even though the right-turn indicator on the semi trailer was on. The following vehicle would then pull to the right side of the semi trailer, resulting in a same-direction sideswipe collision as shown in Figure 4.27.

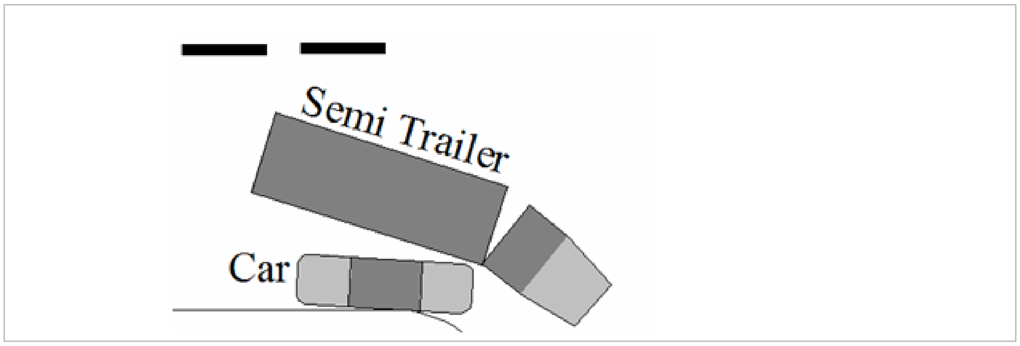


Figure 4.27. Same direction sideswipe crash with a right-turning semi trailer.

4.8 Basic form of individual models

The logistic regression models were developed in the study employing SAS 9.1 software. The SAS procedure PROC LOGISTIC was used for the purpose. Ultimately, a total of eleven logistic regression models were developed in the study.

Five different binary logistic regression models were developed to determine the significant factors associated with the crashes involving at least one vehicle making a right turn from a major road and to assess the impact of right-turn treatments on such crash occurrences. The Model 1 was developed to determine the probability of the occurrence of a crash involving at least one vehicle making a right turn from a System road, given that a crash had occurred. The dataset used in this model included all 10,235 crash history data points. Model 2 to Model 5 were developed to assess the impacts of a right-turn treatment on the occurrence of the crash that involved at least one vehicle making a right turn from a System road. The dataset used to fit these models was the subset that included the crashes with an identified right-turn treatment type (FROM case dataset).

Similarly, five additional models (Model 6 to Model 10) were developed to identify the significant factors contributing to crashes when vehicles travelling on a Cross road attempted to make a right turn onto the System road (TO case dataset). It is to be noted that when a vehicle attempted to pass onto a System road from a Cross road, it was the responsibility of Cross road vehicle to yield to the System road vehicle. The AADT and speed information used in TO-case models pertain to the System road. Right turn treatment information for the Cross road was not collected.

Lastly, one multinomial logistic regression model was developed to determine the factors contributing to crash severity levels. Both ordinal and nominal logistic regression models were used to fit the dataset that contained all 10,235 datapoints.

As a preliminary step of model development, contingency tables of outcome ($Y = 0, 1$) versus the levels of explanatory factors were prepared first to identify cells with zero count. Zero cells cause undesirable numerical outcomes to occur. Appendix A presents the contingency tables as applicable for the models considered in this study. In the next stage of the model development, univariable analyses were carried out to identify potentially significant explanatory factors that could be included in the multivariable regression models. However, AADTC, SPEED and RTTRT (except for Model 1 and To-cases models) are included in all models irrespective of the outcomes of the univariable models and contingency tables.

The 'rule of 10' is often used as a guideline to determine the adequacy of the sample size. The rule of 10 states that a minimum of 10 events per parameters are needed to fit reliable models. Hence, this rule was applied in the initial determination of parameters to include in a particular model. The following sections describe each of the models developed in this study.

4.8.1 Model 1

In Model 1, the outcome crash ($Y = 1$) involved at least one vehicle making a right turn from a System road. The purpose of Model 1 was to determine and estimate factors significantly affecting the crashes that involved at least one vehicle making a right turn from a System road. The model included thirteen main effect explanatory factors. Two-way interactions of some selected explanatory factors were also considered. The dependent variable was dichotomous: $Y = 1$, for the crash that involved at least one vehicle making a right turn from a System road, and $Y = 0$, for the crash that did not involve any vehicle making a right turn from a System road. The total number of '$Y=1$' event of the dependent variable was 469. The model in general, not taking the dummy variables into account for clarity, had the following form, which also included two-way interactions:

$$\begin{aligned}\pi^{*}\,(Y=1) = {} & \beta_0 + \beta_1{*}(\text{DRERR}) + \beta_2{*}(\text{DTIME}) + \beta_3{*}(\text{LIGHT}) + \beta_4{*}(\text{TTCMB}) + \\ & \beta_5{*}(\text{VHDEF}) + \beta_6{*}(\textbf{AADTC}) + \beta_7{*}(\textbf{DRENI}) + \beta_8{*}(\textbf{HCVPR}) + \\ & \beta_9{*}(\textbf{JUNCT}) + \beta_{10}{*}(\textbf{RDCHR}) + \beta_{11}{*}(\textbf{SPEED}) + \beta_{12}{*}(\textbf{SURFC}) + \\ & \beta_{13}{*}(\textbf{WETHR}) + \beta_{14}{*}(\text{AADTC*DRENI}) + \beta_{15}{*}(\text{AADTC*HCVPR}) + \ldots + \\ & \beta_{41}{*}(\text{SURFC*WETHR}) \\ & \text{(Two-way interactions of bold-faced variables considered.)} \qquad \ldots (4.1)\end{aligned}$$

4.8.2 Model 2

In Model 2, the outcome crash event (Y=1) was a rear-end crash type, given that the crash involved at least one vehicle making a right turn from a System road. In this model, the dichotomous dependent variable had the following values:

Y = 1, for the rear-end crash type and
Y = 0, for non-rear-end crash type.

The model included the 15 explanatory factors including two-way and three-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 150. The model statement had the following form:

$$\begin{aligned}\pi^*(Y=1) = {} & \beta_0 + \beta_1*(AADTC) + \beta_2*(DRENI) + \beta_3*(DRERR) + \beta_4*(HCVPR) + \\ & \beta_5*(INATT) + \beta_6*(JUNCT) + \beta_7*(SPEED) + \beta_8*(SURFC) + \beta_9*(VHDEF) \\ & + \beta_{10}*(RTTRT) + \beta_{11}*(DRWAY) + \beta_{12}*(AADTC*SPEED) + \\ & \beta_{13}*(AADTC*RTTRT) + \beta_{14}*(SPEED*RTTRT) + \\ & \beta_{15}*(AADTC*SPEED*RTTRT) \qquad \ldots (4.2)\end{aligned}$$

4.8.3 Model 3

In Model 3, the outcome crash event (Y=1) was a sideswipe (same-direction) crash type, given that the crash involved at least one vehicle making a right turn from a System road. The dichotomous dependent variable in this model had the following values:

Y = 1, for the sideswipe (same direction) crash type and
Y = 0, for non-sideswipe (same direction) crash type.

The model included 10 explanatory factors, including two-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 95. The model had the following form:

$$\begin{aligned}\pi^*(Y=1) = {} & \beta_0 + \beta_1*(AADTC) + \beta_2*(DRENI) + \beta_3*(DRERR) + \beta_4*(INATT) + \\ & \beta_5*(SPEED) + \beta_6*(SURFC) + \beta_7*(RTTRT) + \beta_8*(AADTC*SPEED) + \\ & \beta_9*(AADTC*RTTRT) + \beta_{10}*(SPEED*RTTRT) \qquad \ldots (4.3)\end{aligned}$$

4.8.4 Model 4

In Model 4, the outcome crash event (Y=1) was a right-angle crash type, given that crash involved at least one vehicle making a right turn from a System road. The dichotomous dependent variable in this model had the following values:

Y = 1, for the right-angle crash type and
Y = 0, for non-right-angle crash type.

The model included seven explanatory factors, including two-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 63. The model had the following form:

$$\pi^*(Y=1) = \beta_0 + \beta_1{*}(AADTC) + \beta_2{*}(SPEED) + \beta_3{*}(SURFC) + \beta_4{*}(VISON) + \beta_5{*}(RTTRT) + \beta_6{*}(AADTC{*}RTTRT) + \beta_7{*}(SPEED{*}RTTRT) \quad \ldots (4.4)$$

4.8.5 Model 5

In Model 5, the outcome crash event (Y=1) was a right-turn crash type, given that the crash involved at least one vehicle making a right turn from a System road. In this model, the dichotomous dependent variable had the following values:

Y = 1, for right-turn crash type and
Y = 0, for non-right-turn crash type.

The model included four main effect explanatory factors. The total number of 'Y=1' event of the dependent variable was 40. The model had the following form:

$$\pi^*(Y=1) = \beta_0 + \beta_1{*}(AADTC) + \beta_2{*}(SPEED) + \beta_3{*}(SURFC) + \beta_4{*}(RTTRT) \ldots (4.5)$$

4.8.6 Model 6

The Model 6 was a TO-case model, in which the outcome crash event (Y=1) was a crash due to failure to yield by the vehicle at a Cross road (Stack 5), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. In this model, the dichotomous dependent variable had the following values:

Y = 1, for the crash due to failure to yield by the vehicle at a Cross road and
Y = 0, for the crash due to other reasons.

The model included eleven explanatory factors, including two-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 127. The model had the following form:

$$\pi^*(Y=1) = \beta_0 + \beta_1{*}(AADTC) + \beta_2{*}(SPEED) + \beta_3{*}(DRERR) + \beta_4{*}(VISON) + \beta_5{*}(INATT) + \beta_6{*}(SURFC) + \beta_7{*}(WETHR) + \beta_8{*}(AADTC{*}DRERR) + \beta_9{*}(SPEED{*}DRERR) + \beta_{10}{*}(SPEED{*}SURFC) + \beta_{11}{*}(SPEED{*}AADTC) \quad \ldots (4.6)$$

4.8.7 Model 7

The Model 7 was a TO-case model, in which the outcome crash event (Y=1) was a crash due to failure to yield by the vehicle at Cross road, resulting into an opposing hit (Stack

6), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. In this model, the dichotomous dependent variable had the following values:

Y = 1, for the crash due to failure to yield by the vehicle at a Cross road, and resulted into an opposing hit; and
Y = 0, for the crash due to other reasons not resulting into an opposing hit.

The model included six main effect explanatory factors. The total number of 'Y=1' event of the dependent variable was 32. The model had the following form:

$$\pi^* (Y=1) = \beta_0 + \beta_1*(AADTC) + \beta_2*(SPEED) + \beta_3*(DRENI) + \beta_4*(LIGHT) + \beta_5*(SURFC) + \beta_6*(WETHR) \quad \ldots (4.7)$$

4.8.8 Model 8

The Model 8 was a TO-case model, in which the outcome crash event (Y=1) was a crash due to parallel stopping by vehicles at Cross-road (Stack 7), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. In this model, the dichotomous dependent variable had the following values:

Y = 1, for the crash due to parallel stopping by vehicles at Cross-road and
Y = 0, for the crash due to other reasons.

The model included nine explanatory factors, including two-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 89. The model had the following form:

$$\pi^* (Y=1) = \beta_0 + \beta_1*(AADTC) + \beta_2*(SPEED) + \beta_3*(DRERR) + \beta_4*(INATT) + \beta_5*(WETHR) + \beta_6*(SURFC) + \beta_7*(TTCMB) + \beta_8*(DRERR*SURFC) + \beta_9*(INATT*SURFC) \quad \ldots (4.8)$$

4.8.9 Model 9

The Model 9 was a TO-case model, in which the outcome crash event (Y=1) was a rear-end crash at Cross-road (Stack 8), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. In this model, the dichotomous dependent variable had the following values:

Y = 1, for the rear-end crash at Cross-road and
Y = 0, for other type of crash.

The model included five explanatory factors, including two-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 49. The model had the following form:

$$\pi^* (Y=1) = \beta_0 + \beta_1*(AADTC) + \beta_2*(SPEED) + \beta_3*(INATT) + \beta_4*(SURFC) + \beta_5*(INATT*SURFC) \quad \ldots (4.9)$$

4.8.10 Model 10

The Model 10 was a model, in which the outcome crash event (Y=1) was a crash due to obstructed visibility by a right turning vehicle (Stack 9). In this model, the dichotomous dependent variable had the following values:

Y = 1, for the crash due to obstructed visibility by a right turning vehicle and
Y = 0, for other reasons.

The model included five explanatory factors, including two-way interactions of some selected variables. The total number of 'Y=1' event of the dependent variable was 13. The model had the following form:

$$\pi^* (Y=1) = \beta_0 + \beta_1*(AADTC) + \beta_2*(SPEED) + \beta_3*(RTTRT) + \beta_4*(AADTC*RTTRT) + \beta_5*(SPEED*RTTRT) \quad \ldots (4.10)$$

4.8.11 Model 11

The Model 11 was the crash severity model that was fitted using crashes that involved at least one vehicle making a right turn. The outcome of the model was different severity levels – injury, injury (possible) and property damage. As such, the outcome event has three levels. The level injury included fatal, injury (incapacitating), injury (non-incapacitating), because only one fatal crash and two injury (incapacitating) crashes were reported involving right-turning vehicles. Two types of the logistic regression models were considered – ordinal and nominal. It was found that ordinal logistic regression model fitted the severity data well as compared to the ordinal model.

The severity model included six explanatory factors, including two-way interactions of some selected variables. The explanatory factors used were AADTC, SPEED, DRWAY, RTTRT, SURFC, and CRASHTYPE. The model had the following form:

$$\begin{aligned}\pi^*(Severity) = {} & \beta0 + \beta1*(AADTC) + \beta2*(SPEED) + \beta3*(DRWAY) + \beta4*(RTTRT) + \\ & \beta5*(AADTC)*(SPEED) + \beta6*(AADTC)*(DRWAY) + \\ & \beta7*(AADTC)*(RTTRT) + \beta8*(SPEED)*(DRWAY) + \\ & \beta9*(SPEED)*(RTTRT) + \beta10*(DRWAY)*(RTTRT) + \beta11*(SURFC) + \\ & \beta12*(CRASHTYPE) \quad \ldots (4.11)\end{aligned}$$

4.9 Model assessment

The appropriateness of fitted models was checked using two goodness-of-fit tests described earlier: Hosmer-Lemeshow test and Pearson test. The null hypothesis in both tests was as follows: the model fitted the data. The hypothesis testing was based on a 0.05 level of significance. The deviance test statistic could also be obtained from the SAS software along with the Pearson test statistic. Therefore, the deviance test, with the same null hypothesis as the Pearson test, could also used to assess the appropriateness of fitted models.

In addition to the summary measures of goodness-of-fit tests, logistic regression diagnostics were also used to assess if a model fit is supported over the entire set of covariate space.

4.10 Results

This section provides a brief description of each of the fitted binary logistic regression models. It is to be noted that the explanatory factors used in this study relate to the System roads. The SAS PROC LOGISTIC procedure was used to fit the models.

4.10.1 Model 1

As stated before, in Model 1, the outcome crash involved at least one vehicle making a right turn. Table 4.11 presents the model estimation and odds ratios for Model 1 for significant independent variables when the desired event in the outcome variable was a crash that involved at least one vehicle making a right turn.

The goodness-of-fit test statistics for Model 1 are shown in Table 4.12. The test statistics reveal that P-value, in both tests, is not significant at a 0.05 significance level. Therefore, the null hypothesis that the model fits the data is not rejected, and it is concluded that the model fits the data.

Table 4.11. Model 1 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-3.550	0.110	1051.716	<.0001	-	-	-
AADTC	High	vs	Low	-0.370	0.137	7.345	0.007	0.690	0.528	0.903
HCVPR	High	vs	Low	0.347	0.117	8.868	0.003	1.415	1.126	1.779
JUNCT	Driveway	vs	Intersection	1.675	0.129	169.553	<.0001	-	-	-
SPEED	High	vs	Low	-0.218	0.101	4.623	0.032	0.804	0.660	0.981
SURFC	Wet & slippery	vs	Dry	1.155	0.151	58.580	<.0001	-	-	-
TTCMB	Yes	vs	No	0.475	0.164	8.369	0.004	1.607	1.165	2.217
VHDEF	Yes	vs	No	0.993	0.281	12.457	0.000	2.699	1.555	4.685
WETHR	Not clear	vs	Clear	-0.380	0.170	5.022	0.025	0.684	0.490	0.953
	Somewhat clear	vs	Clear	-0.452	0.128	12.472	0.000	0.636	0.495	0.818
JUNCT* SURFC	Driveway & Wetslippery			-0.561	0.220	6.486	0.011	-	-	-

Table 4.12. Goodness-of-fit test statistics for model 1.

Deviance and Pearson Goodness-of-Fit Statistics:

Criterion	Value	DF	Value/DF	P-value
Deviance	958.122	1506	0.636	1.000
Pearson	1484.958	1506	0.986	0.645

Number of unique profiles: 2700

Hosmer and Lemeshow Goodness-of-Fit Test:

Chi-Square	DF	P-value
4.200	8	0.8386

4.10.2 Model 2

In Model 2, the outcome crash event was a rear-end crash type, given that the crash involved at least one vehicle making a right turn. Table 4.13 presents the model estimation and odds ratios for Model 2, when the desired event in the outcome variable was a rear-end crash type, given that the crash involved at least one vehicle making a right turn. The goodness-of-fit test statistics for Model 2, presented in Table 4.14, show that the model fits the data.

Table 4.13. Model 2 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-3.007	0.382	61.916	<.0001	-	-	-
INATT	Yes	vs	No	1.167	0.227	26.537	<.0001	3.212	2.061	5.008
SPEED	High	vs	Low	0.889	0.243	13.347	0.000	2.432	1.510	3.919
RTTRT	Shared	vs	Exclusive	1.347	0.347	15.100	0.000	3.845	1.949	7.584
DRWAY	Comm. driveway	vs	Intersection	0.805	0.287	7.885	0.005	2.237	1.275	3.925
	Private driveway	vs	Intersection	0.369	0.301	1.505	0.220	1.446	0.802	2.607

Table 4.14. Goodness-of-fit test statistics for model 2.

Deviance and Pearson Goodness-of-Fit Statistics:

Criterion	Value	DF	Value/DF	P-value
Deviance	176.275	147.000	1.199	0.050
Pearson	154.412	147.000	1.050	0.321

Number of unique profiles: 153

Hosmer and Lemeshow Goodness-of-Fit Test:

Chi-Square	DF	P-value
3.3686	6	0.761

4.10.3 Model 3

In Model 3, the outcome crash event was a sideswipe (same-direction) crash type, given that the crash involved at least one vehicle making a right turn. The fitted model parameters, including odds ratios, for Model 3, are shown in Table 4.15. The results of the goodness-of-fit tests for Model 3 are shown in Table 4.16. The results of the tests show that the model fits the data.

Table 4.15. Model 3 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-1.815	0.269	45.439	<.0001	-	-	-
DRERR	Yes	vs	No	1.038	0.293	12.581	0.000	2.824	1.591	5.011
SURFC	Wet & slippery	vs	Dry	-0.542	0.252	4.647	0.031	0.582	0.355	0.952

Table 4.16. Goodness-of-fit test statistics for model 3.

Deviance and Pearson Goodness-of-Fit Statistics:				
Criterion	Value	DF	Value/DF	P-value
Deviance	66.308	51.000	1.300	0.073
Pearson	59.192	51.000	1.161	0.201
Number of unique profiles: 54				
Hosmer and Lemeshow Goodness-of-Fit Test:				
Chi-Square	DF	P-value		
1.1388	2	0.566		

4.10.4 Model 4

Table 4.17 presents the model estimation and odds ratios for Model 4. The desired outcome event in the model was a right-angle crash type, given that the crash involved at least one vehicle making a right turn.

The goodness-of-fit test statistics for Model 4 are presented in Table 4.18. It may be observed from the test statistics that the fitted model is appropriate.

Table 4.17. Model 4 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-1.966	0.206	91.107	<.0001	-	-	-
VISON	Yes	vs	No	1.872	0.736	6.469	0.011	6.501	1.536	27.510
SURFC	Wet & slippery	vs	Dry	0.773	0.293	6.973	0.008	2.166	1.220	3.845

Table 4.18. Goodness-of-fit test statistics for model 4.

Deviance and Pearson Goodness-of-Fit Statistics:				
Criterion	Value	DF	Value/DF	P-value
Deviance	20.7132	26.000	0.797	0.757
Pearson	20.5928	26.000	0.792	0.763
Number of unique profiles: 29				

4.10.5 Model 5

Table 4.19 shows the estimation and odds ratio of the fitted model for Model 5, where the desired outcome event was a right-turn crash type, given that the crash involved at least one vehicle making a right turn. The goodness-of-fit test statistics for Model 5 are shown in Table 4.20. It is concluded from the statistics that the model fits the data.

Table 4.19. Model 5 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-1.649	0.216	58.432	<.0001	-	-	-
AADTC	High	vs	Low	-1.506	0.744	4.092	0.043	0.222	0.052	0.954
SPEED	High	vs	Low	-1.142	0.365	9.805	0.002	0.319	0.156	0.652

Table 4.20. Goodness-of-fit test statistics for Model 5.

Deviance and Pearson Goodness-of-Fit Statistics:

Criterion	Value	DF	Value/DF	P-value
Deviance	18.2537	13.000	1.404	0.148
Pearson	23.2788	13.000	1.791	0.038

Number of unique profiles: 16

Hosmer and Lemeshow Goodness-of-Fit Test:

Chi-Square	DF	P-value
1.793	2	0.408

4.10.6 Model 6

Table 4.21 shows the estimation and odds ratio of the fitted model for Model 6, where the desired outcome event was a crash due to failure to yield by the vehicle at a Cross road (Stack 5), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. The goodness-of-fit test statistics for Model 6 are shown in Table 4.22. It is concluded from the goodness-of-fit test statistics that the model fits the data.

Table 4.21. Model 6 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-2.316	0.429	29.187	<.0001			
AADTC	High	vs	Low	-0.869	0.282	9.486	0.002	0.419	0.241	0.729
SPEED	High	vs	Low	0.572	0.251	5.205	0.023	1.772	1.084	2.895
DRERR	Yes	vs	No	1.464	0.410	12.735	0.000	4.323	1.935	9.660
WETHR	Notclear	vs	Clear	0.349	0.400	0.761	0.383	1.418	0.647	3.105
	Somewhat clear	vs	Clear	0.810	0.277	8.566	0.003	2.249	1.307	3.870
STOPC	No	vs	Yes	0.555	0.282	3.880	0.049	1.742	1.003	3.028

Table 4.22. Goodness-of-fit test statistics for model 6.

Deviance and Pearson Goodness-of-Fit Statistics:				
Criterion	Value	DF	Value/DF	P-value
Deviance	104.906	95	1.104	0.229
Pearson	100.163	95	1.054	0.339
Hosmer and Lemeshow Goodness-of-Fit Test:				
Chi-Square	DF	P-value		
10.009	7	0.188		

4.10.7 Model 7

Table 4.23 shows the estimation and odds ratio of the fitted model for Model 7, where the desired outcome event was a crash due to failure to yield by the vehicle at Cross road, resulting into an opposing hit (Stack 6), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. The goodness-of-fit test statistics for Model 7 are shown in Table 4.24. It is concluded from the goodness-of-fit test statistics that the model fits the data.

Table 4.23. Model 7 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-2.518	0.279	81.634	<.0001			
LIGHT	Nolight	vs	Daylight	1.957	0.643	9.262	0.002	7.076	2.007	24.951
	Somelight	vs	Daylight	0.867	0.473	3.358	0.067	2.379	0.941	6.014
WETHR	Notclear	vs	Clear	0.700	0.496	1.991	0.158	2.014	0.762	5.326
	Somewhat clear	vs	Clear	-1.286	0.648	3.942	0.047	0.276	0.078	0.984

Table 4.24. Goodness-of-fit test statistics for model 7.

Deviance and Pearson Goodness-of-Fit Statistics:				
Criterion	Value	DF	Value/DF	P-value
Deviance	62.748	80	0.784	0.923
Pearson	70.627	80	0.883	0.764
Hosmer and Lemeshow Goodness-of-Fit Test:				
Chi-Square	DF	P-value		
0.899	3	0.826		

4.10.8 Model 8

Table 4.25 shows the estimation and odds ratio of the fitted model for Model 8, where the desired outcome event was a crash due to parallel stopping by vehicles at Cross-road (Stack 7), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. The goodness-of-fit test statistics for Model 8 are shown in Table 4.26. It is concluded from the goodness-of-fit test statistics that the model fits the data.

Table 4.25. Model 8 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-1.253	0.259	23.342	<.0001			
AADTC	High	vs	Low	0.797	0.350	5.197	0.023	2.218	1.118	4.401
SPEED	High	vs	Low	-1.999	0.397	25.320	<.0001	0.136	0.062	0.295
TTCMB	Yes	vs	No	3.058	0.410	55.530	<.0001	21.279	9.521	47.558
STOPC	No	vs	Yes	-1.441	0.475	9.194	0.002	0.237	0.093	0.601

Table 4.26. Goodness-of-fit test statistics for model 8.

Deviance and Pearson Goodness-of-Fit Statistics:				
Criterion	Value	DF	Value/DF	P-value
Deviance	89.953	110	0.818	0.919
Pearson	105.535	110	0.959	0.603
Hosmer and Lemeshow Goodness-of-Fit Test:				
Chi-Square	DF	P-value		
6.725	7	0.458		

4.10.9 Model 9

Table 4.27 shows the estimation and odds ratio of the fitted model for Model 9, where the desired outcome event was a rear-end crash at Cross-road (Stack 8), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road. The goodness-of-fit test statistics for Model 9 are shown in Table 4.28. It is concluded from the goodness-of-fit test statistics that the model fits the data.

Table 4.27. Model 9 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-2.597	0.273	90.749	<.0001			
AADTC	High	vs	Low	0.778	0.333	5.471	0.019	2.176	1.134	4.176
INATT	Yes	vs	No	1.131	0.331	11.664	0.001	3.098	1.619	5.928

Table 4.28. Goodness-of-fit test statistics for model 9.

Deviance and Pearson Goodness-of-Fit Statistics:				
Criterion	Value	DF	Value/DF	P-value
Deviance	25.314	27	0.938	0.557
Pearson	19.431	27	0.720	0.854
Hosmer and Lemeshow Goodness-of-Fit Test:				
Chi-Square	DF	P-value		
0.061	2	0.970		

4.10.10 Model 10

Table 4.29 shows the estimation and odds ratio of the fitted model for Model 10, where the desired outcome event was a crash due to obstructed visibility by a right turning vehicle (Stack 9), given that a crash occurred while attempting to make a right-turn from a Cross road on to a System road. The goodness-of-fit test statistics for Model 10 are shown in Table 4.30. It is concluded from the goodness-of-fit test statistics that the model fits the data.

Table 4.29. Model 10 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept				-2.367	0.349	46.107	<.0001	-	-	-
RTTRT	Shared	vs	Exclusive	-2.055	0.612	11.274	0.001	0.128	0.039	0.425

Table 4.30. Goodness-of-fit test statistics for model 10

Deviance and Pearson Goodness-of-Fit Statistics:

Criterion	Value	DF	Value/DF	P-value
Deviance	8.312	6	1.385	0.216
Pearson	9.505	6	1.584	0.147

4.10.11 Model 11

The score test for the proportional odds assumption is shown in Table 4.31. Table 4.32 shows the estimation and odds ratio of the fitted model for Model 11, where the desired outcome event was a severity level. The last response category (base level) of the severity was injury crash. The goodness-of-fit test statistics for Model 11 are shown in Table 4.33. It is concluded from the goodness-of-fit test statistics that the model fits the data.

Table 4.31. Score test for the proportional odds assumption.

Chi-Square	**DF**	**p-Value**
1.1428	3	0.7667

Table 4.32. Model 11 results.

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**	**Odds Ratio**	**95% Wald Confidence Limits**	
Intercept1	Property Damage			2.5829	0.3934	43.1119	<.0001			
Intercept2	Possible Injury			4.1061	0.4374	88.1272	<.0001			
SPEED	High	vs	Low	-1.1972	0.2745	19.0279	<.0001	0.3020	0.1760	0.5170
RTTRT	Shared	vs	Exclusive	-0.7360	0.3206	5.2681	0.0217	0.4790	0.2560	0.8980
SURFC	Wet & slippery	vs	Dry	0.5345	0.2695	3.9331	0.0473	1.7070	1.0060	2.8940

Table 4.33. Goodness-of-fit test statistics for model 11.

Deviance and Pearson Goodness-of-Fit Statistics:

Criterion	Value	DF	Value/DF	P-value
Deviance	165.703	225.000	0.737	0.999
Pearson	206.112	225.000	0.916	0.812

Number of unique profiles: 115

4.11 Analysis of results

The subsections that follow present the discussions on the results obtained from eleven logistic regression models presented above. The model results are inprepreted in terms of odds ratios and relative risks of the crash events.

4.11.1 FROM-case models (model 1 through model 5)

It is observed from Model 1 results that the crash involving at least one vehicle making a right turn from a System road was significantly associated with eight explanatory factors, including one interaction term. The significant factors were: AADT, heavy commercial vehicles percents, type of cross roads, posted speed limit of roadways, road surface conditions, whether truck-trailer combination was involved, whether vehicular defects were present, and the weather conditions. Earlier, it was also observed during the exploratory analysis that the crash event involving at least one vehicle making a right turn from a System road was a rare event within the set of parameters considered in this study. Therefore, the odds ratios obtained from Model 1 results can be used to make a reasonable estimate of the relative risks. Though odds ratios cannot be obtained for interacting variables, odds ratios for non-interacting variables in Model 1 may be interpreted as follows. The relative risk for the crash that involved at least one vehicle making a right turn from a System road at high AADT was about 30% lower as compared to roadways with low AADT. Similarly, the risk for the crash at high posted speed limit was about 20% lower as compared to the roadways with low posted speed limit. One of the reasons for this is because vehicles are more closely spaced on a roadway with the low speed. Presence of truck-trailer combination, vehicular defects and high percentage of heavy commercial vehicles were all found to contribute to the crash. On the other hand, clear weather was found to be about 35% more dangerous as compared to not-clear and somewhat-clear weather. It seems that drivers tend to be more cautious when the weather is not clear. The probability of a crash involving at least one vehicle making a right turn from System road at different AADT and SPEED condition is presented in Table 4.34.

Table 4.34. Probability of a crash involving at least one vehicle making a right turn from system road.

SPEED	AADT	Probability
High	High	0.016
High	Low	0.024
Low	High	0.020
Low	Low	0.029

Model 2 results presented the model estimations for a rear-end crash type, given that the crash involved at least one vehicle making a right turn from a System road. The occurrence of rear-end crashes was 150 out of 435 FROM-case crashes (Stacks 1 & 2), or about 35%. Four explanatory factors turned out to be significant – the posted speed limit of roadways, right-turn treatment type, the driver inattention, and type of cross roads. The odds ratio column in Table 4.13 tells us that the odds of a crash occurring at roadways with the high posted speed limit was about 2.5 times higher as compared to the odds of a crash occurring at roadways with the low posted speed limit. Similarly, the odds of a crash occurring with an inattentive driver were roughly 3.5 times higher as compared to the odds with an attentive driver. In case of right-turn treatment type, the odds for a crash occurring at an intersection with a shared right-turn treatment was about 4 times higher as compared to the odds with an exclusive right-turn treatment. However, in case of landuse, only commercial driveways were found to significantly affect the right-turn crashes. It was found that the odds of crash occurring at commercial driveways were about 2.3 times higher as compared to the odds of crash at intersections. The relative risk estimated from the fitted model for a rear-end crash occurring at an intersection and a commercial driveway with a shared right-turn treatment as compared to an exclusive right-turn treatment with an attentive driver is presented in Table 4.35. It is observed from the table that the risk for a rear-end crash occurring at an intersection with a shared right-turn treatment as compared to an exclusive right-turn treatment is about 2.8 times higher at low and 2.1 times higher at high posted speed limit. The risk for a rear-end crash occurring at a commercial drivewawy with a shared right-turn treatment as compared to an exclusive right-turn treatment is 2.2 times higher at low and about 1.7 times higher at high posted speed limit. Relative risks of a rear-end crash at commercial driveways versus intersections is presented in Table 4.36.

Table 4.35. Relative risk estimate of rear-end crash at intersections and commercial driveways with shared versus exclusive right-turn treatment.

Speed	**log ODDS**		**Probability**		**Relative Risk**
	Shared	**Exclusive**	**Shared**	**Exclusive**	**P(Shared)/P(Exclusive)**
Intersections					
Low	-0.493	-1.840	0.379	0.137	2.766
High	0.396	-0.951	0.598	0.279	2.145
Driveways					
Low	0.312	-1.035	0.577	0.262	2.202
High	1.201	-0.146	0.769	0.464	1.658

Table 4.36. Relative risks of a rear-end crash at commercial driveways versus intersections.

Speed	**Shared**	**Exclusive**
Low	1.523	1.913
High	1.286	1.664

Model 3 results presented the model estimations for a same-direction sideswipe crash, given that the crash involved at least one vehicle making a right turn from a System road. The frequency for this crash type was 95 out of 435 crashes, or about 22%. The two significant explanatory factors associated with this crash type included road surface conditions and driver error. The odds of crash occurrence with driver error present was about 3 times higher as compared to the odds of crash when the driver committed no error. However, contrary to expectations, the odds of a same-direction sideswipe crash occurrence on a dry road surface were about twice the odds of the crash occurrence on a wet/slippery road surface. It seems drivers tend to be more cautious when they find that the road surface is wet or slippery.

Model estimations for a right-angle crash, given that the crash involved at least one vehicle making a right turn from a System road, were shown in Model 4 results. The data subset with 435 crash data points included 63 right-angle crashes, i.e., about 15% of the total crashes in the dataset. The two explanatory factors found to be significant in the fitted model were road surface conditions and vision obstructions. The odds of a right-angle crash occurring on a wet/slippery road surface were 2.2 times higher compared to the odds of the crash occurring on a dry road surface. Obstructed visibility, on the other hand, resulted in the odds of a crash occurrence being 6.5 times higher as compared to the odds of the crash occurrence when the visibility was not obstructed.

The frequency of a right-turn crash type, given that the crash involved at least one vehicle making a right turn from a System road, was 40 out of 435 crashes, or about 10%. Parameter estimations of the model, when the desired outcome event in the fitted model was the occurrence of a right-turn crash, were shown in Table 4.19 (Model 5 results). Two explanatory factors – AADT and the posted speed limit of roadways – turned out to be significant. The risk of the crash occurrence at high AADT was about 80% lower as compared to the risk at low AADT, whereas the risk of the crash at high speed was about 70% lower as compared to the low posted speed limit.

4.11.2 TO-case models (model 6 through model 10)

Model 6 results presented the model estimations for a crash due to failure to yield by the vehicle at a Cross road (Stack 5), given that the crash occurred while attempting to make a right turn from a Cross road on to a System road (major road). The frequency for this crash type was 127 out of 355 TO-case crashes, or about 36%. Four explanatory factors found to be significant with this crash type included AADT on the major road, posted speed limit on the major road, driver error and weather conditions. It was found that driver error, bad weather conditions and high posted speed limit on major road all contributed to this type of crash. However, high AADT on major road was found to have reduced the likelihood of this type of crash to occur.

Model 7 results presented the model estimations for a crash due to failure to yield by the vehicle at Cross road, resulting into an opposing hit (Stack 6), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road (major road). The frequency for this crash type was 32 out of 355 TO-case crashes, or about 9%. Two explanatory factors found to be significant with this crash type included light conditions and weather conditions. It was found that poor light conditions as well as bad weather conditions both contributed to this type of crash.

Model 8 results presented the model estimations for a crash due to parallel stopping by vehicles at Cross-road (Stack 7), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road (major road). The frequency for this crash type was 89 out of 355 TO-case crashes, or about 25%. Three explanatory factors found to be significant with this crash type included AADT on the major road, posted speed limit on the major road and vehicle type. It was found that high AADT on the major road and involvement of truck-trailer combination both contributed to this type of crash; in case of truck-trailer combination, the odds of crash to occur was as high as 24 times. However, the odds for this type of crash to occur were found to decrease with the increase in posted speed limit on the major road.

Model 9 results presented the model estimations for a rear-end crash between the vehicles at Cross-road (Stack 8), given that a crash occurred while attempting to make a right turn from a Cross road on to a System road (major road). The frequency for this crash type was 49 out of 355 TO-case crashes, or about 14%. The two explanatory factors found to be significant with this crash type were AADT on the major road and driver inattention. It was found that high AADT on the major road and driver inattention both contributed to this type of crash.

Model 10 results presented the model estimations for a crash due to obstructed visibility caused by a vehicle turning right from major road (Stack 9), given that a crash occurred while a vehicle at Cross road was also attempting to make a right turn on to a System road (major road). The frequency for this crash type was 13 out of 355 TO-case crashes, or about 4%. The only explanatory factors found to be significant with this crash type was right-turn treatment type on the major road. It was found that the risk for this crash type to occur at the presence of exclusive right-turn lane at major road approach was about 8 times higher as compared to the major road approach without exclusive right-turn lane. However, it is to be noted that this estimate was made with a small sample size.

4.11.3 Severity model (model 11)

Model 11 estimates the probability of different crash severity. Assuming dry surface conditions, the probability of different severity level expected from a crash involving a vehicle making right turn at different speed condition and right-turn treatment type is presented in Table 4.37.

Table 4.37. Probability of crash severity involving a vehicle making right turns.

Severity Type	**SPEED-RTTRT**			
	High-Shared	**High-Exclusive**	**Low-Shared**	**Low-Exclusive**
Property Damage	0.657	0.800	0.864	0.930
Possible Injury	0.241	0.148	0.103	0.054
Injury	0.102	0.052	0.033	0.016
Total	**1.000**	**1.000**	**1.000**	**1.000**

4.11.4 Summary

The exploratory analysis provided insight into what was the nature and extent of different types of crashes occurring on two-lane roads and what proportion of those are related to conditions where at east one vehicle was turning right. Binary logistic regressions, on the other hand, were chosen as an analysis method to understand the significance of different factors that affect crashes on two-lane roads and those that affect the likelihood of crashes due to right-turn movements. Multinomial logistic regression was chosen as an analysis method to estimate the severity of a crash. Crashes involving at least one vehicle making a right turn from a System road (major road) were found to be 5% of the total crashes; so it can be considered a rare event and the odds ratio can provide an insight into the relative risks of the factors. The significant factors affecting rear-end, side-swipe, right-angle, and the right-turn crashes were different. Rear-end crash risks were influenced by the speed. Similarly, only the rear-end crashes were significantly associated with the type of right-turn treatments at intersections.

4.12 Right turn cost/crash estimate

The expected cost per crash involving a right-turning vehicle was estimated using the results from Model 11 (the severity model). The cost was estimated as a weighted average based on the probability of a crash secerity. The information for the cost per crash for different injury type was obtained from Mn/DOT, and is shown in Table 4.38. The final expected cost per crash involving at least one right-turning vehicle is estimated assuming dry surface condition at intersection, and is shown in Table 4.39.

Table 4.38. Crash type frequency in a crash involving right-turning vehicles.

Severity	Cost/crash ($)
Injury	64,000
Possible injury	32,000
Property damage	4,700

Source: Mn/DOT Office of Investment Management

Table 4.39. Cost per crash involving right-turning vehicles.

Speed	Right-turn treatment	Cost/crash ($)
High	Shared	17,336.20
High	Exclusive	11,817.49
Low	Shared	9,483.06
Low	Exclusive	7,136.30

4.13 Conflict study

4.13.1 Methodology

The conflict analysis in this study was carried out through the use of the TCT. The TCT was employed for its relevance as well as its simplicity to apply in the field. The overall goal of the conflict analysis was to develop a conflict prediction model to determine the relationship between conflict and crash. The conflict of interest in this study was the conflict due to right turns, known as right-turn, same-direction conflict. This type of conflict occurs when the first (lead) vehicle slows to make a right turn, thus endangering the second (following) vehicle with a rear-end crash. In addition, the secondary conflict due to right turns was also of interest. The methodoly, analysis and results used for the conflict study is presented in the sections that follow.

4.13.2 Design of experiment

In the crash anslysis presented before in this report, it was found that only rear-end crash due to right turns was significantly associated with the right-turn treatment type. Other explanatory factors found significant include posted speed limit of roadways and driver inattention. Percent right turns were an important factor that was not available to include in the analysis. Since the right-turn, same-direction conflicts as well as the associated secondary conflicts are treated as surrogate measures for rear-end crashes due to right turns, it was logical to include the right-turn treatment type, posted speed limit and percent right turns as variables in such conflict study. For the purpose of conflict data collection, the experiment was designed as 2^k factorial design, where k = 3 (right-turn treatment type, posted speed limit and percent right turns), resulting into eight treatment combinations. The levels of treatment factors were as follows: right-turn treatment type – exclusive and shared; posted speed limit – high (if more than 40 mph) and low (if otherwise); and percent right turns – high (if more than 5%) and low (if otherwise). It was decided to observe at least 3 replicates for each treatment combination (cell) shown in Table 4.40. The goal of the experiment was to develop a least squares conflict prediction equation using a balanced design. The dependent variable was right-turn, same-direction conflict, including the associated secondary conflict, measured in terms of the number of conflicts per thousand entering vehicles (TEV).

Table 4.40. Design of experiment.

Posted Speed Limit (SPEED)	**Right-turn Treatment Type (RTTRT)**	**Percent Right Turns (RTPCT)**	
		Low (<= 5%)	**High (> 5%)**
Low (≤ 40 mph)	Shared	Cell 1	Cell 5
	Exclusive	Cell 2	Cell 6
High (> 40 mph)	Shared	Cell 3	Cell 7
	Exclusive	Cell 4	Cell 8

4.13.3 Data collection

The field data was collected in Minnesota in the summer of 2007 and 2008, and included intersection geometry, including right-turn treatment type (shared or exclusive lane), conflicts due to right turns per TEV, posted speed limit for the study approach, traffic volumes, time stamp data, and spot speeds with Radar/Laser guns. The data was collected with an intention to capture the conflicts during peak hours. A conflict was considered due to a right turn when a lead vehicle makes a right turn, in response of which an evasive action is performed by a following vehicle to avoid a collision. The following were considered to be an indication or as a result of an evasive action (Weerasuriya and Pietrzyk, 1998): brake light indication, swerve action, front lounging of the vehicle, and squealing of tires. A secondary conflict was observed when an additional vehicle performed an evasive action in response to a right-turn, same-direction conflict. The conflicts were observed within 100 ft (at ‘low’ speed approach), or within 300 ft (at ‘high’ speed approach) from the start of the right-turn treatment. Schematic diagrams of some of the survey locations are presented in Appendix B.

Previous studies (Cottrell, 1981; Hasan and Stokes, 1996) suggested that four hours of conflict data collection at a location would suffice as far as conflicts due to right-turn movements were concerned. The conflicts were, therefore, observed for a continuous four-hour period encompassing peak flow period at morning (7:00 AM - 11:00 AM) or afternoon (2:00 PM - 6:00 PM) during weekdays (Monday through Friday) under dry pavement conditions.

It is to be noted that the experiment designed for this study posed one major problem – it could not be estimated with certainty whether the percent right turns at a location would fall into ‘low’ or ‘high’ category. The fact that percent right turns would be known only after the data collection made it difficult to obtain an appropriate sample of intersection approaches to be surveyed for each cell. Nonetheless, it was desired, for its relevance, to conduct conflict surveys at those intersection approaches also where a crash due to right-turn movements actually occurred. Location selection for field data collection was, therefore, done as follows. First of all, the two-lane unsignalized intersection inventory dataset was obtained from Mn/DOT. This inventory dataset was then divided into two subsets: 1) the subset consisting of intersections where at least one crash due to right turns occurred (referred to as ‘crash locations’), and 2) the subset consisting of intersections where a crash due to right turns did not occur (non-crash locations). Finally, an equal number of data collection sites from both ‘crash locations’ and ‘non-crash locations’ were selected at random. Then, site visits were made to these locations to make sure that conditions had not changed over years, and also to assess the appropriateness of sites for surveying. However, it was soon found to be difficult to obtain the desired replicates of each cell following this approach of site selections. It was, therefore, decided to locate the intersection locations through observation first to find the desired treatment combination and replicate the observations at the same location on several days. The finally selected survey sites are presented in Table 4.41 and Figure 4.28. Selected photographs of the study sites are presented in Figure 4.29. A conflict observer is shown in Fig. 4.30.

Table 4.41. Field sites identification and survey data.

Site	City / Nearest City	Intersection Description	Study Approach	Intersection Type	Right-turn Treatment	Speed (mph)	4-Hour Observation		Observed 4-hour Conflicts (per TEV)
							RT Vol.	Total App. Vol.	
C1R1	Staples	US-10/12th St. NE	US-10 West	+	Shared	30	10	1190	5
C1R2	Dawson	US-212/4th St.	US-212 East	+	Shared	30	11	513	4
C1R3	Moorhead	20th St. S/14th Ave. S	20th St. S North	T	Shared	30	77	1606	1
C2L1	Moorhead	20th St. S/MSCTC Drive	20th St. S North	T	Exclusive	30	48	1687	7
C2L2	Moorhead	20th St. S/MSCTC Drive (Replicated)	20th St. S North	T	Exclusive	30	43	1569	4
C2L3	Moorhead	20th St. S/MSCTC Drive (Replicated)	20th St. S North	T	Exclusive	30	32	1696	0
C3R1	Oakport	Oakport St. N/43rd Ave. N	Oakport St. N South	T	Shared	45	8	205	20
C3R2	Oakport	Oakport St. N/Old Trail	Oakport St. N North	T	Shared	45	7	275	15
C3R3	Aitkin	MNTH-210/CR-54 & CR-56	MNTH-210 West	+	Shared	55	7	558	9
C4L1	Park Rapids	MNTH-34/CR-4	MNTH-34 East	T	Exclusive	55	44	947	11
C4L2	Forest Lake	US-61/250th St.	US-61 North	+	Exclusive	55	41	1722	9
C4L3	Forest Lake	US-61/250th St. (Replicated)	US-61 North	+	Exclusive	55	26	1506	2
C5R1	Moorhead	12th Ave. S/32nd St. Circle S	12th Ave. S West	T	Shared	30	80	903	34
C5R2	Moorhead	12th Ave. S/32nd St. Circle S (Replicated)	12th Ave. S West	T	Shared	30	80	1014	28
C5R3	Staples	US-10/12th St. NE	US-10 East	+	Shared	30	73	990	13
C6L1	Tyler	US-14/CR-8	US-14 East	T	Exclusive	35	36	248	9
C6L2	Moorhead	20th St. S/20th Ave. S	20th St. S North	T	Exclusive	30	155	2308	8
C6L3	Lindstrom	MNTH-8/Akerson St.	MNTH-8 West	+	Exclusive	30	193	2552	7
C7R1	Moorhead	28th Ave. N. (CR-18)/34th St. N	28th Ave. N West	T	Shared	55	115	366	63
C7R2	Moorhead	28th Ave. N. (CR-18)/34th St. N (Replicated)	28th Ave. N West	T	Shared	55	111	371	54
C7R3	Moorhead	28th Ave. N. (CR-18)/40th St. N	28th Ave. N West	+	Shared	55	46	386	32
C8L1	Forest Lake	US-61/250th St.	US-61 South	+	Exclusive	55	97	1024	24
C8L2	St. Bonifacius	MNTH-7/CR-10	MNTH-7 West	+	Exclusive	55	126	1024	21
C8L3	Moorhead	US-75/46th Ave. S.	US-75 North	T	Exclusive	55	129	601	19

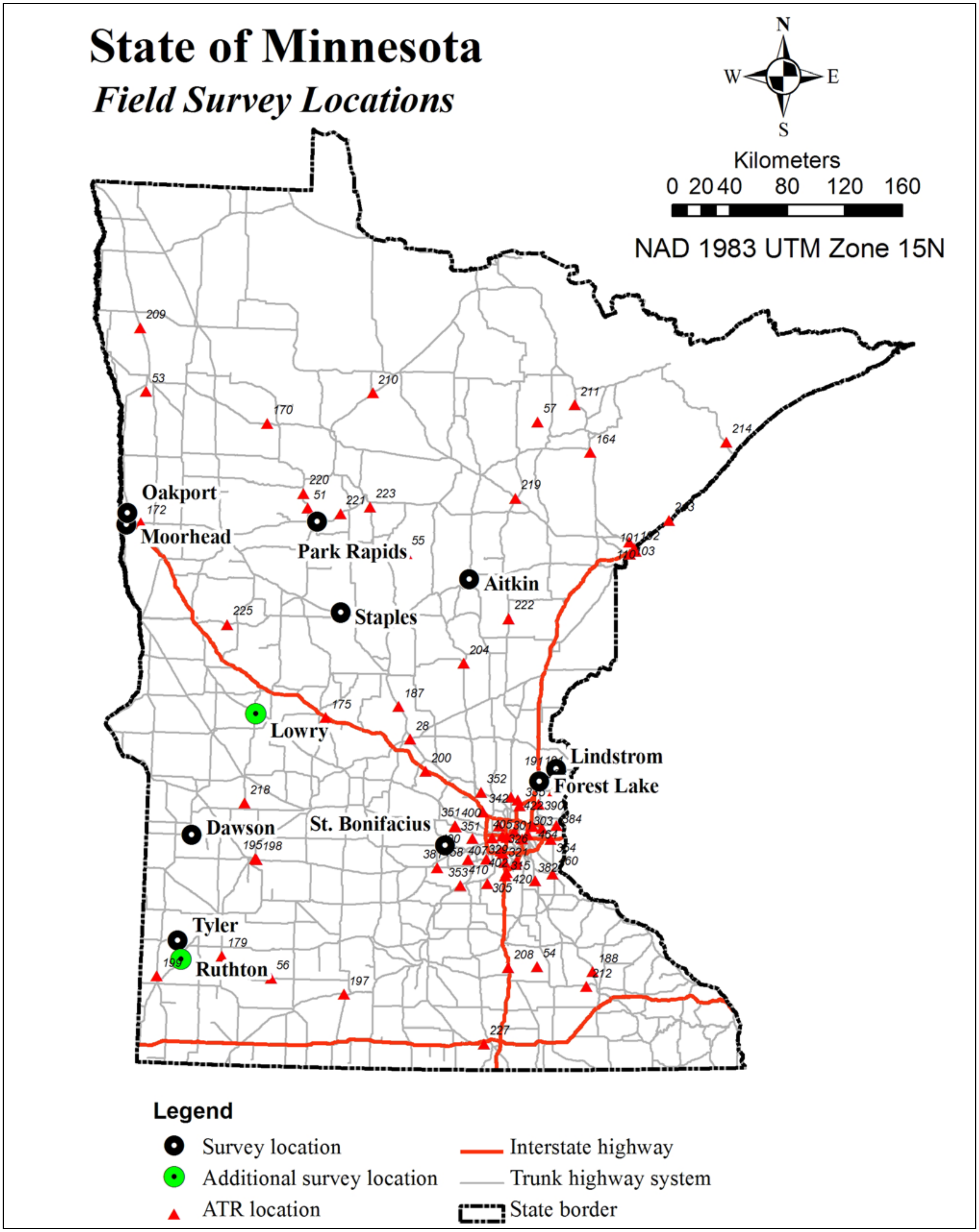


Figure 4.28. Survey locations.

1) Dawson (US-212/4th St.)

Four-legged intersection on US-212 with 4th St. at Dawson, viewed from east approach (crash location – west approach)

3) Ruthton (MNTH-23/CR-10)

Four-legged intersection on MNTH-23 with CR-10 near Ruthton viewed from south approach (crash location – north approach)

2) 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 (crash location – west approach)

4) Forest Lake (US-61/250th St.)

Four-legged intersection on US-61 with 250th St. in Forest Lake with north approach in view (crash location – north approach)

Figure 4.29. Selected pictures of survey locations.

5) Staples (US-10/12th St. NE)

Four-legged intersection on US-10 with 12th St. NE in Staples viewed from west approach, also shows intersecting 11th St. NE and Subway-Dairy Queen driveways (crash location – west approach)

7) Lindstrom (MNTH-8/Akerson St.)

Four-legged intersection on MNTH-8 with Akerson St. in Lindstrom viewed from west approach

6) Park Rapids (MNTH-34/CR-4)

Three-legged intersection on MNTH-34 with CR-4 near Park Rapids viewed from east approach, also shows conflict observer

8) Forest Lake (US-61/240th St.)

Three-legged intersection on US-61 with 240th St. in Forest Lake viewed from south approach

Figure 4.29. (continued)

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

Four-legged intersection on MNTH-7 with CR-10 near Saint Bonifacius viewed from west approach

10) Moorhead (US-75/46th Ave. S.)

Three-legged intersection on US-75 with 46th Ave. S. in Moorhead viewed from north approach

11) Lowry (MNTH-55/CR-114)

Three-legged intersection on MNTH-55 with CR-114 in Lowry viewed from west approach

12) Tyler (US-14/CR-8)

Three-legged intersection on US-14 with CR-8 in Tyler viewed from east approach

Figure 4.29. (continued)

13) Moorhead (28th Ave. N/40th St. N)

Four-legged intersection on 28th Ave. N with 40th St. N in Moorhead as viewed from the west approach

15) Moorhead (12th Ave. S/32 St. Circle S)

Three-legged intersection on 12th Ave. S with 32nd St. Circle S in Moorhead as viewed from the west approach

14) Moorhead (28th Ave. N/34th St. N)

Three-legged intersection on 28th Ave. N with 34th St. N in Moorhead as viewed from the west approach

16) Moorhead (20th St. S/14th Ave. S)

Three-legged intersection on 20th St. S with 14th Ave. S in Moorhead as viewed from the north approach

Figure 4.29. (continued)

17) Moorhead (20th St. S/16th Ave. S)

Four-legged intersection on 20th St. S with 16th Ave. S in Moorhead as viewed from the north approach

18) Moorhead (20th St. S/20th Ave. S)

Three-legged intersection on 20th St. S with 20th Ave. S in Moorhead as viewed from the north approach

19) Moorhead (20th St. S/24th Ave. S)

Three-legged intersection on 20th St. S with 24th Ave. S in Moorhead as viewed from the north approach

20) Moorhead (20th St. S/MSCTC Drive)

Three-legged intersection on 20th St. S with MSCTC Drive in Moorhead as viewed from the north approach

Figure 4.29. (continued)

21) Oakport (Oakport St. N/43rd Ave. N)

Three-legged intersection on Oakport St. N with 43rd Ave. N in Oakport as viewed from the south approach

22) Oakport (Oakport St. N/Old Trail)

Three-legged intersection on Oakport St. N/ with Old Trail in Oakport as viewed from the north approach

Figure 4.29. (continued)

Figure 4.30. Conflict observer.

Time stamp data was collected using TDC-12's, whereas spot speed data was collected using Laser and/or Radar guns. Figure 4.31 shows use of a Laser gun to obtain spot speed. Figure 4.32 shows the data collection strategy at an intersection approach with a shared right turn treatment. Point A is at stop bar. Point B was selected at a known distance away from point A. Point X was chosen at a location where it was assumed that the driving phenomena will not be impacted by the right turn movements; we called it as "right turn influence-free spot speed location".

Point Y represents the position of the conflict observer. It was located at 100 ft (for the 'low' speed approach), or at 300 ft (for the 'high' speed approach) from point A.

Time stamp data were collected at points B and A. Time stamp data was collected to see if SMS for the link matched during calibration process. Spot speeds were collected at points X, B and A. Spot speeds were collected to see if the average speeds at detectors matched during calibration process.

Figure 4.31. Use of a laser gun to collect spot speeds.

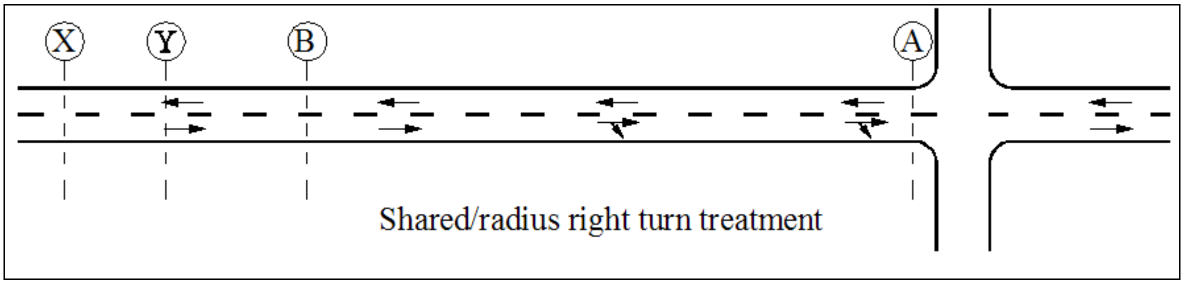


Figure 4.32. Data collection strategies at shared right-turn treatments.

Figure 4.33 shows the data collection strategy at an intersection approach with an exclusive right-turn treatment. The notations have the same meanings as explained in the case of shared right-turn treatment, except that in this case a point C was also chosen at the point where the right-turn taper starts. The point B was selected at a known distance away from point A.

Point Y representing the position of the conflict observer was located at 100 ft (for the 'low' speed approach), or at 300 ft (for the 'high' speed approach) from point C (not point A). Time stamp data were collected at points B, C and A, whereas the spot speeds were collected at points X, B, C and A.

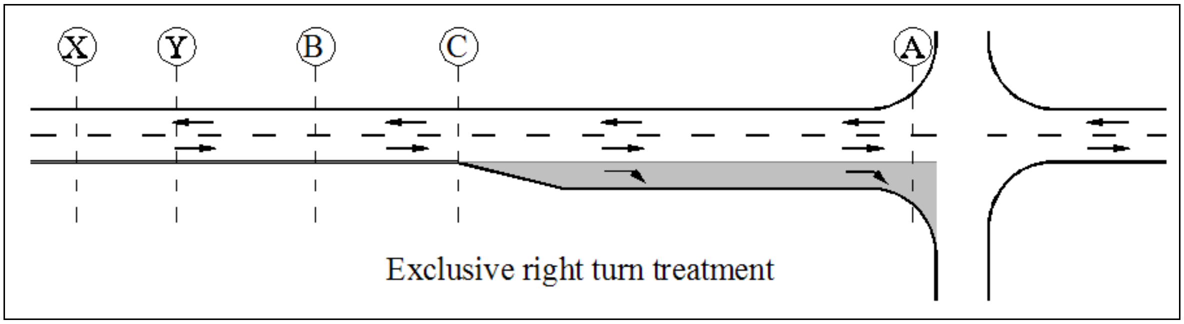


Figure 4.33. Data collection strategies at exclusive right-turn treatments.

4.13.4 Statistical modeling

Researchers in the past have attempted to develop conflict prediction models for conflict due to right turns. Cottrell (1981), based on four-hour conflicts due to right turns observed on both two- and four-lane roads at 21 sites, developed three independent conflict prediction equations for radius, taper and exclusive right-turn treatments as follows:

Radius: PHVCONFL = 1.88*PHVRPCT – 16 … (4.12)
Taper: PHVCONFL = 1.66*PHVRPCT – 5 … (4.13)
Exclusive: PHVCONFL = 1.30*PHVRPCT – 1 … (4.14)

where
PHVCONFL is the peak hour volume-conflict rate – conflicts/1,000 vehicles
PHVRPCT is the peak hour volume – percent right turns

Mounce (1983) formulated three probability statements to estimate the number of through vehicles affected by right turns at driveways. Hasan and Stokes (1996) followed the work carried out by Mounce (1983) to develop an analytical model to predict the number of right-turn, same-direction conflicts, including the associated secondary conflicts, at a radius right-turn treatment on both two- and four-lane roads. The proposed conflict prediction equation for two-lane roads was as follows:

$$V_T = \left(\frac{V_{Turn}}{V_A}\right) * \left(1 - \frac{V_{Turn}}{V_A}\right) * \left(1 - e^{\frac{-V_A T_A}{3600}}\right) * V_A * EFV_{2L} \quad \ldots (4.15)$$

where
VT – Total number of right-turn, same-direction conflicts per hour
VTurn – Right-turn volume (vph)
VA – Total approach volume (vph)
TA – Critical headway (sec)
EFV2L – Equivalent Following Vehicle (minimum value of EFV2L = 1; if negative, EFV2L = 0)

The critical headways determined at different operating speeds are shown in Table 4.42. The EFV2L was found to be related to directional design hour volume (DDHV) and roadway operating speed (U) as follows:

$$EFV2L = -7.13 + 4.32*10^{-6}*(DDHV)^2 + 0.15*U \quad \ldots (4.16)$$

Table 4.42. Critical headways.

Roadway Speed (mph)	**Critical Headway, T_A (sec)**
40	14.22
45	16.67
50	19.11
55	21.56
60	24.00
65	26.44

(Source: Hasan and Stokes, 1996)

In this study, the right-turn, same-direction conflict, including the associated secondary conflict, model was developed as a multiple regression model by using the method of least squares. The general form of the regression model is shown below (Mendenhall and Sincich, 2003):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \quad \ldots (4.17)$$

where
y is the dependent variable;
$x_1, x_2, \ldots, x_k$ are the independent variables (including interactions and higher order terms);
$\beta_1, \beta_2, \ldots, \beta_k$ are the model coefficients; and
ε is the random error.

4.13.5 Safety effectiveness of a right-turn lane at unsignalized intersections and driveways

The safety effectiveness of a right-turn lane in this study was determined by using the conflict prediction equation and crash-conflict rates. The crash-conflict conversion factor has been estimated by the researchers in the past to determine the relationship between crash and conflict. Glauz et al. (1985) developed accident/conflict ratios for various types of conflicts. In their study, 46 signalized and unsignalized intersections in the greater Kansas City area on two- and four-lane roads and operating under both high and low speeds were considered. The report provides discussion of both theoretical concepts and field studies. Using ‘all same direction’ pooled conflict and accident data, they estimated ‘all same direction’ accident/conflict ratio of 1.428×10^{-6} at high volume and 2.663×10^{-6} at medium volume signalized intersection. However, owing to the lack of crash data due to right turns, they were unable to determine the accident/conflict ratio for right-turn, same-direction conflict. Weerasuriya and Pietrzyk (1998) developed crash-conflict ratios for unsignalized three-legged intersections with various lane combinations by using three-year (1992-94) crash data and conflicts observed for 38 intersections in west-central Florida. They estimated the right-turn, same-direction crash-conflict ratio of 2.492×10^{-5} for four-lane three-legged unsignalized intersection. Again, due to the lack of crash data on two-lane roads, they were unable to determine the accident/conflict ratio for those conditions.

In this study, the crash-conflict ratios related to right-turn, same-direction, including the associated secondary conflicts, were determined based on the number of crash and conflict estimated for five year period (2000-02, 2004-05) for which the crash and traffic volume data were available. The expected number of crash due to right turns at a location was determined based on the probability of a crash involving a vehicle turning right from two-lane major road with no control, given that a crash occurred, at an unsignalized intersection at different volume and speed conditions as presented in Table 4.34. The number of crashes involving right-turning vehicles obtained by using the probabilities shown in Table 4.34 was then used to estimate the number of rear-end/sideswipe (same direction) crashes due to right turn movements. The number of these crashes was estimated by using the probabilities, presented in Table 4.43, estimated from Model 2 and Model 3 results, of rear-end/sideswipe (same direction) crash, given that a crash involving right-turning vehicle occurred.

Table 4.43. Probabilities of a rear-end/sideswipe (same direction) crash at an intersection approach.

SPEED[(a)]	**Right-turn treatment type**	**Probability of Crash**
High	Radius	0.913
High	Exclusive	0.594
Low	Radius	0.694
Low	Exclusive	0.452

The crash-conflict ratios, relating rear-end/sideswipe (same direction) crash and right-turn, same-direction, including the associated secondary conflicts, were then employed to determine the crash estimation factors (CEFs) at different conditions, which in turn, were used to determine the overall safety effectiveness of right-turn treatments at intersection approaches. The safety effectiveness of right-turn treatments at driveways was determined based on the relative risks of a rear-end/sideswipe (same direction) crash due to right turns at an approach to a driveway compared to those at an intersection approach. The relative risks of a rear-end/sideswipe (same direction) crash at commercial driveways versus intersection approaches under different speed conditions at dry pavement surface condition determined using Model 2 and Model 3 results are shown in Table 4.44.

Table 4.44. Relative risks of a rear-end/sideswipe (same direction) crash at an approach to a commercial driveway versus an intersection approach.

Speed[(a)]	Right-turn treatment	
	Shared	Exclusive
Low	1.286	1.277
High	1.096	1.311

4.14 Conflict analysis and results

4.14.1 Conflict prediction model

The least squares conflict prediction model was developed using 24 independent observations, including 3 replicates for each cell. The stepwise regression was initially carried out to determine the significant independent variables that included interactions as well as higher order terms. Insignificant variables were then removed from the model considerations. The least squares prediction equation finally obtained was shown as Equation (4.18). The predicted conflicts at shared and exclusive right-turn treatments at different speed and percent right turns are shown in Figure 4.34.

$$\text{RTCPTEV} = 4.37 - 2.97^{*}(\text{RTTRT}) + 1.65^{*}(\text{RTPCT}) + 5.61^{*}(\text{SPEED}) - 0.931^{*}(\text{RTTRT}^{*}\text{RTPCT}) \quad \ldots (4.18)$$

(S = 6.26249, R-Sq = 87.6%, Adj. R-Sq = 85.0%, Pred. R-Sq = 80.88%)

where
RTCPTEV – conflicts due to right turns per TEV;
RTPCT – percent right turns;
RTTRT – right turn treatment type (0 if shared, 1 if exclusive); and
SPEED – posted speed limit (0 if ‘low’, 1 if ‘high’)

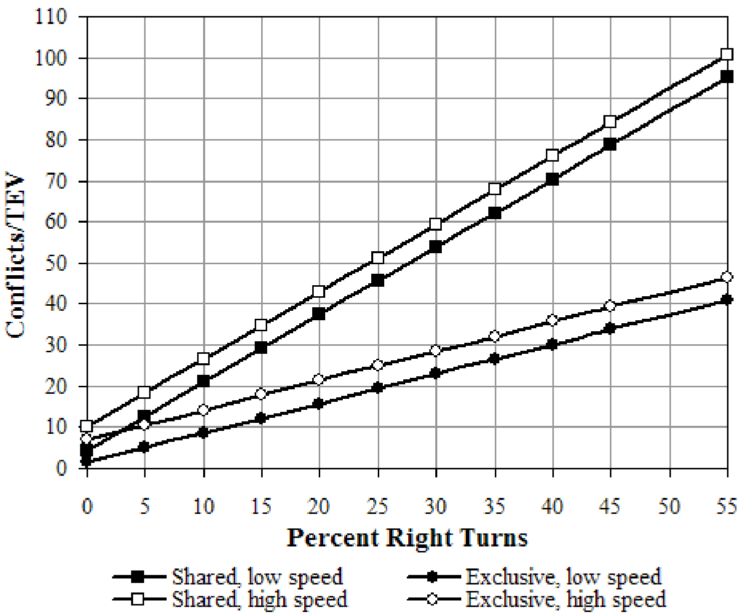


Figure 4.34. Predicted conflicts due to right turns at shared and exclusive right-turn treatments.

4.14.2 Conflict model validations

The R-square (predicted) value of 80.88% compared to the R-square (adjusted) value of 85.0% indicates that the model would predict as well as it fits the existing data. In addition, additional conflict data was collected to assess the suitability of the model. The observed and predicted conflicts are shown in Table 4.45. The paired t-test (T-Value = -0.97, P-Value = 0.362) revealed that the difference between the observed and predicted conflicts was insignificant.

Table 4.45. Comparison of conflicts at additional study sites.

Location (Intersection)	**Study Approach**	**RTTRT**	**SPEED (mph)**	**4-hour Observation**		**Conflict (per TEV)**	
				VOLTOT(a)	**RTPCT**	**Observed**	**Predicted**
Moorhead (20th St. S/20th Ave. S)	20th St. S North	Exclusive	30	1630	4.85	8	5
Moorhead (20th St. S/24th Ave. S)	20th St. S North	Exclusive	30	1691	7.92	7	8
Moorhead (28th Ave. N /34th St. N)	28th Ave. N West	Radius	55	350	28.57	43	58
Forest Lake (US-61/250th St.)	US-61 South	Exclusive	55	2628	20.17	25	22
Ruthton (MNTH-23/CR-10)	MNTH-23 North	Exclusive	55	429	5.13	3	11
Moorhead (20th St. S/16th Ave. S)	20th St. S North	Radius	30	1651	1.51	15	7
Staples (US-10/11th St. NE)	US-10 West	Radius	30	1278	1.56	15	7
Dawson (US-212/4th St.)	US-212 West	Radius	30	562	0.36	0	5
Moorhead (28th Ave. N/40th St. N)	28th Ave. N West	Radius	55	169	19.53	18	43

(a) Total approach volume

It was also desired to see how the conflict model developed in this study would perform with the conflict data collected by Cottrell (1981) and Hasan and Stokes (1996), as well as how their models compared with the conflict data collected in this study. Table 4.46 shows the comparison of conflicts observed by Cottrell (1981) and the conflicts predicted by the model proposed in this study. The paired t-test revealed no significant differences between the predicted and observed conflicts (T-Value = 1.62, P-Value = 0.139). Similarly, Table 4.47 shows the comparison of conflicts observed by Hasan and Stokes (1996) and the conflicts predicted by the model developed in this study; there were no significant differences between the predicted and observed conflicts (paired t-test T-Value = -0.51, P-Value = 0.630).

Table 4.46. Comparison of predicted conflicts with the conflicts observed by Cottrell (1981).

Site Code	**RTTRT**	**SPEED (mph)**	**Average Peak Period(a)**			**Conflict (per TEV)**	
			VOLTOT	**VOLRT(b)**	**RTPCT**	**Observed**	**Predicted**
R1	Radius	55	479	94	20	50	43
R2	Radius	55	782	57	7	43	22
R3	Radius	45	593	20	3	13	15
R4	Radius	45	343	129	38	110	73
R5	Radius	35	260	114	44	68	77
R6	Radius	55	421	51	12	33	30
L1	Exclusive	55	369	191	52	59	45
L2	Exclusive	55	473	47	10	19	15
L3	Exclusive	55	1063	77	7	16	13
L4	Exclusive	35	739	83	11	3	10

(a) Average of 2 two-hour peak periods.

(b) Total right-turn volume.

Table 4.47. Comparison of predicted conflicts with the conflicts observed by Hasan and Stokes (1996).

Site Code	**RTTRT**	**SPEED (mph)**	**DDHV(a) (vph)**	**VOLRT (vph)**	**RTPCT(b)**	**VOLTOT(c) (4-hour)**	**Conflict**		
							Observed (4-hour)	**Observed (per TEV)(d)**	**Predicted (per TEV)**
R1	Radius	45	281	6	2.14	1124	6	6	14
R2	Radius	55	428	54	12.62	1712	145	85	31
R3	Radius	40	362	44	12.15	1448	14	10	25
L1	Excl	55	58	3	5.17	232	1	5	11
L2	Excl	55	180	39	21.67	720	4	6	23
L3	Excl	55	335	116	34.63	1340	14	11	32
L8	Excl	55	381	127	33.33	1524	11	8	31

(a) Directional design hour volume.

(b) Assumed to be applicable for four-hour period.

(c) (DDHV)*4.

(d) (4-hour observed conflicts)*1000/VOLTOT

4.14.3 Crash-conflict ratios estimation

The crash-conflict ratios related to right-turn movements were determined based on the estimated crash-conflict ratios at study sites. First, the total number of conflicts, as shown in Table 4.48, over a period of five years, corresponding to the crash data years, at the study approaches was estimated using Equation (7). In order to do so, five-year average directional AADT was estimated at each survey approach by using the AADT datasets obtained from Mn/DOT for each crash data year. Percent right turns over the period of five crash data years at the study approaches was assumed to have the same values as observed over the length of field survey. Posted speed limits were obtained at sites and were verified over the length of data years through the speed datasets obtained from Mn/DOT. It was also made sure by using the videolog data maintained by Mn/DOT that the right-turn treatments at study approaches remained the same over the length of data years.

Next, the expected number of crashes due to right-turn movements during five-year study period, and the related crash-conflict ratios, at the study approaches were determined as presented in Table 4.49. The crash-conflict ratio estimates related to right-turn movements at shared and exclusive right-turn treatments are shown in Table 4.50. It is to be noted that ‘crash locations’ where crash due to right turns actually occurred were consciously included for field surveys in this study, because it was felt relevant to observe conflicts at such approaches. Therefore, it was inappropriate to use the actual number of right-turn related crashes reported at study locations in order to estimate the crash-conflict ratios related to right-turn movements. The use of probability estimates, presented in Table 4.34 and Table 4.43, of a crash was more appropriate to have unbiased estimates of the expected number of rear-end/sideswipe (same direction) crashes due to right-turn movements at a study location.

Table 4.48. Estimation of 5-year conflicts at study sites.

Site Code	Location (Intersection)	Study Approach	Hour of Obs.	Percent Right Turns[(a)]	Right-turn Treat.	Speed (mph)	Predicted Conflicts (per TEV)
R1	Aitkin (MNTH-210/CR-54 & CR-56)	MNTH-210, East	3	0.6	Radius	55	11
R2	Aitkin (MNTH-210/CR-54 & CR-56)	MNTH-210, West	7	1.9	Radius	55	13
R3	Dawson (US-212/4th St.)	US-212, East	4	2.1	Radius	30	8
R4	Dawson (US-212/4th St.)	US-212, West	4	0.4	Radius	30	5
R5	Staples (US-10/11th St. NE)	US-10, West	4	1.5	Radius	30	7
R6	Staples (US-10/12th St. NE)	US-10, East	4	7.3	Radius	30	16
R7	Staples (US-10/12th St. NE)	US-10, West	4	0.8	Radius	30	6
R8	Staples (US-10/Subway-Dairy Queen Drives)	US-10, West	4	0.2	Radius	30	5
L1	Forest Lake (US-61/250th St.)	US-61, North	11	2.6	Excl.	55	9
L2	Forest Lake (US-61/250th St.)	US-61, South	11	14.3	Excl.	55	17
L3	Lindstrom (MNTH-8/Akerson St.)	MNTH-8, West	4	8.0	Excl.	30	7
L4	Moorhead (US-75/46th Ave. S)	US-75, North	4	21.8	Excl.	55	23
L5	Ruthton (MNTH-23/CR-10)	MNTH-23, North	11	3.5	Excl.	55	10
L6	Ruthton (MNTH-23/CR-10)	MNTH-23, South	4	2.2	Excl.	55	9
L7	St. Bonifacius (MNTH-7/CR-10)	MNTH-7, East	5	15.7	Excl.	55	18
L8	St. Bonifacius (MNTH-7/CR-10)	MNTH-7, West	6	12.1	Excl.	55	16

(a) Percent right turns, assumed to be applicable over five years.

Table 4.49. Estimation of crash-conflict ratios related to right-turn movements.

Site Code (1)	Total 5-year Crash (2)	Average 5-year Directional AADT (3)	Total 5-year Conflicts (4)	Expected 5-year Crash involving Right-turning vehicle (5)	Expected 5-year Rear-end/Sideswipe Crash due to Right Turns (6)	Crash-Conflict Ratio (x 10^{-6}) (7)
R1	2	2,143	43,037	0.048	0.044	1.018
R2	2	2,143	51,514	0.048	0.044	0.850
R3	5	2,249	32,447	0.145	0.101	3.102
R4	5	2,249	20,469	0.145	0.101	4.918
R5	7	5,400	68,108	0.140	0.097	1.427
R6	6	5,400	161,668	0.120	0.083	0.515
R7	6	5,400	56,780	0.120	0.083	1.467
R8	2	5,400	45,776	0.040	0.028	0.607
L1	8	5,133	83,484	0.128	0.076	0.910
L2	8	5,133	161,901	0.128	0.076	0.469
L3	2	8,534	111,721	0.040	0.018	0.162
L4	1	2,083	86,211	0.024	0.014	0.165
L5	2	1,655	28,852	0.048	0.029	0.988
L6	2	1,655	25,847	0.048	0.029	1.103
L7	18	4,228	141,293	0.432	0.257	1.815
L8	18	4,228	121,337	0.432	0.257	2.114

(2) All reported multiple vehicle crashes during five years (excluding crashes involving parked vehicles, bikes, motor cycles, and vehicles backing up).

(3) Considered 50% of the average five-year AADT.

(4) Conflicts over five-year period, estimated as (Predicted conflicts per TEV)*(Average 5-year directional AADT)*5*365/1000. The 'time of day' and the 'day of week' were not significant in crashes involving vehicles turning right from two-lane major road at unsignalized intersections and driveways.

(5) Estimated as column (2)*(Probability of crash from Table 4.34).

(6) Estimated as column (5)*(Probability of crash from Table 4.43).

(7) Estimated as column (6) / column (4).

Table 4.50. Crash-conflict ratio estimates related to right-turn movements.

Right-turn Treatment	Number of Observation	Crash-Conflict Ratio (x 10^{-6})			
		Mean	St. Dev.	SE Mean	95% CI
Shared	8	1.738	1.522	0.538	(0.465, 3.011)
Exclusive	8	0.966	0.717	0.253	(0.367, 1.565)

4.15 Safety effectiveness of a right-turn lane

4.15.1 At intersections

The crash-conflict ratios estimated in this paper may be used to estimate the rear-end/sideswipe (same direction) crashes at shared right-turn treatment and exclusive right-turn lane. In order to determine the overall safety effectiveness of a right-turn lane, taking into account all types of crash, a crash estimation factor (CEF) was determined as the ratio of crash-conflict ratio to the probabilities of rear-end/sideswipe (same direction) crash presented in Table 4.43. The CEFs at different conditions are presented in Table 4.51.

Table 4.51. Crash estimation factors.

Speed	**Right-turn Treatment Type**	**CEF ($x\ 10^{-6}$)**
Low	Radius	2.503
Low	Exclusive	2.137
High	Radius	1.904
High	Exclusive	1.627

The overall safety effectiveness of a right-turn lane was estimated by determining the expected number crashes involving right-turning vehicles using Equation (4.19) and the CEFs shown in Table 4.51. The expected number of crashes and crash savings per year at different percent right turns, AADT and speed at an exclusive right-turn lane over a shared right-turn treatment at an intersection approach is shown in Figures 4.35 – 4.40.

$$X = C^{*}(CEF), \qquad \ldots (4.19)$$

where

X – Expected number of crash involving right-turning vehicles per TEV;

C – Expected number of right-turn, same-direction including the associated secondary conflicts per TEV, and

CEF – Crash estimation factor taken from Table 4.51.

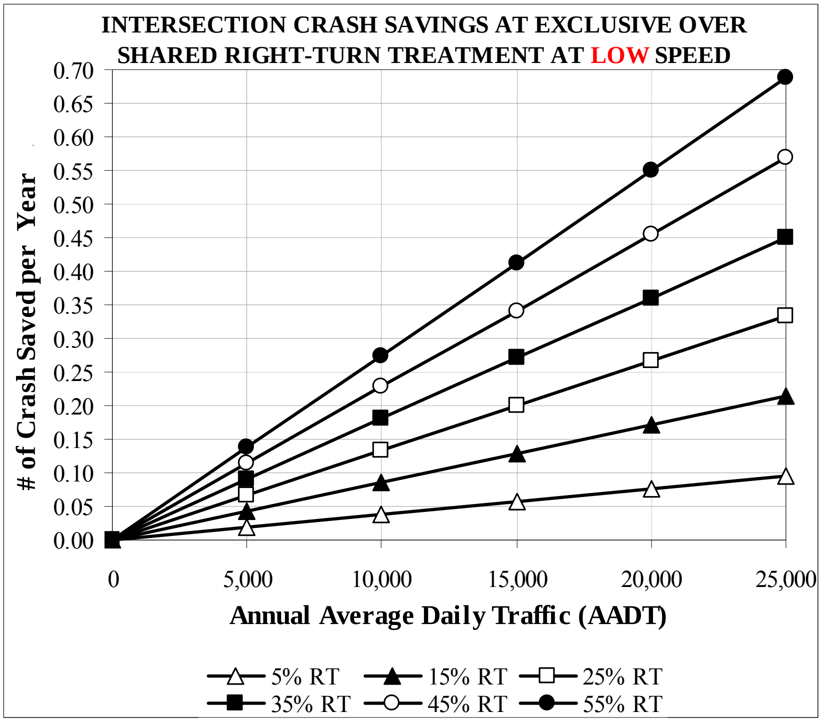


Figure 4.35. Right turn crashes saved at exclusive over shared right turn movement at low speed.

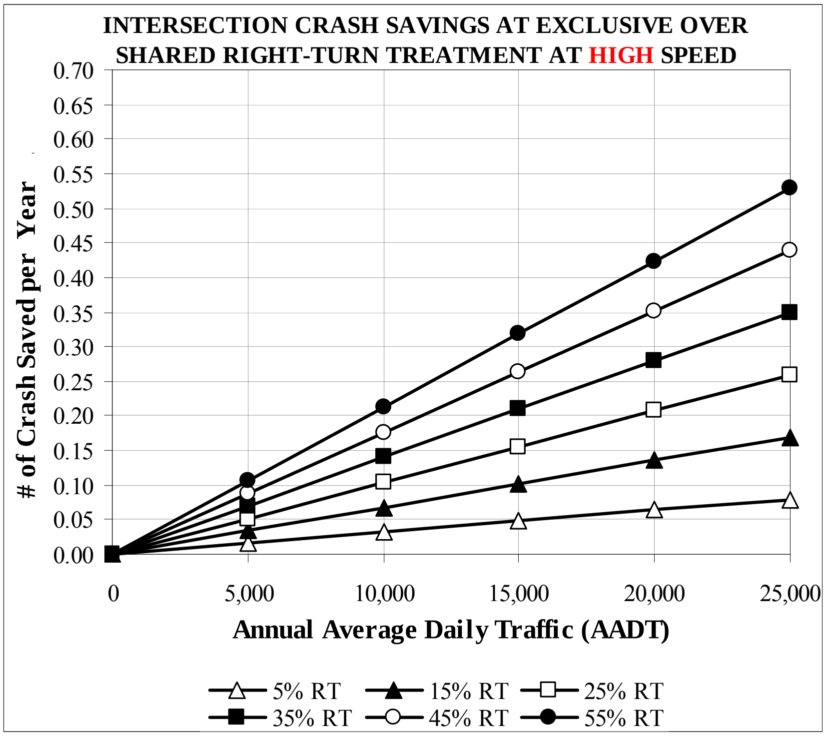


Figure 4.36. Right turn crashes saved at exclusive over shared right turn movement at high speed.

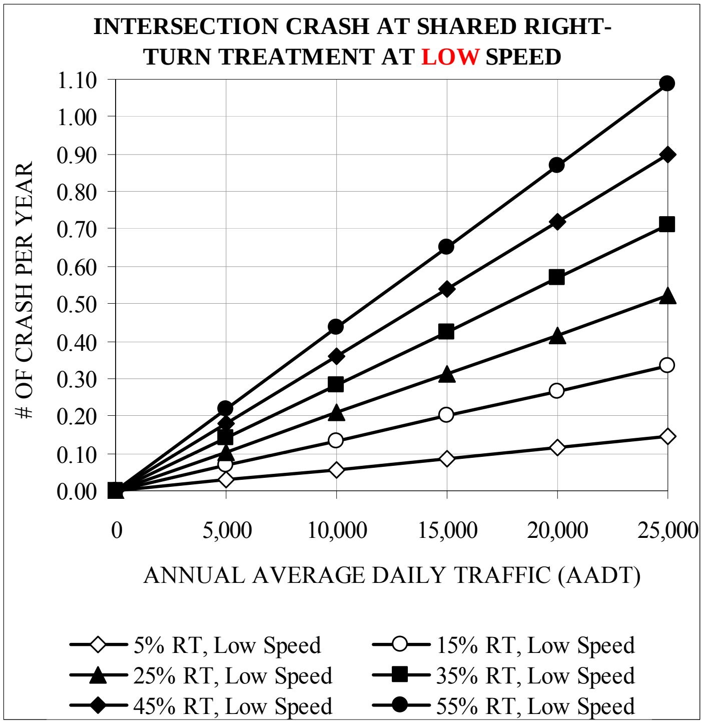


Figure 4.37. Right turn crashes per year at shared right turn movement at low speed.

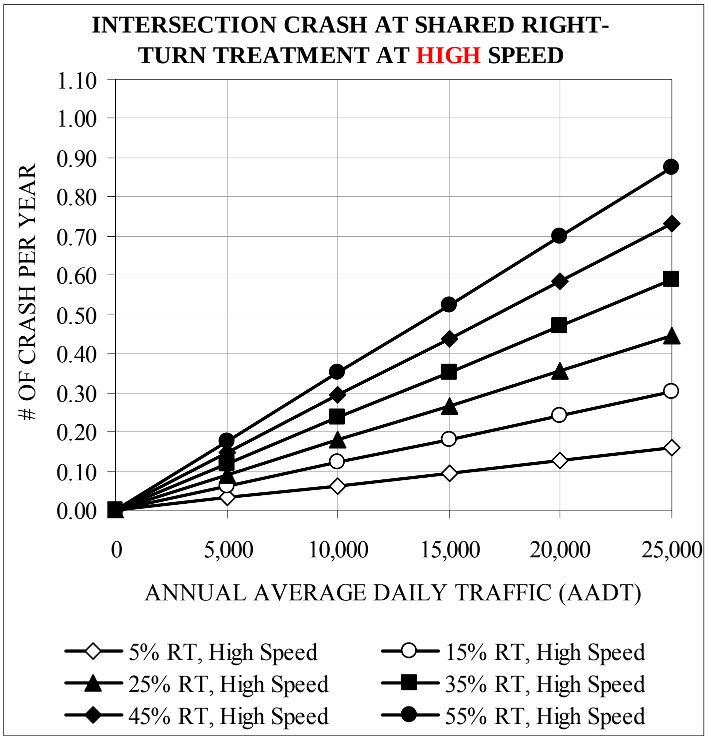


Figure 4.38. Right turn crashes per year at shared right turn movement at high speed.

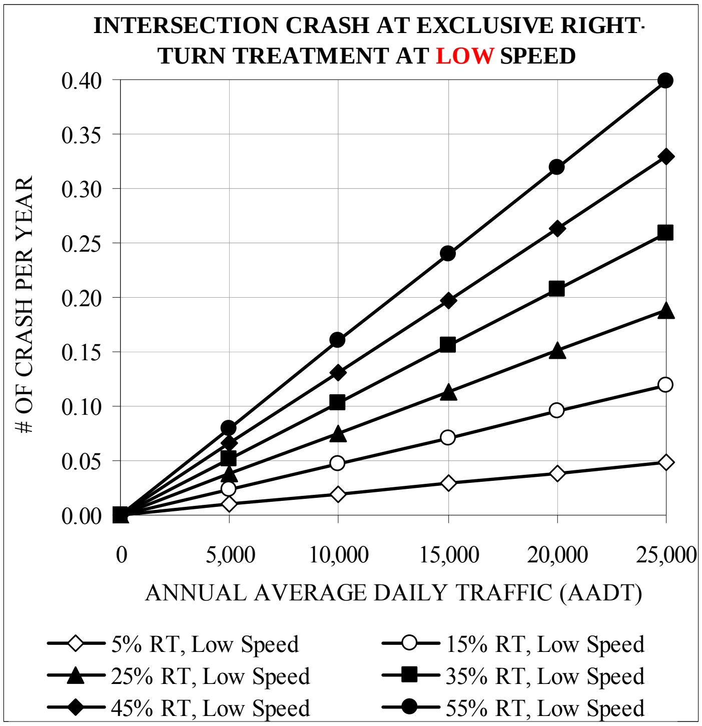


Figure 4.39. Right turn crashes per year at exclusive right turn movement at low speed.

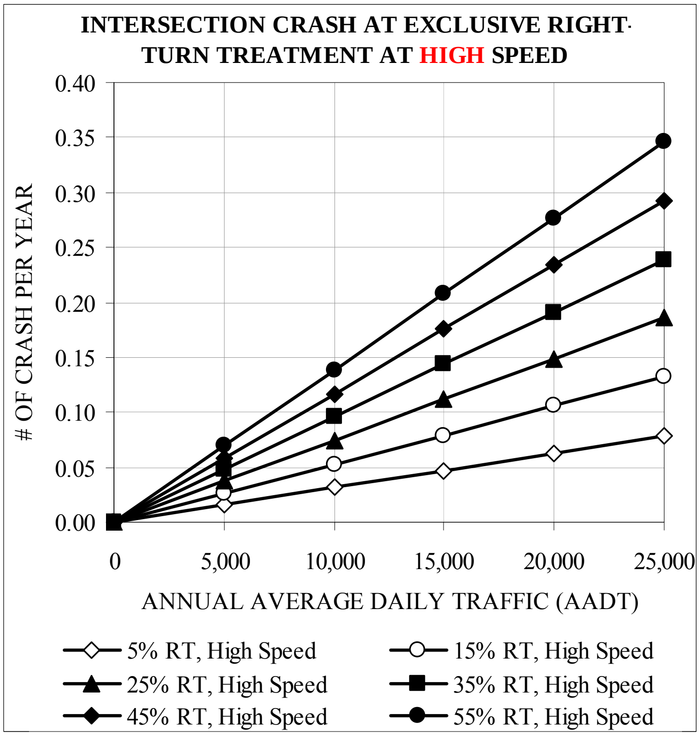


Figure 4.40. Right turn crashes per year at exclusive right turn movement at high speed.

4.15.2 At driveways

The safety effectiveness of a right-turn lane at an approach to a driveway was determined by applying the relative risks of a rear-end crash at driveways, presented in Table 4.44, to the crash estimates at intersection approaches. The expected number of crahes and crash savings at different percent right turns, AADT and speed at an exclusive lane over shared treatment at an approach to a driveway are shown in Figure 4.41 through 4.46.

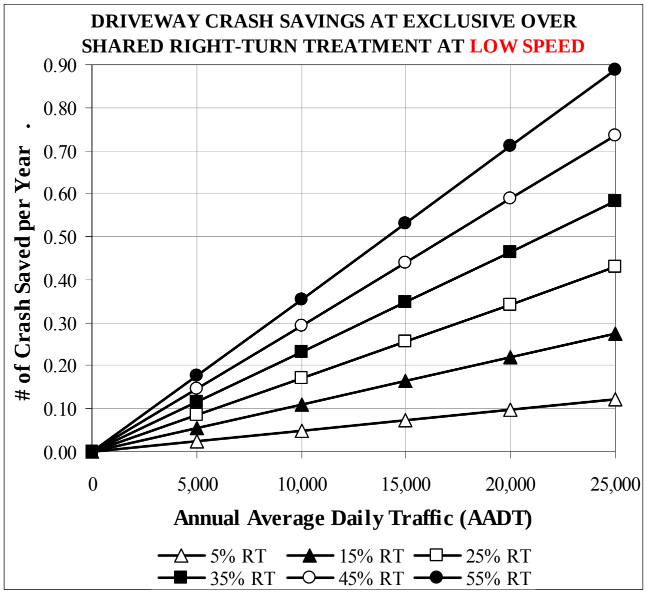


Figure 4.41. Driveway crash savings at low speed.

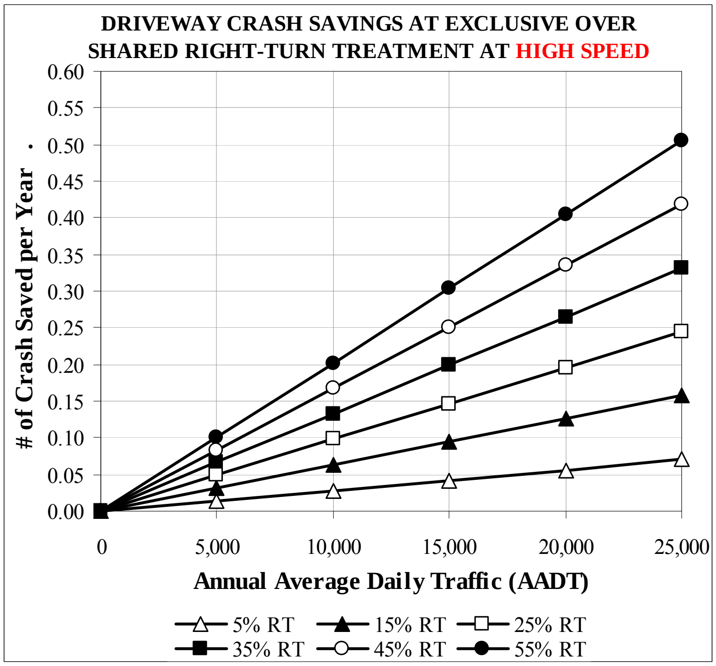


Figure 4.42. Driveway crash savings at high speed.

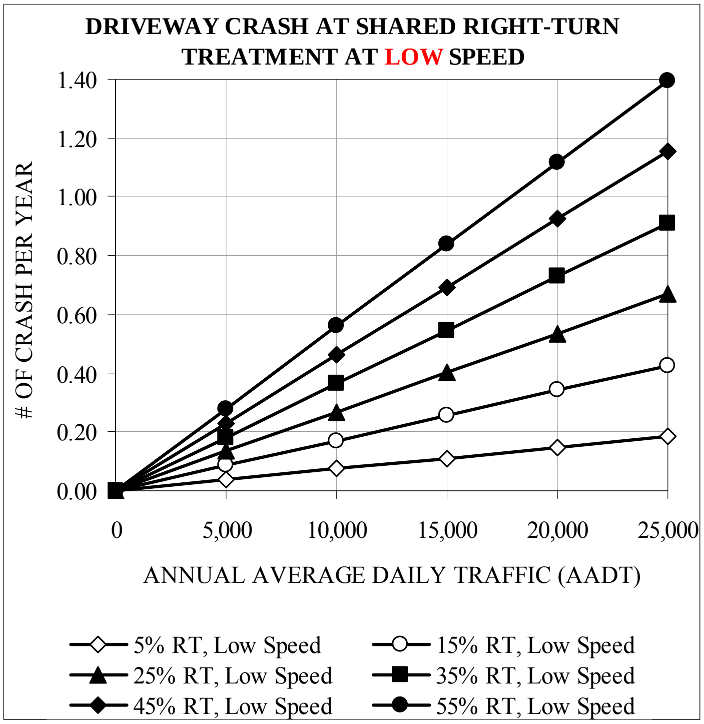


Figure 4.43. Driveway crash savings at shared right turn movement at low-speed.

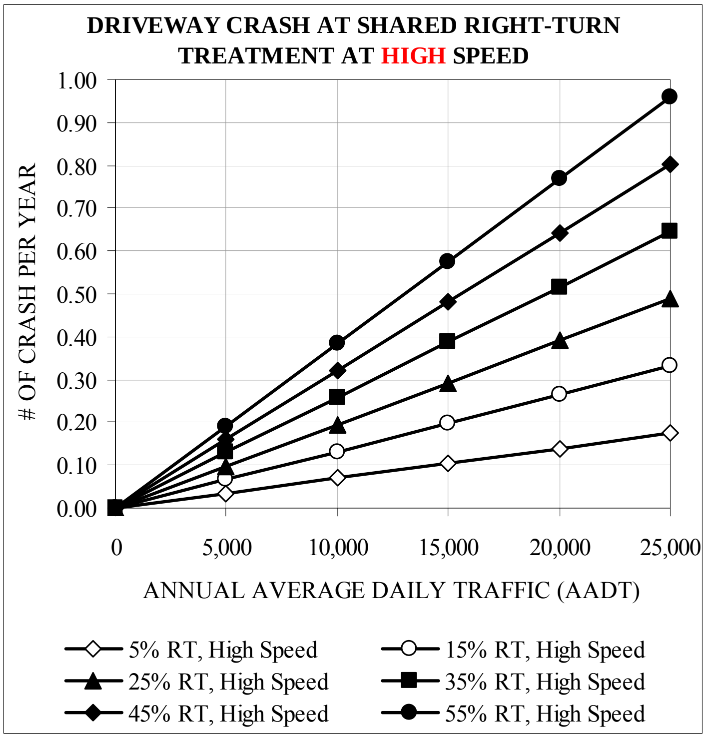


Figure 4.44. Driveway crash savings at shared right turn movement at high-speed.

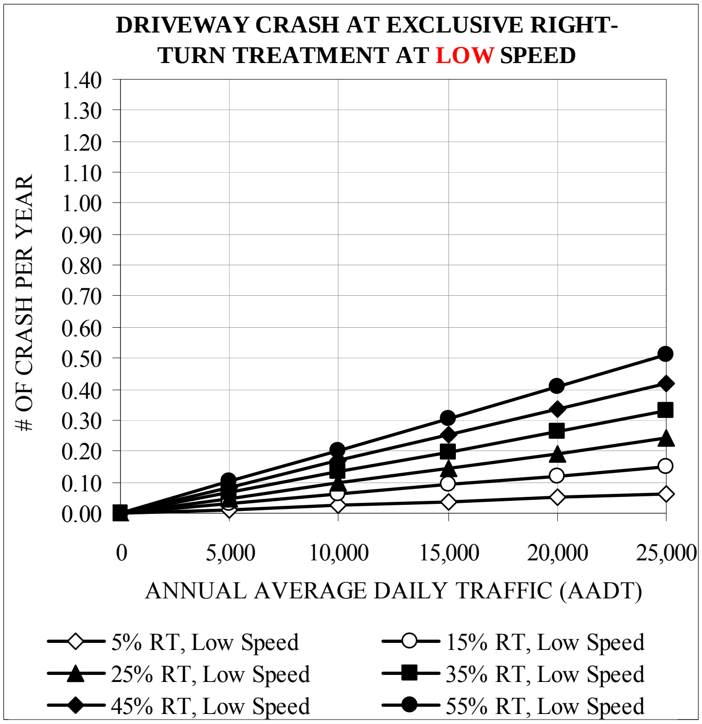


Figure 4.45. Driveway crash savings at exclusive right turn movement at low-speed.

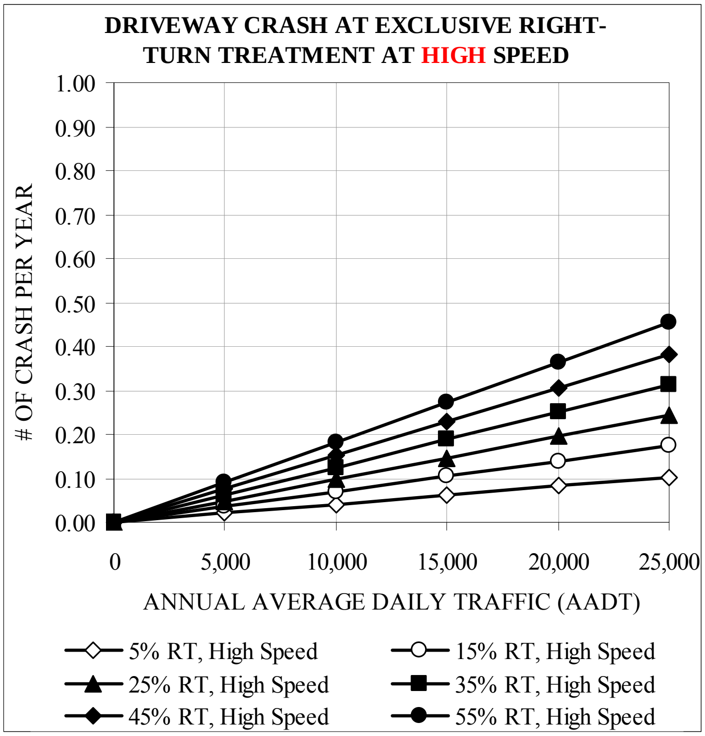


Figure 4.46. Driveway crash savings at exclusive right turn movement at high-speed.

Chapter 5 Operational Analyses

5.1 Operational analysis approach

Operational impact analysis and assessment were done to determine the delay to through vehicles due to right turning vehicles and the excess fuel consumed because of the same. The analysis and assessments were done using simulation software and statistical analysis. The basic steps involved in the approach are described in the following sub-sections.

5.1.1 Understanding the context

Shared right-turn movement not only increases delays and fuel consumption, but it also makes intersections more vulnerable to traffic crashes and environmental pollution. The number and nature of conflict points, and the extent of the areas of conflict, are greatly influenced by right-turning vehicles. The overall assessment of a right-turn lane looks at both safety and operational perspectives. In this regard, this study has a good connection with the safety aspect as well. Hence, in the data collection process, common locations were chosen for both safety and operational impact studies in an aim to identify the significance of factors related to them for developing corresponding models for assessing the effectiveness of right-turn lanes.

In terms of the type of intersections, both 3-legged and 4-legged intersections were taken into account for this study. It was also determined that these intersections had no controls on major approach. The driving phenomena for 3-legged and 4-legged intersections were same in some respects and different in other respects. The essential difference was existence of left turn movements. The ranges of speed and volume studied were consistent with what was found for such contexts in the accident database, as well as in intersection inventory files. In this study, right-turn lane configurations were analyzed as rght-turn pocket length in CORSIM® and were analyzed for 0 ft, 100 ft, 200 ft, 300 ft, 400 ft, 480 ft, and 500 ft.

5.1.2 Base model development

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.

5.1.3 Data collection

After performing some simulations on the base model, the data collection plan was prepared. The locations were selected randomly from 5,400 intersections in the intersection inventory files obtained from MN DOT. These locations were identified as covering a broad range of conditions and were spread all over the state of Minnesota. As mentioned earlier, the plan was to include all four categories of intersections: high volume-high speed, high volume-low speed, low volume-high speed, and low volume-low speed. Depending upon traffic conditions, especially right-turn volumes, data was collected from both approaches (in the case of 4-legged intersections) and some from only one approach of the intersection (for 3-legged intersections). Morning and evening peak hours were selected for collecting time-stamp data as well as speed and volume data. The physical inventory of each 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.

5.1.4 Data processing

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.

5.1.5 Simulation model calibration

After a careful study of the data, intersections were selected for calibration. From the list of shared 3- legged intersections, Moorhead-3, Lowry, and Forest Lake were chosen. In the case of 3- legged intersections with exclusive treatment, Moorhead-1, Park Rapids, and Lindstorm were selected. Similarly from the list of 4- legged intersections, Aitkin, and Dawson, as shared 4-legged, and Ruthton and St. Bonafacious, as exclusive 4-legged intersections, were selected. A sensitivity analysis was performed on the base models to assess the sensitivity of the parameters needed for calibration. The base models were re-networked with the respective dimensions of the intersections. The corresponding field-measured input variables were entered into the networks. The four calibrated base models of Moorhead-1, Moorhead-3, Aitkin, and St. Bonafacious were matched with other intersections.

5.1.6 Analysis and performing simulations

Assigning the levels of variables is an important task in simulation. On the basis of the literature review and the preliminary exploratory analysis using the base model, the input variables were selected and assigned appropriate levels. A total of 2450 combinations were simulated. Ten runs were selected for each combination. Thus, a total of 24,500 simulations were performed. The calibrated models were so adjusted to make the configuration of the link length, with the treatment, 800 ft. The length of the turn pocket was set to 0 ft, 100 ft, 200 ft, 300 ft, 400 ft, 480 ft, and 500 ft. Network files for each combination were replicated and assigned with the variables from the combination. Simulations were then performed. The output files generated from the CORSIM® software were stored in respective folders, and a computer program was developed using SAS® software to read the required output values. Data processing was performed to compute average values of delay and fuel consumption.

5.1.7 Examination of simulation results

The graph plots were made with delay and fuel consumptions on the Y-axis versus volumes on the X-axis for different right-turn percentages corresponding to particular speed values. Analysis was done for the nature of variation of delay and fuel consumption with respect to volumes. This analysis was important as it explained the performance of shared and exclusive right-turn treatments with respect to different approach traffic volumes at different levels of right-turning volumes at a particular speed. The analysis was made for high-speed and low-speed conditions for both 3-legged and 4-legged intersections.

5.1.8 Statistical analysis and model development

To assess the nature of the relationship between the dependent variables, delay and fuel consumption, with the independent variables as speed, volumes and the percentage of right-turn lane, the statistical methods were used. Multiple regression method was used to develop relationships and 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.

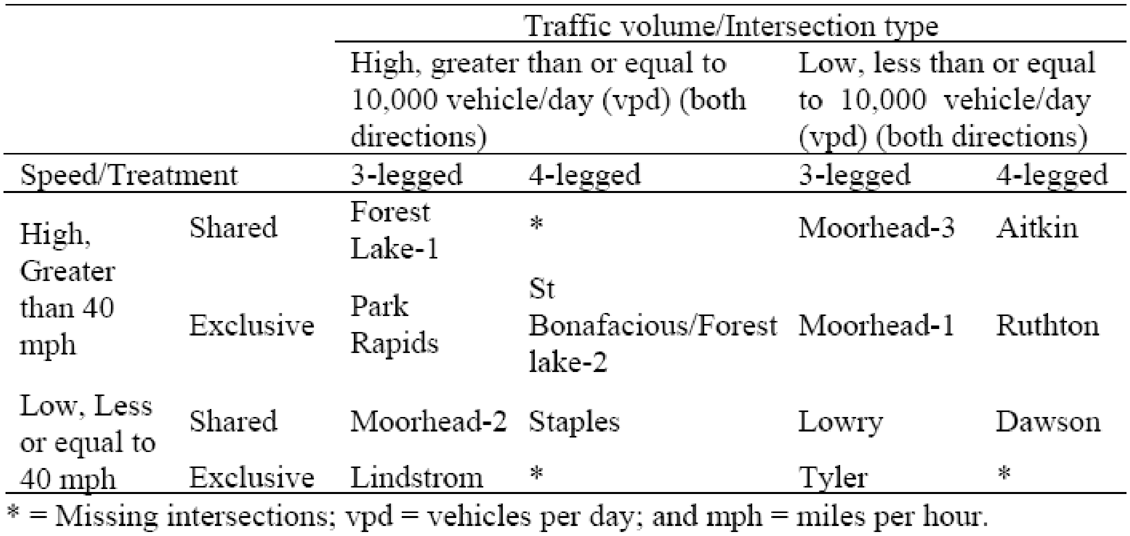
5.2 Field data collection

Field site were selected such as to cover broad range of conditions that were relevant of the right turn lane contexts. Data were obtained at 13 intersections as described in detail in previous chapter. Traffic volume, spot speed, and time stamp data at each of these 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. Data were collected using radar speed device, JAMAR TDC-12, laptops with Traffic Tracker software, and using visual observation.

5.2.1 Strategy

The strategy was made to collect data on a wide basis so that a broad range of conditions for different scenarios in Minnesota could be studied. The site locations were chosen randomly all over Minnesota. Data were collected from the unsignalized approach of the main street for both 4-legged and 3-legged intersections. Furthermore, the division was done according to volumes and speeds. Volumes greater than 1,000 vehicles per day (vpd) and speed greater than 40 mph were considered high. Four categories were made: high volume-high speed, high volume-low speed, low volume-high speed, and low volume-low speed intersections. Each category has subcategories for shared and exclusive right-turn treatment. Table 5.1 represents the divisions in detail with the name of the locations surveyed.

Table 5.1. Division of intersections for data collection.



		Traffic volume/Intersection type			
		High, greater than or equal to 10,000 vehicle/day (vpd) (both directions)		Low, less than or equal to 10,000 vehicle/day (vpd) (both directions)	
Speed/Treatment		3-legged	4-legged	3-legged	4-legged
High, Greater than 40 mph	Shared	Forest Lake-1	*	Moorhead-3	Aitkin
	Exclusive	Park Rapids	St Bonafacious/Forest lake-2	Moorhead-1	Ruthton
Low, Less or equal to 40 mph	Shared	Moorhead-2	Staples	Lowry	Dawson
	Exclusive	Lindstrom	*	Tyler	*

* = Missing intersections; vpd = vehicles per day; and mph = miles per hour.

5.2.2 Detailed methodology for data collection

The main purpose of the data collection was to fulfill the data requirement for calibration and field validation of the simulation models. The plan was based upon ideas obtained from the exploratory analysis of preliminary based model simulations and the literature review. Time stamp data provides volumes and the space mean speed of the vehicles when processed. In order to record the time stamp data, three locations A, B, and C were chosen, as shown in Figure 5.1, for the intersection with an exclusive right-turn lane. For shared case, time stamps were recorded at two locations, A and B, as shown in Figure 5.2. The observation point A, in both cases, is the point at the stop line of the intersections. Point B in case of exclusive case is the beginning of the taper. Hence, the distance from A to B is the length of the right-turn lane. Point C is located 200 ft. from point B. For shared case, point B is 500 ft. apart from point A; the lesser distance was considered in cases where a 500 ft. distance was not feasible. Free-flow speed data was recorded from the points at a distance from the intersection where vehicles can be visually observed as being unimpeded. In general, these points were located more than 600 ft. from the intersection, if it was feasible by intersection geometry.

For time stamp data collection, TDC-12 was used. TDC-12 records time stamps as well as vehicle counts. In some locations, laptops with software developed to record the time stamps were also used for the same purpose. For the measurement of spot speeds, a radar gun was used. The data was collected between 7-11 A.M. and between 2-6 P.M. One to one and a half hour period time stamps were recorded.

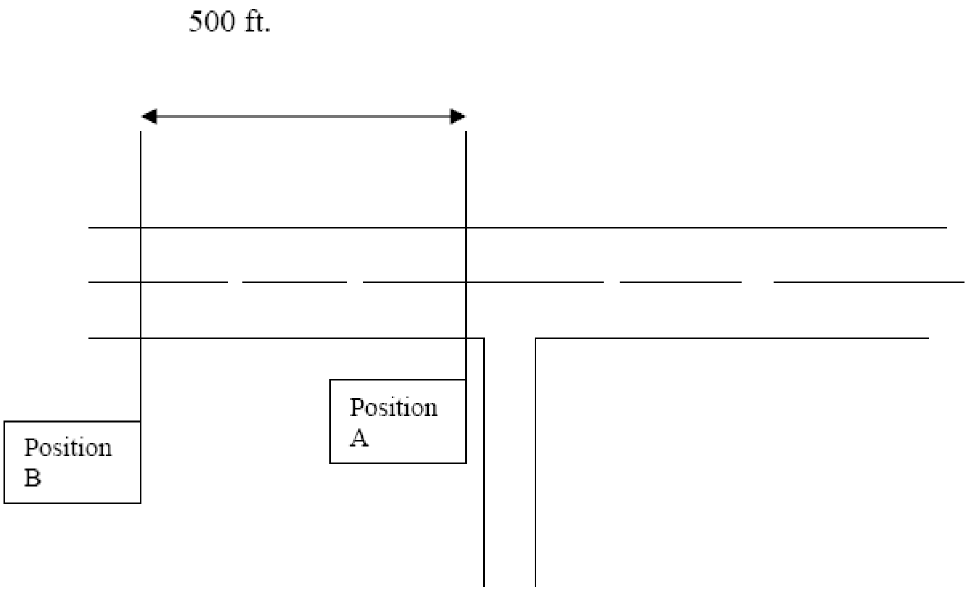


Figure 5.1. Uncontrolled approach on a two-lane roadway without a right-turn lane.

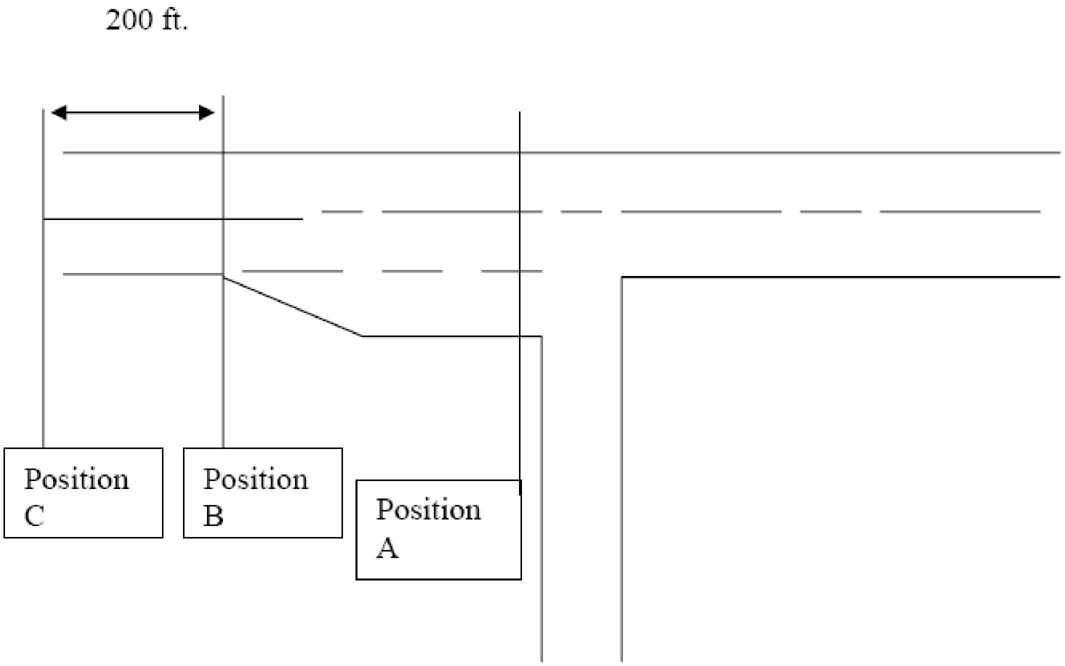


Figure 5.2. Uncontrolled approach on a two-lane roadway with a right-turn lane.

5.2.3 Data processing

Data processing includes the steps involved in the processing of lane geometry data, records from TDC-12, a traffic tracker, and the radar gun to make them readily usable for calibration and validation purposes. Lane geometry data was recorded from the site and compiled with intersection drawings. Later, the data was tabulated making it readily usable for developing base models for calibration and validation purposes. The Lane geometry corresponds to the Table 5.2.

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 arithmetic means. 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 as shown in Table 5.3. Although all the spot speed data were not used later in the study, the records were maintained in an organized way.

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 a file type 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 in Figures 5.1 and 5.2. The data were processed to calculate the travel time for all vehicles, the respective travel time 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-minute as well as seconds per through vehicles. Table 5.4 corresponds to the sample record of space mean speeds.

- Time for travel (B to A) = Time stamp at B – Time stamp at A
- Time for travel (C to A) = Time stamp at C – Time stamp at A
- Total time for travel for through vehicles = Summation of individual times of travel of all through vehicles
- Total time for travel for right-turning vehicles = Summation of individual time of travel of all right-turning vehicles
- Total time for travel for through vehicles in free-flow speed = (link length/ free-flow speed) * Number of through vehicles
- 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
- Delay (veh-min) for through vehicles = Total time of travel for through vehicles – Total time for travel for through vehicles in free-flow speed
- Delay (secs/through vehicles) = (Delay (veh-min) * 60)/ Number of through vehicles

Table 5.2. Turn lane geometry.

		Length of right-turn lane (feet)			
Locations	Approach	Taper	Full width	Total	Junction of
Aitkin	NB	Not Applicable			
	SB				M210/CR-54/CR-56
Forest Lake-1	SB	Not Applicable			U61/240th St
Lindstrom	EB	173	188	361	M8/Akerson St.
St. Bonafacious	WB	200	240	440	M7/CR-10
Ruthton	NB	180	280	460	
	SB	186	276	462	M23/CR-10
Tyler	WB	75	160	235	U14/CR-8
Lowry	EB	Not Applicable			M55/CR-114
Dawson	EB	Not Applicable			U212/4th Street
St. Bonafacious	EB	180	250	430	M7/CR-10
Forest Lake-2	NB	200	240	440	U61/250th St
	SB	185	280	465	
Staples	EB	Not Applicable			U10/11th St.NE
	WB	Not Applicable			U10/Subway-Dairy Queen Driveway
Park Rapids	SB	157	142	299	M34/CR-4
Moorhead-1	SB	170	240	410	U75/46th Ave. S.
Moorhead-2	EB	Not Applicable			12 Ave/15th St
Moorhead-3	NB	Not Applicable			24 Ave N/ 34 St N

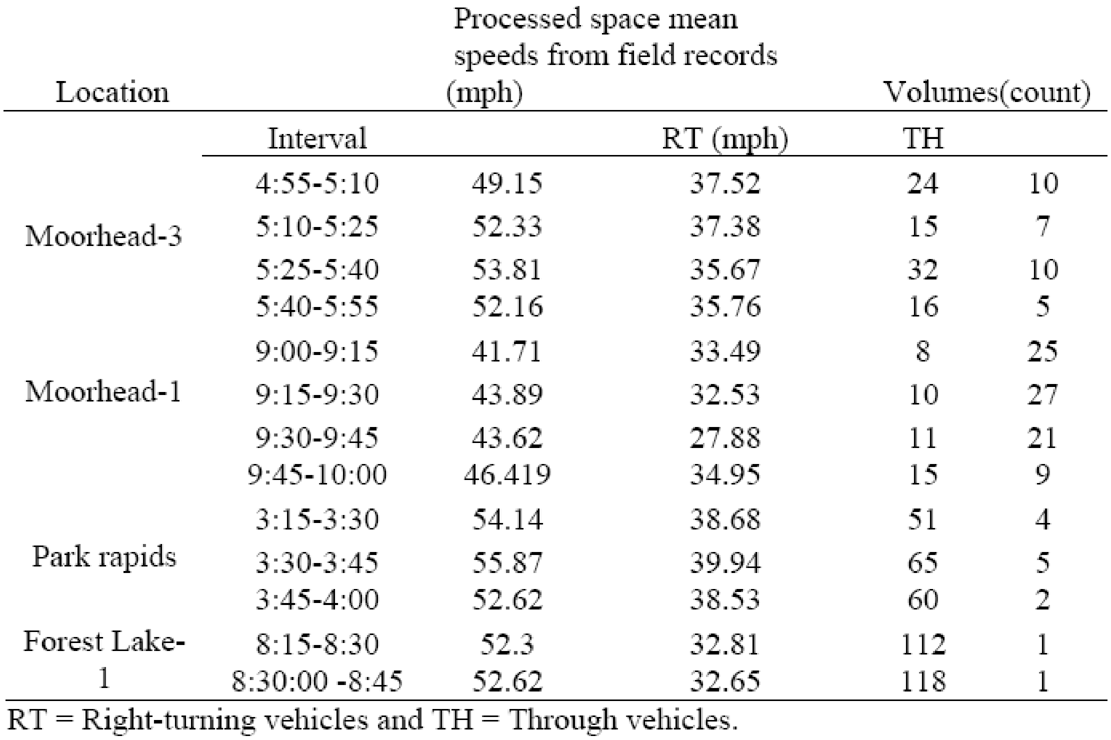
NB = Northbound; SB = Southbound; EB = Eastbound; and WB = Westbound.

Table 5.3. Spot speeds at different locations.

Locations		A(TH) (mph)	A(RT and TH combined) (mph)	B (mph)	C (mph)	RT-turn speed (mph)
Atkins	NB	57.818	57.818	58.97		
	SB	58	58	57.075		
Forest Lake-1	SB	53.967	52.54	54.105		9
Lindstrom	EB	38.119		34.23	34.66	22.08
St. Bonafacious	WB	57.26		56.2	53.82	18.86
Ruthton	NB	59.425		60.8	60.54	13
	SB	58.67		58.26		12.22
Tyler	WB	39.86	35.71	37	34.2	15.67
Lowry	EB	34.75	23.65	37.64		15.75
Dawson	EB	30.049	30.049	27.875		
St. Bonafacious	EB	56.525		50.6375		15.8
Forest Lake-2	NB	54.9875		53.86	54.086	14
	SB	52.07		48.056	54.0778	12.14
Staples	EB	29.23	26.7(also including LT)			13.69
	WB	30.024	30.024	30.6625(TH)	31.75(TH)	B-7.9,C-19
Park Rapids	SB	52.71	45.297	51.2875	54.7	15.25
Moorhead-1	SB	47.915	44.516	42.04		14.33
Moorhead-2	EB	27.52	27	19.7		11
Moorhead-3	NB	51.0625	44.144	49.45		15

RT = Right-turning vehicles; TH = Through vehicles; LT = Left-turning vehicles; NB = Northbound; SB = Southbound; EB = Eastbound; and WB = Westbound.

Table 5.4. Sample table for space mean speeds.



Location		Processed space mean speeds from field records (mph)		Volumes(count)	
	Interval		RT (mph)	TH	
Moorhead-3	4:55-5:10	49.15	37.52	24	10
	5:10-5:25	52.33	37.38	15	7
	5:25-5:40	53.81	35.67	32	10
	5:40-5:55	52.16	35.76	16	5
Moorhead-1	9:00-9:15	41.71	33.49	8	25
	9:15-9:30	43.89	32.53	10	27
	9:30-9:45	43.62	27.88	11	21
	9:45-10:00	46.419	34.95	15	9
Park rapids	3:15-3:30	54.14	38.68	51	4
	3:30-3:45	55.87	39.94	65	5
	3:45-4:00	52.62	38.53	60	2
Forest Lake-1	8:15-8:30	52.3	32.81	112	1
	8:30:00 -8:45	52.62	32.65	118	1

RT = Right-turning vehicles and TH = Through vehicles.

5.3 Modeling and simulation

CORSIM® was used to model and simulate right-turn movements under various conditions. The specific steps involved were preliminary base model development, model calibration, performing simulations, and processing outputs from over 24,500 simulation runs. Figure 5.3 illustrates the various steps and how they interlink.

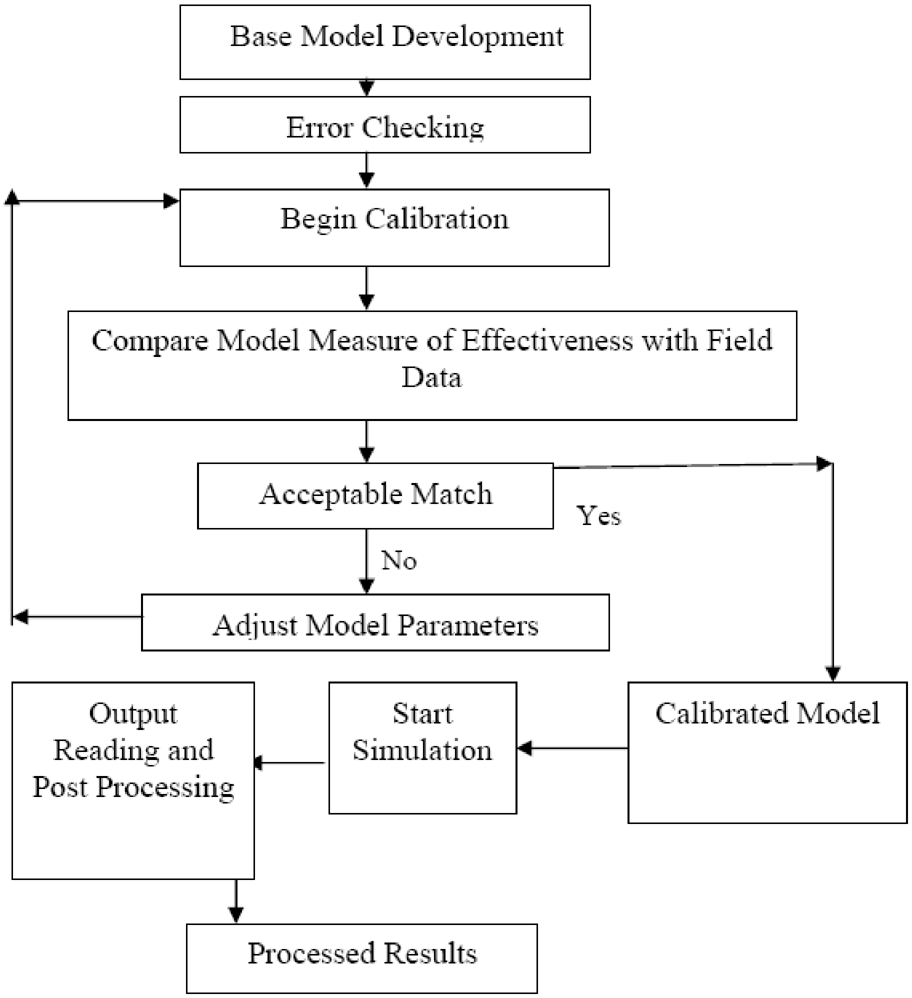


Figure 5.3. Flow chart for modeling and simulation process.

5.3.1 Base model development and preliminary investigation

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 Figures 5.4 and 5.5. The main purpose of the preliminary models was to carryout the exploratory analysis that could aid in the later parts of the study.

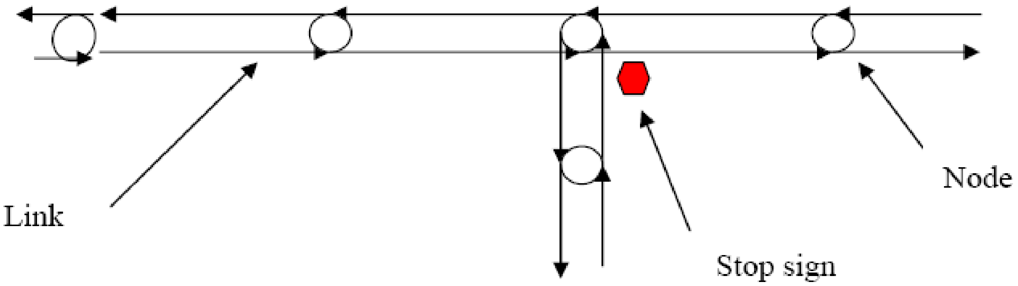


Figure 5.4. Link-node diagram in CORSIM® for 3-legged intersections.

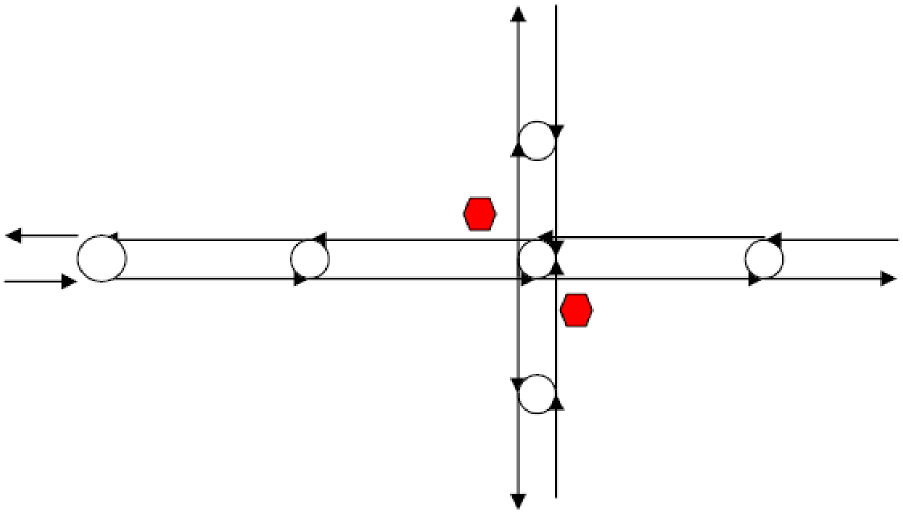
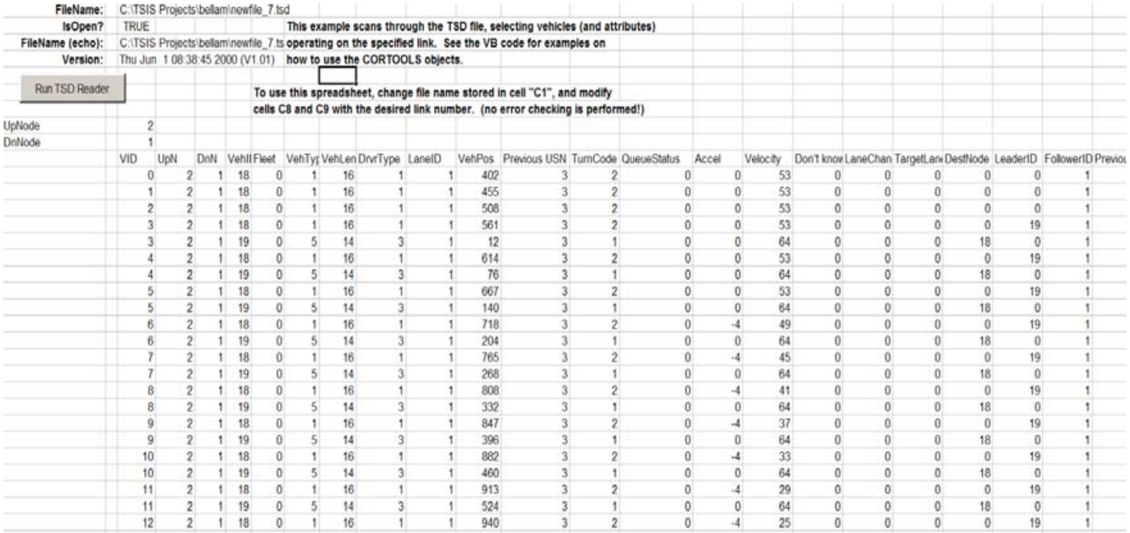


Figure 5.5. Link-node diagram in CORSIM® for 3-legged intersections.

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.

It was felt necessary to understand the car following logic behind the simulation. For this specific purpose, the Time Step Data (TSD) files generated during simulation runs were retrieved using the codes developed by Dr. John Leonard from the Georgia Institute of Technology. The sample is shown in Figure 5.6. The TSD files are binary files known as time step data, which gives vehicle trajectory data as positions, velocities and accelerations, according to the driver and vehicle type, and corresponds to each time step of one second.



FileName: C:\TSIS Projects\bellam\newfile_7.tsd
IsOpen? TRUE **This example scans through the TSD file, selecting vehicles (and attributes)**
FileName (echo): C:\TSIS Projects\bellam\newfile_7.ts **operating on the specified link. See the VB code for examples on**
Version: Thu Jun 1 08:38:45 2000 (V1.01) **how to use the CORTOOLS objects.**

To use this spreadsheet, change file name stored in cell "C1", and modify
cells C8 and C9 with the desired link number. (no error checking is performed!)

UpNode 2
DnNode 1

VID	UpN	DnN	VehII	Fleet	VehTy	VehLen	DrvrType	LaneID	VehPos	Previous USN	TurnCode	QueueStatus	Accel	Velocity	Don't know	LaneChan	TargetLan	DestNode	LeaderID	FollowerID	Previou
0	2	1	18	0	1	16	1	1	402	3	2	0	0	53	0	0	0	0	0	1	
1	2	1	18	0	1	16	1	1	455	3	2	0	0	53	0	0	0	0	0	1	
2	2	1	18	0	1	16	1	1	508	3	2	0	0	53	0	0	0	0	0	1	
3	2	1	18	0	1	16	1	1	561	3	2	0	0	53	0	0	0	0	19	1	
3	2	1	19	0	5	14	3	1	12	3	1	0	0	64	0	0	0	18	0	1	
4	2	1	18	0	1	16	1	1	614	3	2	0	0	53	0	0	0	0	19	1	
4	2	1	19	0	5	14	3	1	76	3	1	0	0	64	0	0	0	18	0	1	
5	2	1	18	0	1	16	1	1	667	3	2	0	0	53	0	0	0	0	19	1	
5	2	1	19	0	5	14	3	1	140	3	1	0	0	64	0	0	0	18	0	1	
6	2	1	18	0	1	16	1	1	718	3	2	0	-4	49	0	0	0	0	19	1	
6	2	1	19	0	5	14	3	1	204	3	1	0	0	64	0	0	0	18	0	1	
7	2	1	18	0	1	16	1	1	765	3	2	0	-4	45	0	0	0	0	19	1	
7	2	1	19	0	5	14	3	1	268	3	1	0	0	64	0	0	0	18	0	1	
8	2	1	18	0	1	16	1	1	808	3	2	0	-4	41	0	0	0	0	19	1	
8	2	1	19	0	5	14	3	1	332	3	1	0	0	64	0	0	0	18	0	1	
9	2	1	18	0	1	16	1	1	847	3	2	0	-4	37	0	0	0	0	19	1	
9	2	1	19	0	5	14	3	1	396	3	1	0	0	64	0	0	0	18	0	1	
10	2	1	18	0	1	16	1	1	882	3	2	0	-4	33	0	0	0	0	19	1	
10	2	1	19	0	5	14	3	1	460	3	1	0	0	64	0	0	0	18	0	1	
11	2	1	18	0	1	16	1	1	913	3	2	0	-4	29	0	0	0	0	19	1	
11	2	1	19	0	5	14	3	1	524	3	1	0	0	64	0	0	0	18	0	1	
12	2	1	18	0	1	16	1	1	940	3	2	0	-4	25	0	0	0	0	19	1	

Figure 5.6. Snapshot of TSD data retrieved in Excel□ using the codes developed by John Leonard.

Figure 5.7 corresponds to the effect of right-turning vehicles to the following through vehicles plotted with data from the TSD file corresponding to DDHV=1000 vph and speed= 51.3 ft/sec. This is a plot based upon the simulation of the preliminary base model with a shared treatment and the link length of 1,000 ft. run with default values. From the plot, it is clear that the effect of deceleration of the lead right-turning vehicle (RT), during the right-turn maneuver, is transmitted to the following through vehicles Fv-1 and Fv-2. Both following vehicles return back to their original speed after attaining some minimum velocities when the effect of right-turning vehicle is no more.

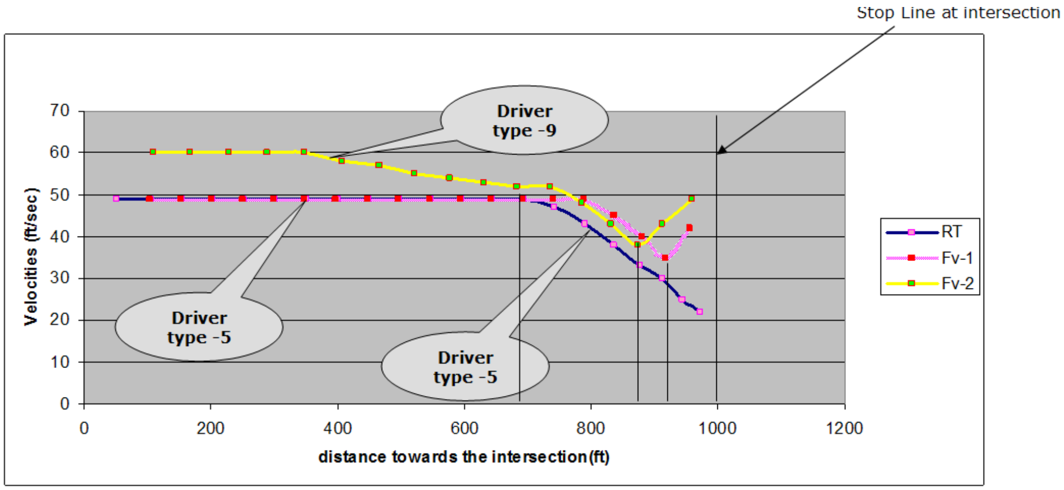
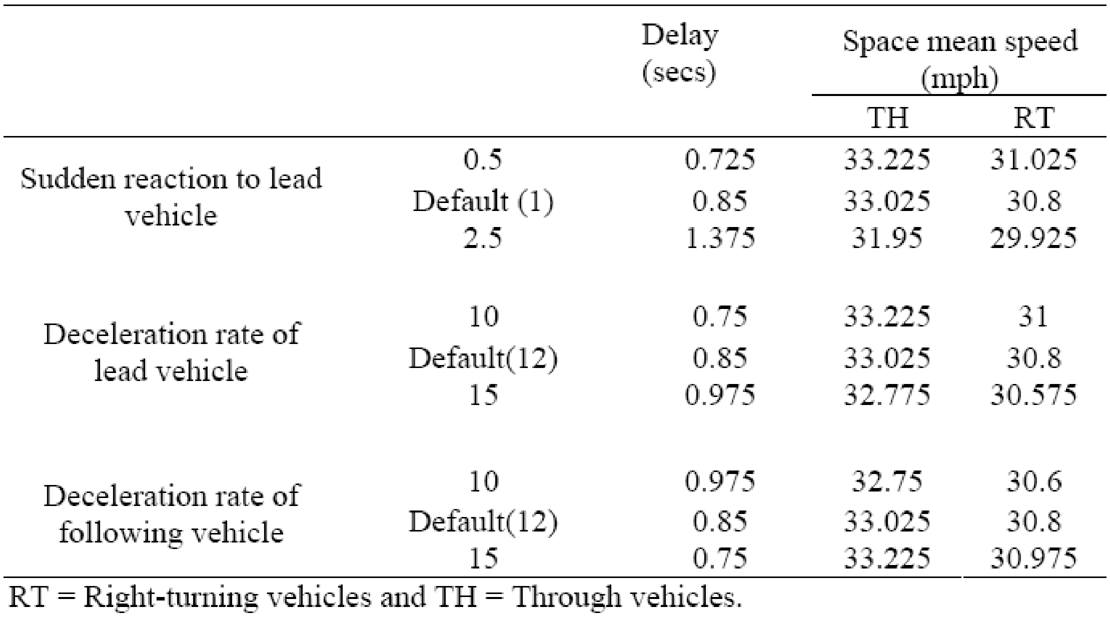


Figure 5.7. Velocity differential exhibited by following-through vehicles due to right-turning vehicles.

The preliminary base models were also useful in making the data collection plan as they provided information about the type of data that needed to be collected and positions where observations were to be made. The sensitivity analysis performed on different parameters on uncalibrated models helped in identifying the key parameters that needed to be altered for model calibration. Table 5.5 corresponds to a sample sensitivity analysis. A couple of trial runs were made, altering the initialization period. It was found that the equilibrium could be achieved when the initialization period was 4 minutes or more. On that basis, the initialization period was fixed at 5 minutes or more. To find out the minimum number of runs required, trials were made using the equation provided by the CORSIM® guide, which was based on variance and expected error. Since the variance could change in each set of input variable combinations, the minimum required run would vary from case to case. In order to main consistency and convenience, it was decided that 10 numbers of runs would be used for all of the simulation work.

Table 5.5. An example of sensitivity analysis (speed = 35 mph, volume = 100 vph, RT%=30).



		Delay (secs)	Space mean speed (mph)	
			TH	RT
Sudden reaction to lead vehicle	0.5	0.725	33.225	31.025
	Default (1)	0.85	33.025	30.8
	2.5	1.375	31.95	29.925
Deceleration rate of lead vehicle	10	0.75	33.225	31
	Default(12)	0.85	33.025	30.8
	15	0.975	32.775	30.575
Deceleration rate of following vehicle	10	0.975	32.75	30.6
	Default(12)	0.85	33.025	30.8
	15	0.75	33.225	30.975

RT = Right-turning vehicles and TH = Through vehicles.

5.3.2 Model 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 were altered and the effect was observed in output values of speeds and delay. However, the most parameters were found to have no effect on speed and delay except a few as 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. 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 decile distribution of the free-flow speed multiplier according to the driver type categorised based upon field measured free-flow speeds. The driver type distributions that were taken into account in default and calibrated models are shown in Figures 5.8-5.11. The percentage multiplier of free-flow speed is a very sensitive factor that can bring considerable change in Measures of Effectiveness (MoE's). Time to react to a sudden deceleration is also a very sensitive factor and generally not used if the desired calibration could be achieved by altering other parameters.

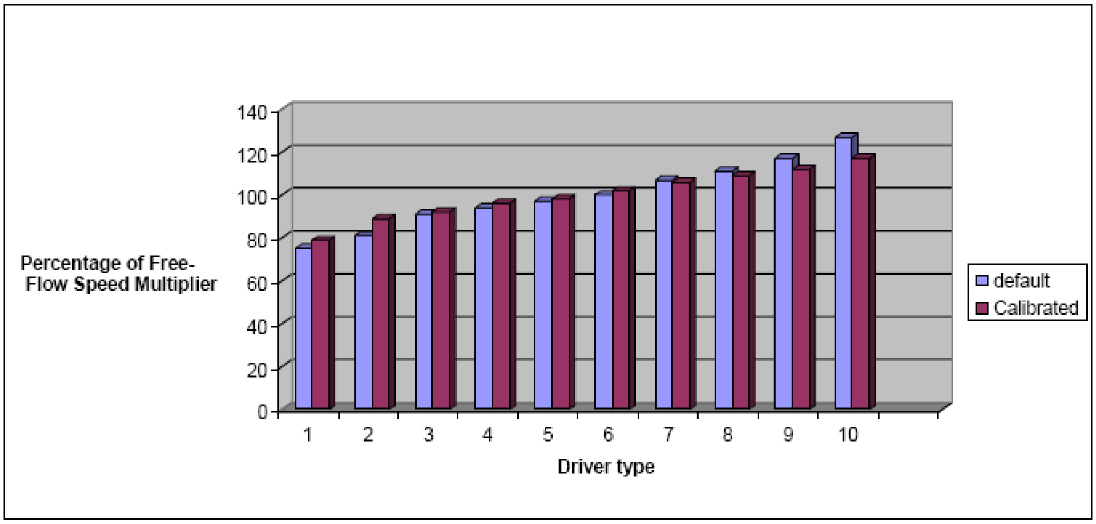


Figure 5.8. Free-flow distribution for 3-legged shared (Moorhead-3).

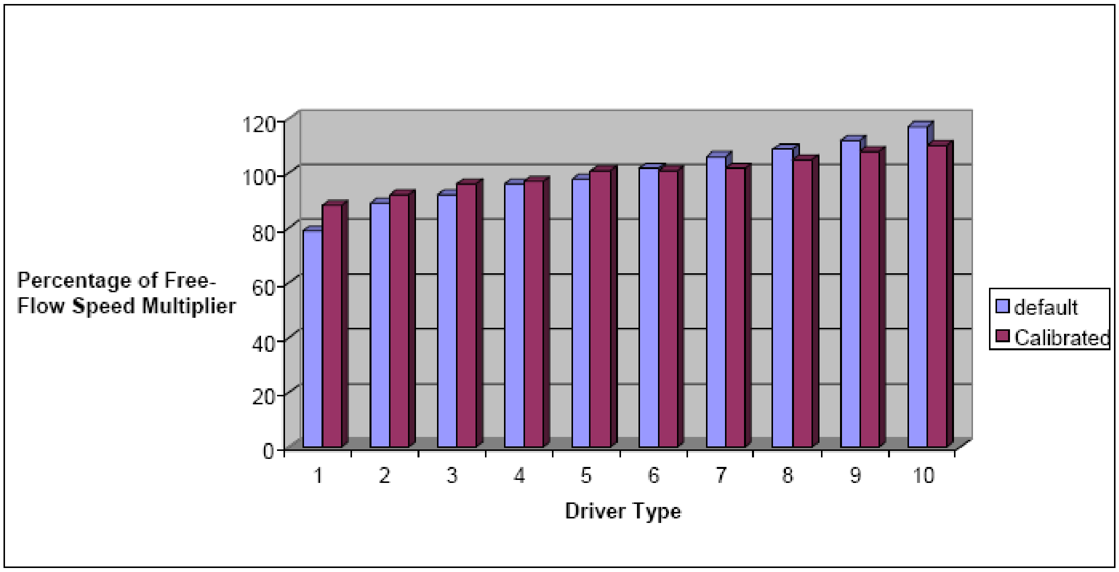


Figure 5.9. Free-flow distribution for 3-legged exclusive (Moorhead-1).

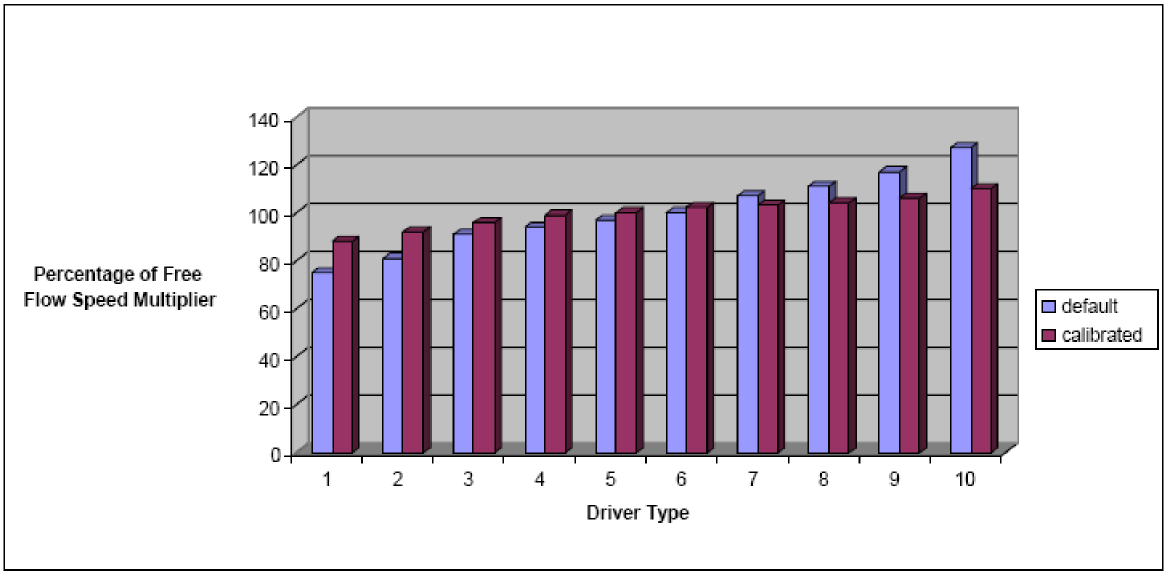


Figure 5.10. Free-flow distribution for 4-legged shared (Aitkin).

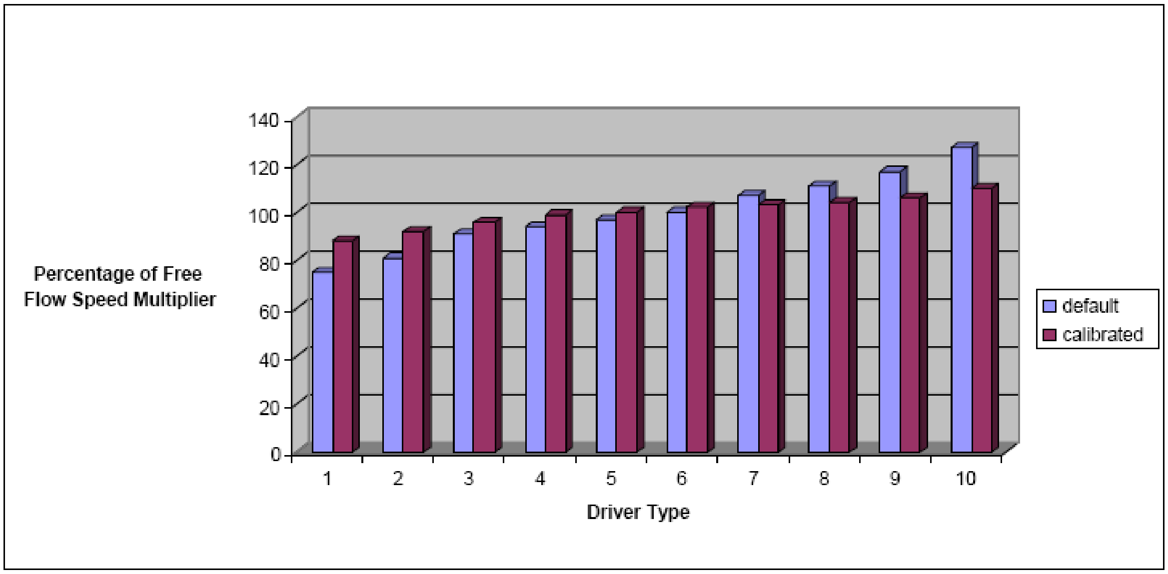


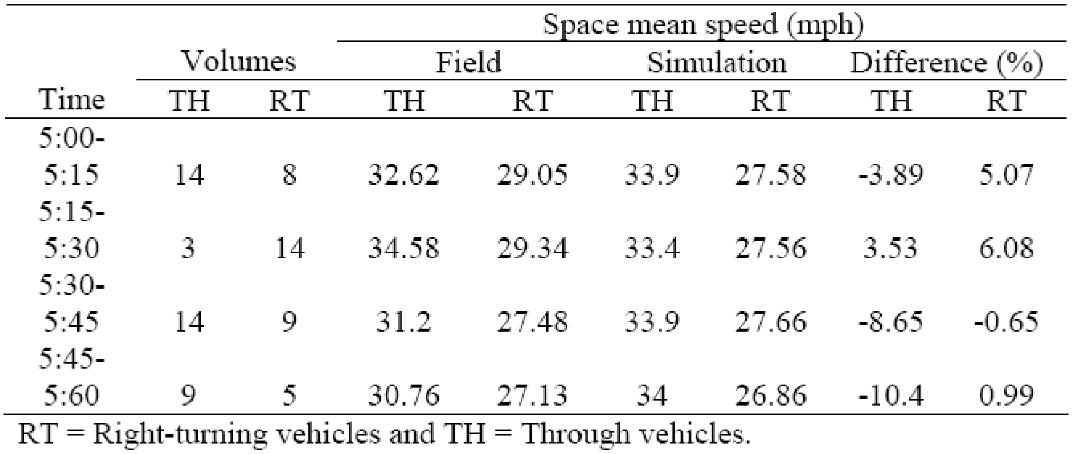
Figure 5.11. Free-flow distribution for 4-legged exclusive (St. Bonafacious).

The four base models were developed considering one for 3-legged shared, one for 3-legged exclusive, one for 4-legged shared, and one for 4-legged exclusive intersections. The shared, 3-legged base model was developed according to the intersection geometry of Moorhead-3, and similarly, the exclusive model was set according to the geometry of Moorhead-1. In the case of 4-legged, Aitkin and St. Bonafacious were replicated in the simulation models. Fifteen-minute interval data were used for calibration. During calibration, the space mean speed in CORSIM® output and the average spot speed obtained by placing the detectors in the link were compared with field values from data collection. To match the simulated values with field-measured values, parameters in

NETSIM setup, like maximum allowable turning speed, a deceleration of lead and following vehicles, and a sudden reaction to the lead vehicles, were altered. From the free-flow speed data measured during field data collection, the decile distribution of free-flow speed, according to the driver type, was entered, replacing the default values. The same calibrated models were transferred to other 3-legged intersections, changing only the intersection geometry and the input variables as speed, total volumes, and volumes of right-turning vehicles. Moorhead-3 was matched up with other shared junctions: Lowry (the junction of M55/CR-114) and Forest Lake-1(the junction of U61/240th St). Similarly, Moorhead-1 was matched up with Park Rapids (the junction of M34/CR-4) and Lindstorm (the junction of M8/Akerson St.). The same procedure was used for 4-legged intersections. The shared junction Aitkin (the junction of M210/CR-54/CR-56) was matched with Dawson (U212/4th Street). Similarly, as an exclusive case, St. Bonifacious (the junction of M7/CR-10) was matched with Ruthton (M23/CR-10). In this way, four calibrated base models, two for 3-legged and two for 4-legged, were prepared.

The results (Tables 5.6-5.14) show that the space mean speed from the simulation for each 15-minute interval, especially for through vehicles, matches the field- measured values.

Table 5.6. Calibration of Lowry (junction of M55/CR-114).



			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
5:00-5:15	14	8	32.62	29.05	33.9	27.58	-3.89	5.07
5:15-5:30	3	14	34.58	29.34	33.4	27.56	3.53	6.08
5:30-5:45	14	9	31.2	27.48	33.9	27.66	-8.65	-0.65
5:45-5:60	9	5	30.76	27.13	34	26.86	-10.4	0.99

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.7. Calibration of Forest Lake -1 (junction of US61/240th St).

	Space mean speed (mph)							
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
8:15-8:30	112	1	52.3	32.8	52.35	29.7	0.096	-10.47
8:30:00 -8:45	118	1	52.6	32.7	52.94	32.34	0.604	-0.959

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.8. Calibration of Moorhead-1 (junction of U75/46th Ave. S.).

			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference	
Time	TH	RT	TH	RT	TH	RT	TH	RT
9:00-9:15	8	25	41.7	33	46.98	32.61	-12.6	2.63
9:15-9:30	10	27	43.9	33	45.83	32.89	-4.42	-1.1
9:30-9:45	11	21	43.6	28	46.81	32.82	-7.31	-17.7
9:45-10:00	15	9	46.4	35	47.73	32.78	-2.82	6.21

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.9. Calibration of Park Rapids (junction of M34/CR-4).

			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
3:15-3:30	51	4	54.1	39	54	34.12	0.31	11.78
3:30-3:45	65	5	55.9	40	53.7	34.74	3.86	13.01
3:45-4:00	60	2	52.6	39	53.4	35.05	-1.4	9.031

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.10. Calibration of Lindstorm (junction of M8/Akerson St.).

Spot speed at C (mph)				Spot speed at B (mph)			
Field	Counts	Simulation	Difference	Field	Counts	Simulation	Difference
34	77	34.26	-0.088	34	65	33.87	1.0517

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.11. Calibration of Aitkin (junction of M210/CR-54/CR-56).

			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
5:00-5:15	40	3	56.11	43.1	55.75	39.23	0.64%	9.04%

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.12. Calibration of Dawson (U212/4th St.).

			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
10:30-10:45	29	1	24.9	23.2	29.6	23	-18.87%	1.29%

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.13. Calibartion of St. Bonifacious (M7/CR10).

			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
5:05-5:20	60	9	52	33.98	59.41	36.52	-14.20%	-7.49%
5:20-5:35	63	6	59	38.56	59.41	36.42	0.07%	5.54%
5:35-5:50	59	5	60	38.7	59.44	36.87	0.47%	4.74%
5:50-6:05	68	11	61	37.76	59.17	36.42	3.55%	3.54%

RT = Right-turning vehicles and TH = Through vehicles.

Table 5.14. Calibration of Ruthton (M23/CR-10).

			Space mean speed (mph)					
	Volumes		Field		Simulation		Difference (%)	
Time	TH	RT	TH	RT	TH	RT	TH	RT
10:15-10:30	20	1	55	33.52	59	36.08	-6.83%	-7.63%
10:45-11:00	18	3	57.3	29.73	59	36.02	-2.66%	-21.14%
11:00-11:15	14	2	57	33.94	58	36.21	-2.26%	-6.70%

RT = Right-turning vehicles and TH = Through vehicles.

5.3.3 Independent variables and their levels

The total volumes of vehicles (vph), the free-flow speed of vehicles (mph), the percentage of right-turning vehicles, right-turn pocket length were selected as independent factors that govern the delay and fuel consumption on the particular approach of each intersection. Levels were assigned for each variable. In case of volumes, 5 levels as 100 vph, 300 vph, 500 vph, 1000 vph, and 1500 vph were assigned. Similarly, five levels of speeds were set as 30 mph, 35 mph, 40 mph, 45 mph, and 55 mph. Seven levels for the percentage of right-turning vehicles were assigned as 0%, 1%, 5%, 10%, 15%, 30%, and 50%. Seven levels for right-turn pocket lengths were assigned as 0 ft, 100 ft, 200 ft, 300 ft, 400 ft, 480 ft, and 500 ft.

Hence the total number of combinations = 5*5*7*7 = 1,225
Considering the number of runs = 10, the total number of required runs = 1,225 * 10
Hence, the simulations were conducted for 1,050 combinations, resulting in 12,250 runs.

5.3.4 Simulations

From the observed trajectory from TSD files, 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 from 0 to 500 ft. The naming convention for the link with shared treatment was kept 2-1 and the exclusive treatment was kept at 3-1. Traffic network files were replicated for each input combination for a total of 2,450. Ten runs were made for each combination using run-time extension codes.

Giving the location of MoE's from a fixed coordinate, the SAS® was able to read the values corresponding to the location. The values delay (secs per through vehicles), delay (vehicle minutes), fuel consumption for vehicles 1 and 5 were noted. Processing was done to calculate the average values of delay and fuel consumption from the 10 runs. The final tables with average delay and fuel consumption for each case, with the respective values of speed, volumes, percentage of right-turn and the percentage of left-turns, were prepared.

5.3.5 Statistical analysis of simulation results

Minitab® software was used to statistically analyze the simulation results obtained from 24,500 simulations. First the average values of the 10 runs were made. Thus, there were 2450 different data to analyze. The right turn percentages were used to develop corresponding right turn volume information. The hourly volumes were divided by 4 to reflect the fact that the simulation was done for 15 minutes. These 15 minute direction volumes were multiplied by right turn percentages to obtain right turn volumes for 15 minutes. Also, it was kept in mind that the fuel consumption was in gallons for 15 minutes. Several different combinations of independent variables (speed, volume, right turn volume, and right-turn treatment) were tried. First, it was tried without interaction terms and then both two-way and three-way interactions were tried. The final delay and fuel consumption models are discussed in following sub-sections.

5.3.6 Delay model

Several delay models were tried and looked at while establishing the final regression model. The simulation results from over thousands of simulation looking into the results of delays from shared conditions as well as from conditions with right turn pocket lengths of 100, 200, 300, 400, and 500 ft were used to develop the regression model shown below in Table 5.15.

Table 5.15. Delay model.

```
The regression equation is
DL-SPT = 0.912 - 0.0197 SR + 0.0102 VRT + 0.00228 V -
0.0116 VRTxRT


Predictor         Coef     SE Coef       T      P
Constant       0.91211     0.03940   23.15  0.000
SR          -0.0197355   0.0009069  -21.76  0.000
VRT          0.0102320   0.0004461   22.94  0.000
V           0.00228117  0.00007054   32.34  0.000
VRTxRT      -0.0115663   0.0004540  -25.48  0.000


S = 0.273042   R-Sq = 67.7%   R-Sq(adj) = 67.6%
```

Where
DL-SPT is delay in seconds per through vehicle
SR is approach speed in mph
V is directional approach volume (vehicles per 15 minutes)
VRT is right turn volume in vph (vehicles per 15 minutes)
RT is right turn treatment (is 0 if right turn pocket length is zero, is 1 otherwise)

The aim was to then develop annual delay values. For this first daily delay values had to be established. To determine daily delay values the volume during each 24 hour period was established. To do so data from eight ATR (ATR# 388, 390, 220, 221, 407, 425, 460, 458), which were spread throughout Minnesota were used. These ATR locations were consistent with locations from where the field data collection was done.

The daily distribution obtained by 5840 data points from these 8 ATR locations in both directions of traffic and over each day of the year. The daily distribution thus obtained is shown in Table 5.16 below.

Table 5.16. Daily traffic distributions.

Hour	Pi	Hour	Pi	Hour	Pi	Hour	Pi
0-1	0.008	6-7	0.036	12-13	0.064	18-19	0.064
1-2	0.005	7-8	0.054	13-14	0.063	19-20	0.047
2-3	0.004	8-9	0.050	14-15	0.067	20-21	0.038
3-4	0.003	9-10	0.052	15-16	0.077	21-22	0.031
4-5	0.005	10-11	0.056	16-17	0.084	22-23	0.021
5-6	0.016	11-12	0.061	17-18	0.081	23-24	0.012

Using same data set a relationship was obtained between highest hour volume (considered in this research as design directional hour volume (DDHV) and the average annual daily traffic (AADT) was established as shown in Table 5.17 below.

Table 5.17. Relationship between DDHV and AADT.

```
The regression equation is
MaxHV = - 25.5 + 0.113 DADT


Predictor       Coef   SE Coef        T      P
Constant     -25.492     3.130    -8.15  0.000
DADT        0.112622  0.000439   256.36  0.000


S = 134.121   R-Sq = 91.8%   R-Sq(adj) = 91.8%
```

The delay values were in second per through vehicle. Therefore, for each time period numbers of through vehicles were determined using right turn percentages and hourly volume for each hour in question. The delay values in second per vehicle were then multiplied by number of through vehicles to get total seconds of delay during any particular hour. All the seconds of delays in each hour were then summed up to get total delays in seconds during the day. This number was then multiplied by 365 to get annual delays.

The delay savings were obtained by subtracting total annual delays with right turn lanes of certain pocket length from the annual delays resulting from shared right turn movement without right turn lane.

5.3.7 Fuel consumption model

The excess fuel consumed during every 15 minute simulation was noted down. The simulation results from over thousands of simulation looking into the results of excess fuel consumed from shared conditions as well as from conditions with right turn pocket lengths of 100, 200, 300, 400, and 500 ft were used to develop the regression model shown below in Table 5.18.

Table 5.18. Excess fuel consumption model.

```
The regression equation is
FUEL = - 0.150 + 0.00361 SR + 0.000889 VRT + 0.00440 V -
0.000263 VRTxRT


Predictor         Coef     SE Coef        T      P
Constant      -0.14967     0.01037   -14.43  0.000
SR           0.0036060   0.0002387    15.11  0.000
VRT          0.0008886   0.0001174     7.57  0.000
V           0.00440046  0.00001856   237.04  0.000
VRTxRT      -0.0002628   0.0001195    -2.20  0.028


S = 0.0718578   R-Sq = 98.5%   R-Sq(adj) = 98.5%
```

Where
FUEL is fuel consumption in gallons per 15 minutes
SR is approach speed in mph
V is directional approach volume (vehicles per 15 minutes)
VRT is right turn volume in vph (vehicles per 15 minutes)
RT is right turn treatment (is 0 if right turn pocket length is zero, is 1 otherwise)

The aim was to then develop annual delay values. In order to develop annual fuel consumption values daily fuel consumption values were computed. This was dependent on daily volume information disaggregated over 24 hour period as shown under discussion of daily delay computation.

The excess fuel consumption values were in gallons per 15 minute so they were multiplied by 4 to obtain total excess gallons consumed during a particular hour. So for each 24 hour period excess gallons consumed were determined and summed up to obtain the daily value of excess fuel consumed. This was then multiplied by 365 to get annual excess fuel consumption for both shared conditions and conditions with right turn lane.

Chapter 6 Development of Warrants

This chapter describes process to develop bases for warrants. In addition, it provides warrants for right-turn lanes.

6.1 Safety cost savings

The safety cost savings are computed by subtracting safety costs under shared condition and under exclusive right turn movement case. There were differences in safety cost savings at low speed and high speed. Residential driveway/private field approach was not found significant with reference to the crash occurring at an intersection. Commercial/public driveway was found significant with reference to the crash occurring at an intersection. Therefore, only commercial/public driveway is considered in the analysis. More interesting was the fact that safety cost savings for right turn lanes near commercial driveways was more than that near intersections. This clearly indicates the influence of land use.

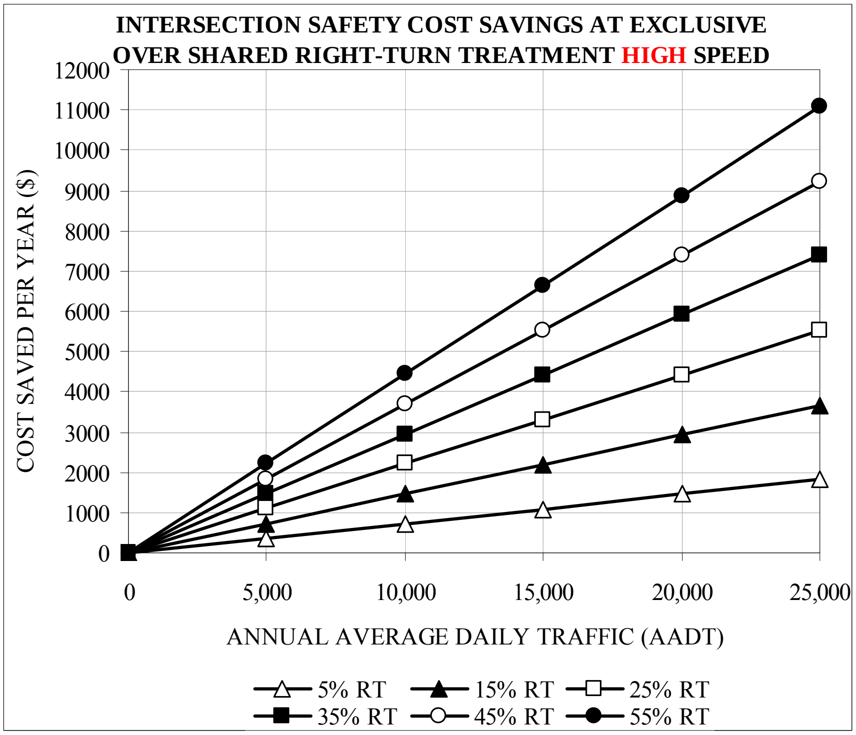


Figure 6.1. Annual safety cost savings at high speed at intersections.

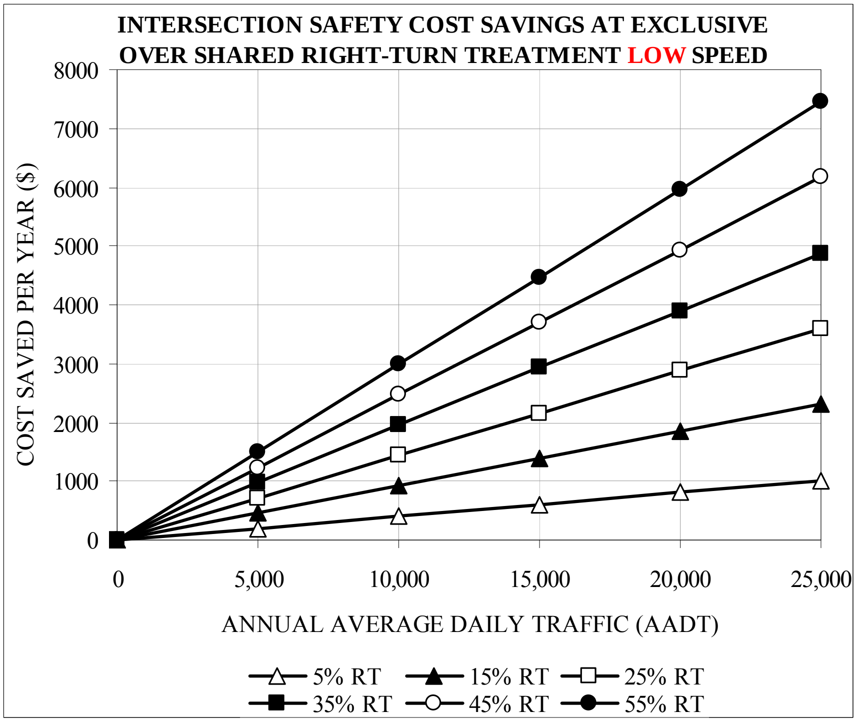


Figure 6.2. Annual safety cost savings at low speed at intersections.

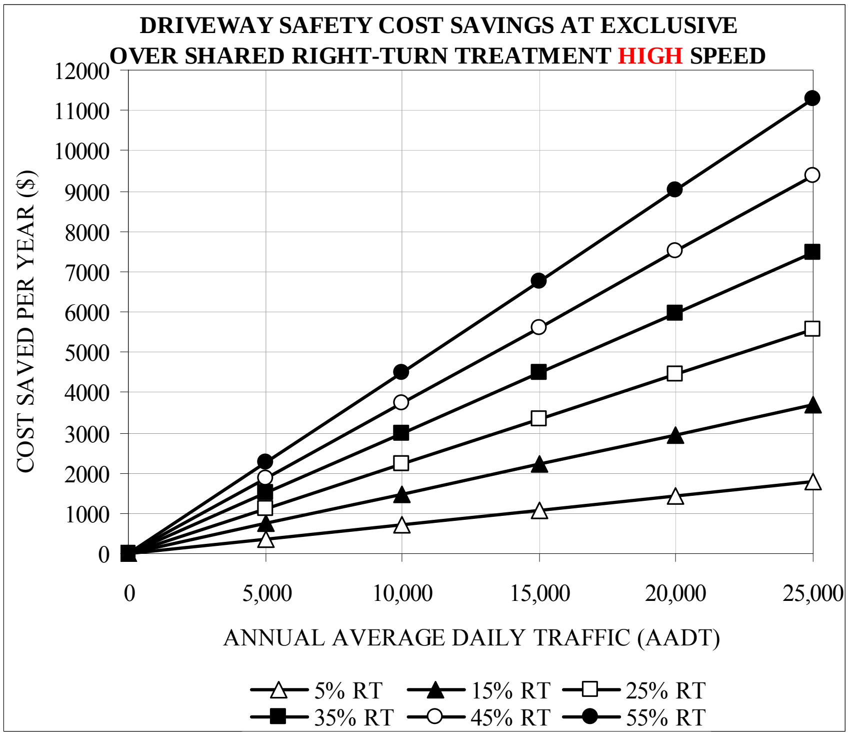


Figure 6.3. Annual safety cost savings at high speed at driveways.

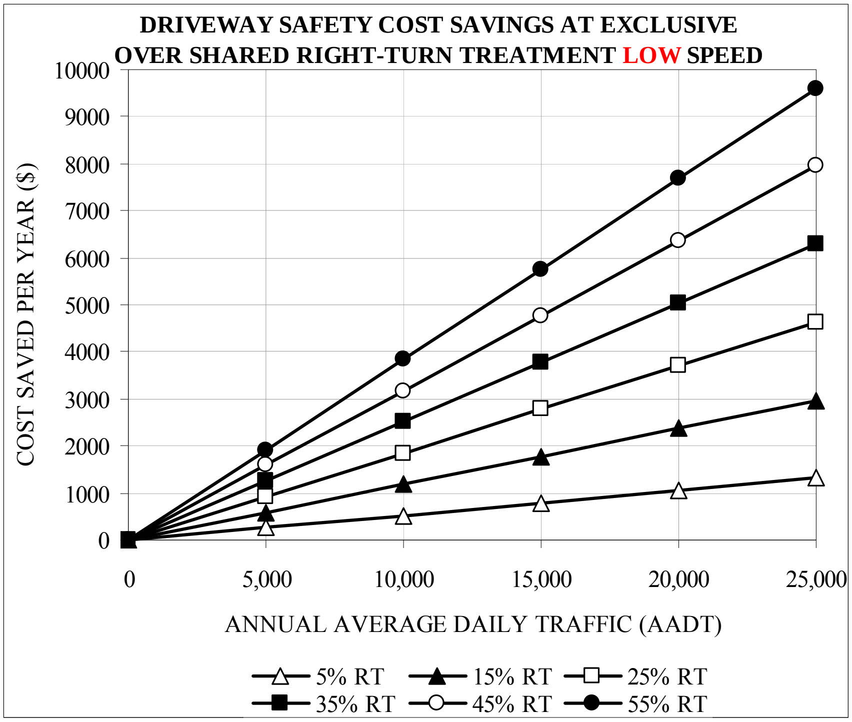


Figure 6.4. Annual safety cost savings at low speed at driveways.

6.2 Operational cost savings

The operational cost savings are computed by subtracting operational costs under shared condition and under exclusive right turn movement case. There is specific trend of increase in operational cost savings as right turn percentage increases and as AADT or DDHV increases. The operational savings are also sensitive to fuel prices. Given the current fuel price rise, savings were calculated for both $3 per gallon price and $4 per gallon price. The value of time was assumed to be $13 per hour.

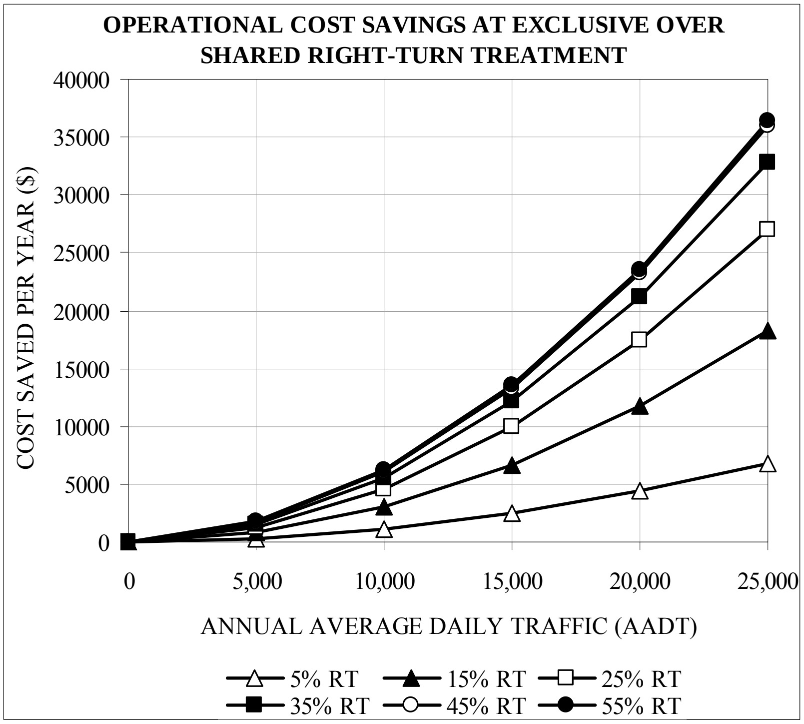


Figure 6.5. Annual operational cost savings (fuel cost $3/gallon, delay cost $13/hr).

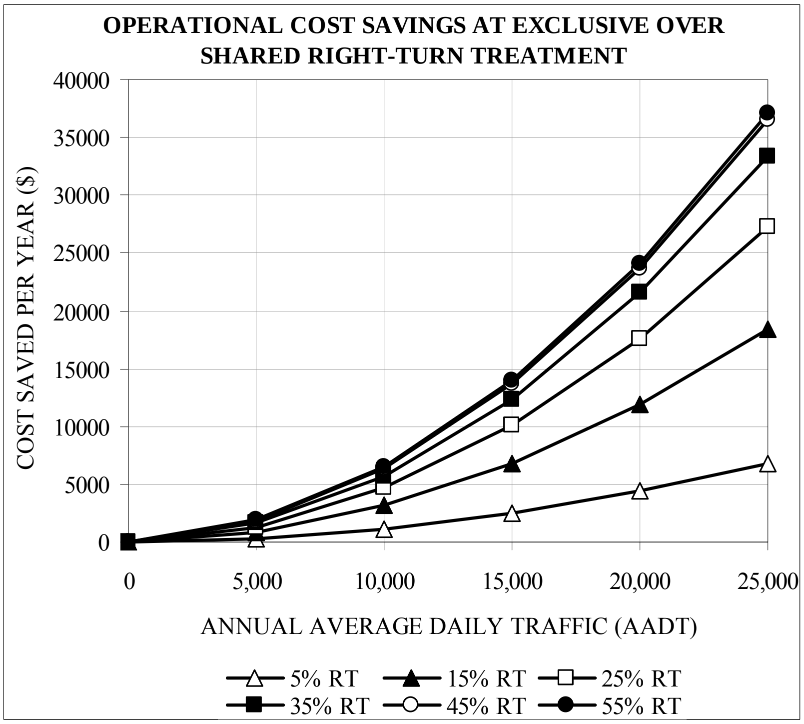


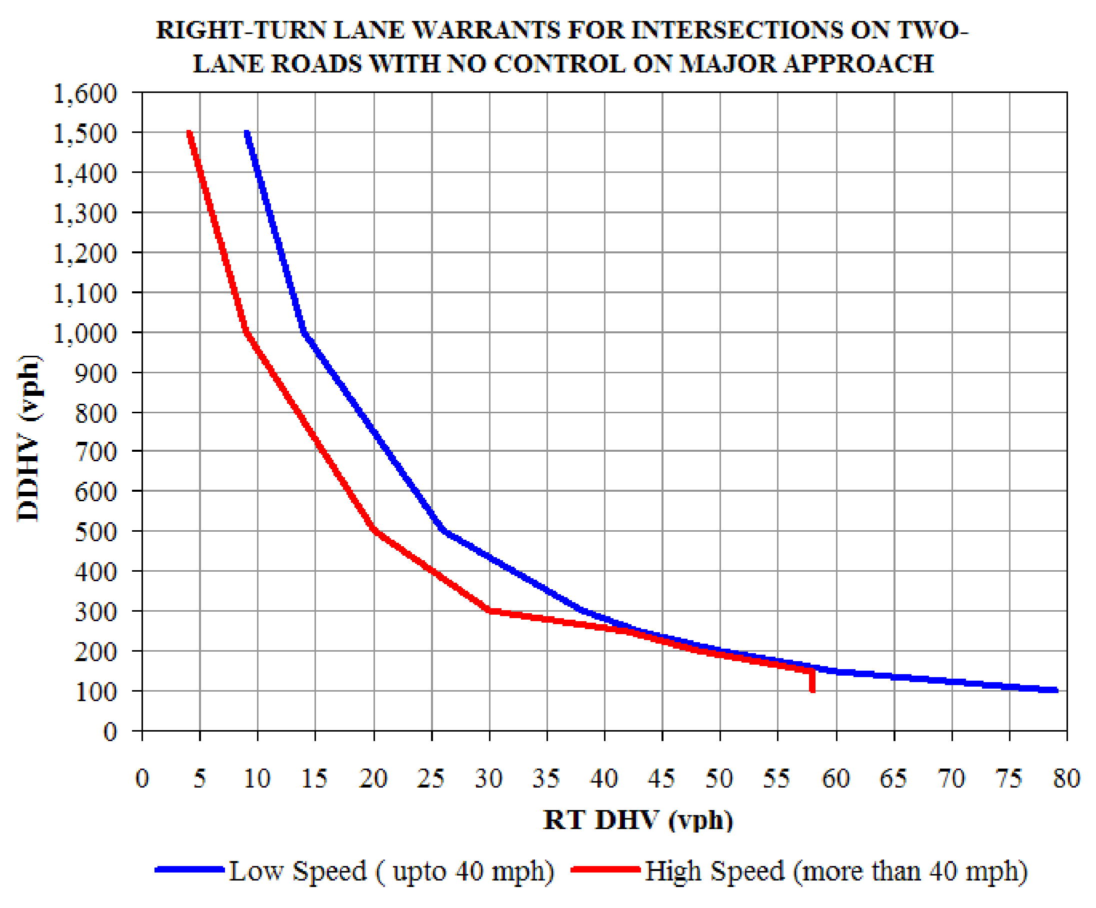
Figure 6.6. Annual operational cost savings (fuel cost $4/gallon, delay cost $13/hr).

6.3 Right-turn lane costs

The right-turn lane construction has both fixed and variable costs. In addition, there are right-of-way costs. Most of the determination regarding right turn-lane is within existing right-of-way by Mn/DOT. The fixed costs were computed based on activities such as preliminary engineering, mobilization, field laboratory, general clearning and grubbing, and traffic control devices. The variable costs are related to length of right-turn lanes (pockets). This cost includes consideration of taper and full lane width as right turn lane/pocket length is increased. The variable cost items include excavation, paving, sodding, and sidewalks. During final Technical Panel Meeting it was identified that right-turn lane costs vary from 20,000 to 60,000. Thus, warrants were prepared for different right turn lane cost scenarios--$20,000, 30,000, 40,000, 50,000, and 60,000.

6.4 Thresholds and charts for warrants

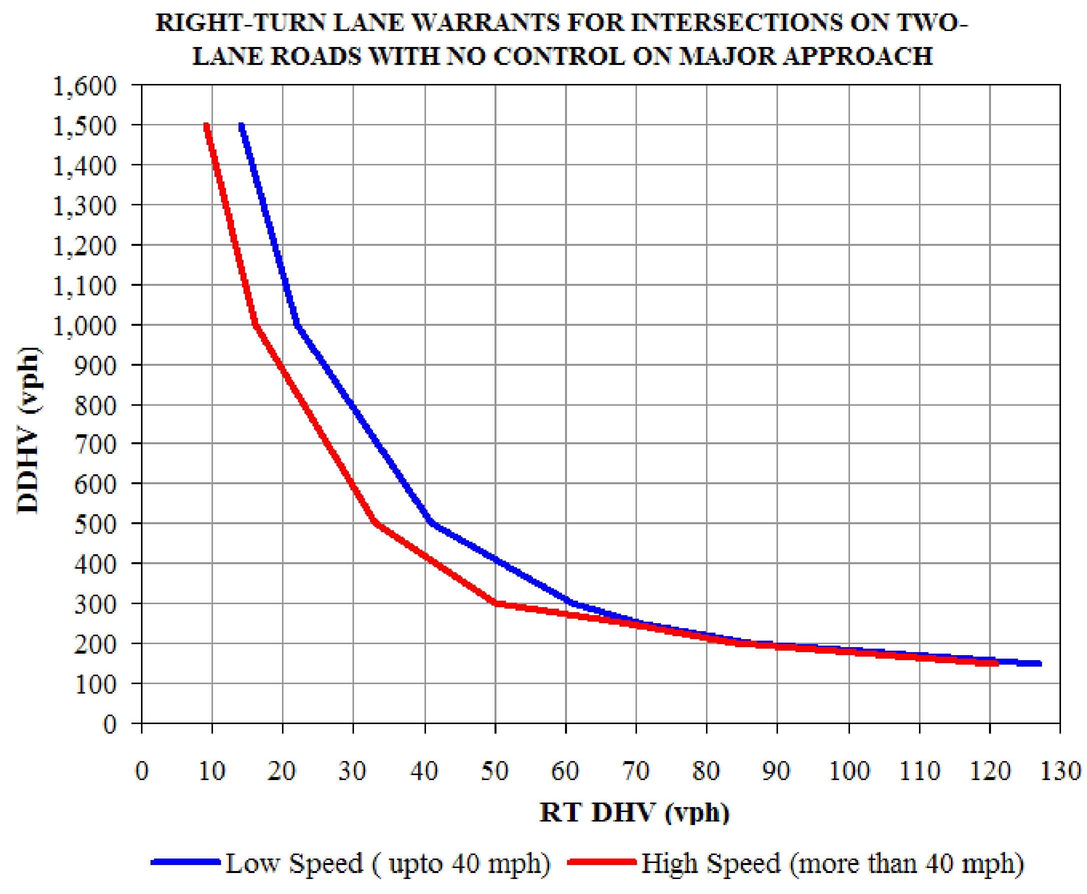
The underlying basis for developing thresholds and charts for warrants for right turn lane was to strike a balance between right turn lane costs and the operational and safety cost savings resulting from right turn lanes. The right turn lane cost ($ 20,000 to $ 60,000) was annualized using the period of analysis of 20 years and interest rate of 3.2 percent (as used by Office of Investment Management within Mn/DOT for benefit-cost studies). The resulting warrants are shown in Figures 6.7 to 6.26.



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $20,000 / Cost of Fuel = $3)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	79	60	50	43	38	26	14	9
> 40	58	58	48	42	30	20	9	4

Figure 6.7. Right-turn lane warrants for intersections (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $20,000).

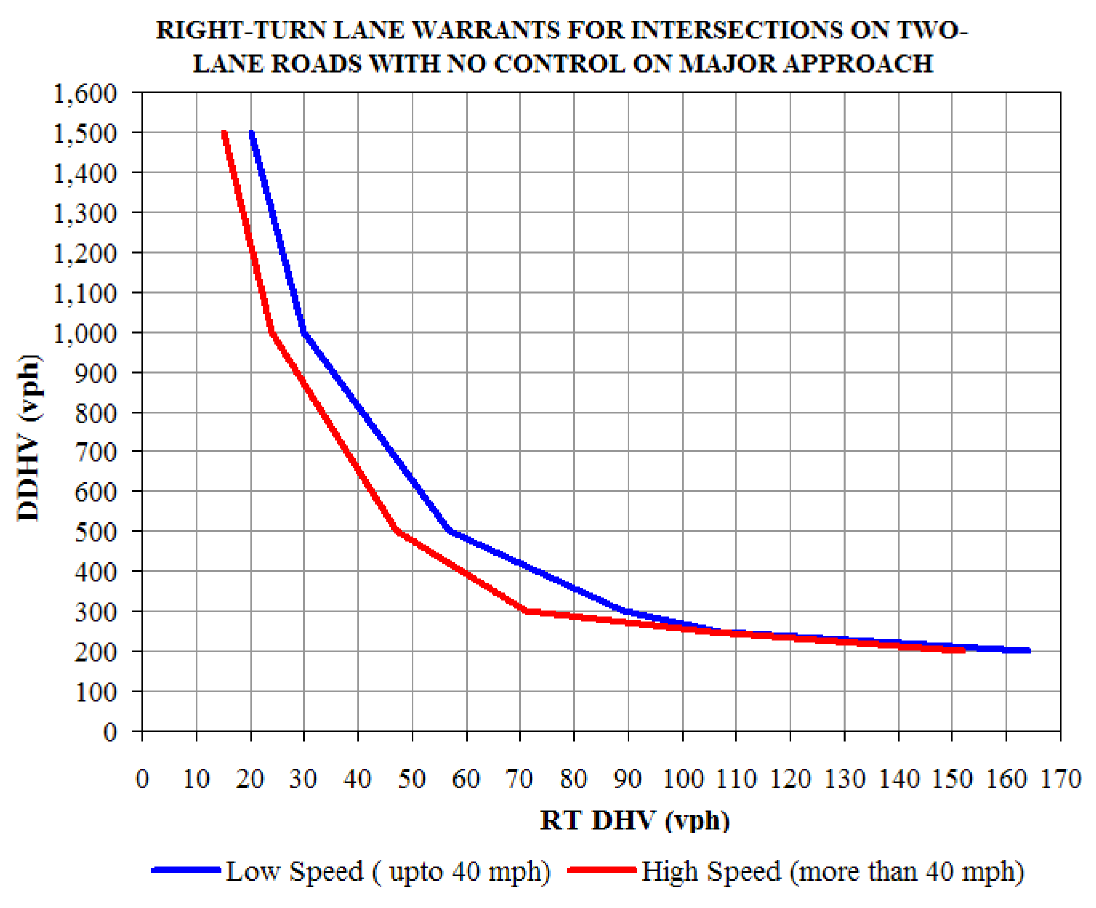


Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane

(Right-turn Lane Cost = $30,000 / Cost of Fuel = $3)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	127	86	71	61	41	22	14
> 40	NA	121	84	69	50	33	16	9

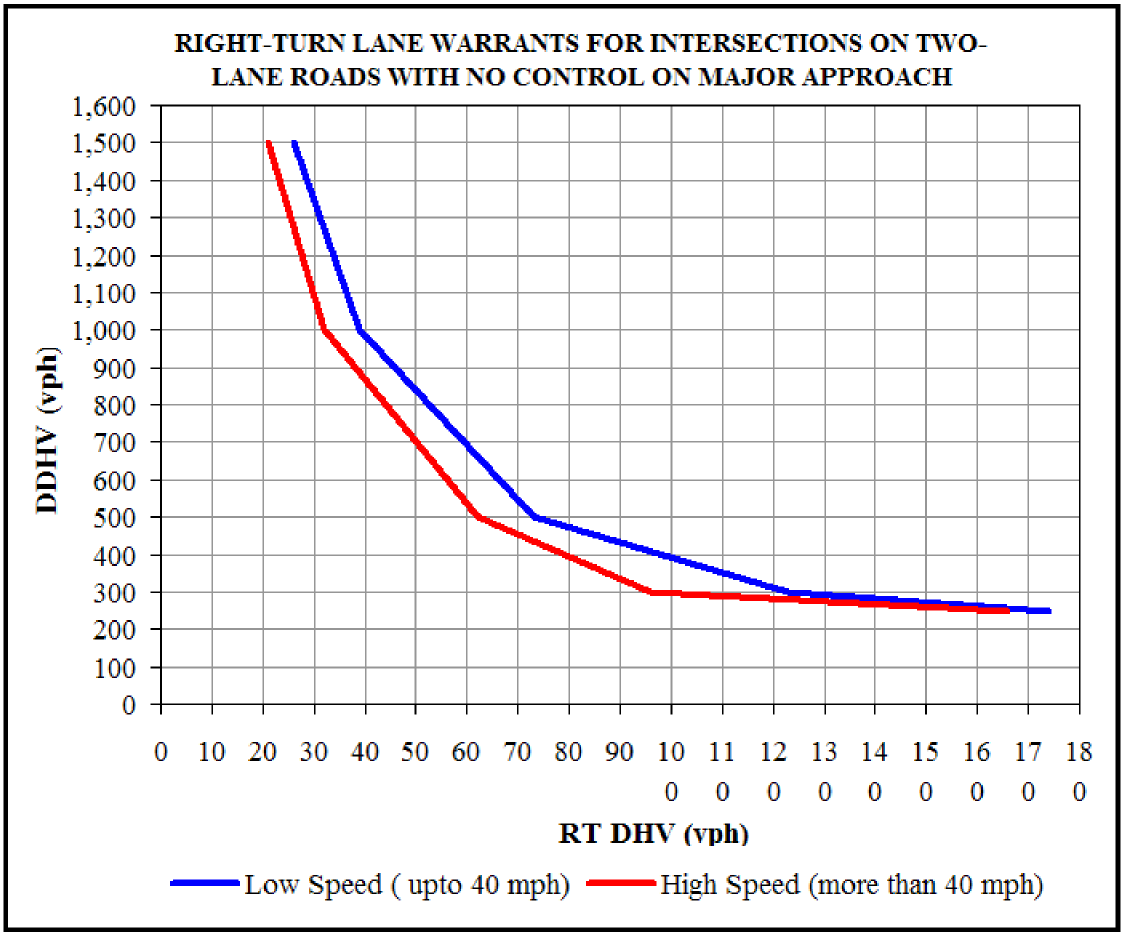
Figure 6.8. Right-turn lane earrants for intersections (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $30,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $40,000 / Cost of Fuel = $3)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	164	107	89	57	30	20
> 40	NA	NA	152	105	71	47	24	15

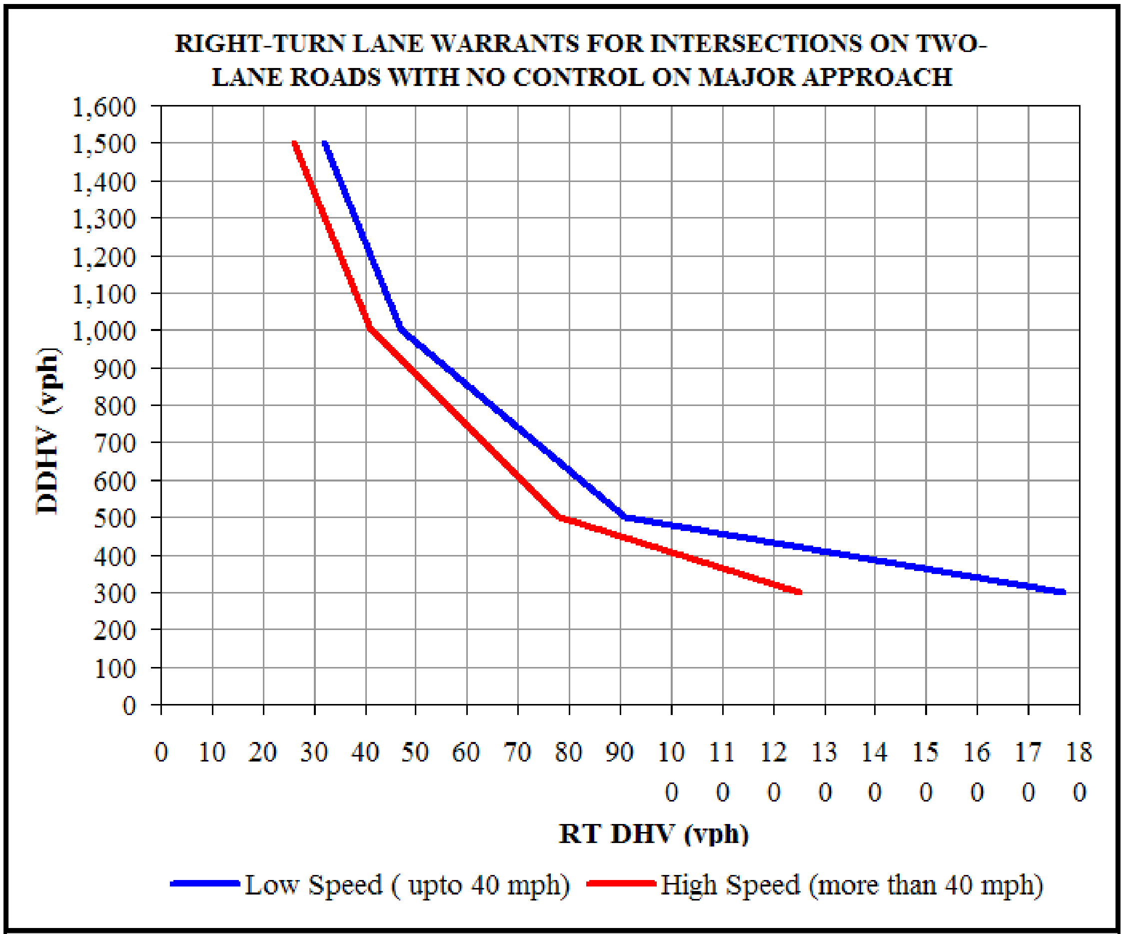
Figure 6.9. Right-turn lane warrants for intersections (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $40,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $50,000 / Cost of Fuel = $3)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	174	123	73	39	26
> 40	NA	NA	NA	166	96	62	32	21

Figure 6.10. Right-turn lane warrants for intersections (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $50,000).

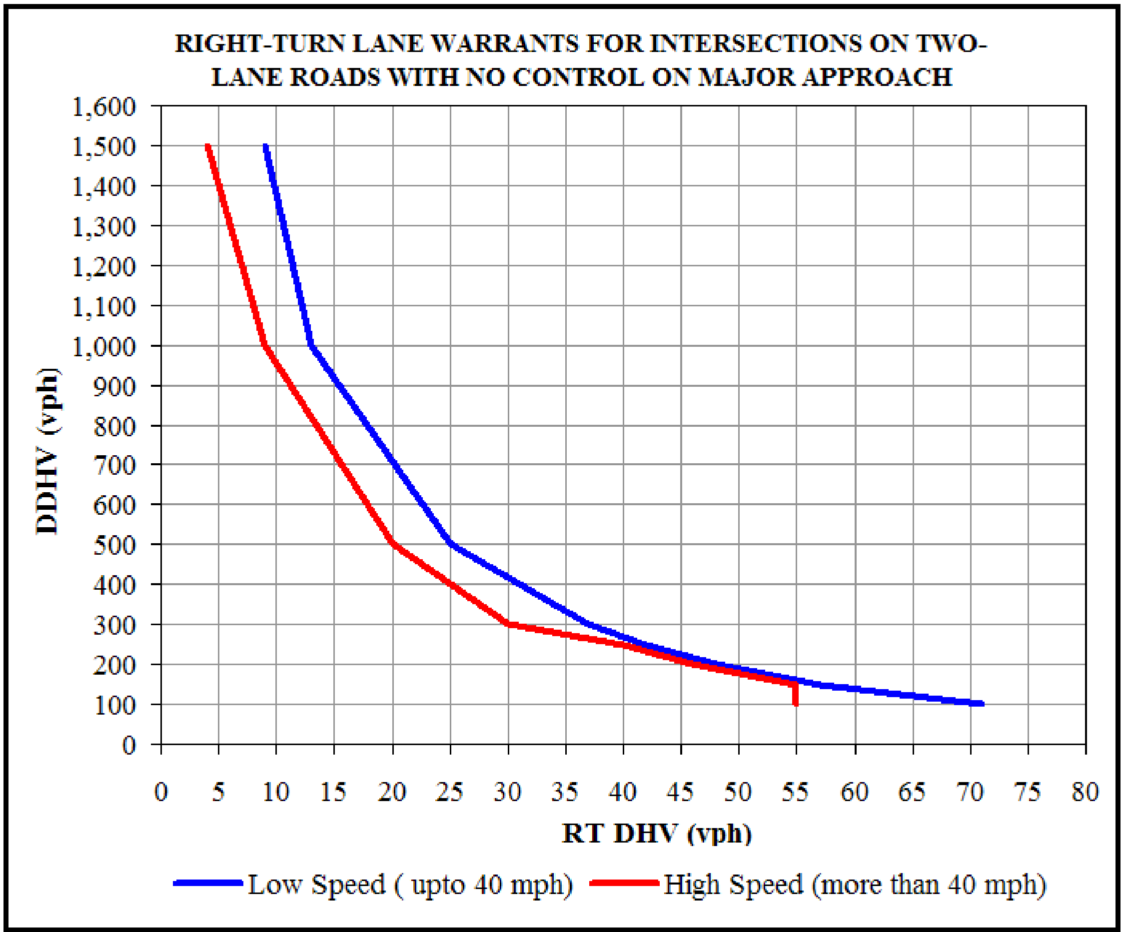


Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane

(Right-turn Lane Cost = $60,000 / Cost of Fuel = $3)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	NA	177	91	47	32
> 40	NA	NA	NA	NA	125	78	41	26

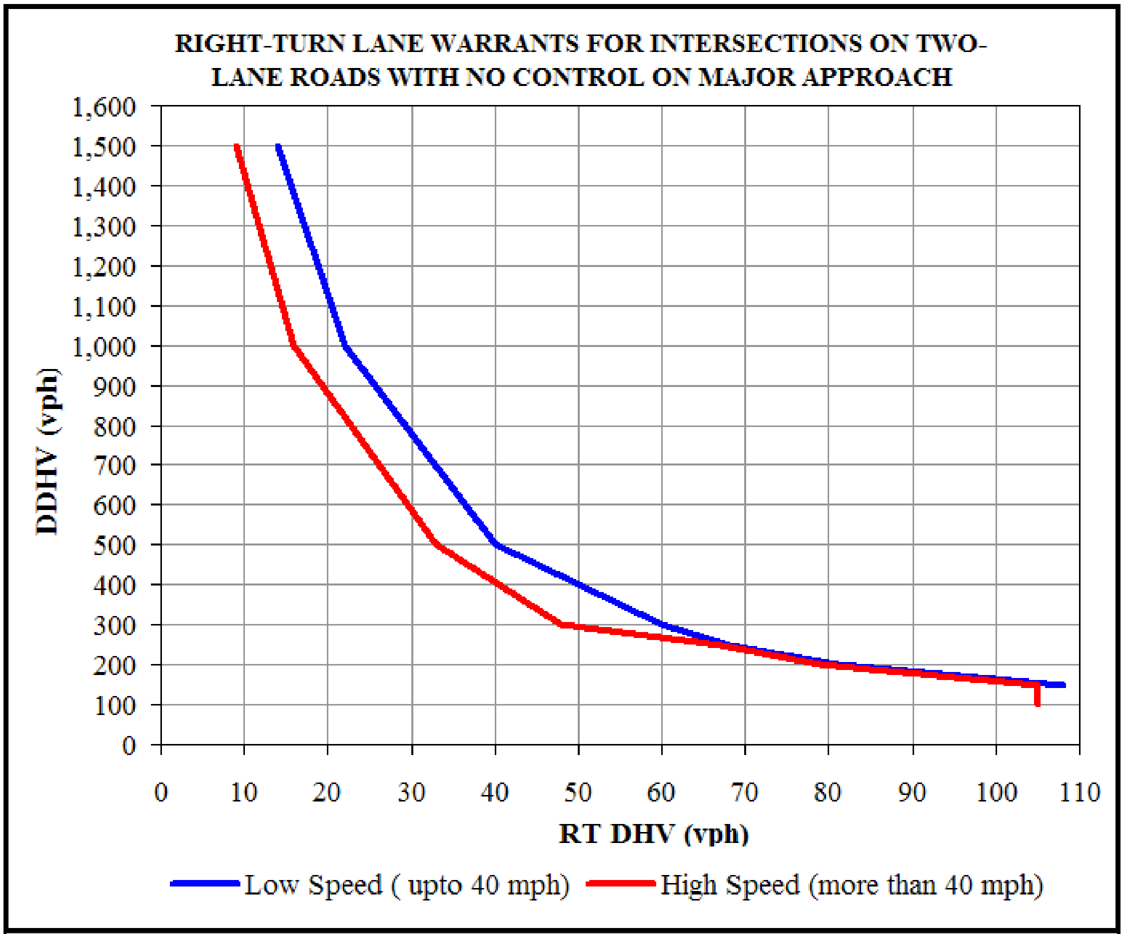
Figure 6.11. Right-turn lane warrants for intersections (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $60,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $20,000 / Cost of Fuel = $4)

Speed (mph)	DDHV (vph)							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	71	57	48	42	37	25	13	9
> 40	55	55	46	40	30	20	9	4

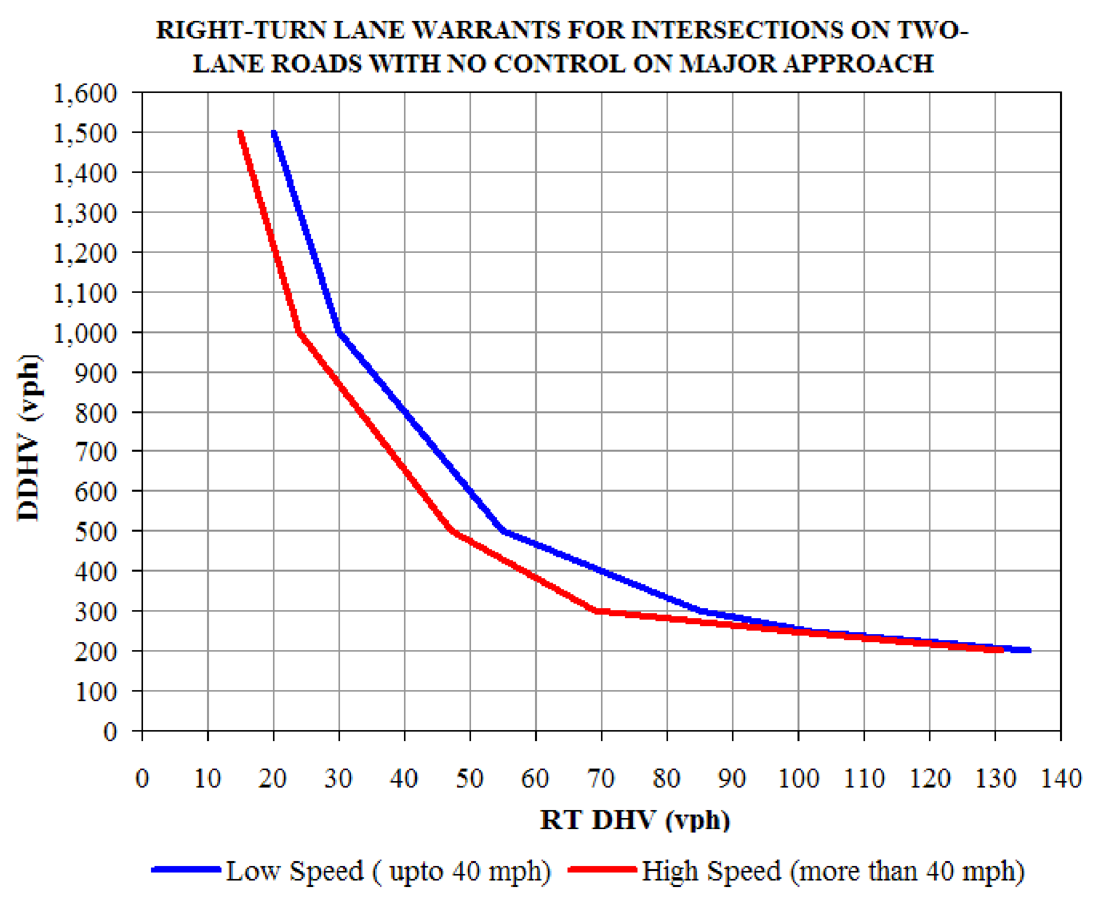
Figure 6.12. Right-turn lane warrants for intersections (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $20,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $30,000 / Cost of Fuel = $4)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	108	81	68	60	40	22	14
> 40	105	105	79	67	48	33	16	9

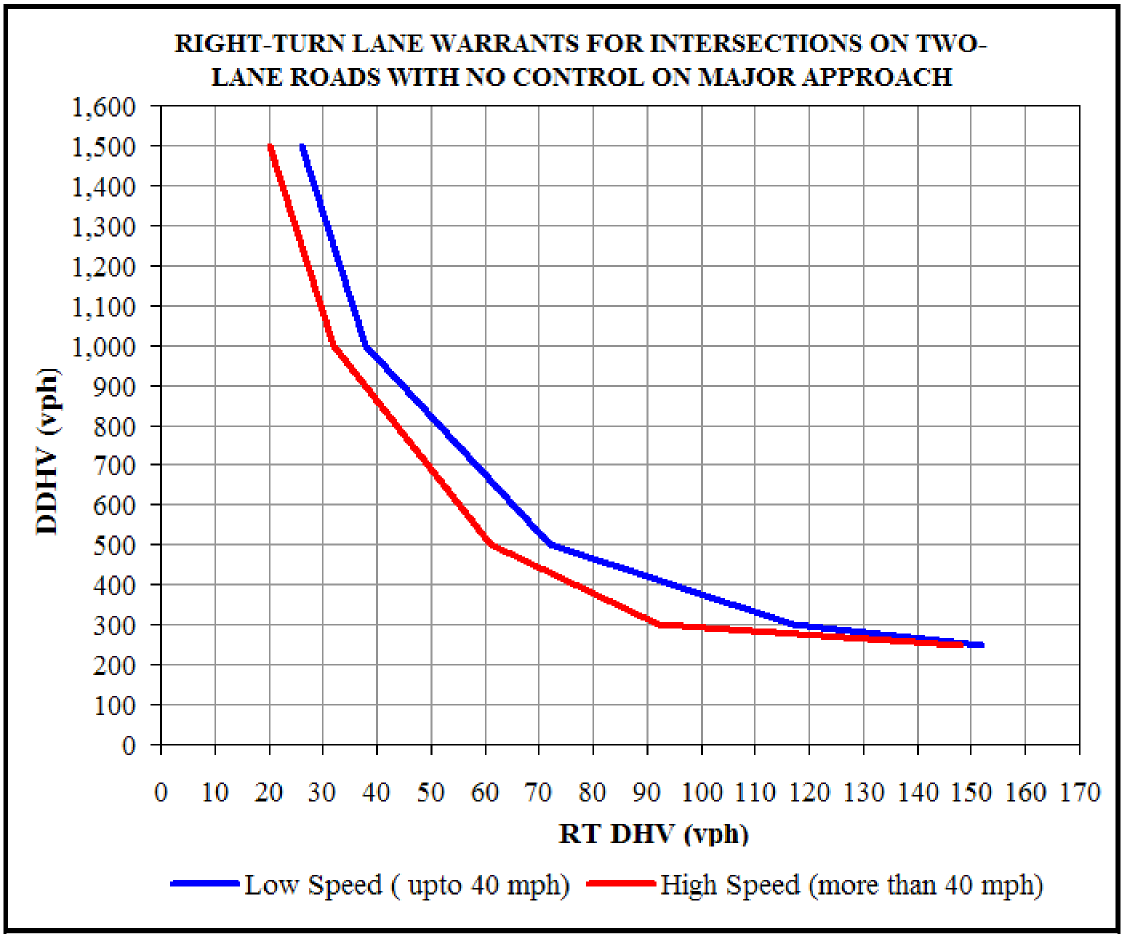
Figure 6.13. Right-turn lane warrants for intersections (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $30,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $40,000 / Cost of Fuel = $4)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	135	102	85	55	30	20
> 40	NA	NA	131	99	69	47	24	15

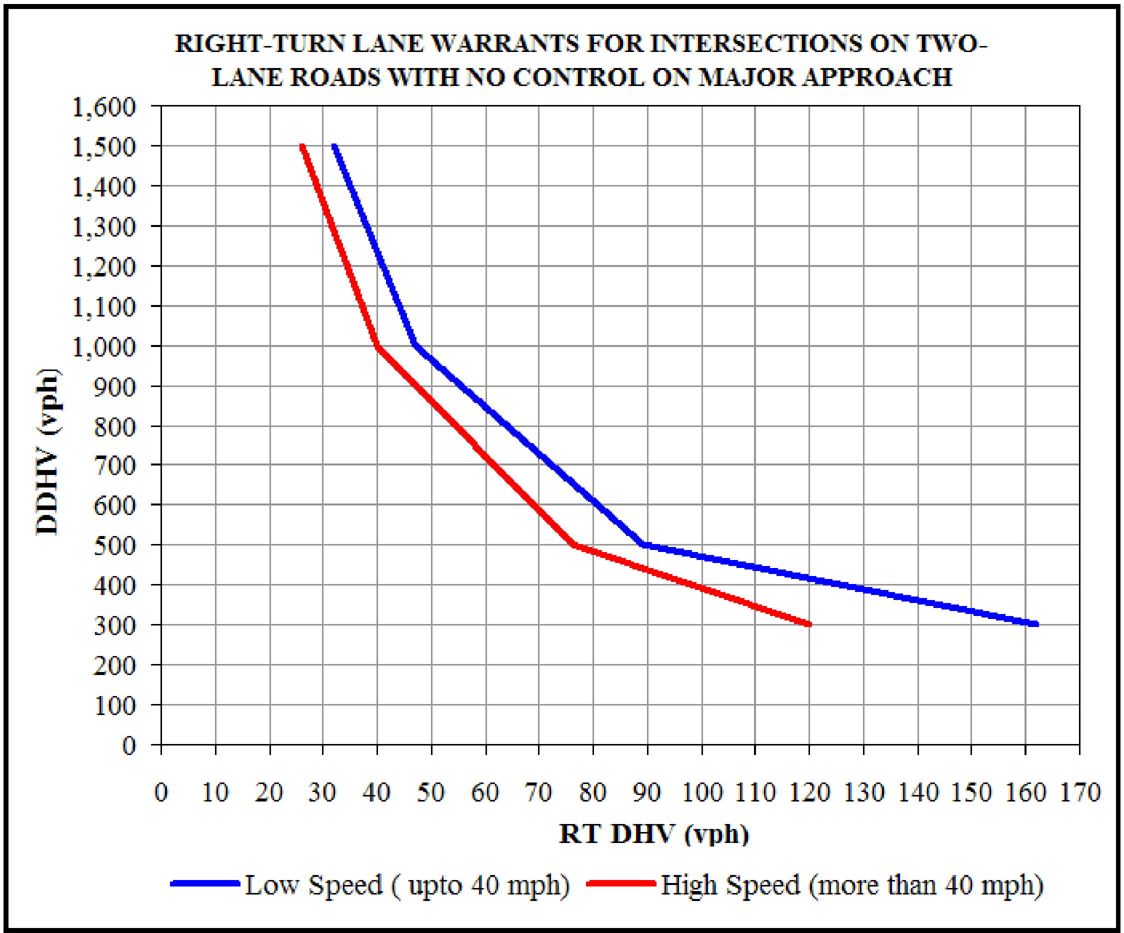
Figure 6.14. Right-turn lane warrants for intersections (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $40,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $50,000 / Cost of Fuel = $4)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	152	117	72	38	26
> 40	NA	NA	NA	148	92	61	32	20

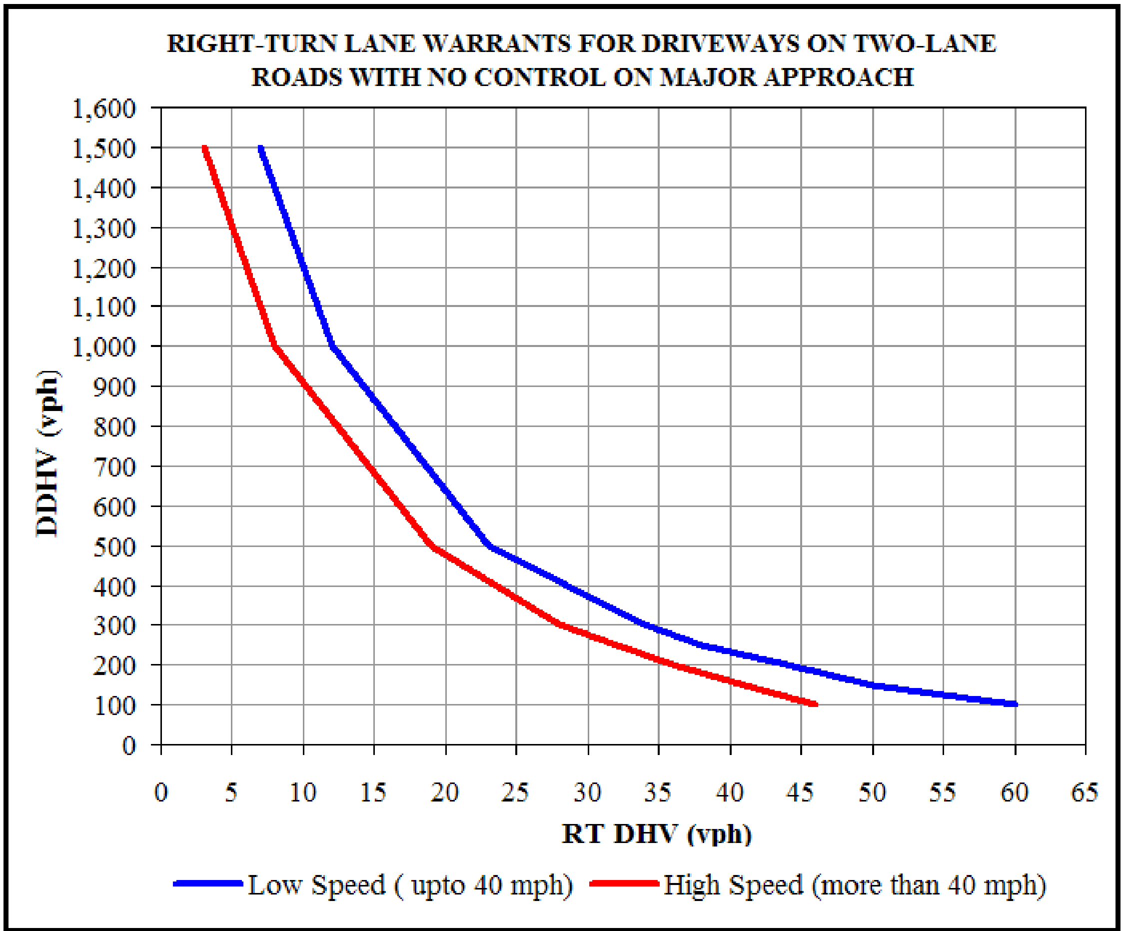
Figure 6.15. Right-turn lane warrants for intersections (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $50,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $60,000 / Cost of Fuel = $4)

Speed (mph)	DDHV (vph)							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	NA	162	89	47	32
> 40	NA	NA	NA	NA	120	76	40	26

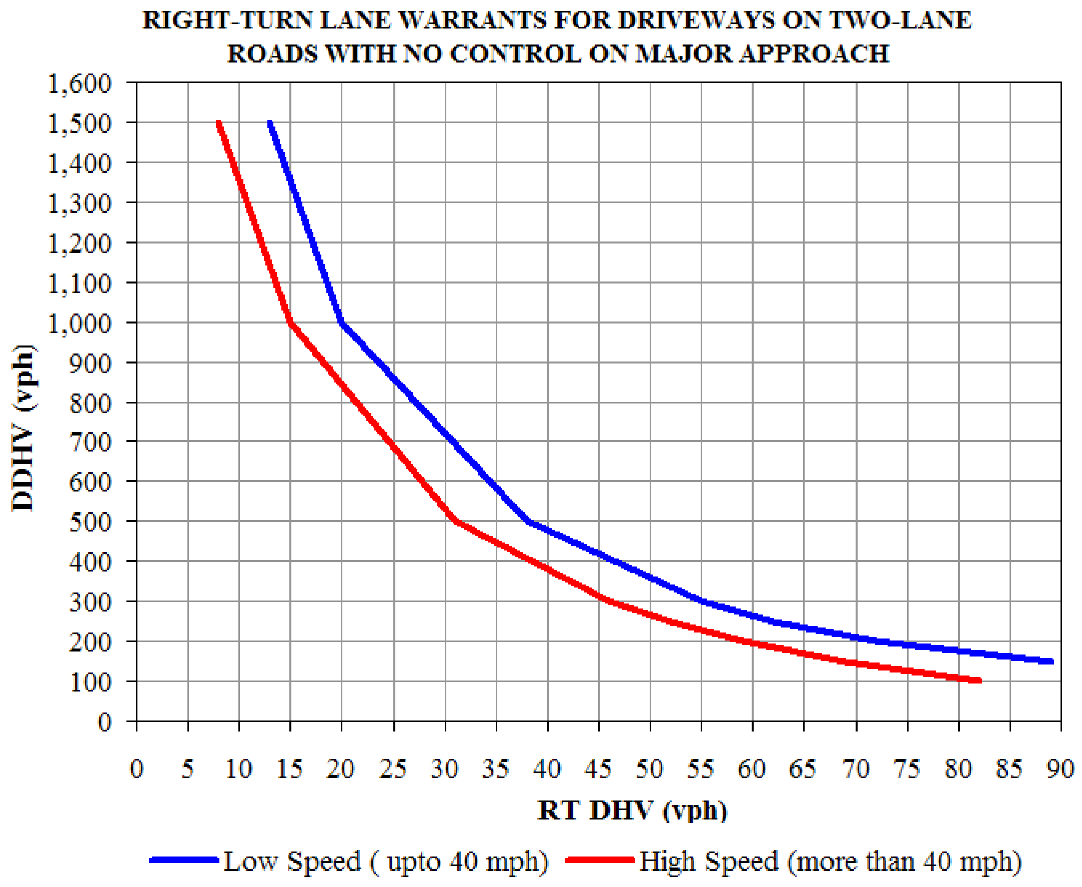
Figure 6.16. Right-turn lane warrants for intersections (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $60,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $20,000 / Cost of Fuel = $3)

Speed (mph)	DDHV (vph)							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	60	50	44	38	34	23	12	7
> 40	46	41	36	32	28	19	8	3

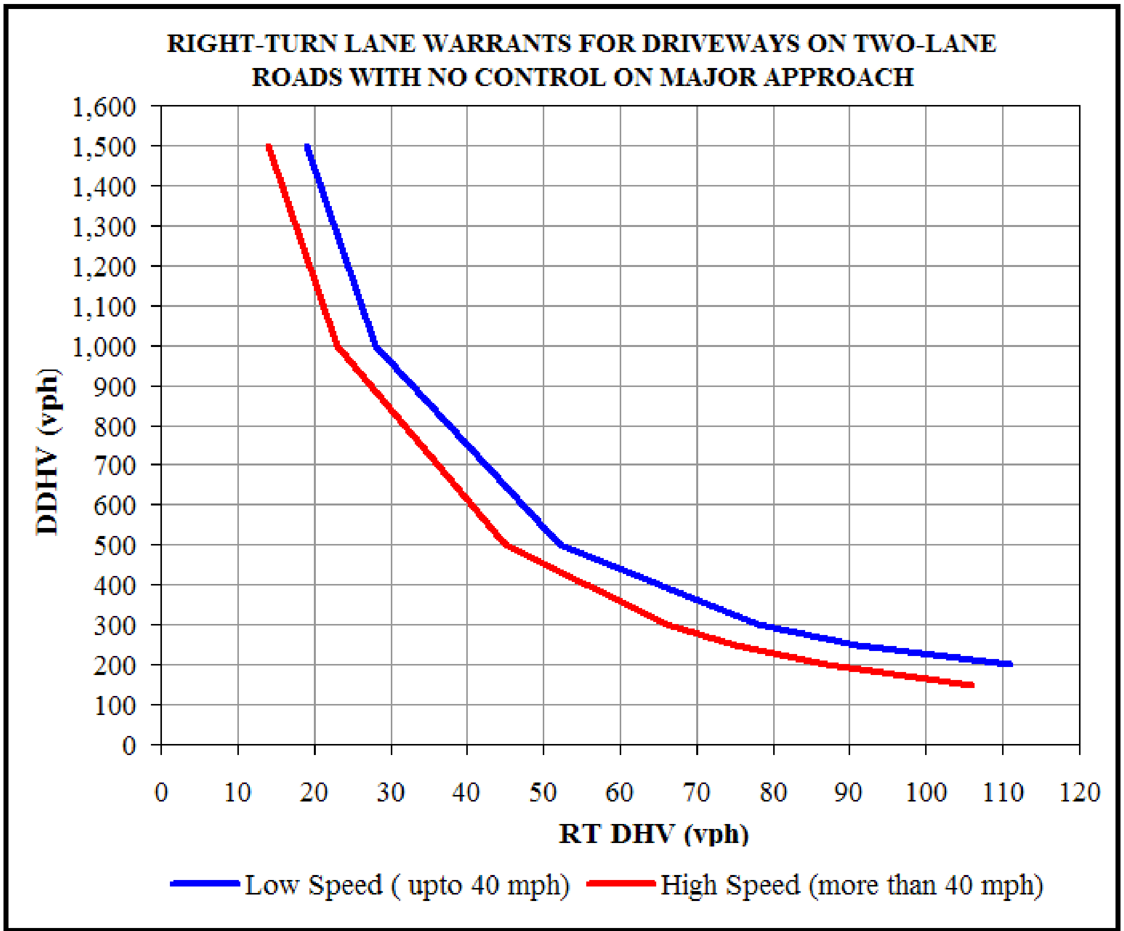
Figure 6.17. Right-turn lane warrants for driveways (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $20,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $30,000 / Cost of Fuel = $3)

Speed (mph)	DDHV (vph)							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	89	72	62	55	38	20	13
> 40	82	69	59	52	46	31	15	8

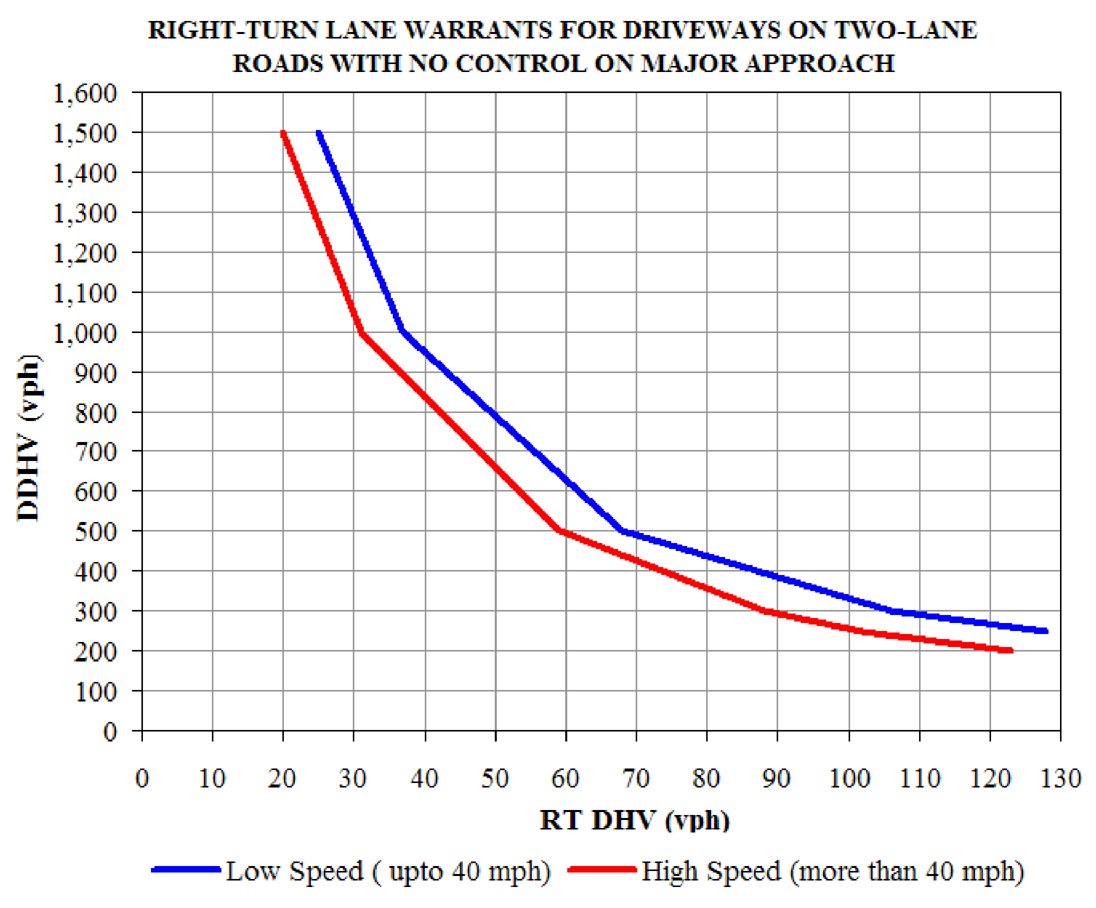
Figure 6.18. Right-turn lane warrants for driveways (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $30,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $40,000 / Cost of Fuel = $3)

Speed (mph)	DDHV (vph)							
	100	150	200	250	300	500	1,000	1,500
≤ 40	NA	NA	111	91	78	52	28	19
> 40	NA	106	87	75	66	45	23	14

Figure 6.19. Right-turn lane warrants for driveways (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $40,000).

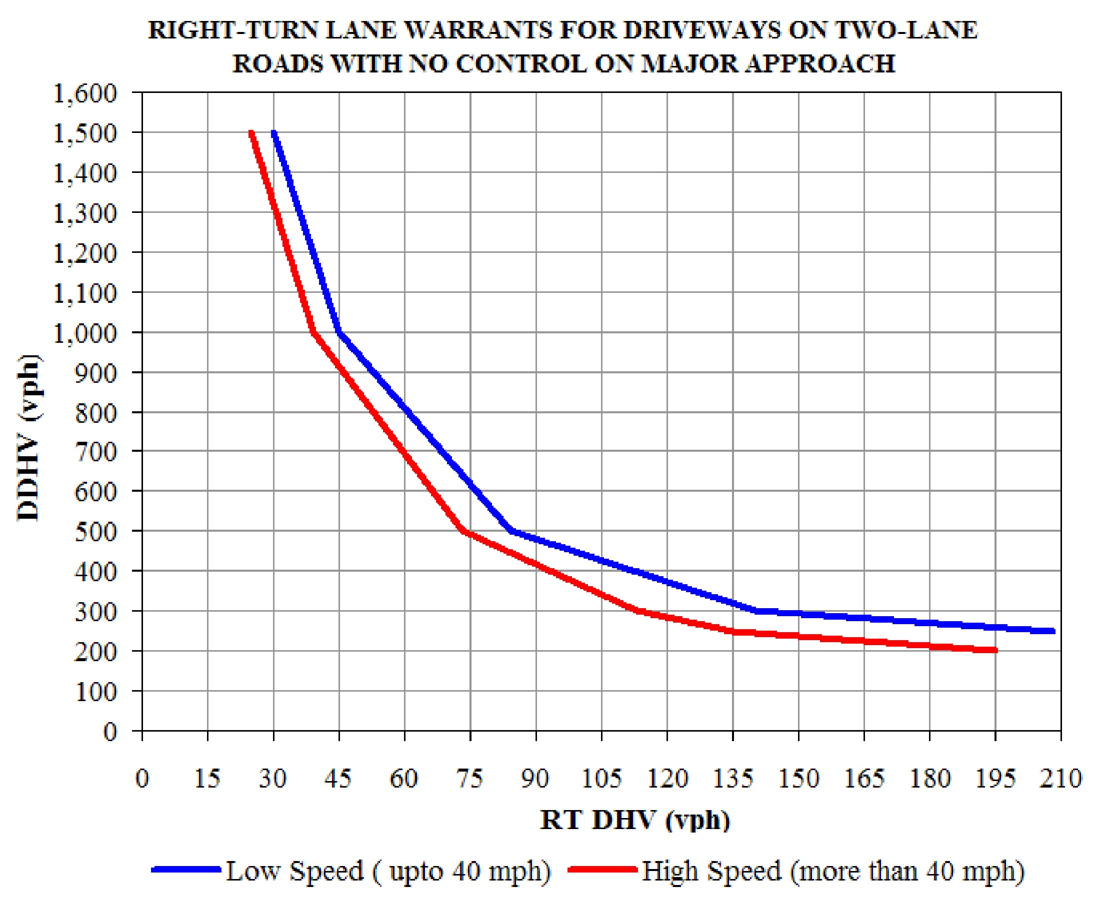


Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane

(Right-turn Lane Cost = $50,000 / Cost of Fuel = $3)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	128	106	68	37	25
> 40	NA	NA	123	102	88	59	31	20

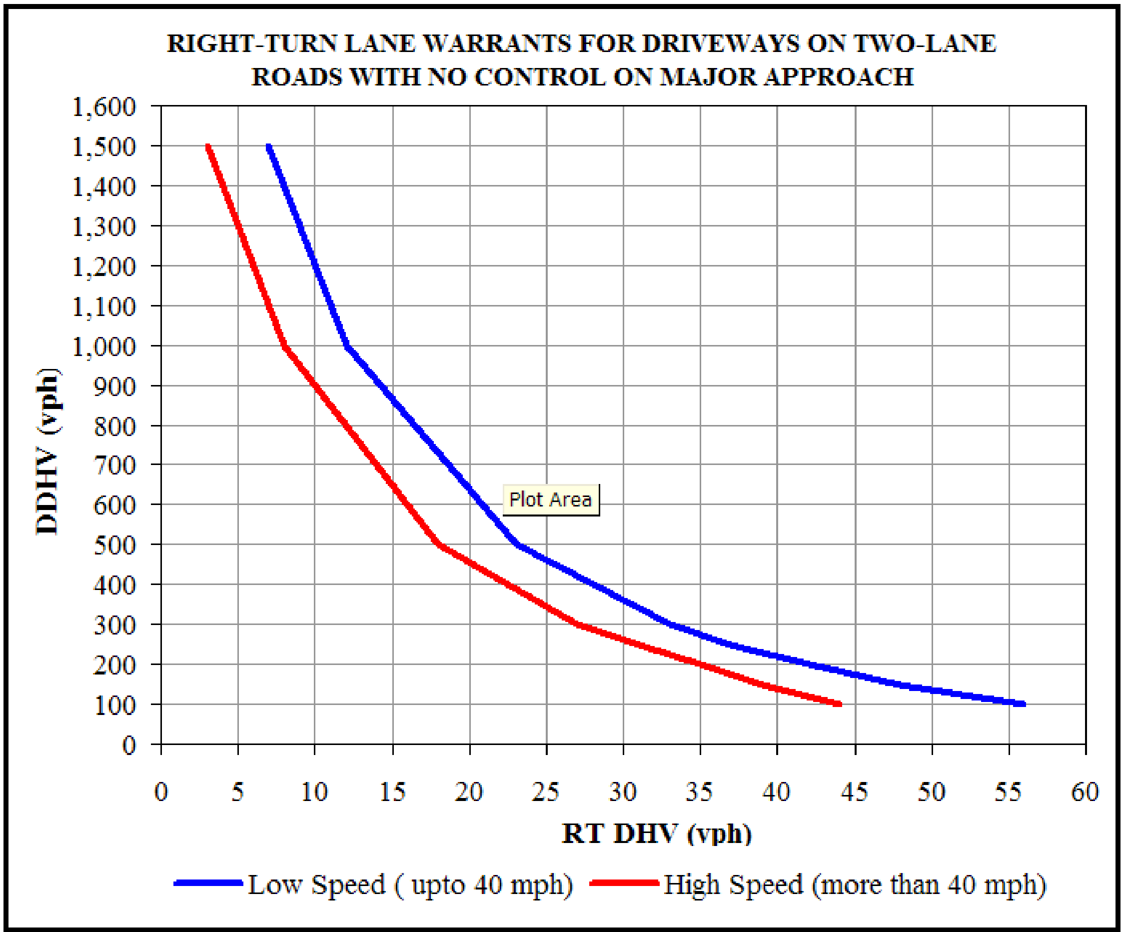
Figure 6.20. Right-turn lane warrants for driveways (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $50,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $60,000 / Cost of Fuel = $3)

Speed (mph)	DDHV (vph)							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	208	140	84	45	30
> 40	NA	NA	195	135	113	73	39	25

Figure 6.21. Right-turn lane warrants for driveways (fuel cost $3/gallon, delay cost $13/hr, right-turn lane cost $60,000).

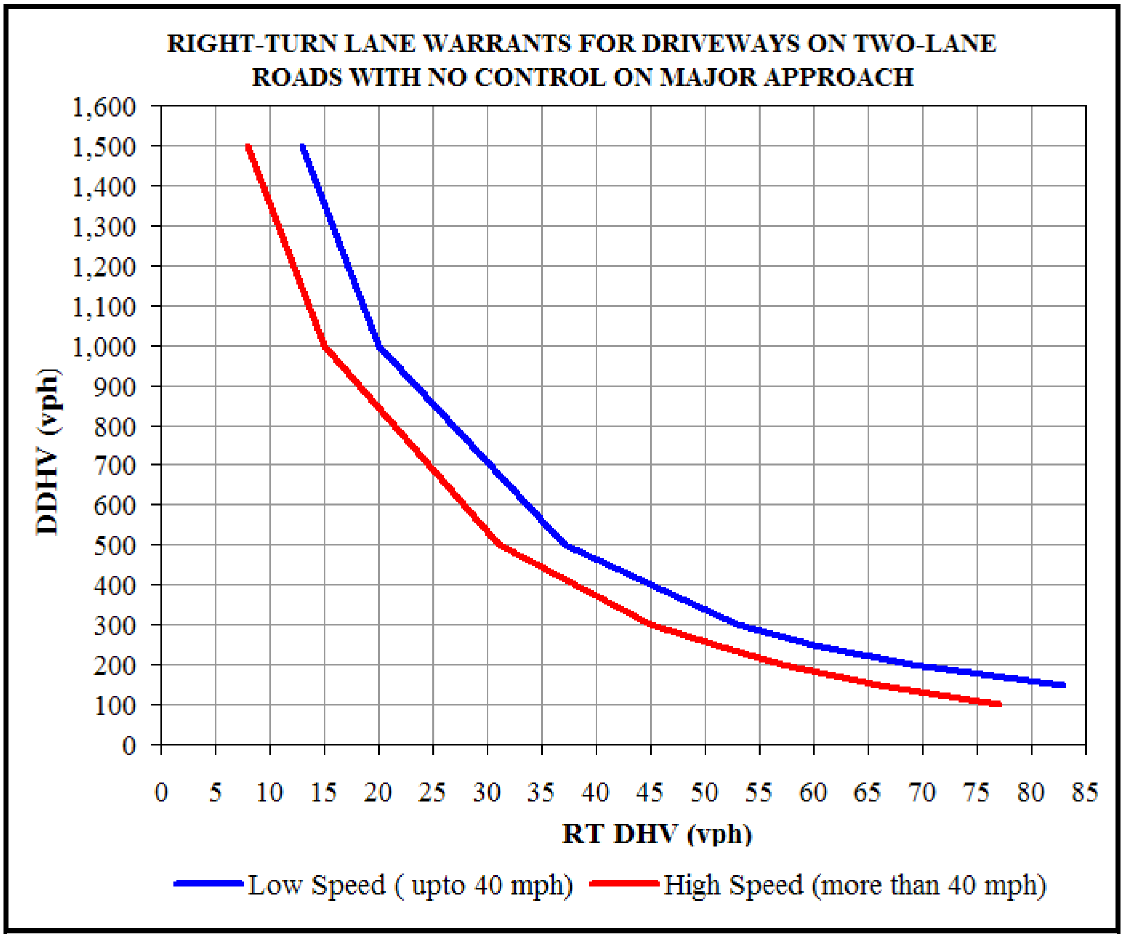


Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane

(Right-turn Lane Cost = $20,000 / Cost of Fuel = $4)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	56	48	42	37	33	23	12	7
> 40	44	39	35	31	27	18	8	3

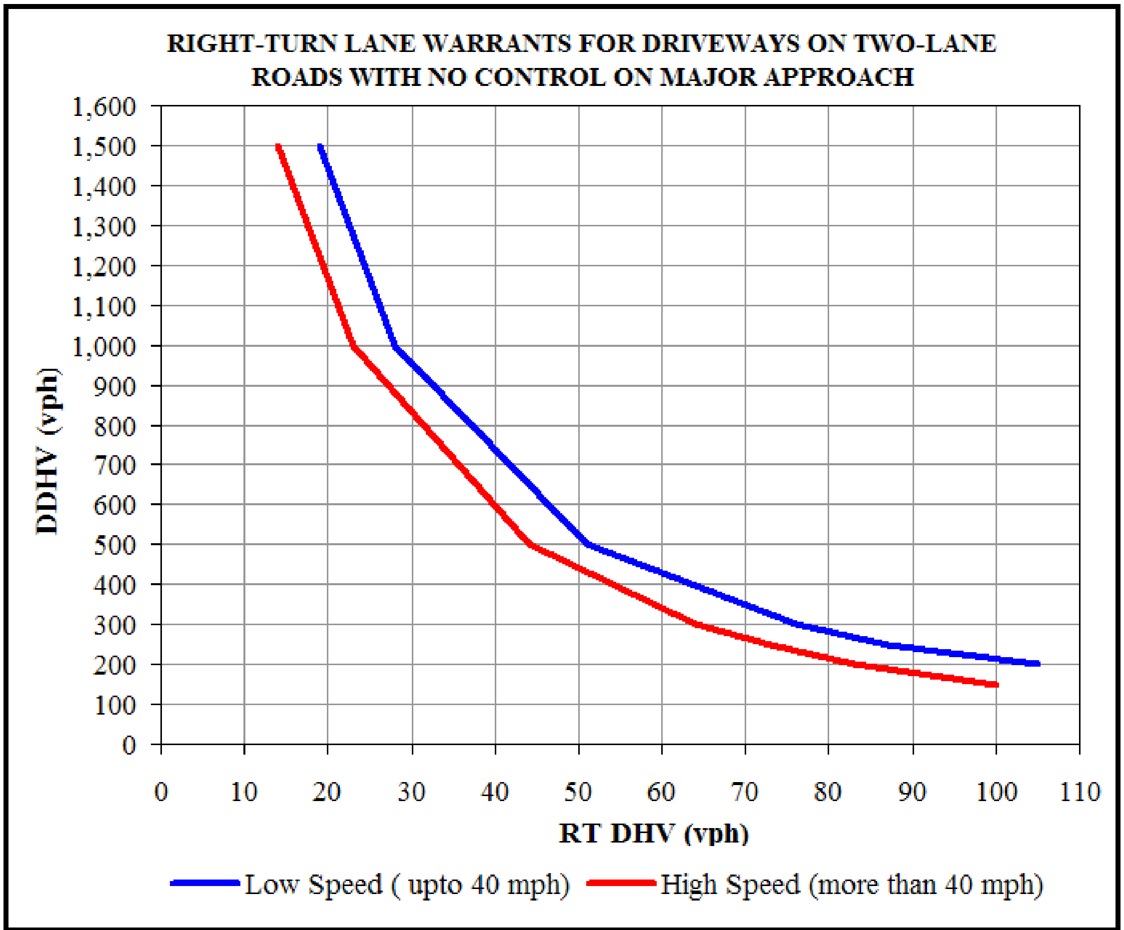
Figure 6.22. Right-turn lane warrants for driveways (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $20,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $30,000 / Cost of Fuel = $4)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	83	69	60	53	37	20	13
> 40	77	66	57	51	45	31	15	8

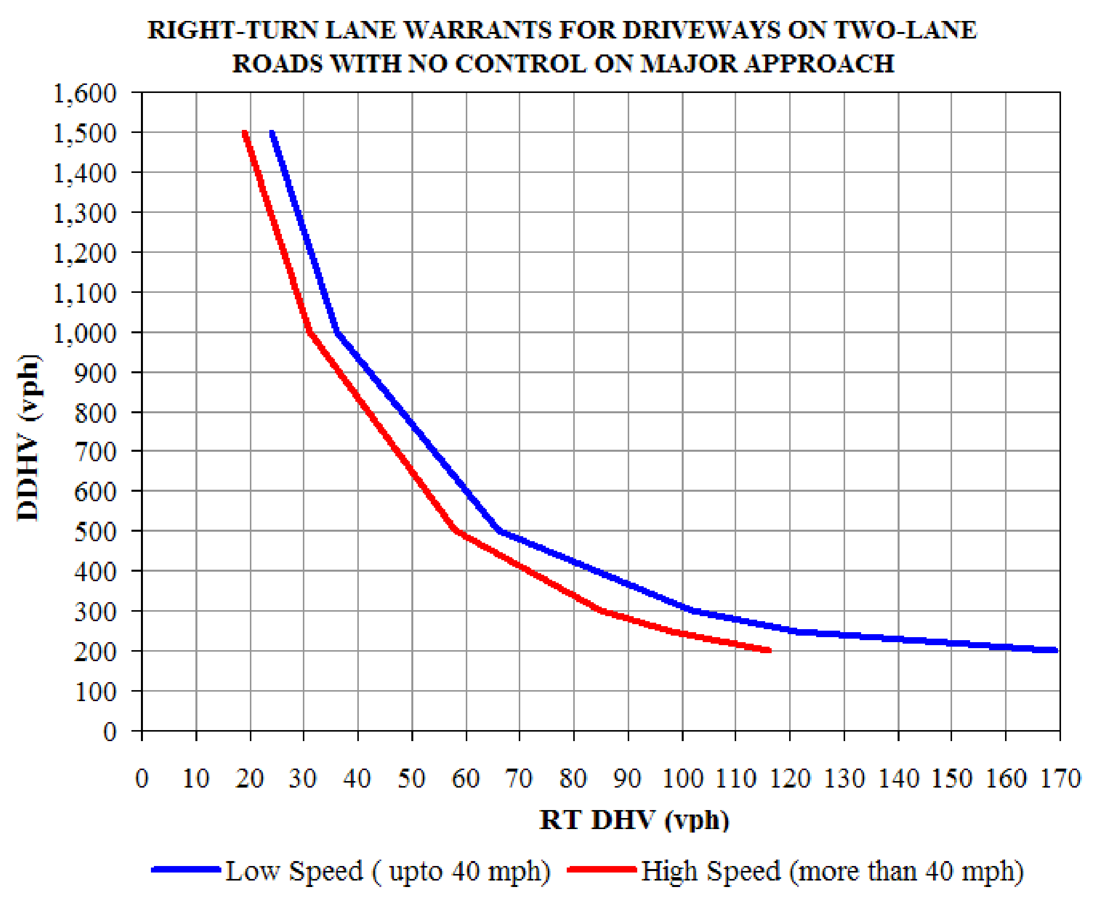
Figure 6.23. Right-turn lane warrants for driveways (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $30,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $40,000 / Cost of Fuel = $4)

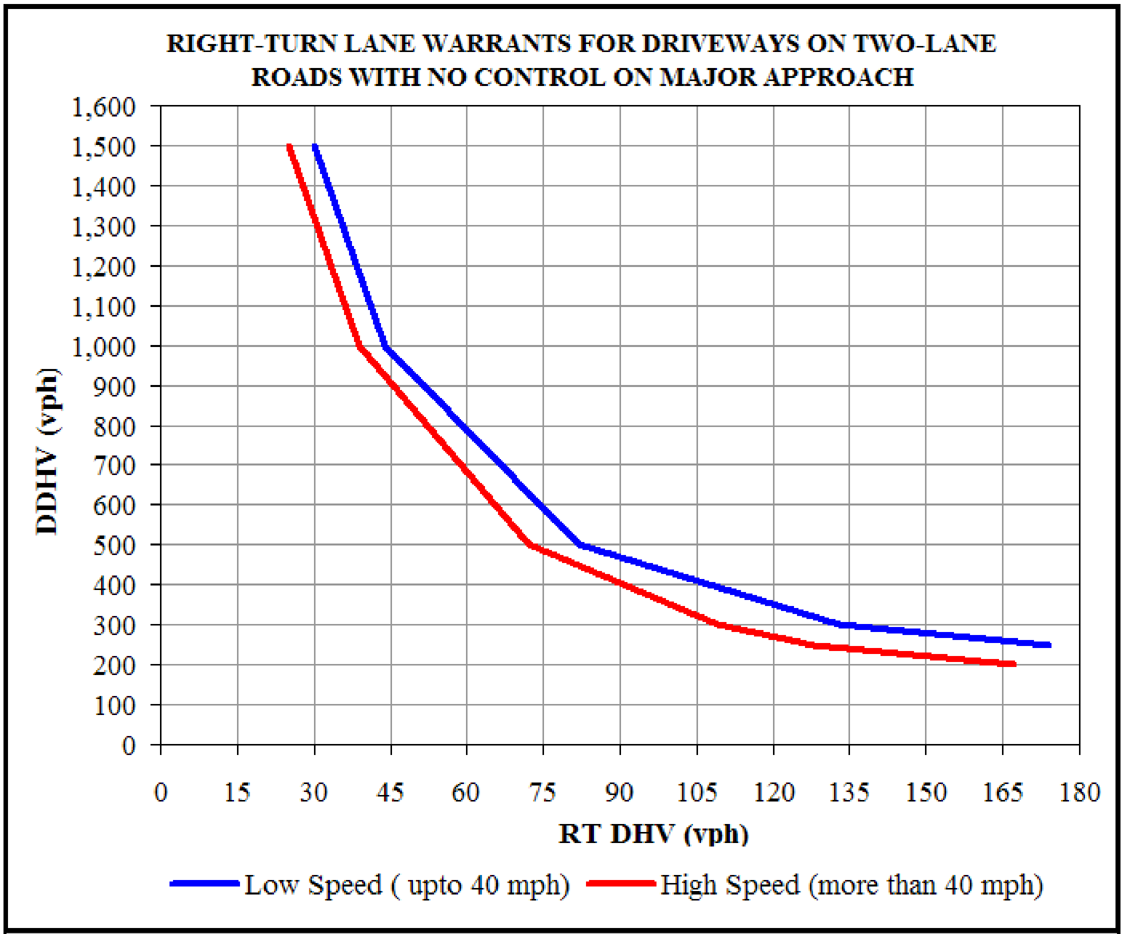
Speed (mph)	DDHV (vph)							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	105	87	76	51	28	19
> 40	NA	100	83	73	64	44	23	14

Figure 6.24. Right-turn lane warrants for driveways (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $40,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane (Right-turn Lane Cost = $50,000 / Cost of Fuel = $4)								
Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	169	121	102	66	36	24
> 40	NA	NA	116	98	85	58	31	19

Figure 6.25. Right-turn lane warrants for driveways (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $50,000).



Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane
(Right-turn Lane Cost = $60,000 / Cost of Fuel = $4)

Speed (mph)	**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
≤ 40	NA	NA	NA	174	133	82	44	30
> 40	NA	NA	167	128	109	72	39	25

Figure 6.26. Right-turn lane warrants for driveways (fuel cost $4/gallon, delay cost $13/hr, right-turn lane cost $60,000).

Chapter 7 Conclusions and Recommendations

7.1 Conclusions

The conclusions are drawn in the areas of right turn lane guidelines, safety impacts, operational impacts, and bases and establishment of warrants.

7.1.1 Right turn lane guidelines

Right turn lane guidelines exist, but they are not clear and convincing for contexts dealing with two-lane roads where main highways do not have any control. Even if the guidelines that were developed were based on analysis of few intersections in a local area of state. This study examined and assessed on a statewide basis.

7.1.2 Safety impacts

The main conclusions from the analysis of crash data are as follows:

- The following crash types constituted, between them, more than 90% of the crashes that involved at least one vehicle making a right turn: the rear-end, sideswipe (same-direction), right-angle, and the right-turn. This indicates that a crash involving right-turn movements of vehicles can be analyzed in terms of rear-end, sideswipe (same-direction), right-angle, and right-turn crashes;
- The crash related to a right-turn movement of traffic is significantly associated with the following explanatory factors: the posted speed limit of roadways, road surface conditions, weather conditions, whether the vehicle has defects, and the days of a week in terms of weekdays or weekends;
- Given that the crash involved at least one vehicle making a right turn, the significant factors influencing the probability of the occurrence of a rear-end crash are: the posted speed limit of roadways, right-turn treatment type at an intersection, and driver inattention;
- Given that the crash involved at least one vehicle making a right turn, the significant factors influencing the probability of the occurrence of a same-direction sideswipe crash are: the road surface conditions and driver error;
- Given that the crash involved at least one vehicle making a right turn, the significant factors influencing the probability of the occurrence of a right-angle crash are: the road surface conditions and visibility;
- Given that the crash involved at least one vehicle making a right turn, the weather conditions are the most significant explanatory factor influencing the probability of the occurrence of a right-turn crash;
- Given that the crash involved at least one vehicle making a right turn, the right-turn treatment at an intersection was found to significantly influence only rear-end crashes;

- The risk of a rear-end crash happening at an intersection with a shared right-turn treatment as compared to that with an exclusive right-turn treatment is about 3.0 times higher at low posted speed limit, and 2.5 times higher at medium and high posted speed limit of roadways; and
- Simulation of right-turn movements and the related conflicts was only relevant for rear-end crashes in determining the safety effectiveness of right-turn treatments.

A unique way of assessing safety effects of right turn lanes have been found using field based conflict data. Logisitic regression has been very useful to establish probabilities, relative risks, odd ratios, and severities.

7.1.3 Operational impacts

Operational impacts were associated with delays to through vehicles and excess fuel consumption. Field collected data was used to calibrate CORSIM model for developing models to assess operational impacts. The data collected were used to validate the simulation model results also. Based on calibrated simulation models, predictive equations to assess operational costs under shared and exclusive conditions were established. Right turn pocket lengths, right turn percentages, volumes, and speed were key variables affecting operational impacts.

7.1.4 Land use impacts

There was distinct difference between probabilities of accident occurrence of different severities at intersections and commercial driveways. This has been an illuminating finding. As a result, right-turn lanes have higher safety effectiveness at driveways than at intersections.This lesson can be used effectively in practice.

7.1.5 Warrants for right turn lanes

For given DDHV and speed, warrants in terms of right turn volumes and percent of right turn in directional traffic has been established for contexts dealing with intersections and driveways on two-lane roads, where there are no control on main highways.

7.2 Recommendations

Some of the recommendations for future research are discussed in sub-sections below.

7.2.1 Implementing the findings

Among the immediate application of the findings is in providing additional details in the road design manual with regard to the warrant for right turn lanes on two lane roads where there are no controls on main highways. A good discussion with design and traffic engineers will be very productive. For some actual sites this warrant should be applied and see if it makes sense.

Another good implementation would be development of a spreadsheet based model to allow the design and traffic engineers to do “what if” scenario or sensitivity analyses for different contexts in much flexible and efficient manner. This could then serve as an important tool.

7.2.2 Data needs to improvement assessments

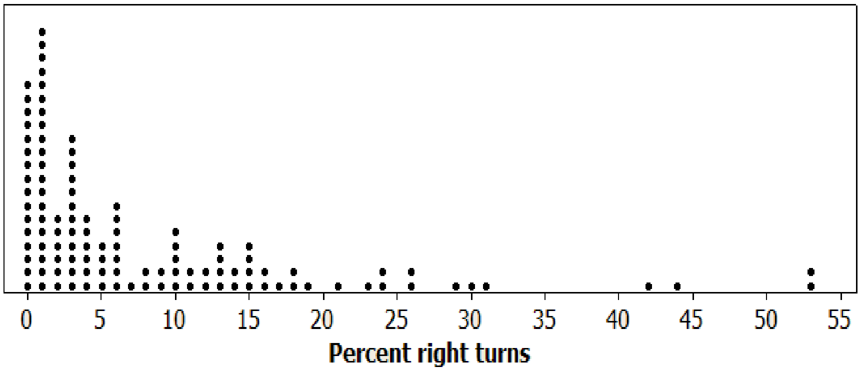
Intersection inventory database should include the right turn geometry information for all approaches at intersections. Accident location information can be improved also. Right turn lane cost data is not well established and more effort in this direction could help improve the warrants further.

7.2.3 Enhancing safety assessments

The simulation based conflict model can enhance the safety assessment further. However, development of such simulation based models should be done with much more comprehensive data collection over a period of 4 days at least for each approach for which conflict data are collected.

1. The speed levels considered in this study were ‘high’ (speed > 40 mph) and ‘low’ (speed <= 40 mph). These broad classifications of speed levels may overestimate/ underestimate conflicts due to right turns at specific speed limit, and, hence, may not give true picture of safety costs. It is, therefore, recommended that conflict studies be carried out in such a way that different speed levels, such as 30, 35, 40, 45, 50, 55, 60, 65 mph, are taken in account to improve the conflict model. Any one of the following two methods may be adopted: (1) field conflict surveys at locations with different speeds, and (2) conflict analysis through simulations. Such models should provide better estimates of right-turn conflicts at a specific value of posted speed limit, and also be more compatible with crash severity models to estimate the cost of a crash.

2. Higher right-turn percentages were found to be not well represented in the conflict data collected to develop the right-turn conflict model as shown in the following dotplot based on the collected data. It is, therefore, recommended that additional conflict data representing higher percent right turns be collected or conflict models be developed through simulations.



3. It is also recommended that the crash-conflict ratio be validated or improved. For this purpose, the crash data for years 2006 and 2007 may be used, if available.

7.2.4 Enhancing operational assessments

The right turn pocket use is not the very best but results obtained were reasonable. The effect of taper is not well addressed in CORSIM and should be understood better. More calibration and validation must be done in this regard to improve the models.

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Appendix A: Contingency Tables

Appendix A: Contingency Tables

This appendix presents the contingency tables of outcome (Y = 0, 1) versus the levels of explanatory factors as applicable for eleven different logistic regression models considered in safety study. Contingency table helps in identifying zero cells that yield a point estimate for one of the odds ratios of either zero or infinity. Including such a variable in a logistic regression model causes undesirable numerical outcomes to occur.

Table A.1. Contingency table for the explanatory factors included in model 1.

Explanatory Factors	**Whether the crash involved at least one vehicle making a right turn from System road?**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*3*	*2*	*5*	*0.05*
High	2,206	73	2,279	22.27
Low	7,557	394	7,951	77.68
Total	**9,766**	**469**	**10,235**	**100.00**
Driver error or driver inattention (DRENI)				
Yes	9,056	413	9,469	92.5
No	710	56	766	7.5
Total	**9,766**	**469**	**10,235**	**100**
Driver error (DRERR)				
Yes	7,256	325	7,581	74.1
No	2,510	144	2,654	25.9
Total	**9,766**	**469**	**10,235**	**100.00**
Time of day (DTIME)				
Night	1,443	64	1,507	14.7
Day	8,323	405	8,728	85.3
Total	**9,766**	**469**	**10,235**	**100.00**
Heavy commercial vehicle traffic (HCVPR)				
*Not known**	*3*	*2*	*5*	*0.0*
High	2,017	125	2,142	20.9
Low	7,746	342	8,088	79.0
Total	**9,766**	**469**	**10,235**	**100.00**
Driver inattention (INATT)				
Yes	4,540	178	4,718	46.1
No	5,226	291	5,517	53.9
Total	**9,766**	**469**	**10,235**	**100.00**

Table A.1. (continued)

Explanatory Factors	**Whether the crash involved at least one vehicle making a right turn from System road?**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Intersection type (JUNCT)				
Driveway	1,207	175	1,382	13.5
Intersection**	8,559	294	8,853	86.5
Total	**9,766**	**469**	**10,235**	**100.00**
Light conditions (LIGHT)				
*Not known**	*48*	*5*	*53*	*0.5*
No light	522	23	545	5.3
Some light	1,133	63	1,196	11.7
Daylight	8,063	378	8,441	82.5
Total	**9,766**	**469**	**10,235**	**100.00**
Road character (RDCHR)				
*Not known**	*105*	*9*	*114*	*1.1*
Curve & grade	302	13	315	3.1
Curve & level	548	19	567	5.5
Straight & grade	1,355	55	1,410	13.8
Straight & level	7,456	373	7,829	76.5
Total	**9,766**	**469**	**10,235**	**100.00**
Posted speed limit (SPEED)				
*Not known**	*46*	*5*	*51*	*0.5*
High	5,833	256	6,089	59.5
Low	3,887	208	4,095	40.0
Total	**9,766**	**469**	**10,235**	**100.00**
Road surface conditions (SURFC)				
*Not known**	*56*	*3*	*59*	*0.6*
Wet & slippery	2,269	184	2,453	24.0
Dry	7,441	282	7,723	75.5
Total	**9,766**	**469**	**10,235**	**100.00**
Tractor-trailer combination involved (TTCMB)				
Yes	634	50	684	6.7
No	9,132	419	9,551	93.3
Total	**9,766**	**469**	**10,235**	**100.00**
Vehicular defects (VHDEF)				
Yes	135	16	151	1.5
No	9,631	453	10,084	98.5
Total	**9,766**	**469**	**10,235**	**100.00**
Weather conditions (WETHR)				
*Not known**	*41*	*3*	44	0.4
Not clear	1,242	90	1,332	13.0
Somewhat clear	2,841	112	2,953	28.9
Clear	5,642	264	5,906	57.7
Total	**9,766**	**469**	**10,235**	**100.00**

* Not included in the analysis.

** Only 3-legged or 4-legged intersections were considered.

Table A.2. Contingency table for the explanatory factors included in model 2.

Explanatory Factors	**Crash event was a rear-end crash and involved at least one vehicle making a right turn from System road**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*1*	*1*	*2*	*0.5*
High	42	25	67	15.4
Low	242	124	366	84.1
Total	**285**	**150**	**435**	**100.0**
Driver error or driver inattention (DRENI)				
Yes	243	136	379	87.1
No	42	14	56	12.9
Total	**285**	**150**	**435**	**100.0**
Driver error (DRERR)				
Yes	201	91	292	67.1
No	84	59	143	32.9
Total	**285**	**150**	**435**	**100.0**
Heavy commercial vehicle traffic (HCVPR)				
*Not known**	*1*	*1*	*2*	*0.5*
High	83	35	118	27.1
Low	201	114	315	72.4
Total	**285**	**150**	**435**	**100.0**
Driver inattention (INATT)				
Yes	83	91	174	40.0
No	202	59	261	60.0
Total	**285**	**150**	**435**	**100.0**
Intersection type (JUNCT)				
Driveway	87	79	166	38.2
Intersection**	198	71	269	61.8
Total	**285**	**150**	**435**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*3*	*1*	*4*	*0.9*
High	134	97	231	53.1
Low	148	52	200	46.0
Total	**285**	**150**	**435**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*2*	*1*	*3*	*0.7*
Wet & slippery	124	53	177	40.7
Dry	159	96	255	58.6
Total	**285**	**150**	**435**	**100.0**
Vehicular defects (VHDEF)				
Yes	7	9	16	3.7
No	278	141	419	96.3
Total	**285**	**150**	**435**	**100.0**

Table A.2. (continued)

Explanatory Factors	**Crash event was a rear-end crash and involved at least one vehicle making a right turn from System road**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Right turn treatment (RTTRT)				
Shared	201	136	337	77.5
Exclusive	84	14	98	22.5
Total	**285**	**150**	**435**	**100.0**
Intersection type, From case only (DRWAY)				
Comm. driveway	45	39	84	19.3
Pvt. driveway	40	40	80	18.4
Intersection	200	71	271	62.3
Total	**285**	**150**	**435**	**100.0**

* Not included in the analysis.

** Only 3-legged or 4-legged intersections were considered.

Table A.3. Contingency table for the explanatory factors included in model 3.

Explanatory Factors	**Crash event was a sideswipe (same direction) crash and involved at least one vehicle making a right turn from System road**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*1*	*1*	*2*	*0.5*
High	55	12	67	15.4
Low	284	82	366	84.1
Total	**340**	**95**	**435**	**100.0**
Driver error or driver inattention (DRENI)				
Yes	288	91	379	87.1
No	52	4	56	12.9
Total	**340**	**95**	**435**	**100.0**
Driver error (DRERR)				
Yes	214	78	292	67.1
No	126	17	143	32.9
Total	**340**	**95**	**435**	**100.0**
Driver inattention (INATT)				
Yes	144	30	174	40.0
No	196	65	261	60.0
Total	**340**	**95**	**435**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*4*	*0*	*4*	*0.9*
High	182	49	231	53.1
Low	154	46	200	46.0
Total	**340**	**95**	**435**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*3*	*0*	*3*	*0.7*
Wet & slippery	146	31	177	40.7
Dry	191	64	255	58.6
Total	**340**	**95**	**435**	**100.0**
Right turn treatment (RTTRT)				
Shared	267	70	337	77.5
Exclusive	73	25	98	22.5
Total	**340**	**95**	**435**	**100.0**

* Not included in the analysis.

Table A.4. Contingency table for the explanatory factors included in model 4.

Explanatory Factors	**Crash event was a right-angle crash and involved at least one vehicle making a right turn from System road**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*2*	*0*	*2*	*0.5*
High	54	13	67	15.4
Low	316	50	366	84.1
Total	**372**	**63**	**435**	**100.0**
Driver error or driver inattention (DRENI)				
Yes	329	50	379	87.1
No	43	13	56	12.9
Total	**372**	**63**	**435**	**100.0**
Time of day (DTIME)				
Night	49	12	61	14.0
Day	323	51	374	86.0
Total	**372**	**63**	**435**	**100.00**
Driver inattention (INATT)				
Yes	154	20	174	40.0
No	218	43	261	60.0
Total	**372**	**63**	**435**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*2*	*2*	*4*	*0.9*
High	199	32	231	53.1
Low	171	29	200	46.0
Total	**372**	**63**	**435**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*3*	*0*	*3*	*0.7*
Wet & slippery	146	31	177	40.7
Dry	223	32	255	58.6
Total	**372**	**63**	**435**	**100.0**
Obstructed visibility (VISON)				
Yes	13	5	18	4.1
No	359	58	417	95.9
Total	**372**	**63**	**435**	**100.0**
Right turn treatment (RTTRT)				
Shared	293	44	337	77.5
Exclusive	79	19	98	22.5
Total	**372**	**63**	**435**	**100.0**

* Not included in the analysis.

Table A.5. Contingency table for the explanatory factors included in model 5.

Explanatory Factors	**Crash event was a right-turn crash and involved at least one vehicle making a right turn from System road**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*2*	*0*	*2*	*0.5*
High	65	2	67	15.4
Low	328	38	366	84.1
Total	**395**	**40**	**435**	**100.0**
Driver error or driver inattention (DRENI)				
Yes	348	31	379	87.1
No	47	9	56	12.9
Total	**395**	**40**	**435**	**100.0**
Time of day (DTIME)				
Night	59	2	61	14.0
Day	336	38	374	86.0
Total	**395**	**40**	**435**	**100.0**
Driver inattention (INATT)				
Yes	169	5	174	40.0
No	226	35	261	60.0
Total	**395**	**40**	**435**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*4*	*0*	*4*	*0.9*
High	218	13	231	53.1
Low	173	27	200	46.0
Total	**395**	**40**	**435**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*2*	*1*	*3*	*0.7*
Wet & slippery	155	22	177	40.7
Dry	238	17	255	58.6
Total	**395**	**40**	**435**	**100.0**
Weather conditions (WETHR)				
*Not known**	*3*	*0*	3	0.7
Not clear	74	13	87	20.0
Somewhat clear	100	2	102	23.4
Clear	218	25	243	55.9
Total	**395**	**40**	**435**	**100.0**
Right turn treatment (RTTRT)				
Shared	306	31	337	77.5
Exclusive	89	9	98	22.5
Total	**395**	**40**	**435**	**100.0**

* Not included in the analysis.

Table A.6. Contingency table for the explanatory factors included in model 6.

Explanatory Factors	**Crash due to fauilure to yield by the vehicle at Cross road (Stack 5)**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*0*	*3*	*3*	*0.8*
High	88	25	113	31.8
Low	140	99	239	67.3
Total	**228**	**127**	**355**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*0*	*3*	*3*	*0.8*
High	83	62	145	40.8
Low	145	62	207	58.3
Total	**228**	**127**	**355**	**100.0**
Driver error (DRERR)				
Yes	169	119	288	81.1
No	59	8	67	18.9
Total	**228**	**127**	**355**	**100.0**
Obstructed visibility (VISON)				
Yes	17	4	21	5.9
No	211	123	334	94.1
Total	**228**	**127**	**355**	**100.0**
Driver inattention (INATT)				
Yes	75	31	106	29.9
No	153	96	249	70.1
Total	**228**	**127**	**355**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*1*	*0*	*1*	*0.3*
Wet & slippery	52	29	81	22.8
Dry	175	98	273	76.9
Total	**228**	**127**	**355**	**100.0**
Weather conditions (WETHR)				
Not cleat	23	17	40	11.3
Somewhat clear	56	43	99	27.9
Clear	149	67	216	60.8
Total	**228**	**127**	**355**	**100.0**

* Not included in the analysis.

Table A.7. Contingency table for the explanatory factors included in model 7.

Explanatory Factors	**Crash due to failure to yield by the vehicle at Cross road - opposing hit (Stack 6)**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*3*	*0*	*3*	*0.8*
High	106	7	113	31.8
Low	214	25	239	67.3
Total	**323**	**32**	**355**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*3*	*0*	*3*	*0.8*
High	126	19	145	40.8
Low	194	13	207	58.3
Total	**323**	**32**	**355**	**100.0**
Driver error or inattention (DRENI)				
Yes	292	28	320	90.1
No	31	4	35	9.9
Total	**323**	**32**	**355**	**100.0**
Light conditions (LIGHT)				
*Not known**	*5*	*0*	*5*	*1.4*
No light	10	6	16	4.5
Some light	46	8	54	15.2
Day light	262	18	280	78.9
Total	**323**	**32**	**355**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*0*	*1*	*1*	*0.3*
Wet & slippery	72	9	81	22.8
Dry	251	22	273	76.9
Total	**323**	**32**	**355**	**100.0**
Weather conditions (WETHR)				
Not cleat	32	8	40	11.3
Somewhat clear	96	3	99	27.9
Clear	195	21	216	60.8
Total	**323**	**32**	**355**	**100.0**

* Not included in the analysis.

Table A.8. Contingency table for the explanatory factors included in model 8**.**

Explanatory Factors	**Crash due to parallel stopping of vehicles at Cross-road (Stack 7)**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*3*	*0*	*3*	*0.8*
High	77	36	113	31.8
Low	186	53	239	67.3
Total	**266**	**89**	**355**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*3*	*0*	*3*	*0.8*
High	131	14	145	40.8
Low	132	75	207	58.3
Total	**266**	**89**	**355**	**100.0**
Driver error (DRERR)				
Yes	225	63	288	81.1
No	41	26	67	18.9
Total	**266**	**89**	**355**	**100.0**
Tractor-trailer combination involved (TTCMB)				
Yes	21	47	68	19.2
No	245	42	287	80.8
Total	**266**	**89**	**355**	**100.0**
Driver inattention (INATT)				
Yes	80	26	106	29.9
No	186	63	249	70.1
Total	**266**	**89**	**355**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*1*	*0*	*1*	*0.3*
Wet & slippery	64	17	81	22.8
Dry	201	72	273	76.9
Total	**266**	**89**	**355**	**100.0**
Weather conditions (WETHR)				
Not cleat	37	3	40	11.3
Somewhat clear	71	28	99	27.9
Clear	158	58	216	60.8
Total	**266**	**89**	**355**	**100.0**

* Not included in the analysis.

Table A.9. Contingency table for the explanatory factors included in model 9**.**

Explanatory Factors	**Rear-end crash at Cross-road (Stack 8)**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*3*	*0*	*3*	*0.8*
High	89	24	113	31.8
Low	214	25	239	67.3
Total	**306**	**49**	**355**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*3*	*0*	*3*	*0.8*
High	125	20	145	40.8
Low	178	29	207	58.3
Total	**306**	**49**	**355**	**100.0**
Driver inattention (INATT)				
Yes	79	27	106	29.9
No	227	22	249	70.1
Total	**306**	**49**	**355**	**100.0**
Road surface conditions (SURFC)				
*Not known**	*1*	*0*	*1*	*0.3*
Wet & slippery	69	12	81	22.8
Dry	236	37	273	76.9
Total	**306**	**49**	**355**	**100.0**

* Not included in the analysis.

Table A.10. Contingency table for the explanatory factors included in Model 10

Explanatory Factors	**Crash due to right turning vehicle obstructed visibility (Stack 9)**		**Grand Total**	
	No	**Yes**	**# of event**	**%**
Traffic volume (AADTC)				
*Not known**	*2*	*0*	*2*	*0.4*
High	67	5	72	16.1
Low	366	8	374	83.5
Total	**435**	**13**	**448**	**100.0**
Posted speed limit (SPEED)				
*Not known**	*4*	*0*	*4*	*0.9*
High	231	7	238	53.1
Low	200	6	206	46.0
Total	**435**	**13**	**448**	**100.0**
Right turn treatment type on System road (RTTRT)				
Shared	337	4	341	76.1
Exclusive	98	9	107	23.9
Total	**435**	**13**	**448**	**100.0**

* Not included in the analysis.

Table A.11. Contingency table for the qualitative explanatory factors in model 11.

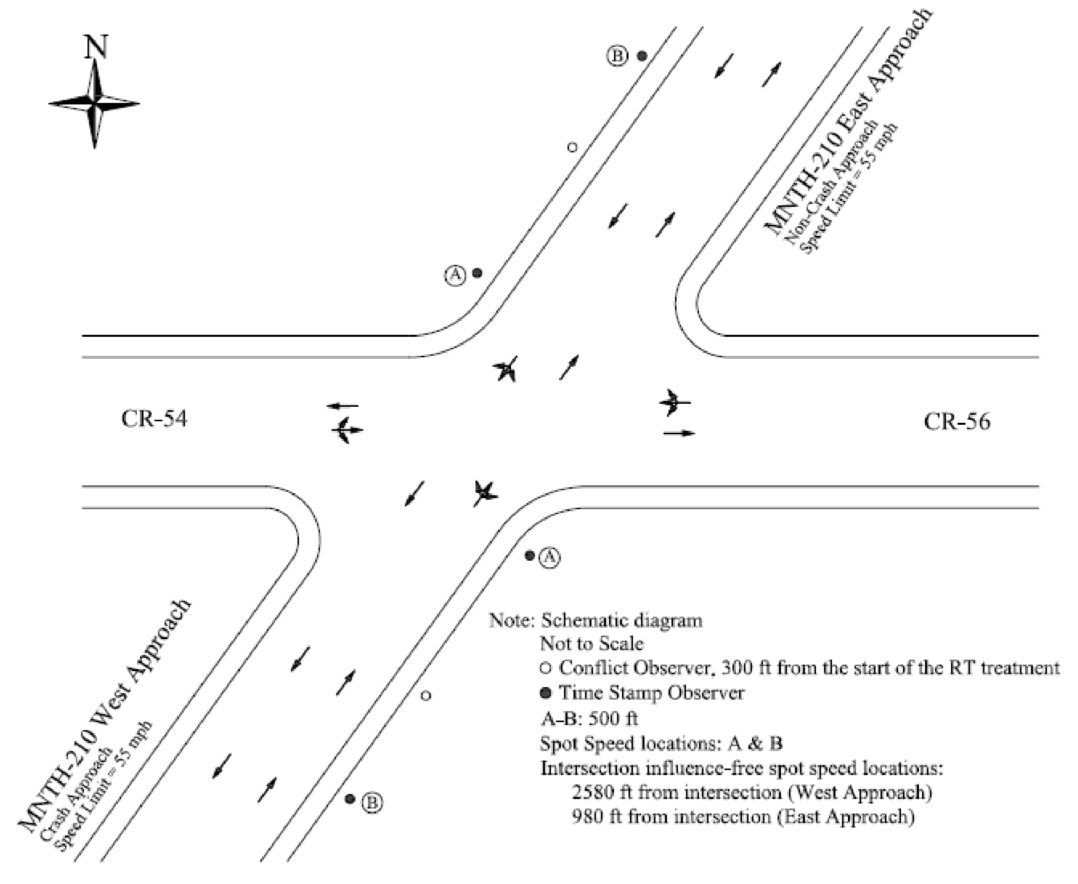
	Severity					
	Fatal	**InjuryI**	**InjuryNI**	**InjuryP**	**Propdam**	**Total**
TTCMB (Whether tractor-trailer combination involved?)						
Yes	24	24	90	117	411	666
No	101	188	1,262	2,229	5,567	9,347
Total	**125**	**212**	**1,352**	**2,346**	**5,978**	**10,013**
JUNCT (Intersection/driveway)						
Driveway	9	20	164	308	856	1,357
Intersection	116	192	1,188	2,038	5,122	8,656
Total	**125**	**212**	**1,352**	**2,346**	**5,978**	**10,013**
WETHR (Weather condition)						
Notclear	14	24	154	301	813	1,306
Somewhatclear	34	72	395	727	1,673	2,901
Clear	77	116	803	1,318	3,492	5,806
Total	**125**	**212**	**1,352**	**2,346**	**5,978**	**10,013**
SURFC (Surface conditions)						
Wet & slippery	20	43	255	537	1,539	2,394
Dry	105	169	1,097	1,809	4,439	7,619
Total	**125**	**212**	**1,352**	**2,346**	**5,978**	**10,013**
CRASHTYPE (Type of crash)						
Head-on	14	12	43	38	64	171
Left-turn	6	23	93	166	538	826
Rear-end	9	49	456	1,045	2,159	3,718
Right-angle	91	117	658	887	2,083	3,836
Sideswipe (opposing)	1	0	19	31	116	167
Sideswipe (same dirn.)	1	2	12	43	378	436
Other*	3	9	71	136	640	859
Total	**125**	**212**	**1,352**	**2,346**	**5,978**	**10,013**

* includes right-turn crash, 'ran-off-road' crash, and other crashes.

Appendix B: Schematic Diagrams of Survey Locations

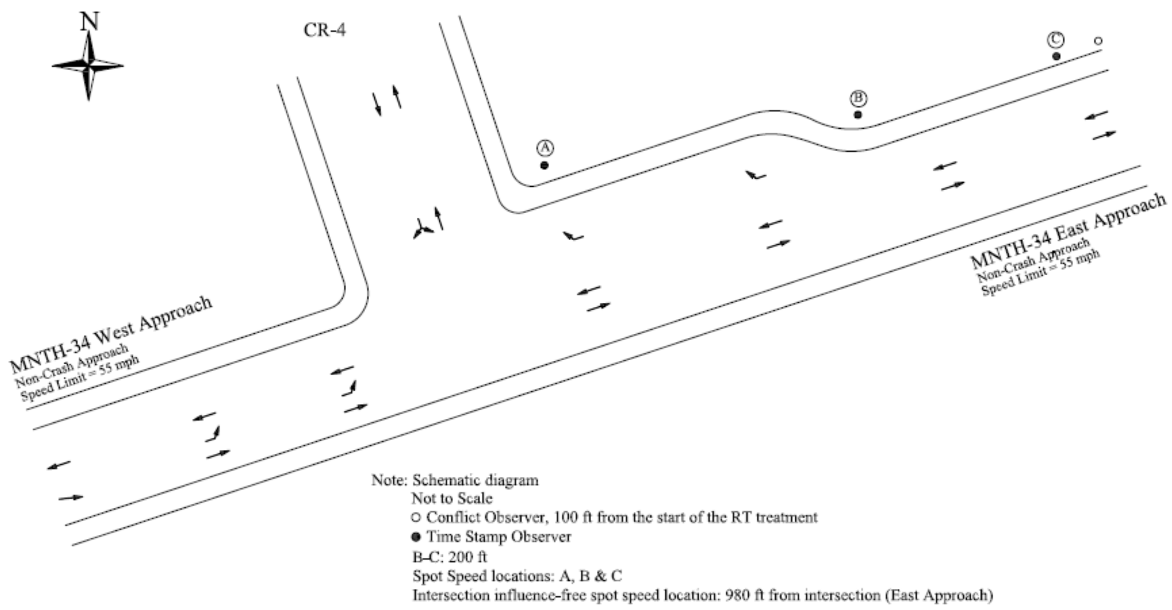
Appendix B: Schematic Diagrams of Survey Locations

This appendix provides additional details regarding intersections where field data were collected in form of schematic diagrams.



Aitkin, MN; Intersection: MNTH-210/CR-54 & CR-56

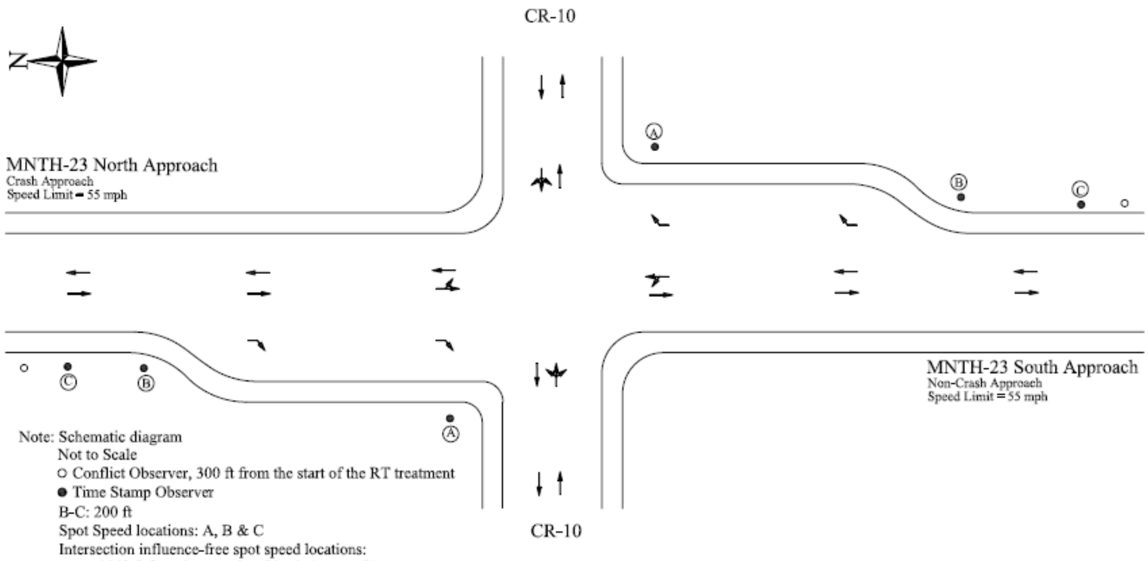
Low volume, high speed, 4-legged, shared



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 100 ft from the start of the RT treatment
● Time Stamp Observer
B–C: 200 ft
Spot Speed locations: A, B & C
Intersection influence-free spot speed location: 980 ft from intersection (East Approach)

Park Rapids, MN; Intersection: MNTH-34/CR-4

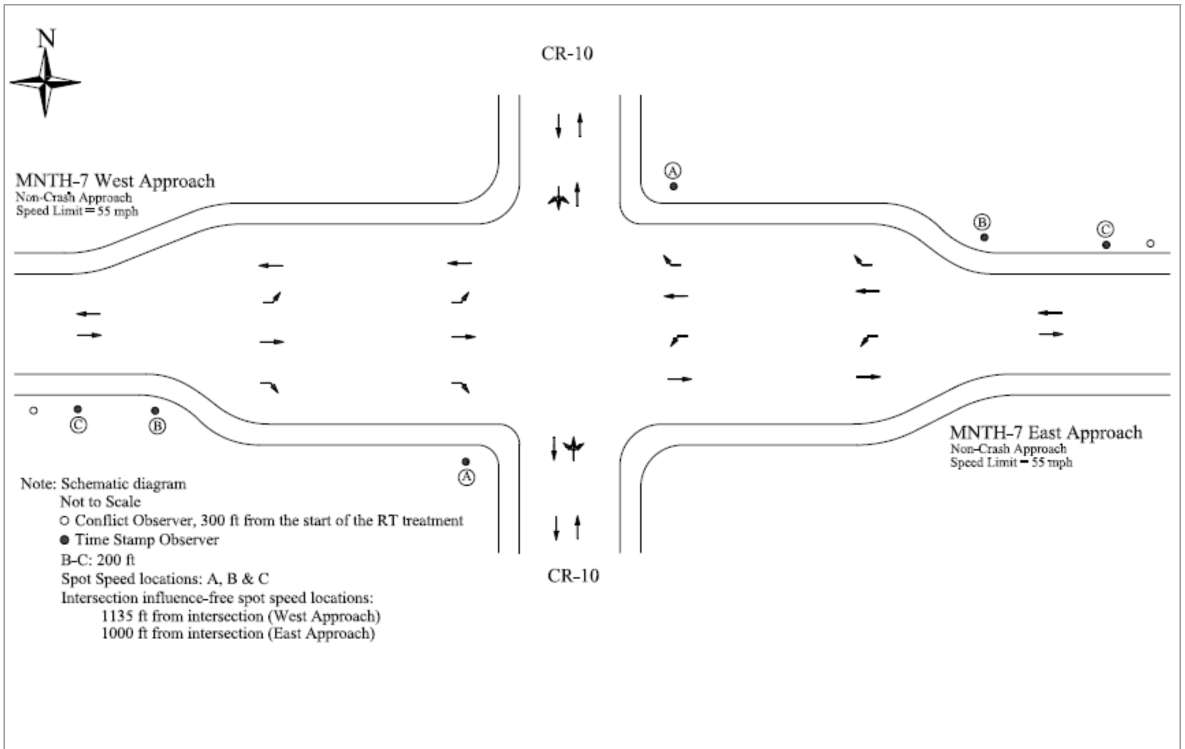
High volume, high speed, 3-legged, exclusive



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 300 ft from the start of the RT treatment
● Time Stamp Observer
B-C: 200 ft
Spot Speed locations: A, B & C
Intersection influence-free spot speed locations:
1550 ft from intersection (North Approach)
1000 ft from intersection (South Approach)

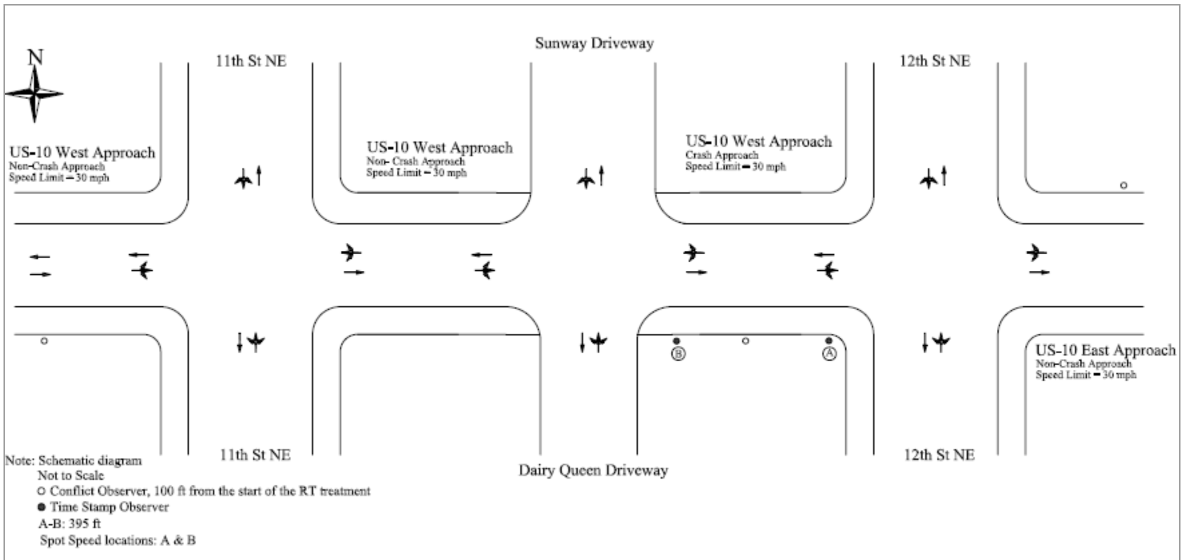
Ruthton, MN; Intersection: MNTH-23/CR-10

Low volume, high speed, 4-legged, exclusive



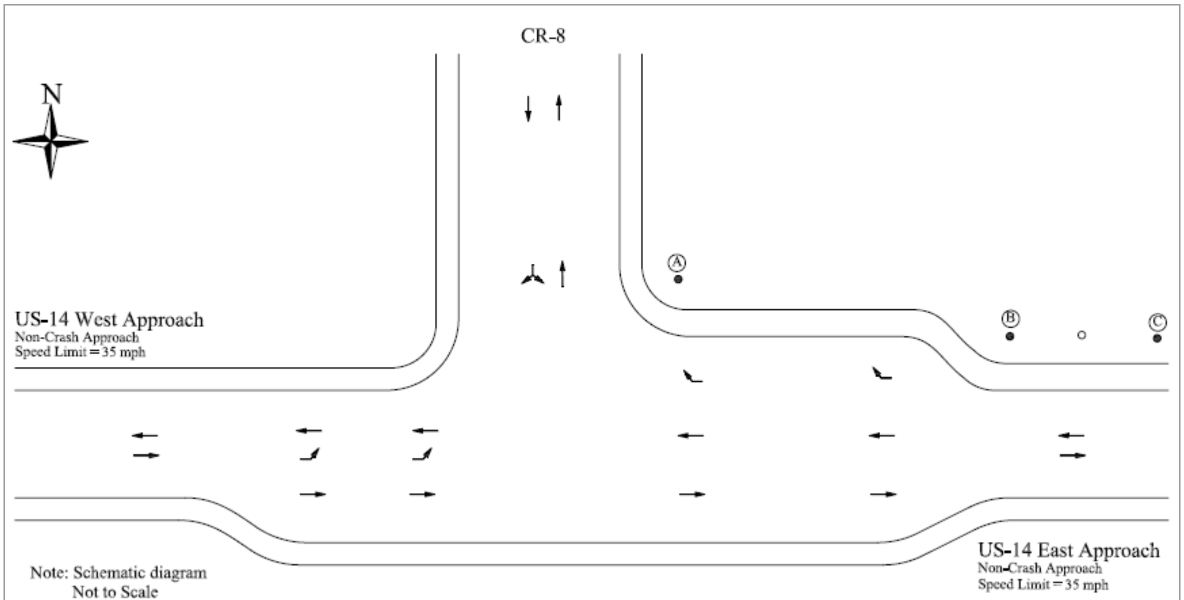
Saint Bonifacius, MN; Intersection: MNTH-7/CR-10

High volume, high speed, 4-legged, exclusive



Staples, MN; Intersection: US-10/12th St. NE (Crash Location); US-10/Subway-Dairy Queen Driveways; US-10/11th St. NE

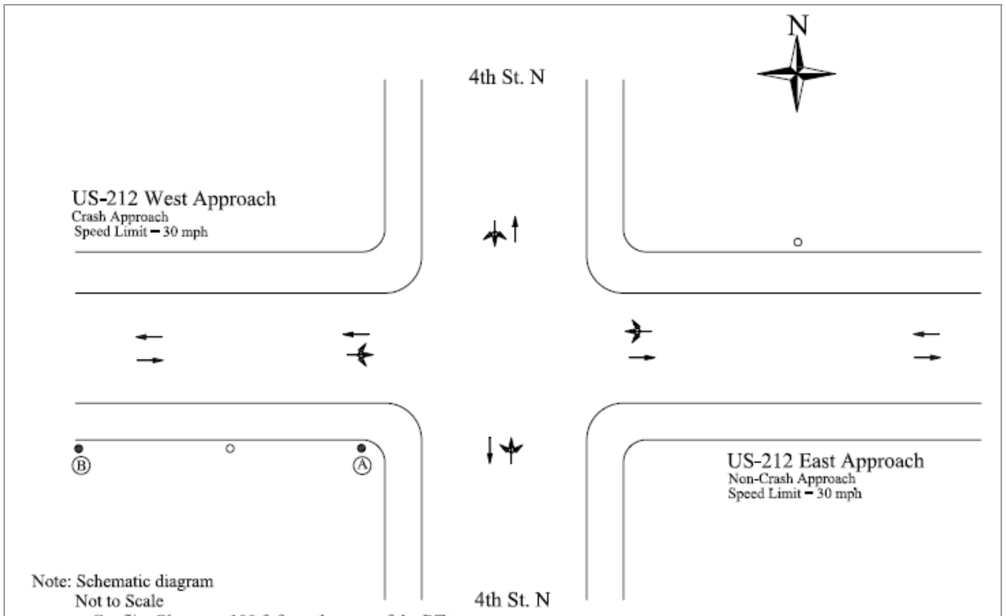
High volume, low speed, 4-legged, shared



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 100 ft from the start of the RT treatment
● Time Stamp Observer
B-C: 200 ft
Spot Speed locations: A, B & C
Intersection influence-free spot speed location: 500 ft from intersection (East Approach)

Tyler, MN; Intersection: US-14/CR-8

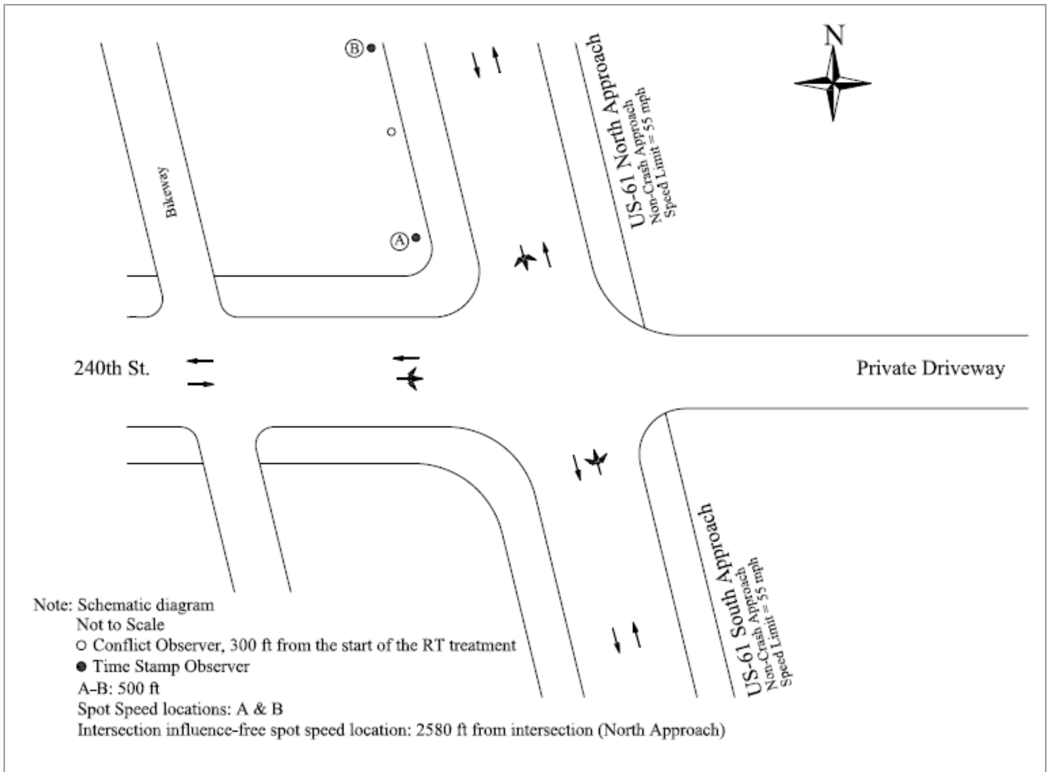
Low volume, low speed, 3-legged, exclusive



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 100 ft from the start of the RT treatment
● Time Stamp Observer
A-B: 250 ft
Spot Speed locations: A & B
Intersection influence-free spot speed location: 550 ft from intersection (West Approach)

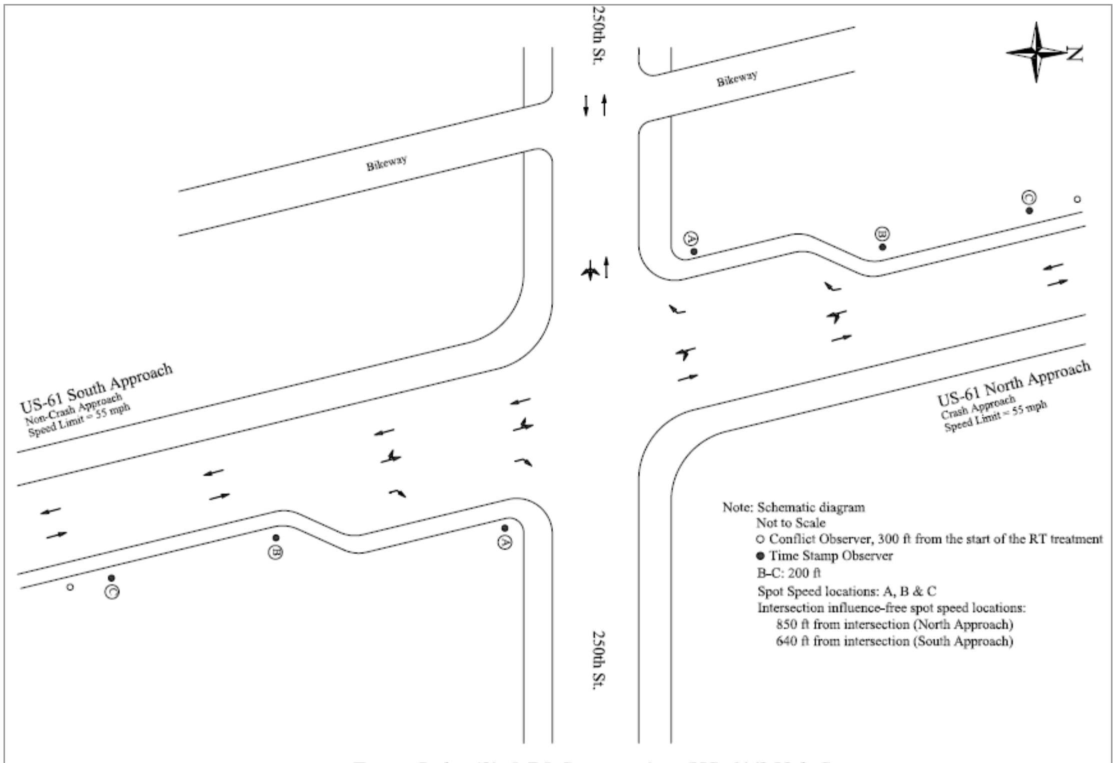
Dawson, MN; Intersection: US-212/4th St.

Low volume, low speed, 4-legged, shared



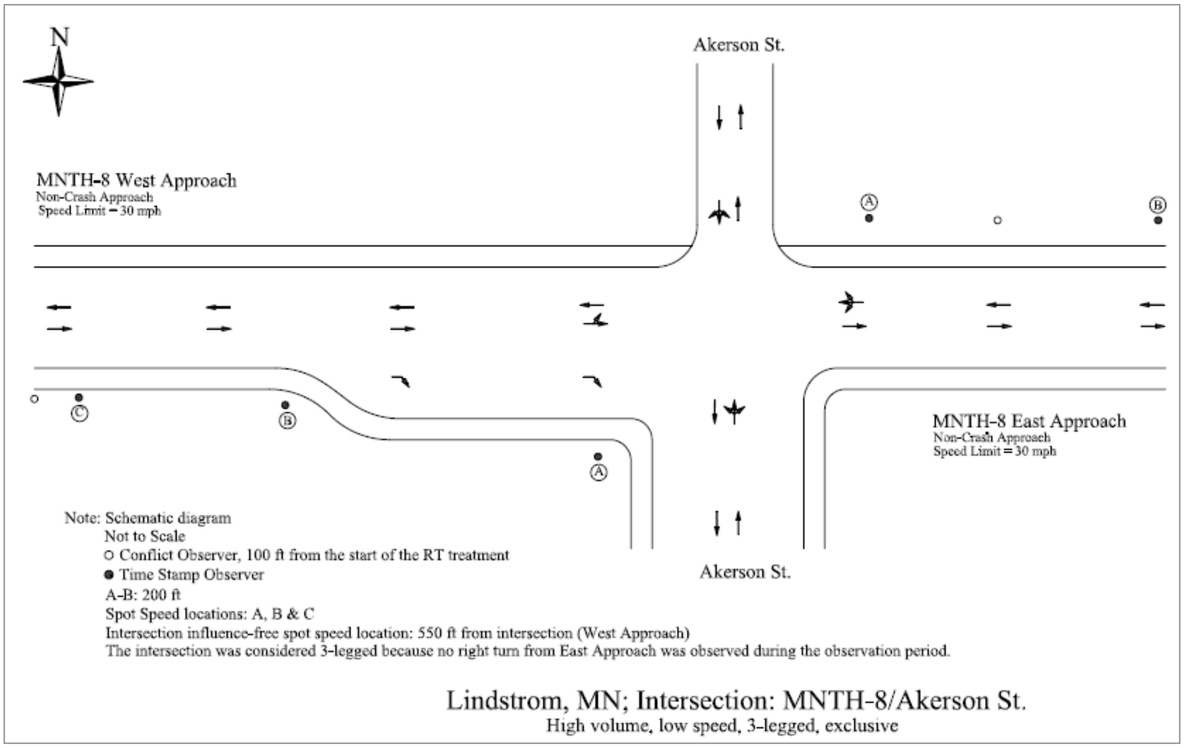
Forest Lake (1), MN; Intersection: US-61/240th St.

High volume, high speed, 3-legged, shared



Forest Lake (2), MN; Intersection: US-61/250th St.

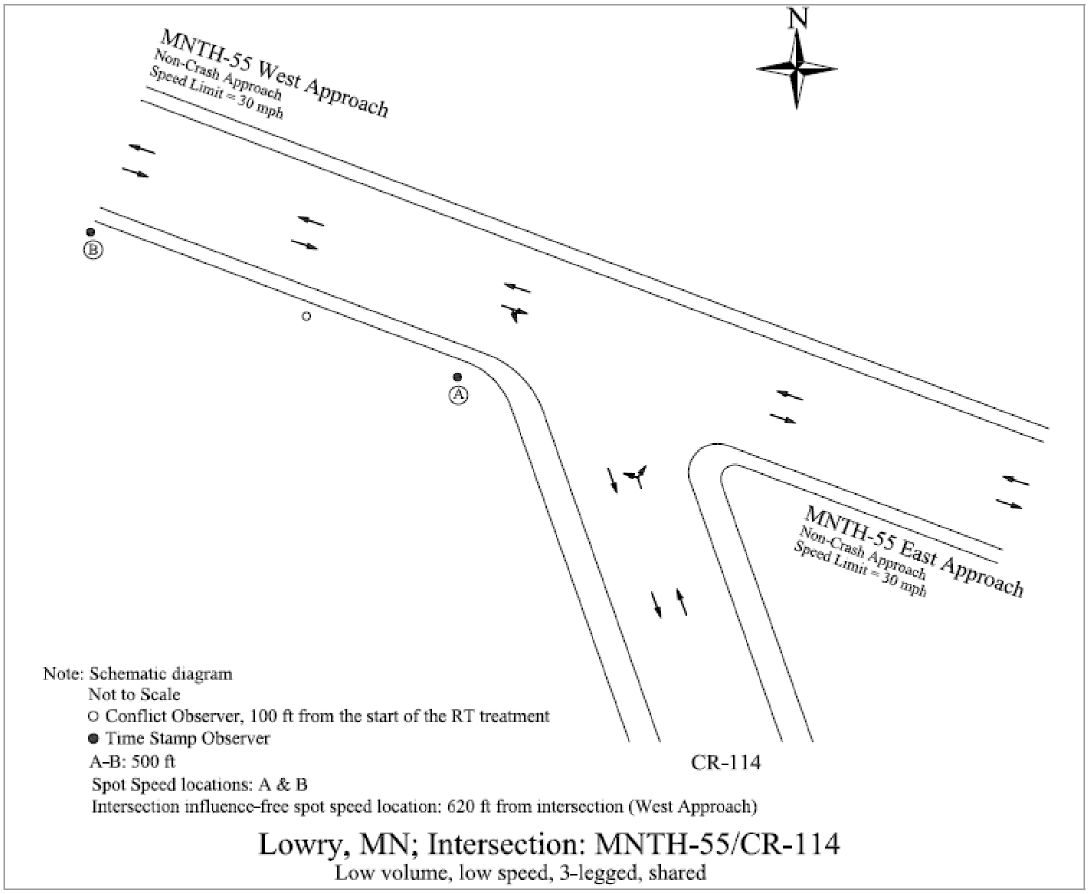
High volume, high speed, 4-legged, exclusive



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 100 ft from the start of the RT treatment
● Time Stamp Observer
A-B: 200 ft
Spot Speed locations: A, B & C
Intersection influence-free spot speed location: 550 ft from intersection (West Approach)
The intersection was considered 3-legged because no right turn from East Approach was observed during the observation period.

Lindstrom, MN; Intersection: MNTH-8/Akerson St.

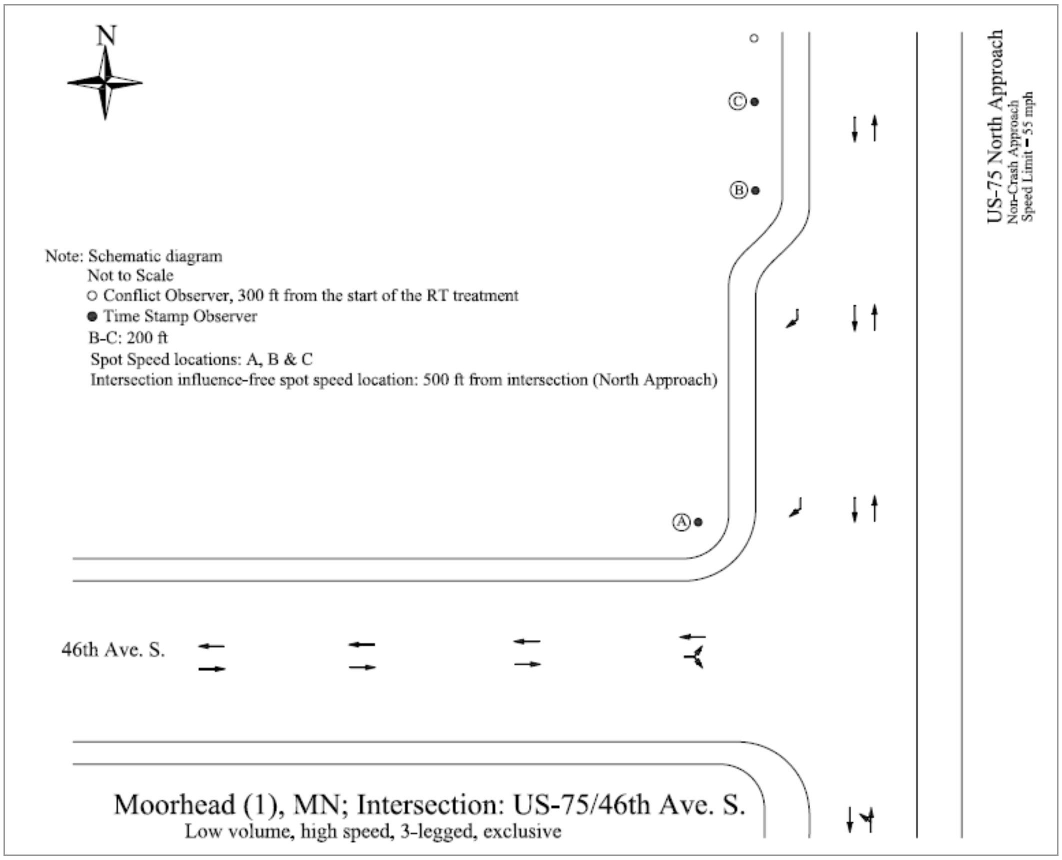
High volume, low speed, 3-legged, exclusive



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 100 ft from the start of the RT treatment
● Time Stamp Observer
A-B: 500 ft
Spot Speed locations: A & B
Intersection influence-free spot speed location: 620 ft from intersection (West Approach)

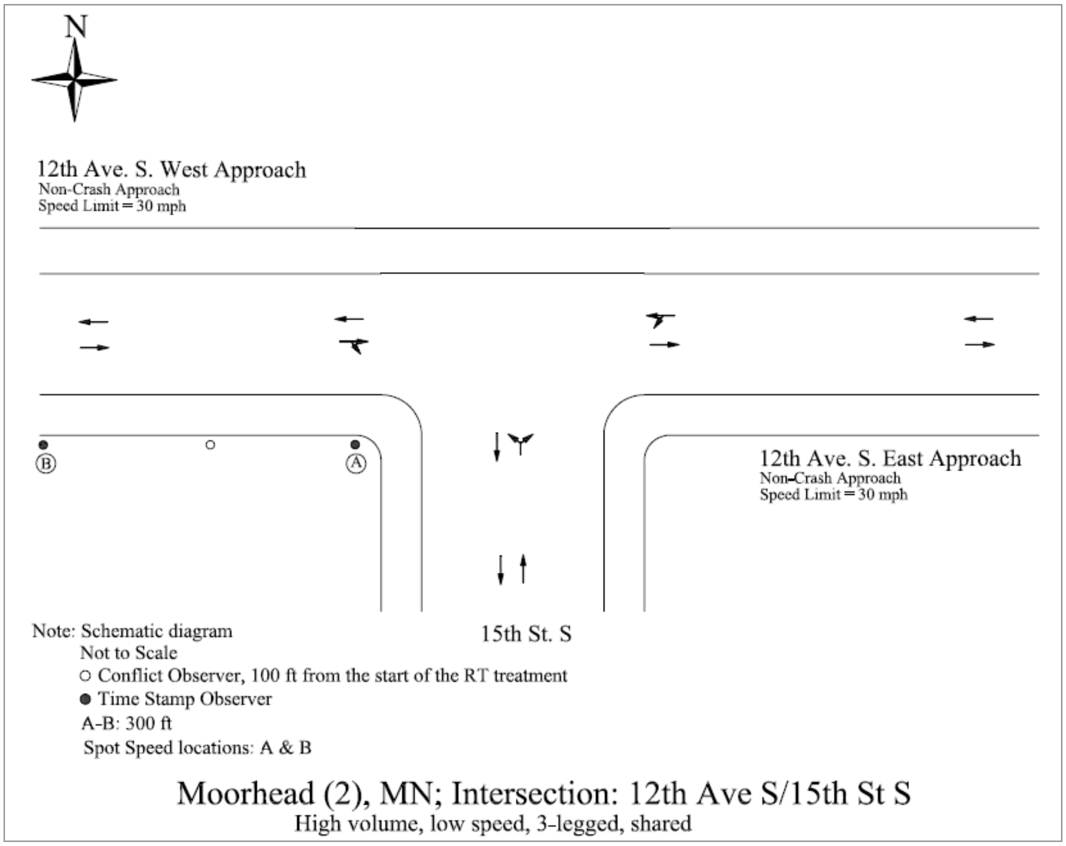
Lowry, MN; Intersection: MNTH-55/CR-114

Low volume, low speed, 3-legged, shared



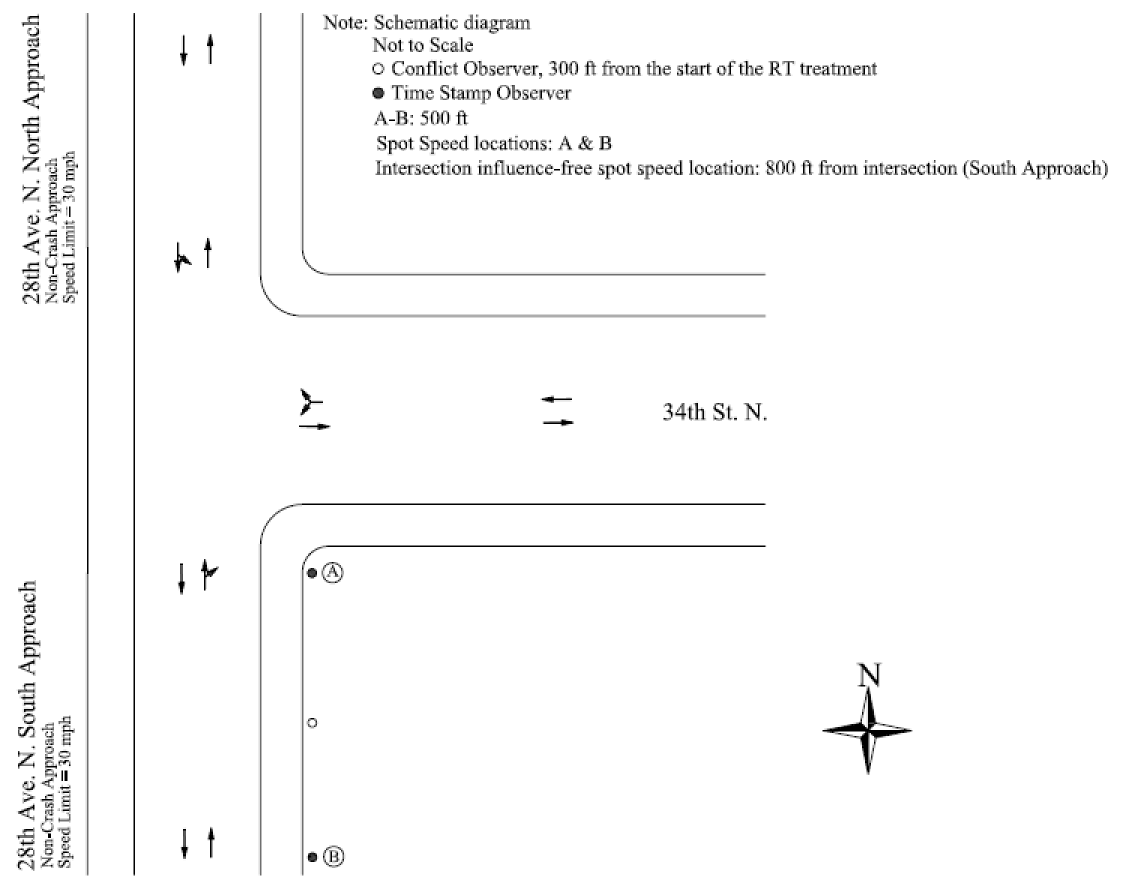
Note: Schematic diagram
Not to Scale
○ Conflict Observer, 300 ft from the start of the RT treatment
● Time Stamp Observer
B-C: 200 ft
Spot Speed locations: A, B & C
Intersection influence-free spot speed location: 500 ft from intersection (North Approach)

Moorhead (1), MN; Intersection: US-75/46th Ave. S.
Low volume, high speed, 3-legged, exclusive



Note: Schematic diagram
Not to Scale
○ Conflict Observer, 100 ft from the start of the RT treatment
● Time Stamp Observer
A-B: 300 ft
Spot Speed locations: A & B

Moorhead (2), MN; Intersection: 12th Ave S/15th St S
High volume, low speed, 3-legged, shared



Moorhead (3), MN; Intersection: 28th Ave. N./34th St. N.

Low volume, high speed, 3-legged, shared