SAFETY EFFECTIVENESS AND SAFETY-BASED VOLUME WARRANTS OF RIGHT-TURN LANES AT UNSIGNALIZED INTERSECTIONS AND DRIVEWAYS ON TWO-LANE ROADWAYS

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Safety Effectiveness and Safety-Based Volume Warrants of Right-Turn Lanes

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Disagreements regarding to what degree right-turn lanes improve or worsen the safety of intersections and driveways provided the motivation and the need for this study. The objectives of this study were to: a) carry out an in-depth study to determine the safety impacts of right-turn movements in different contexts, and b) develop safety-based volume warrants for right-turn lanes if safety indeed improves. Lack of adequate study on the applicability of past warrants and guidelines for the specific context of right-turn movements made from major uncontrolled approaches at unsignalized intersections, and particularly driveways, on two-lane roadways provided the scope for this study.

Five-year historical data of statewide traffic crashes reported on Minnesota's two-lane trunk highways were analyzed using binary/multinomial logistic regressions. Conflicts due to right turns were analyzed by fitting least squares conflict prediction models based on the data obtained from field surveys and traffic simulations. The safety impacts of right-turn lanes were determined through crash-conflict relationships, crash injury severity, and crash and construction costs.

The study found that the probabilities of right-turn movement related crash ranged from 1.6 to 17.2% at intersections and from 7.8 to 38.7% at driveways. Rear-end, same-direction-sideswipe, right-angle and right-turn crash types constituted 96% of right-turn movement related crashes. Rear-end crash probabilities varied from 13.7 to 46.4% at approaches with right-turn lanes and from 37.9 to 76.9% otherwise. The ratios of rear-end/same-direction-sideswipe crashes to conflicts were 0.759×10^{-6} at approaches with right-turn lanes and 1.547×10^{-6} otherwise.

Overall, right-turn lanes reduced right-turn movement related crash occurrences and conflicts by 85% and 80%, respectively. Right-turn lanes also reduced crash injury severity, hence, reducing the economic cost by 26%. Safety benefits, in dollars, realized with the use of right-turn lanes at driveways were 29% and 7% higher compared to those at intersections at low and high speed conditions respectively for similar traffic conditions. Depending on roadway conditions, interest rate and construction costs, the safety-based volume thresholds ranged from 3 to 200 right turns per hour during the design hour at intersection approaches, and from 2 to 175 right turns at driveway approaches.

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AADT	Annual average daily traffic (both directions)
ATR	Automatic traffic recorder
CCR	Crash-conflict ratio
CEF	Crash estimation factor
DAADT	Directional annual average daily traffic
DDHV	Directional design hour volume
DOT	Department of Transportation
FHWA	Federal Highway Administration
GIS	Geographic information system
HCV	Heavy commercial vehicles
Mn/DOT	Minnesota Department of Transportation
mph	Miles per hour
MVM	Million vehicle miles
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
RE/SS crash	Rear-end or same-direction-sideswipe crash
RTDHV	Right turns during the design hour
TCT	Traffic conflicts technique
TEV	Thousand entering vehicles
vpd	Vehicles per day
vph	Vehicles per hour

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CHAPTER 1. INTRODUCTION

1.1 Background

Traffic crashes are the leading cause of death in the United States of America. The 2005 and 2006 traffic crash facts based on the reports prepared by the National Highway Traffic Safety Administration (NHTSA) are presented in Table 1.1. Out of six million total traffic crashes reported each year, roughly 42% were occurred on two-lane roadways. The economic cost of traffic crashes was estimated at a staggering sum of $230.6 billion each year. Moreover, the social cost associated with the traffic crashes cannot be ignored; in addition to the loss of human lives, the loss of the bread winner in a family due to death or disability can be overwhelming.

Table 1.1. The traffic crash facts

Description	Year 2005		Year 2006	
	# of Crashes	% of Crashes	# of Crashes	% of Crashes
Total traffic crash	6,159,000	100.0	5,973,000	100.0
Total traffic crash on two-lane roadways	2,638,000	42.8	2,476,000	41.5
Total intersection/intersection-related crashes	2,523,000	41.0	2,422,000	40.5
Intersection/intersection-related crashes due to right turns*	214,455	3.5	205,870	3.4
Traffic crash victims				
# of Persons Killed	43,443		42,642	
# of Persons Injured	2,699,000		2,575,000	
Economic cost of traffic crashes (2000)	$230.6 billion		$230.6 billion	

* Estimated in this study @ 8.5% of the total intersection/intersection-related crashes based on the five-year historical data of statewide traffic crashes reported on Minnesota's two-lane trunk highways. Source: NHTSA (2006); NHTSA (2007).

The intersection or intersection-related crashes constitute the bulk of total traffic crashes, accounting for as much as 41% of the total crashes (Table 1.1). The intersection traffic crashes involving two or more vehicles are generally grouped into various crash types depending on the type of turn movements involved, the nature of conflicts and the crash diagrams as presented in Figure 1.1.

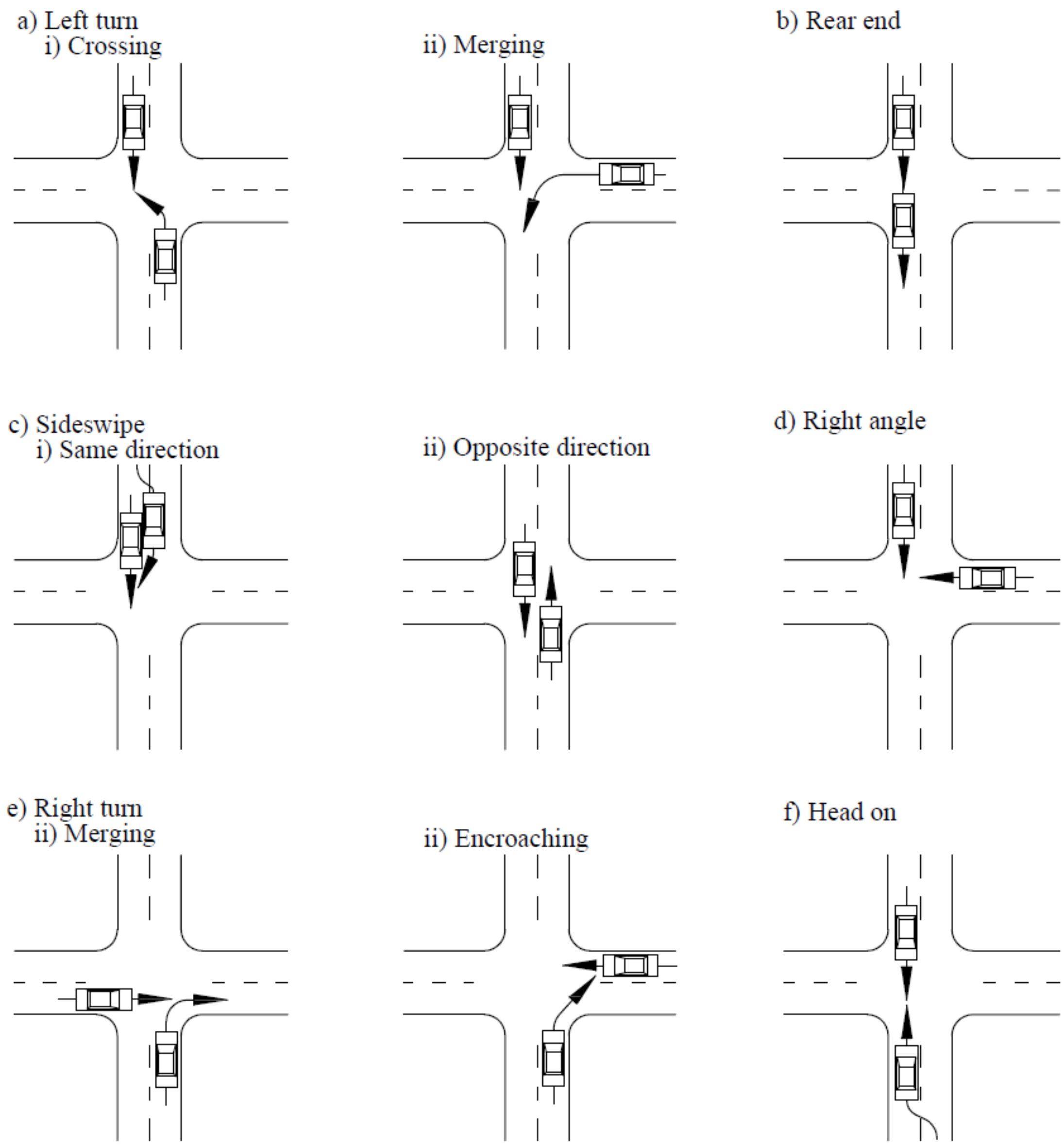


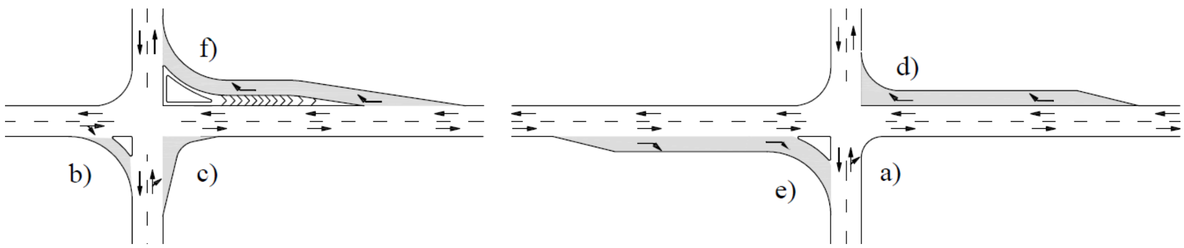
Figure 1.1. Intersection traffic crash types.

The left-turn crashes involve left-turning vehicles and may be considered as related to either crossing or merging conflicts, mostly due to failure by left-turning vehicles to yield to the through traffic. The rear-end crashes occur when the front of a vehicle hits the rear of lead vehicle and are generally related to the diverging conflicts involving vehicles travelling in the same direction. The sideswipe crashes occur when the sides of vehicles strike each other. The sideswipe crashes are further classified into two types, same direction and opposite direction, depending on whether the vehicles were travelling in the same direction or the opposite directions. The right-angle crashes are related to the crossing conflicts involving vehicles approaching from different intersection approaches. Usually classified into angle crashes (the crashes that are not head-on, rear-end or sideswipe), the collision angles in right-angle crashes are about a right angle. The right-turn crashes involve right-turning vehicles and are related to the merging conflicts due to the right-turning vehicles that fail to yield to the through vehicles from cross roadway. Right-turn crashes also occur when the right-turning vehicles hit the vehicles on the cross roadway by encroaching on to the opposing lanes. The head-on crashes typically occur when the vehicles cross road centerlines or medians and crashes into the approaching vehicles. The rear-end and angle crashes are the most common crash types, each constituting about 30% of all reported crashes (NHTSA 2006; NHTSA 2007).

Of the various turning movements made at intersections, the safety impacts of right-turn movements are considered less severe, primarily leading to rear-end or same-direction-sideswipe crashes. However, the right-turn movements do significantly contribute to the total traffic crashes (Table 1.1). The vehicles slowing to turn right increase the risks of rear-end crashes involving the following through vehicles that fail to slow down. Likewise, there are the risks of sideswipe crashes associated with the merging conflicts between the right-turning vehicles and the through vehicles from cross roads. The crashes that result from inappropriate lane-change/turning maneuvers by the vehicles making a right turn as well as those resulting from unsuccessful swerving maneuvers attempted by the following through vehicles to avoid rear-end crashes with the vehicles making a right turn may be classified as same-direction-sideswipe crashes.

To facilitate right-turn movements and to improve traffic safety as well as operational efficiency at intersections, special right-turn treatments as determined suitable for the prevailing or anticipated road and traffic conditions are provided at approaches to road intersections. The safety improvements are generally quantified in terms of the expected number and the cost of crashes saved, whereas the improved operational efficiency is measured in terms of the reduction in delays to through vehicles and the concomitant reduction in fuel consumptions and vehicular emissions. The costs of implementing suitable right-turn treatments at intersection approaches are justified by the improved operations and the perceived safety benefits they provide to the road users.

The right-turn treatments at road intersections may be defined as geometric treatments provided with an intention to facilitate the right-turn movements of traffic, so that the least interference is caused to the through traffic, thereby improving the operational efficiency and the traffic safety at intersections. Three basic types of right-turn treatments are provided depending on the road environment and traffic conditions: radius, taper, and full-width lane treatment. Figure 1.2 presents various right-turn treatment types. A radius right-turn treatment (a), where the traveled lane is shared by both right-turning vehicles and through vehicles, is a treatment with no special right-turn treatment other than a radius between the intersection approaches. The radius treatment may, sometimes, include a turning roadway (b). A taper right-turn treatment (c) is one step further in the form of a taper over a radius type. A full-width lane treatment (d), involving exclusive right-turn movements, includes an extra full-width lane separating right-turning traffic from through traffic. A turning roadway may also be provided together with the exclusive lane (e). It is considered obvious that the full-width lane treatment is the superior type among three basic right-turn treatment types. However, it has been reported that the right-turning vehicles that had moved to the exclusive lane would sometimes obstruct the line of sight of vehicles yielding at the cross road. In order to address this issue, a new configuration of exclusive lane treatment called the offset right-turn lane treatment (f) has been designed recently. The full-width lane, in this case, is offset further from the traveled lane, so that the configuration provides an unobstructed line of sight to the vehicles yielding at cross road.



a) Radius right-turn treatment.
b) Radius right-turn treatment with a turning roadway.
c) Taper right-turn treatment.
d) Exclusive right-turn lane treatment.
e) Exclusive right-turn lane treatment with a turning roadway.
f) Offset right-turn lane treatment.

Figure 1.2. Right-turn treatment types.

1.2 Motivation for the study

A number of studies have been carried out in the past that dealt with the impacts of right-turn lanes on traffic safety (Cottrell 1981; McCoy et al. 1984; McCoy and Bonneson 1996; Vogt and Bared 1998; Dixon et al. 1999; Bauer and Harwood 1996; Bauer and Harwood 2000; Harwood et al. 2000; Harwood et al. 2002; Fitzpatrick and Schneider 2005; Fitzpatrick et al. 2006; Kim et al. 2006; Wang and Abdel-Aty 2006; Ye et al. 2009). It was found that there is a lack of agreement in the findings of these studies, which were primarily based on the historical data of traffic crashes. Some studies found that right-turn lanes were safety effective (Harwood et al. 2000; Harwood et al. 2002; Ale 2007), whereas the others have found that right-turn lanes were associated with the increase in the number of intersection-related crashes (Vogt and Bared 1998; Fitzpatrick and Schneider 2005; Kim et al. 2006). Some studies found that the safety effects of right-turn lanes were statistically insignificant (Cottrell 1981; McCoy et al. 1984; McCoy and Bonneson 1996). Some studies have assumed that right-turn lanes are safety effective (McCoy et al. 1993; Hasan and Stokes 1996; Yang 2008).

Unavailability of sufficient sample size of crash history data to researchers in the past may have been a reason for the lack of agreement in the research findings with regard to the safety impacts of right-turn lanes. There has also been a tendency in the past to analyze the safety impacts of right-turn lanes based on the total intersection crashes (McCoy et al. 1984; Bauer and Harwood 1996; Vogt and Bared 1998; Bauer and Harwood 2000; Kim et al. 2006; Wang and Abdel-Aty 2006). The National Cooperative Highway Research Program (NCHRP) Report 500 (Neuman et al. 2003) recommends analyzing the total crashes at intersections and the crashes related to right-turn movements separately in order to determine the safety effectiveness of right-turn lanes.

It was also found that the safety impacts of right-turn lanes have generally been determined as a point estimate; e.g. 10% reduction in total crashes, twice more likely to involve in a crash, etc. The key research challenge is to determine the safety impacts of right-turn lanes as a function of a broad range of conditions – road, traffic and environment conditions as well as various user-related variables. The turn-volume information is usually not a part of crash history data, and, therefore, the right-turn volumes were not included in many previous studies that were based on the historical data of traffic crashes. However, the NCHRP Report 500 identifies the need of incorporating traffic volumes, including right-turn volumes, to represent the exposure in case of a crash analysis involving right-turning vehicles. A United States Federal Highway Administration (FHWA) study (Joksch and Kostyniuk 1997) also indicated turning volumes as a plausible candidate for exposure measure for the turn-related intersection crash analysis. Many other researchers have also recommended including right-turn volumes in the analysis in order to determine the safety impacts of right-turn treatments (Fitzpatrick et al. 2006; Kim et al. 2006; Hochstein 2006). It remains to be seen whether the right-turn volumes play a significant role in determining the safety impacts of right-turn lanes.

On the other hand, a few studies in the past that did include right-turn volumes in their analysis assumed that the right-turn lanes eliminate the rear-end crashes, primarily caused due to speed differentials between right-turning vehicles and through vehicles (McCoy et al. 1993; Hasan and Stokes 1996; Yang 2008). A few others concluded that the crashes were not a significant factor in determining the need for a right-turn lane (Cottrell 1981; McCoy and Bonneson 1996). The validity of such assumptions or conclusions may need to be examined in the light of extensive crash history data that are now available. Moreover, the safety effectiveness of right-turn lanes, evaluated in terms of the economic cost of rear-end crashes saved by providing right-turn lanes, was determined on a fixed cost per crash basis (McCoy et al. 1993; Hasan and Stokes 1996), which does not reflect the crash injury severity expected to vary from one crash to another. The NCHRP Report 491 (McGee et al. 2003) suggests applying the crash severity weights in determining the dollar values of a traffic crash. In addition to rear-end crashes, the safety effectiveness of right-turn lanes should also be analyzed by taking into account other crash types that are caused by a right-turning vehicle.

It was therefore necessary to undertake an in-depth study to look into the safety impacts of right-turn lanes in a broad range of conditions, and to develop their safety-based volume warrant guidelines if right-turn lanes are found safety effective. The idea was to also incorporate the safety impacts of right-turn volumes, and to analyze the total intersection crashes as well as the frequency and the injury severity of various types of intersection crashes involving right-turning vehicles. It was expected that the findings from this study would provide valuable insights in understanding the safety impacts of right-turn lanes in a broad range of conditions.

1.3 Scope of the study

This study, a portion of which was funded by the Minnesota Department of Transportation (Mn/DOT), looks specifically into the safety impacts of right-turn movements and the related need for right-turn lanes at uncontrolled approaches to unsignalized intersections and driveways on two-lane roadways. The specific context of right-turn movements studied in this study pertains to the vehicles making right-turn movements from a major roadway approach with or without a right-turn lane on to a cross roadway or a driveway. The taper right-turn treatment was not studied because of the lack of the historical data of traffic crashes involving right-turn movements from taper right-turn treatments. All the relevant historical, inventory and field data required for the successful completion of this study were obtained from the State of Minnesota.

1.4 Organization of the dissertation

This study examines the safety effectiveness of right-turn lanes at unsignalized intersections and driveways on two-lane roadways as a function of various significant explanatory factors related to road, traffic and environment conditions as well as user-related variables. The safety-based volume warrants for right-turn lanes were also developed. The dissertation consists of seven chapters.

Chapter 1 introduces the background and also discusses the need for the study. The scope of the study was also highlighted. Chapter 2 presents the review of the literature. The focus of the review was on the literature that dealt with the safety impacts of right-turn lanes. Chapter 3 presents the outline of the methodologies adopted to determine the safety effectiveness of right-turn lanes and their safety-based volume warrants. The methodologies are also discussed in greater details in the subsequent chapters. Chapter 4 presents the variety of crash analyses that were carried out in this study, including exploratory analyses and the logistic regression models that were developed to determine the conditional crash probabilities and the economic costs of crashes caused by right-turning vehicles. The efforts needed for collection, conflation and reduction of various data obtained from multiple data sources for crash analyses are also presented. Chapter 5 describes the conflict analyses that were carried out through traffic conflicts technique based on the data obtained from field surveys as well as through traffic conflict simulations. The conflict analyses were carried out using the method of least squares to incorporate the impacts of right-turning volumes on the safety effectiveness of right-turn lanes. Chapter 6 combines the results obtained from the crash and the conflict analyses, and determines the safety effectiveness of right-turn lanes at approaches to unsignalized intersections and driveway approaches. The safety-based volume warrants for right-turn lanes have also been developed and presented in this chapter. Chapter 7 presents the key findings and the significant contributions of this study as well as the recommendations. References and appendices are included at the end of this dissertation.

CHAPTER 2. LITERATURE REVIEW

The focus of the literature review was on the studies that dealt with the safety impacts of right-turn movements and right-turn lanes, as well as on those that dealt with the volume warrants for right-turn lanes. Studies based on both the historical data of traffic crashes and the traffic conflicts as surrogate safety measures were considered. The various statistical methods used in the past in the analysis of crash history data were also noted.

2.1 Safety studies based on the historical data of traffic crashes

Cottrell (1981), while developing the criteria for the treatment of right-turn movements on rural roadways, reviewed three-year crash history data of nineteen unsignalized intersections located on two-/four-lane rural roadways in Virginia. Following an analytical evaluation of the history of crashes, the study concluded that the crashes were not a significant factor in determining the treatment for right-turn movements. McCoy et al. (1984) studied the cost effectiveness of turning lanes on uncontrolled approaches of rural intersections. Three-year crash history data of ninety approaches on rural two-lane roadways in Nebraska were analyzed to determine the safety impacts of turning lanes. Using matched-pairs t-tests, the study found no statistically significant safety effects of turning lanes, including those of exclusive right-turn lanes. However, based on the mean crash rates estimated for different approach categories (approaches with paved shoulders or approaches without paved shoulders), the right-turn lanes provided at approaches without paved shoulders were determined to result in 40% reduction in rear-end or same-direction-sideswipe crashes and 30% reduction in right-turn crashes.

Similarly, McCoy and Bonneson (1996), while developing the volume warrants for free right-turn lanes at unsignalized intersections on rural two-lane highways, analyzed five-year crash history data of eighty-nine unsignalized intersection approaches on rural two-lane highways in Nebraska. The study found no statistically significant differences between the approaches with and without free right-turn lanes with respect to the frequency, severity, or types of crashes.

Vogt and Bared (1998) analyzed five-year crash history data of 389 three-legged unsignalized intersections on two-lane rural roads in Minnesota using a negative binomial modeling approach. The presence of right-turn lanes was found to increase the likelihood of intersection crashes. However, the study indicated the potential association between crashes and higher turning movements at the intersections with right-turn lanes.

Dixon et al. (1999) analyzed the safety impacts of right-turn treatments at signalized intersections using two-year crash history data obtained from Cobb County in Atlanta metro area in Georgia. By comparing various right-turn treatments based on the frequency of crashes, the study found that the sideswipe crash rate was higher at approaches with exclusive right-turn lanes, whereas the right-angle crash rate was lower at right-turn treatments with traffic islands. A further in-depth comparative analysis using traffic volumes, conflicts and road type was suggested to determine the safety impacts of various right-turn treatments.

Bauer and Harwood (1996) and Bauer and Harwood (2000) analyzed at-grade intersection crashes using lognormal, Poisson and negative binomial regression methods. Three-year crash history data of 14,432 three-/four-legged signalized/unsignalized stop-controlled intersections on rural/urban roads in California were used in the studies. Right-turn lanes on rural roads were found safety effective, whereas the right-turn lanes in urban areas were found to be associated with an increase in the number of crashes. Similarly, right-turn channelization was found to result in an increase in total multiple-vehicle crashes and fatal-injury crashes.

Harwood et al. (2000) reviewed the published literature on the safety impacts of right-turn lanes through an expert panel of road safety professionals. Based on the accident modification factors developed by the panel, it was concluded that a right-turn lane along one major approach to a stop-controlled intersection on two-lane rural roadway reduces the intersection-related crashes by 5%. Harwood et al. (2002) carried out a comprehensive study of the safety impacts of intersection left- and right-turn lanes. Based on the crash history data obtained from 280 improved and 300 similar unimproved unsignalized/ signalized intersections on rural two-/four-lane roadways in eight US states, the safety evaluations of the turn lanes were carried out using the matched-pair approach, the before-after evaluation with a comparison group, and the before-after study using Empirical Bayes methods. The study found that a right-turn lane along one major-road approach reduces the total intersection crashes at a rural unsignalized intersection by 14% and at an urban signalized intersection by 4%.

Fitzpatrick and Schneider (2005) and Fitzpatrick et al. (2006) analyzed turn speeds and crashes within right-turn lanes at intersections located in College Station and Irving in Texas. The safety impacts of right-turn lanes were estimated based on the analytical evaluations of three-year crash history records of nine urban/suburban intersections. The study found that a crash involving right-turning vehicle was expected every nine years at approaches with right-turn lanes and every twenty-five years at approaches without right-turn lanes. The study however indicated the need of a larger, more comprehensive study to provide a definitive advice on the safety effects of right-turn lanes.

Kim et al. (2006) analyzed total intersection crashes as well as the crashes categorized by crash types (angle, head-on, rear-end, same-direction-sideswipe, pedestrian-involved crashes) using negative binomial and Poisson regression models based on two-year crash history data of 165 rural unsignalized/signalized four-legged intersections of two-lane roadways located in Georgia. The study found that the presence of right-turn lanes was associated with the higher number of rear-end and total intersection crashes; however, this was suspected as a case of endogeneity problem: locations with right-turn lanes had experienced high numbers of crashes to justify their installation.

Wang and Abdel-Aty (2006) analyzed rear-end crashes at signalized intersections using three-year longitudinal data at 208 signalized intersections and spatially correlated data for 476 signalized intersections located in Florida. Using generalized estimating equations with negative binomial link function, the study found that channelized /exclusive right-turn lanes on minor roadways reduced the number of rear-end crashes. The right-/left-turn lanes on major roadways, used as surrogate variables for the magnitude of right-/left-turning volumes, were associated with the increase in the number of rear-end crashes.

Ale (2007) analyzed three-year historical data of statewide traffic crashes reported on two-lane trunk highways in Minnesota at unsignalized intersections/driveways using logistic regressions. The study found that right-turn lanes provided at uncontrolled intersection/driveway approaches were safety effective. The relative risks of rear-end crashes at intersection approaches without right-turn lanes were found to be 2.5 to 3.0 times higher compared to those at approaches with right-turn lanes.

Ye et al. (2009), using multivariate Poisson regression model with multivariate normal heterogeneity, developed and estimated simultaneous-equations model of crash frequency by collision type based on two-year crash history data from a sample of 165 rural two-lane intersections located in thirty eight counties in Georgia. The study found that major-/minor-road traffic volumes contributed positively to the frequency of angle, head-on and rear-end crashes. The number of right-turn lanes on the major roadway was found to contribute positively to the frequencies of rear-end and same-direction-sideswipe crashes.

2.2 Safety studies based on traffic conflicts technique

Traffic crashes are not only random events, but crashes at a particular roadway location are rare events. As a result, the safety evaluation of a specific roadway location based on the crash data, though ideal measure of safety, is not feasible in most cases. It is not only impractical, but unethical as well to let the crashes to accumulate in order to provide for a sufficient crash database for the safety analyses. Surrogate measures of safety are, therefore, widely used in traffic safety studies to identify roadway locations with potential safety problems. These measures do not depend on crash occurrence but rather the occurrence of conditions considered to be related to crashes.

A variety of surrogate safety measures have been proposed, including traffic conflict, speed, speed differential, delay, superelevation, curvature, etc. (Gettman and Head 2003). However, the traffic conflicts are the most widely used surrogate safety measures in intersection-related traffic safety studies. The use of traffic conflicts as a surrogate safety measure is the objective of what is known as traffic conflicts technique (TCT). The TCT was developed in order to objectively and quickly measure and evaluate the crash potential of a roadway location in the absence of reliable and adequate crash history data.

The NCHRP Report 219 (Glauz and Migletz 1980) defines ‘traffic conflict’ 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." The report identifies and defines a total of twelve conflict types (Figure 2.1), excluding the conflicts involving pedestrians. In addition, a traffic event called 'secondary conflict' is defined as "an additional vehicle that is conflicted with by an instigating vehicle that slowed or swerved in response to some other conflict situation." Through comprehensive analyses of traffic conflicts involving extensive field tests at more than twenty-four intersections located in the greater Kansas City metropolitan area, the report provides the discussion of both theoretical concepts and field studies in an attempt to formalize and standardize the TCT procedures. The report also includes a TCT procedures manual and the theoretical framework for the relationship between traffic conflicts and crashes.

The validity of TCT in deriving useful inferences on the level of traffic safety at intersections has been adequately discussed in the literature (Glauz and Migletz 1980; Glauz et al. 1985; Hauer and Garder 1986; Chin and Quek 1997). If designed carefully, the TCT procedures can be applied to address specific traffic safety issue to derive useful results that may be impossible to obtain based on the analyses of crash history data (Chin and Quek 1997). However, as noted earlier, Glauz and Migletz (1980) suggests that reliable and adequate crash history data, if available, should take precedence over the conflict data in traffic safety studies.

The TCT procedures have largely been formalized over their long history in order that the variations in the conflict data incorporated by the subjectivity of field observers are minimized, as well as to facilitate and ensure intra-observer repeatability and inter-observer reliability through technique tractability and observer training (Glauz and Migletz 1980;

Parker and Zegeer 1988; Parker and Zegeer 1989). Parker and Zegeer (1988) deals with the procedures for analyzing and interpreting the results of traffic conflict surveys. Parker and Zegeer (1989) provides for the step-by-step procedures on how to observe and collect traffic conflict data at signalized and unsignalized intersections.

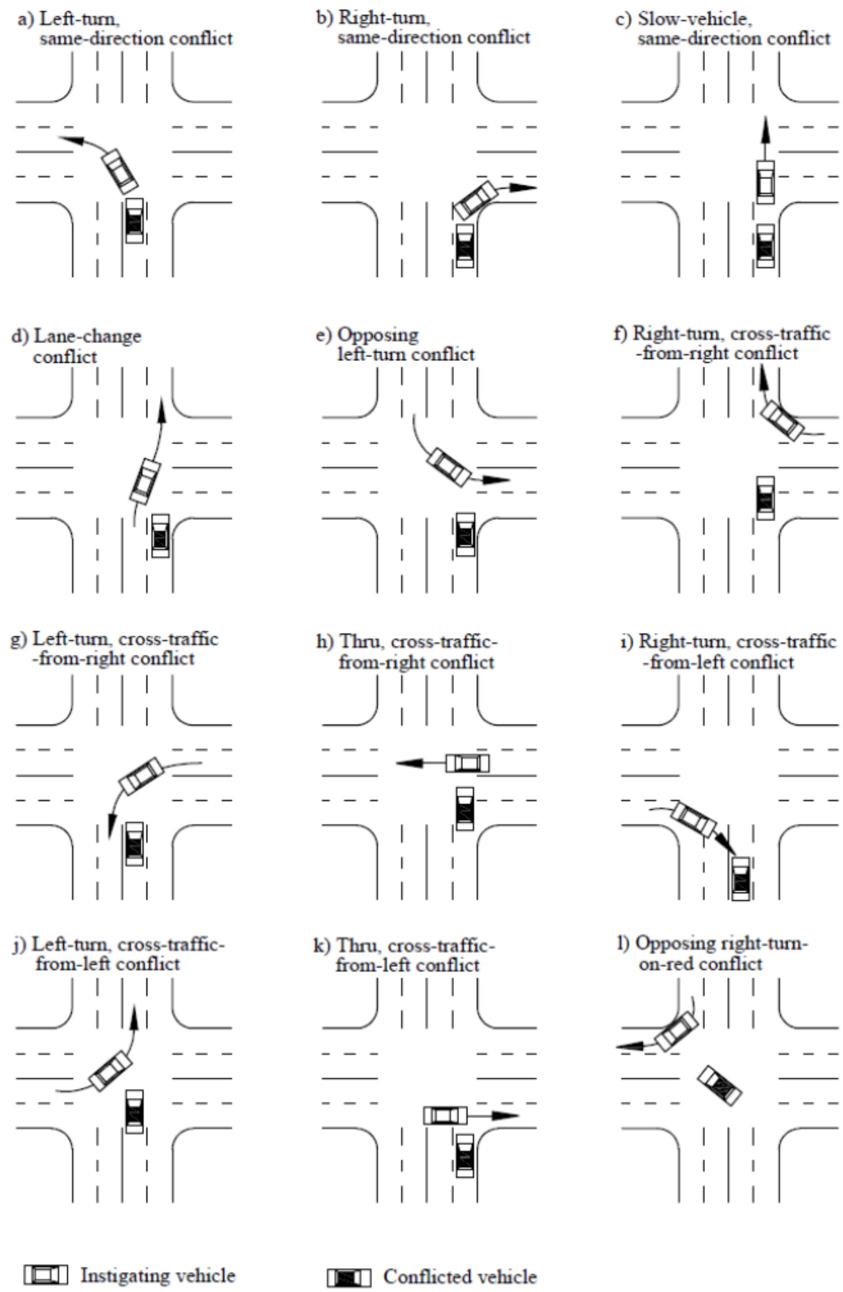


Figure 2.1. Traffic conflict types.

In this study, the traffic conflicts of interest were the conflicts known as ‘right-turn, same-direction’ conflicts. This type of conflicts occurs when the first (lead) vehicle slows to make a right turn, thus endangering the second (following) vehicle of a collision (Figure 2.1 b). The second vehicle brakes or swerves, then continues through the intersection. The secondary conflicts due to right-turn, same-direction conflicts that have already taken place were also of interest.

2.2.1 Field-based studies

Since its inception in late 1960’s (Perkins and Harris 1968), the TCT procedures have been used in numerous traffic safety studies (Glauz et al. 1985; Crowe 1990; Sadegh et al. 1991; Rao and Rengaraju 1997; Tarrall and Dixon 1998; Weerasuriya and Pietrzyk 1998; Katamine 2000a; Katamine 2000b; Lu et al. 2001). The nature and frequency of various secondary conflicts was discussed in Katamine (2000b), based on the field data observed at fifteen unsignalized intersections located in Amman, Jordan.

Some researchers have employed the TCT procedures to develop conflict value tables to identify intersections with high risk of potential crash. Crowe (1990) developed conflict value tables for three-legged unsignalized intersections by observing conflicts at ten three-legged unsignalized intersections in Houston area. The intersections surveyed involve two-/four-lane major roads. The mean number of right-turn, same-direction conflicts was found to be 51 (65 including the secondary conflicts) for an eleven-hour day (7:00 AM to 6:00 PM), observed during weekdays (Monday through Friday) on dry pavement condition.

Similarly, Weerasuriya and Pietrzyk (1998) developed expected conflict value tables for three-legged unsignalized intersections by observing conflicts at thirty-eight intersections that involved various lane combinations in west-central Florida. The conflicts were observed during a four-hour observation period on weekdays (Monday through Thursday) between 7:00 AM and 6:00 PM on dry pavement condition. The mean right-turn, same-direction conflict counts observed was 3.92 for three-legged 2x2 intersections, 2.83 for three-legged 2x4 intersections and 16.00 for three-legged 2x6 intersections.

Cottrell (1981) was the first to employ TCT to develop the criteria for the treatment of right-turn movements on rural roadways. The field surveys of conflicts due to right-turning vehicles were carried out at twenty one rural unsignalized intersections involving two-/four-lane roadways in Virginia. The study found 40 to 70% reductions in the peak-hour same-direction, rear-end conflicts due to right-turning vehicles on two-lane roadways with a full-width right-turn lane treatment. Based on the observed four-hour conflicts due to right-turning vehicles, three individual conflict prediction equations for radius, taper and exclusive right-turn lane treatments were developed as presented below:

$$\text{PHVCONFL} = \begin{cases} 1.9*(\text{PHVRPCT}) + 16, & \text{if radius treatment;} \\ 1.7*(\text{PHVRPCT}) - 5, & \text{if taper treatment;} \\ 1.3*(\text{PHVRPCT}) - 0.4, & \text{if exclusive treatment;} \end{cases} \tag{2.1}$$

where PHVCONFL is peak hour volume conflict rate (conflicts/1,000 vehicles); and PHVRPCT is peak hour volume percent right turns.

2.2.2 Analytical/simulation-based studies

Mounce (1983) formulated several probability statements to estimate the number of mainline through vehicles affected by right-turn movements at driveways. Hasan and Stokes (1996) adapted these probability statements to develop analytical models to predict the number of through vehicles that are affected by right turns (same as right-turn, same-direction conflicts, including the associated secondary conflicts) at radius right-turn treatments at approaches to unsignalized intersections and driveways on both two- and four-lane roadways. The proposed conflict prediction equation for two-lane roadways was as provided below:

$$V_T = \frac{V_{Turn}}{V_A}.\left(1 - \frac{V_{Turn}}{V_A}\right).\left(1 - e^{\frac{-V_A T_A}{3600}}\right).V_A.EFV_{2L}; \quad (2.2a)$$

$$EFV_{2L} = -7.13 + 4.32x10^{-6}.(DDHV)^2 + 0.15.U; \quad (2.2b)$$

where V_T is the total number of conflicts, including the associated secondary conflicts, per hour caused by right-turning vehicles; V_{Turn} is right-turn volume, vehicles per hour (vph); V_A is total approach volume (vph); T_A is critical headway (sec); EFV_{2L} is 'equivalent following vehicle' for two-lane roadways; DDHV is directional design hour volume (vph); and U is roadway operating speed, miles per hour (mph).

The critical headways at different roadway operating speeds are presented in Table 2.1. The minimum value of equivalent following vehicle (EFV_{2L}) is one. The EFV_{2L} is set to zero if its estimated value is negative.

Table 2.1. 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).

Iyaz (1997) and Ratrout et al. (2004) used TRANSYT-7F traffic simulation software to simulate the same-direction, rear-end traffic conflicts caused by left-turning, right-turning, lane-changing and slow vehicles at signalized intersections located in Saudi Arabia. The simulated conflicts were used to validate and improve the same-direction, rear-end traffic conflict prediction models developed earlier to evaluate the traffic safety at signalized intersections. Rao and Rengaraju (1998) developed a simulation model, formulated and implemented in C language, to estimate the number of conflicts at urban uncontrolled intersections operating under heterogeneous traffic conditions found in India.

In recent years, the increased use of traffic simulation software in transportation studies has given rise to the popularity of assessing traffic safety through surrogate safety measures (Archer 2005; Eisele and Toycen 2005; Huguenin et al. 2005; Muchuruza 2006; Gettman et al. 2008; Cunto and Saccomanno 2008). Two primary reasons for this can be readily identified. First, the simulation allows for the safety evaluations of alternative traffic facility designs before they have actually been built or deployed. Second, the field-based traffic safety studies require highly trained personnel and extensive resources to collect, extract and analyze safety information. The need for and the relevance of using simulation methodologies in traffic safety assessment are indicated in an FHWA project report (Gettman and Head 2003). The report also presents a comprehensive review of the capabilities of various existing traffic simulation models to support the derivation of surrogate safety measures.

Various surrogate safety measures, primarily based on TCT, from the traffic simulation models have been discussed and proposed (Archer and Kosonen 2000; Gettman and Head 2003; Archer 2005; Muchuruza 2006). Aside from using total conflict counts, the conflict events have also been categorized based on several measures of severity of the conflict event. Among them, the time-to-collision (TTC) and the post-encroachment time (PET) during a traffic conflict event have appeared more frequently as the measures of severity of a conflict event from traffic simulation models (Campbell et al. 1996; Archer and Kosonen 2000; Eisele and Frawley 2004; Archer 2005; Eisele and Toycen 2005; Tarko and Songchitruksa 2005; Muchuruza 2006; Gettman et al. 2008). The TTC is defined as the expected time for two vehicles to collide if they remain at their present speed and on the same path without taking evasive maneuvers, whereas as the PET is defined as the time lapse between the end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision (Gettman and Head 2003).

2.3 Studies related to crash-conflict relationships

Although surrogate safety measures provide methods to assess the safety of traffic facilities, many studies, such as those involving benefit-cost analysis, require that traffic safety be quantified in terms of the number of crashes. Researchers in the past have attempted to establish relationships between crashes and surrogate safety measures, including traffic conflicts (Glauz et al. 1985; Salman and Al-Maita 1995; Weerasuriya and Pietrzyk 1998; Kaub and Kaub 2000; Mauro and Cattani 2004). Glauz and Migletz (1980), Glauz et al. (1985) and Archer (2005) have discussed the relevance and the need of understanding and determining relationships between traffic conflicts and crashes. The limited amount of available crash data in the past has been indicated as the major hurdle in establishing such relationships (Campbell et al. 1996). Archer (2005) has also indicated the importance of developing statistical models to adequately predict the number of crashes based on surrogate safety measures to add to the value of traffic safety analysis work.

Glauz et al. (1985) estimated crash-conflict ratios corresponding to various traffic conflict types based on three-year crash history data and observed traffic conflicts. The extensive 576 observer-days of conflict data, representing nearly 90,000 traffic conflicts, were observed at forty-six signalized/unsignalized intersections located in the greater

Kansas City metropolitan area on two-/four-lane roadways operating under various posted roadway speed limit conditions. The study provides the philosophy behind the crash-conflict ratios and their use in crash estimations. The same-direction crash-conflict ratios estimated were 1.428×10^{-6} at high volume and 2.663×10^{-6} at medium volume signalized intersection based on the "all same direction" pooled conflicts and the actual crashes at study locations considered to be associated with such conflicts.

Salman and Al-Maita (1995) evaluated traffic safety at three-legged unsignalized intersections by developing various conflict and crash prediction models based on the extensive field work conducted at eighteen unsignalized three-legged intersections located in Amman, Jordan. The relationship between crash and conflict was found to be linear.

Weerasuriya and Pietrzyk (1998) determined crash-conflict ratios for different conflict types at unsignalized three-legged intersections involving roadways with various lane configurations. These ratios were determined based on three-year crash history data and the traffic conflicts observed at thirty-eight intersections in west-central Florida. The estimated right-turn, same-direction crash-conflict ratio was 2.492×10^{-5} for four-lane three-legged unsignalized intersection. Tiwari et al. (1998) examined the relationship between fatal crashes and conflict rates observed at mid-block at fourteen locations operating under mixed traffic streams in Delhi, India. The study found a weak association between fatal crashes and conflicts. Kaub and Kaub (2000) developed a general algorithm for conflict-opportunity-based software to predict the number of crashes at both signalized and unsignalized intersections. The software was validated by comparing the number of crashes predicted per year with the historical annual average crashes at various study locations using the crash data provided by Florida DOT.

Mauro and Cattani (2004) proposed a model to estimate the number of traffic crashes at medium or large roundabouts based on the concept of ‘potential conflict’, which was defined as a situation in which a vehicle performs some maneuvers in a particular context that may or may not lead to a crash. Crash-conflict ratio coefficients were derived for different crash categories (failure to yield after stopping, failure to yield without stopping, run off the roadway, rear end) based on potential conflicts and the history of crashes recorded at a number of roundabouts located in various European countries and Australia. The rear-end injury crash-conflict ratio was determined to be 3.02×10^{-8}.

FHWA recently developed a software tool known as Surrogate Safety Assessment Model (SSAM) that uses traffic simulation models for deriving surrogate safety measures for the safety evaluations of traffic facilities (Gettman et al. 2008). The SSAM is compatible with four existing traffic simulation models – VISSIM, AIMSUN, Paramics and TEXAS. The model was validated through various validation efforts that involved theoretical validation, field validation and sensitivity analysis. The field validation efforts involved performing several validation tests to compare the simulation-based conflict data with the real-world crash records of eighty-three four-legged signalized intersections located in British Columbia, Canada. These intersections were modeled and simulated in VISSIM traffic simulation software and then assessed with the SSAM. The correlation between conflicts and crashes was established by developing a regression model, which estimated average yearly crash frequencies at an intersection as a function of average hourly conflict frequencies found by SSAM. It was found that the conflict frequencies were significantly correlated with the actual crash data. The ratio of traffic conflicts to actual crashes was found to be approximately 20,000 to 1, or a crash-conflict ratio of 5.00×10^{-5}.

2.4 Studies related to the warrants for right-turn treatments

The discussions on right-turn lanes and the need for them have been documented in Policy on Geometric Design of Highways and Streets (AASHTO 2004) and Highway Capacity Manual (HCM 2010). The provisions of right-turn lanes as a strategy for improving the traffic safety at unsignalized intersections and the various related strategy attributes have been documented in NCHRP Report 500 (Neuman et al. 2003). Gluck et al. (1999), as a part of NCHRP 420 study, reported on the impact of access management techniques, and also looked into the role and the use of right-turn lanes as a part of the broader strategy for access management for a corridor. The NCHRP Report 491 (McGee et al. 2003) and the NCHRP Report 500 (Neuman et al. 2003) suggest carrying out benefit-cost analyses to justify intersection improvements.

Different methodologies have been used in the past to determine the volume warrants for right-turn lanes. One of the key needs is to identify and study conflicts that 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 concerned, the conflicts to deal with are merging and diverging. Both merging and diverging conflicts can potentially result into rear-end or sideswipe crashes.

Cottrell (1981) was the first reporting of right-turn related study, carried out in Virginia, which tried to establish the volume thresholds for determining the need for right-turn treatments at unsignalized intersections on two-/four-lane rural roadways. The volume thresholds were established based on a synthesis of relationships among the field data, the standards employed by many other states at that time and judgment. The variables considered include approach volume, posted roadway speed limit and right-turn volume.

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

McCoy et al. (1993) developed warrant guidelines for right-turn lanes for urban two- and four-lane highways in Nebraska based on benefit-cost analysis that took into account both operational and safety benefits that the right-turn lanes were estimated to provide to road users. The study noted that the safety effects of right-turn lanes were not adequately quantified in the past mainly due to the limitations of available crash data. As such, the safety effectiveness of right-turn lanes was quantified based on a relationship previously established between speed differentials and crashes (Figure 2.2). The underlying message in this relationship is that the chance of being involved in a crash increases as the speed of a vehicle deviates from the average speed of traffic (Solomon 1964). The speed differentials between right-turning vehicles and through vehicles at intersection approaches without right-turn lanes were estimated to determine the expected number of rear-end crashes at such approaches. It was assumed that such rear-end crashes would be eliminated by providing right-turn lanes. The dollar value of the safety benefits of providing right-turn lanes were then evaluated at a fixed rate of $9,300 per rear-end crash.

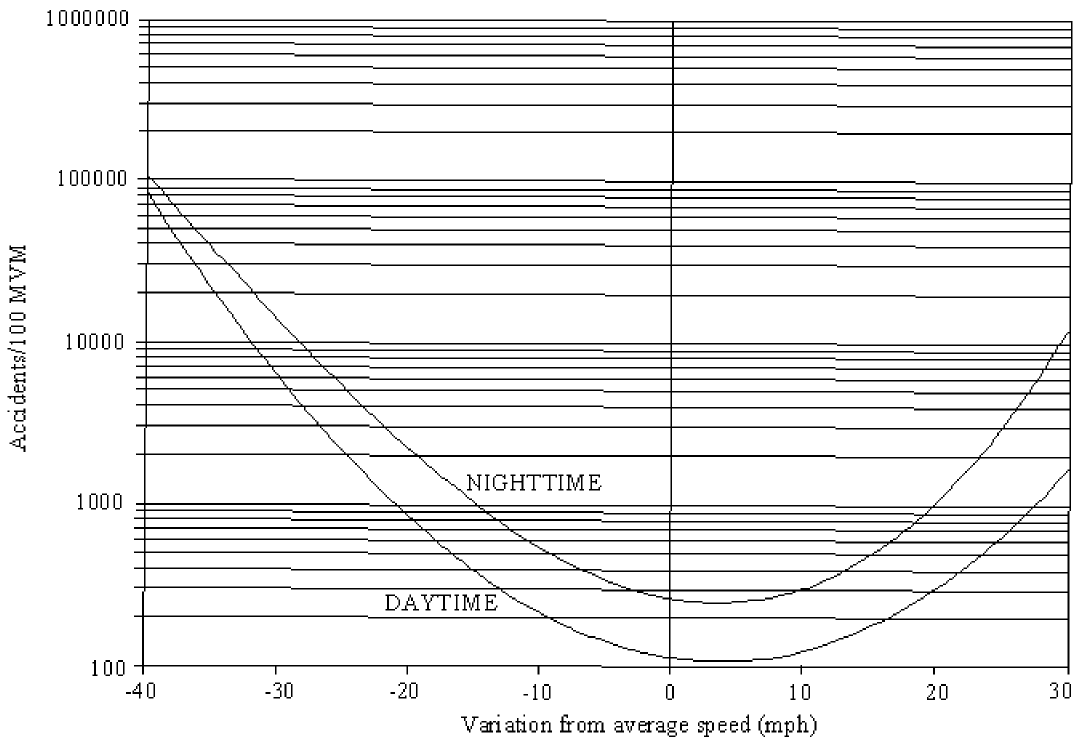


Figure 2.2. Relationship between speed differentials and accidents.
Source: Solomon (1964). Note: MVM – Million vehicle miles.

Hasan and Stokes (1996) also followed the benefit-cost approach to develop the volume warrants for right-turn treatments at the approaches to unsignalized intersections and driveways on rural two- and four-lane highways in Kansas. The safety benefits of providing right-turn lanes were quantified by adopting the same methodology formulated by McCoy et al. (1993) discussed above. McCoy and Bonneson (1996) developed volume warrants for free right-turn lanes at approaches to unsignalized intersections on rural two-lane highways based on the operational cost savings that free right-turn lanes were estimated to provide. The study found that the safety effects of free right-turn lanes were not significant, and were not incorporated in the benefit-cost analysis that was performed to determine the volume thresholds for free right-turn lanes.

Hadi and Thakkar (2003) used speed differentials as a surrogate safety measure to evaluate the need for right-turn lanes at unsignalized intersections based on the data obtained from simulations as well as the field data collected from two locations in Florida. Yang (2008) proposed a methodology based on the risk probabilities of potential rear-end crashes caused by the decelerating right-turning vehicles, and derived a set of warrant curves for establishing the volume warrants for free right-turn lanes on two-lane roadways.

2.5 Statistical methods used in crash history data analyses

Crash history data play a vital role in the highway safety analysis, and have generally been analyzed as discrete dependent variable models. The choice of specific regression method is highly influenced by the nature of the data – whether the crash history data are event specific or location specific. Event specific crash data include all relevant crashes that have occurred within the study area during the study period; if a particular location did not experience any crashes during the study period, then that location would not appear in the data. The location specific crash data, on the other hand, are further disaggregated by their locations (or some physical attributes); if a particular location did not experience any crashes during the study period, then that location would appear in the data as a location with zero crash. The NCHRP Report 20-45 discusses on how to identify the appropriate statistical technique for a specific data analysis problem in transportation research (Washington et al. 2002). The report also elaborates on various continuous and discrete dependent variable models, including theoretical bases, data needs, model assumptions and requirements, and model problems, fixes and interpretations.

Literature suggests that the location specific count data of crash history were mostly analyzed using lognormal, Poisson, Gamma, or negative binomial regression methods (Bauer and Harwood 1996; Vogt and Bared 1998; Vogt 1999; Bauer and Harwood 2000; Ladrón de Guevara et al. 2004; Oh et al. 2004; Kim et al. 2006; Wang and Abdel-Aty

2006). The before-after studies were another widely used method to analyze the location specific crash history data (Agent 1988; Hauer 1997; Pant et al. 1999; Thomas and Smith 2001; Harwood et al. 2002; Hovey and Chowdhury 2005).

On the other hand, the event specific traffic crash history data, generally observed over a larger geographical area, have mostly been analyzed as probability models using the logistic regression approach. Walker (1996) developed methodology application for NHTSA on how logistic regression techniques could be used in traffic safety studies. Dissanayake and Lu (2002) developed a set of sequential binary logistic regression models to predict the severity of single-vehicle crashes involving young drivers using the Florida traffic crash database. Christian et al. (2003) used logistic regressions to investigate the factors associated with motorcycle crashes and traumatic brain injury based on the history of crashes reported in Kentucky. 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 using five-year historical data of traffic crashes reported in Connecticut. Donnell and Mason (2004) developed multinomial logistic regression models relating median-related crash severity with different explanatory variables by using roadway inventory data and five-year crash history records of Pennsylvania Interstate highways. Yan et al. (2005) studied the characteristics of rear-end crashes reported in Florida at signalized intersections using the quasi-induced exposure concept and multiple logistic regression models, and identified several significant rear-end crash risk factors related to traffic environment, driver and vehicle types. Wang and Abdel-Aty (2008) analyzed left-turn crash injury severity using partial proportional odds models based on five-year crash history data obtained for 197 four-legged signalized intersections located in the Central Florida area. The logistic regression methods have also been used in several other traffic safety studies (Zhang et al. 2000; Sohn and Shin 2001; Al-Ghamdi 2002; Bedard et al. 2002; Quddus et al. 2009).

2.6 Summary

The foregoing presented the review of literature with a focus on the safety impacts of right-turn lanes and their volume-based warrants. The studies reviewed include those that were either based on traffic crashes or traffic conflicts as a surrogate safety measure. The various statistical methods used to analyze the historical data of traffic crashes were also noted. The whole exercise was important to obtain an insight into the nature and the extent of problem being addressed in this study, as well as to formulate an appropriate methodology to realize the intended goals of this study.

It was found that quite a few studies analyzed the safety impacts of right-turn lanes, primarily based on the historical data of traffic crashes. However, there was a lack general agreement in their findings. While some studies demonstrated that the right-turn lanes were safety effective, the others have found that the right-turn lanes were associated with the negative safety implications. Some studies also found that the safety effects of right-turn lanes were statistically insignificant, whereas few others proceeded to determine their volume warrants assuming that they were safety effective. It was also noted that the safety impacts of right-turn lanes, determined based on crash history data, were mostly estimated in terms of point estimates. It is not clear whether such estimates hold true in a broad range of conditions. For practical purposes, e.g., warrant guidelines, the need is to quantify the safety impacts of right-turn lanes as a function of roadway conditions encountered or expected at an intersection location.

One reason frequently mentioned in literature on why right-turn lanes might possibly be associated with the increase in crash frequencies could be the fact that the right-turn lanes are typically installed when the right-turn movements, and, therefore, the opportunities for crashes, are high. It has been argued that such endogeneity problem gets reflected in the crash history data as well – the approaches with right-turn lanes had experienced high number of crashes to justify their installations (Vogt and Bared 1998; Kim et al. 2006). Kim et al. (2006) suggested the use of right-turn traffic volumes in the analysis to address the bias introduced by the endogeneity. Similarly, Fitzpatrick et al. (2006) and Hochstein (2006) have highlighted the need of incorporating the right-turn traffic volumes in the analysis before reaching any definitive conclusions with regard to the safety impacts of right-turn lanes. The NCHRP Report 500 (Neuman et al. 2003) also indicated the need of traffic volumes, including right-turn volumes, to represent the exposure in the analysis of crashes involving right-turning vehicles. The NCRHP Report 500 has also recommended analyzing the total intersection crashes and the crashes involving right-turning vehicles separately to assess the safety impacts of right-turn lanes.

It, however, needs to be pointed out that the turning movement counts at intersections are not an integral part of the automated traffic volume data that are collected round the clock throughout the year and are maintained by several state and federal agencies. Turning movement counts are usually obtained over a certain number of day(s) at selected locations depending on the data needs. As such, the turning movement variables are generally not available to researchers analyzing the statewide crash history data. In such situations, the application of traffic conflicts technique, based on field surveys or through traffic simulation, seems to provide an opportunity to analyze the safety effects of turning movements at intersections either to supplement the results obtained by analyzing crash history data or to directly estimate the expected number of crashes resulting from such movements. Researchers in the past have attempted to establish the relationships between traffic crashes and conflicts. However, the crash-conflict relationship for the conditions similar to the context of right-turn movements being analyzed in this study was not found.

The assessment of the safety impacts of turning movements is particularly important while determining the volume thresholds to justify a targeted intersection improvement. It was found that a number of studies, related to the volume-based warrant guidelines for right-turn lanes, have taken into account the effects of the variations in right-turn volumes (Cottrell 1981; McCoy et al. 1993; Hasan and Stokes 1996; McCoy and Bonneson 1996; Yang 2008). The safety effectiveness of exclusive right-turn lanes was, however, determined based on the premise that right-turn lanes eliminate rear-end crashes caused due to the speed differentials between right-turning vehicles and through vehicles (McCoy et al. 1993; Hasan and Stokes 1996; Yang 2008). It remains to be seen whether such assumption is appropriate and valid in the light of extensive crash history data now available to researchers. Similarly, the safety impacts of right-turn lanes should not only be analyzed in terms of rear-end crashes, but also with reference to other crash types that involve right-turning vehicles, as well as in terms of various other intersection-related factors other than the speed differentials.

The NCHRP Reports 491 and 500 recommend adopting a benefit-cost approach to justify the targeted intersection improvements. Such benefit-cost approach has been used in the past; however, the safety benefits of right-turn lanes in such analyses were evaluated in terms of a fixed cost per crash (McCoy et al. 1993; Hasan and Stokes 1996). Given that the varying operating conditions, such as roadway speed, traffic volume, treatment type, etc., affect the level of crash injury severities, the appropriateness of using a fixed cost for a crash needs to be examined. The NCHRP Report 491 suggests applying the crash severity weights while determining the dollar values of a crash (McGee et al. 2003).

Finally, it was found that a variety of regression methods have been used in the past in the analysis of the historical data of traffic crashes. The choice of specific regression method appears to be dependent on the data structure. Logistic regression methods were found to be widely used method in case of crash history data that were event specific, i.e. each location in the crash data experienced at least one crash.

CHAPTER 3. METHODOLOGY

The safety effectiveness and safety-based volume warrants of right-turn lanes at unsignalized intersections and driveways on two-lane roadways were determined in three broad steps: a) crash analysis (Chapter 4), b) conflict analysis (Chapter 5) and c) crash-conflict ratio analysis (Chapter 6) that tied together the results obtained from crash and conflict analyses. This chapter presents the overall methodologies adopted to carry out these analyses. Methodologies are presented in greater details in subsequent chapters.

3.1 Crash analysis

The goals of crash analyses were to estimate various conditional probabilities associated with a crash caused by a vehicle making a right turn from an uncontrolled approach of a major roadway on to a cross road. The expected costs associated with such crashes were also estimated.

3.1.1 Data collection and data preparation

The various data required for crash analysis were: crash history data, traffic volume data, roadway speed and through-lane data, intersection inventory data, videolog data, GIS shapefiles and crash reports. In addition, Google Earth™ images were retrieved case by case basis as a supplementary data source. The need and the relevance of each of these data sources are described in the next chapter. The data preparation involved data conflation and data reduction. Since archived data from multiple data sources were used, these exercises were required to obtain a set of data relevant and consistent with the study contexts.

3.1.2 Exploratory analysis

Exploratory analysis provides a basis for objective analysis to find the patterns in the data that are not predicted by the researcher's current knowledge or pre-conceptions. In this study, the exploratory analyses in terms of crash trends and crash shares by individual variables were carried out first to get an idea of the nature and the extent of crashes caused by vehicles making right turns from uncontrolled major roadway approaches. The exploratory analyses provided important information and revealed the need and the appropriateness of developing binary as well as multinomial logistic regression models in order to determine the safety effectiveness of right-turn lanes. The exploratory analyses were also instrumental in identifying the dependent and independent variables in such regression models.

3.1.3 Binary logistic regression model

Multivariable binary logistic regression models were developed to estimate the conditional probabilities associated with a crash caused by a vehicle making a right turn from a major roadway approach. A binary logistic regression model uses the dependent (or response or outcome) variable (Y) with two levels (or classes or categories), say, Y=1 and Y=0. The model describes a linear relationship between the logit, which is the natural logarithm of odds, and a set of predictors (or explanatory or independent factors). The relationship can then be worked out to estimate the response probabilities. For example, given a set of qualitative explanatory factors (variables), such as ‘low’ posted roadway speed limit, ‘high’ traffic volume condition, ‘dry’ road surface condition, etc., the probabilities of a crash due to a right-turning vehicle can be estimated by fitting a binary logistic regression model to the data in which the dependent variable (Y) was designed in terms of two events: (i) the crash was caused by a right-turning vehicle (Y=1) and (ii) the crash was not caused by a right-turning vehicle (Y=0). The model has the form shown below (SAS 2008):

$$\text{logit}(\pi) = \ln\left(\frac{\pi}{1-\pi}\right) = \alpha + \beta'.x; \quad (3.1)$$

where π is P(Y=1|x), the probability that Y=1; α is intercept parameter; β is the vector of slope parameters; and x is the vector of explanatory factors.

3.1.4 Multinomial logistic regression model

Since the level of crash injury severity varies from one crash to another depending on various contributing factors, the cost of a crash is expected to vary accordingly. The varying nature of crash injury severity was, therefore, taken into account in the estimated costs by estimating these costs as a weighted average cost. The weights used were the probabilities of a crash injury severity in a crash caused by a right-turning vehicle. Such probabilities of a particular crash injury severity were estimated by fitting a multivariable multinomial logistic regression model.

A multinomial logistic regression model requires the outcome variable with more than two levels on ordinal or nominal scales. In case of crash injury severity analysis, the levels of the response variable, for example, could be fatal crash, injury crash, and property-damage-only crash, for which either ordinal or nominal scales could be appropriate depending on the data in hand. In this study, the crash injury severity analysis was carried out using ordinal-response model. The suitability of a nominal-response model was also examined, but it was found that the ordinal-response model fitted the data well compared to a nominal-response model.

The ordinal-response multinomial logistic regression model with the response variable (Y) with k+1 levels of ordinal values, denoted by 1, 2, ..., k, k+1, is fitted as a common-slopes cumulative model, which is a parallel-lines regression model based on the cumulative probabilities of the response categories. The model with a logit link function is often referred to as the proportional odds model. The appropriateness of proportional odds model is assessed by carrying out the score test for the proportional odds assumption, in which a small p-value rejects the null hypothesis that the proportional odds assumption was appropriate. The proportional odds model has the form shown below (SAS 2008):

$$\ln\left(\frac{\gamma_i}{1-\gamma_i}\right) = \alpha_i + \beta'.x; \quad i = 1,2,...,k; \quad P(Y = k+1 \mid x) = 1 - \sum_{i=1}^{k} P(Y = i \mid x); \qquad (3.2)$$

where γ_i is $P(Y \leq i \mid x)$, the cumulative probability that the response falls in the i^{th} category or below; α_i is the i^{th} intercept parameter; β is the vector of slope parameters; x is the vector of explanatory factors; P(Y=i|x) is the probability of the i^{th} response category; and P(Y=k+1|x) is the probability of the reference category.

3.1.5 Logistic regression model development strategies

One of the problems often encountered in the process of logistic regression model development lies in deciding which explanatory factors to include in the model when there are many explanatory factors to choose from. Generally, only a limited number of explanatory factors can be included in the model due to the limited number of observations. In such situations, Hosmer and Lemeshow (2000) recommended using univariable analysis results in order to identify the potential significant factors from a list of available explanatory factors. It was suggested that any explanatory factor with the p-value less than 0.25 from the univariable test is a candidate for the multivariable model along with all variables considered important.

Another commonly encountered problem, in the development of logistic regression model with qualitative variables, pertains to what is known as complete or quasicomplete separation in the data, depending on the positions of zero cells in the contingency table (Altman et al. 2004). Cells in a contingency table represent conditions formed by the intersections of the categories of variables; for example, a contingency table of two variables, each with two categories, consists of four cells. A zero cell refers to the cell with zero count of observation. When zero cells exist, the maximum likelihood estimates do not exist; so, the model does not converge resulting in undesirable numerical outcomes. Therefore, the contingency table helps in identifying the cells with zero count that yield a point estimate for one of the odds ratios of either zero or infinity (Hosmer and Lemeshow 2000). Some of the corrective measures to address the complete or quasicomplete separations in the data include: reclassifying the dependent variable, reclassifying the qualitative independent variable, or deleting the problematic independent variable from the model. Various other approaches to deal with such problems in the data have been suggested (Allison 1999; Hosmer and Lemeshow 2000; Altman et al. 2004).

All of the logistic regression models developed in this study were fitted using SAS® 9.1 program based on the stepwise model selection procedures. The stepwise selection procedure starts with no predictors in the model. It examines each predictor that could possibly be added to the model and then adds the most significant predictor. In the next step, the procedure adds the next most significant predictor. It then checks to see if any of the previously included predictors have now become insignificant, and if so it removes that predictor from the model. Predictors are, therefore, entered into the model and removed from the model in such a way that each forward selection step can be followed by one or more backward elimination steps. The procedure continues until there are no more significant predictors to add into the model.

3.1.6 Assessment of the adequacy of fitted logistic regression models

The adequacy of fitted logistic regression models were assessed based on the Pearson and Deviance goodness-of-fit tests. The Hosmer and Lemeshow goodness-of-fit test was also performed to assess the model fit in case of binary logistic regression models. Small p-values in these tests reject the null hypothesis that the fitted model is adequate. For example, at 95% confidence level, the null hypothesis is rejected if the p-value is less than 0.05. In addition, regression diagnostics, such as the plot of a change in the deviance or Pearson Chi-square due to deleting an individual observation versus estimated logistic probability and the plot of leverages versus estimated logistic probability, were used to see if the model fit was supported over the entire set of covariate space. SAS (2008) and Hosmer and Lemeshow (2000) provide for the elaborate treatment of goodness-of-fit tests and regression diagnostics.

3.2 Conflict analysis

One piece of information not available from any data source mentioned earlier was the information related to right-turn volume, which is one of the most important variables in the formulation of volume warrants for right-turn lanes. It is also reasonable to expect some kind of association between right-turn volumes and crashes due to right-turning vehicles. The conflict analyses using traffic conflicts technique (TCT) through both field surveys and conflict simulations were, therefore, carried out to determine the effects of right-turn volumes on the safety effectiveness of right-turn lanes. The TCT was employed in this study for reasons, such as its relevance, a well-suited and an appropriate way to incorporate right-turn volumes in the overall analysis, as well as the ease and accuracy with which it could be applied quickly in the field and in the simulation environment. The goal was to develop least squares conflict prediction models to estimate the expected number of right-turn, same-direction conflicts, including the associated secondary conflicts, which were considered surrogate safety measures for rear-end/same-direction-sideswipe (RE/SS) crashes caused by right-turning vehicles.

3.2.1 Conflict analysis through field surveys

The conflict analysis through field surveys involved developing a least squares conflict prediction model based on the following field data: right-turn, same-direction conflicts, including the associated secondary conflicts, approach volumes, right-turn volumes, posted roadway speed limits, and right-turn treatment types. The observed number of conflicts was the dependent variable.

A right-turn, same-direction conflict was observed when an evasive maneuver to avoid a rear-end, or potentially a same-direction-sideswipe, crash was seen to be performed by a following vehicle in response to a lead vehicle that slowed down to make a right turn. The following were considered to be an instance or an indication of an evasive action: brake light indication, swerve action, front lounging of the vehicle and squealing of tires (Weerasuriya and Pietrzyk 1998). A secondary conflict was observed when an additional vehicle performed an evasive action in response to a vehicle already conflicted with a right-turn, same-direction conflict. The right-turn, same-direction conflicts, including the associated secondary conflicts are henceforth simply referred to as ‘conflicts’ or ‘conflicts due to right turns’. The conflicts due to right turns were observed within 100 feet (ft) or more from the start of the right-turn treatment at an approach with less than or equal to 40 miles per hour (mph) posted roadway speed limit, and within 300 ft or more at an approach with more than 40 mph posted roadway speed limit (Glauz and Migletz 1980; Cottrell

1981; Parker and Zegeer 1989; Crowe 1990; Hasan and Stokes 1996). The conflict observer positions and the potential conflict situations are shown in Figure 3.1.

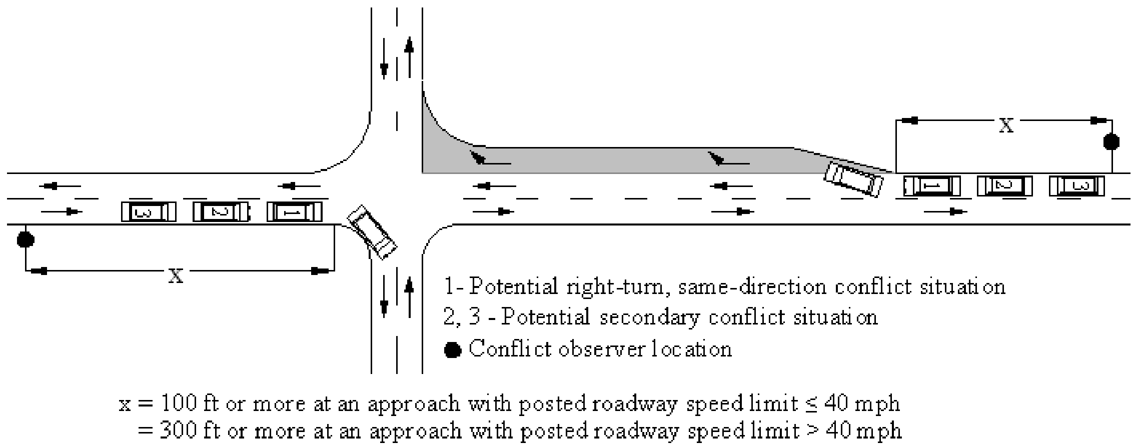


Figure 3.1. Conflict observer locations and potential conflict scenarios.

Previous studies (Cottrell 1981; Hasan and Stokes 1996; Weerasuriya and Pietrzyk 1998) also suggested that four hours of conflict data collection at a location would suffice as far as the conflicts due to right turns were concerned. The conflict data were, therefore, collected for a continuous four-hour period encompassing peak flow period either at AM peak (7:00 - 11:00 AM) or PM peak (2:00 - 6:00 PM) during weekdays (Monday through Friday) under dry road surface condition.

3.2.2 Conflict analysis through simulation

CORSIM (Corridor Simulation) and VISSIM ("Verkehr in Stadten Simulation" – traffic in cities simulation) are two simulation models widely used in traffic studies. Both of these traffic simulation models were evaluated for their suitability to use in this study. The CORSIM and VISSIM models have been comprehensively reviewed in the past (ITS 2000; Bloomberg and Dale 2000; Gettman and Head 2003; Kim 2006). There are advantages as well as disadvantages associated with each of them. However, it was found that researchers have generally preferred VISSIM for traffic conflict simulations for reasons, such as greater flexibility of VISSIM models in terms of roadway design, vehicle performance and road user behavior (Archer 2005; Eisele and Toycen 2005; Gettman et al. 2008; Cunto and Saccomanno 2008; Archer and Young 2009). In this study, the VISSIM models were used since the simulation outputs generated by VISSIM models were found more suitable to obtain the desired performance measure – the conflicts due to right turns in this case. It was also possible in VISSIM to simulate conflicts in a time step less than one second, which is desirable in traffic conflict simulations.

The VISSIM is a time-based microscopic simulation model developed to model urban traffic and public transit operations. The model takes into account both driver behavior and vehicle characteristics. Moreover, the stochastic nature of traffic is simulated by incorporating several parameters, such as vehicle arrivals, speed, acceleration, deceleration, weight, type, driving behavior, etc. that use stochastic distributions.

However, the greater flexibility in VISSIM simulation models also meant the greater need of various field data. The field data related to right-turn treatment types and geometry, approach and right-turn volumes, traffic compositions, posted roadway speed limits and desired speed distributions, including observed right-turning speed distribution, were collected as the input data for VISSIM model developments, whereas the field data related to time headway distributions and spot-speed distributions of vehicles at various points in the traffic stream of interest were obtained for VISSIM model calibrations.

After the VISSIM models have been developed and calibrated, the number of simulated conflicts due to right turns, defined as the number of following vehicles that applied brakes to maintain a safe distance to the lead vehicle that slowed down either to make a right turn or in response to an already conflicted vehicle, were obtained by post-processing the vehicle record files generated by the simulations. Vehicle record files are output files that contain information, such as speed, acceleration, interaction state (free-flowing, following, braking), following distance, etc. at every pre-defined time step for each vehicle. These files were used as inputs to VBA programs in MS Excel written to count the number of conflicts due to right turns using the logic presented in Figure 3.2.

The calibrated VISSIM models were validated by comparing the number of simulated conflicts with the number of conflicts observed at field. The validated VISSIM models were then used to obtain the number of conflicts due to right turns at both radius and exclusive right-turn lane treatments at a wide range of approach volumes, right-turn volumes and posted roadway speed limits.

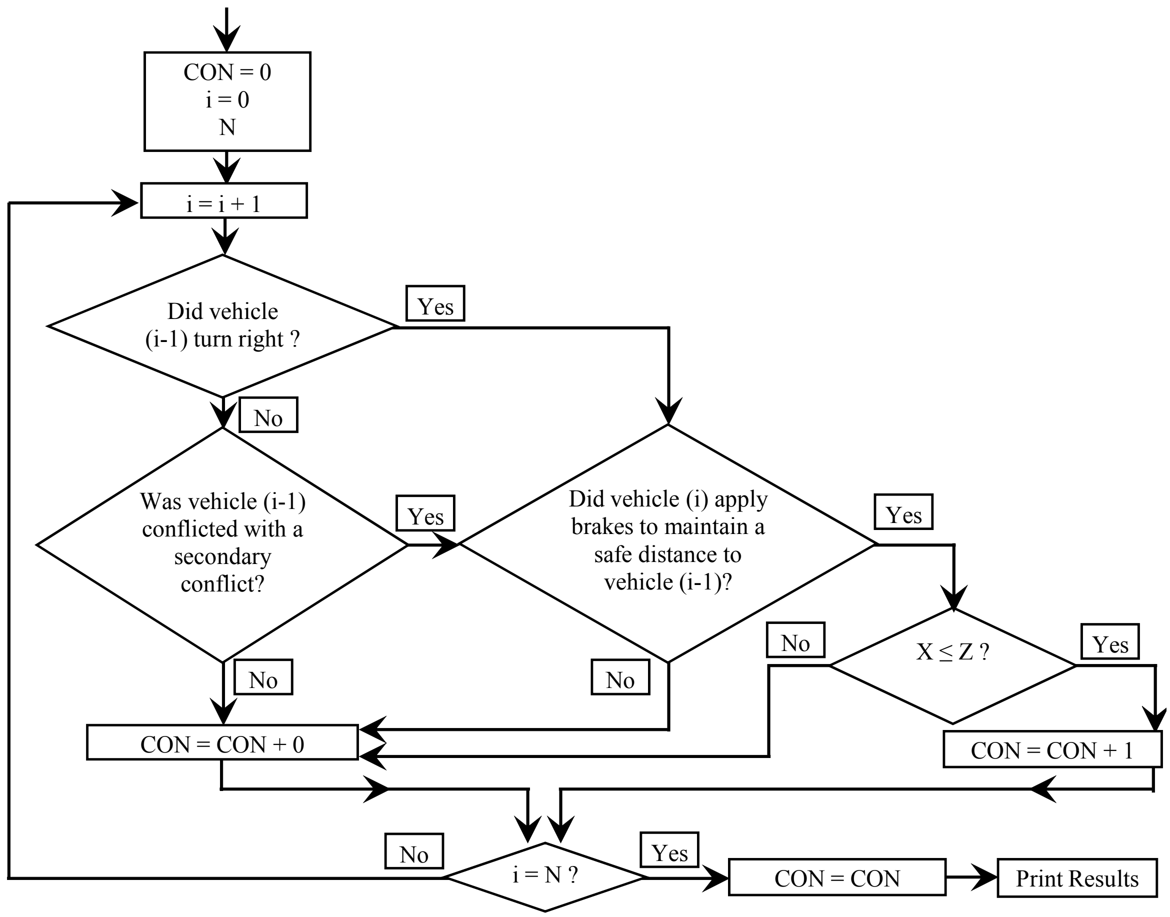
3.2.3 Multiple regression model

The conflict prediction models to predict the number of conflicts due to right turns were developed as multiple regression models by using the method of least squares. Mendenhall and Sincich (2003) was referred for regression theories and assumptions, model building techniques, variables screening methods, model fit assessments and other regression-related issues. The general form of a multiple regression model is shown below:

$$y = \beta_0 + \beta_1.x_1 + \beta_2.x_2 + ... + \beta_k.x_k + \varepsilon; \qquad (3.3)$$

where y is dependent variable; β_0 is intercept parameter; β_1, β_2, …, β_k are model coefficients; x_1, x_2, …, x_k are independent variables, including interaction/higher order terms; and ε is random error.

Separate least squares conflict prediction models, depending on the type of data used, were developed using Minitab® 15 software; ‘field model’ was developed using the data obtained from field observations, whereas ‘simulation model’ was developed using the data obtained from conflict simulations. The appropriateness and the predicting capabilities of field and simulation models were examined and compared. The finally selected conflict prediction models were validated by comparing the number of predicted and observed conflicts at various study sites as discussed in Chapter 5.



CON	: total number of conflicts due to right turns in a simulation run;
N	: total number of vehicles during a simulation run;
Vehicle (i)	: the current i^{th} vehicle; $i = 1, 2, \ldots, N$;
Vehicle (i-1)	: the $(i-1)^{th}$ lead vehicle; $i = 1, 2, \ldots, N$;
X	: the approaching distance of the i^{th} vehicle from the STOP bar;
Z	: conflict zone = (Right-turn pocket length) + (Taper length) + 100 ft (at least), if speed ≤ 40 mph; and = (Right-turn pocket length) + (Taper length) + 300 ft (at least), if speed > 40 mph.

Figure 3.2. Logic flow chart to estimate the number of simulated conflicts.

3.3 Safety effectiveness of right-turn lanes

Crash analyses provided relationships to estimate the expected number of crashes caused by right-turning vehicles during a given time period at a given roadway approach with either radius or exclusive right-turn lane treatment. Similarly, conflict analyses provided relationships that could be used to estimate the expected number of conflicts due to right turns during the same time period at the same roadway approach. While the crash analyses did not analyze the effects of right-turn volumes, the conflict analyses did. The crash and the conflict estimates were then combined through what are referred to as 'crash-conflict ratios' (CCRs) and 'crash estimation factors' (CEFs) to estimate the number of crashes caused by right-turning vehicles in a broad range of conditions as represented by various significant contributing factors, including right-turn traffic volumes.

As mentioned earlier, it needs to be noted that the conflicts due to right turns were considered as surrogate measures of safety for rear-end/same-direction-sideswipe (RE/SS) crashes caused by vehicles making right turns. The CCRs relating crashes to conflicts were derived at each study site as the expected number of RE/SS crashes for each conflict due to a right turn. The estimated site-specific CCRs were then used to derive the mean CCR for each right-turn treatment type. The mean CCRs provided a way to estimate the number of RE/SS crashes at either radius right-turn treatments or exclusive right-turn lanes.

On the other hand, the CEFs, determined as the ratio of mean CCR to the probability of RE/SS crash, adjusted the CCRs to estimate the expected number of crashes due to right turns by taking into account all crash types at either radius or exclusive right-turn lane treatment. The estimated conflicts factored by CEFs were the estimates of all types of crashes caused by right-turning vehicles.

The safety effectiveness of right-turn lanes at intersection approaches, in terms of the number or the cost of crashes due to right turns saved per year by providing right-turn lanes, was determined by subtracting the number or the cost of crashes estimated at approaches with exclusive right-turn lanes from those without right-turn lanes (radius treatments). The safety effectiveness of right-turn lanes at driveway approaches was determined by adjusting the corresponding savings estimated at intersection approaches based on the relative risks of an RE/SS crash at driveway approaches compared to those at intersection approaches.

3.4 Safety-based volume warrants for right-turn lanes

The safety-based volume warrant guidelines for right-turn lanes were determined by using a benefit-cost approach. The cost used was the total cost of constructing a right-turn lane. Various cost scenarios of constructing a right-turn lane were considered, since the cost of constructing a right-turn lane depends on many factors, such as location, availability of land, materials, equipment, etc. The safety benefits of providing a right-turn lane, on the other hand, were determined in terms of the economic cost savings resulting from a fewer number of crashes due to right turns at approaches with right-turn lanes compared to those without right-turn lanes. The safety-based volume warrants for right-turn lanes indicate the minimum number of right turns during design hour at which the expected safety benefits of providing a right-turn lane exceed its construction cost. Since the expected safety benefits of right-turn lanes at driveway approaches were higher compared to those at intersection approaches, separate sets of warrant guidelines for right-turn lanes were developed for intersection and driveway approaches.

3.5 Summary

This chapter presented the methodologies adopted in this study. The methodologies are summarized in Figure 3.3. The study was carried out in three broad parts: crash analysis, conflict analysis and crash-conflict ratio analysis that involved combining the results obtained from the crash and the conflict analyses to estimate the safety effectiveness of right-turn lanes, and to develop their safety-based volume warrants.

The crash analyses were performed based on the archived data that were obtained from various data sources. The goals of these analyses were to estimate the conditional probabilities and the costs associated with a crash caused by a right-turning vehicle by fitting binary as well as multinomial logistic regression models.

The conflict analyses were carried out in order to incorporate the effects of right-turn traffic volumes on the safety effectiveness of right-turn lanes. These analyses were performed based on the data obtained from both field surveys and conflict simulations through the use of TCT. The purpose of conflict simulations, carried out by using VISSIM simulation models, was to obtain greater variation in the conflict data, since the variation in conflict data was found to be difficult to obtain through field surveys. The goals of conflict analyses were to estimate the number of conflicts due to right turns by fitting appropriate least squares multiple regression models to either observed or simulated conflict data.

The safety effectiveness of right-turn lanes was determined by tying together the results obtained from the crash and the conflict analyses through CCRs and CEFs. While the CCRs provided a method to estimate the number of RE/SS crashes at either radius or exclusive right-turn lane treatment, the CEFs provided a way to estimate the number of all crashes caused by right-turning vehicles. The safety effectiveness was determined in terms of the number as well as the economic cost of crashes due to right turns saved per year by providing right-turn lanes. The taper right-turn treatment type was not analyzed in this study because of the lack of relevant data involving taper treatment.

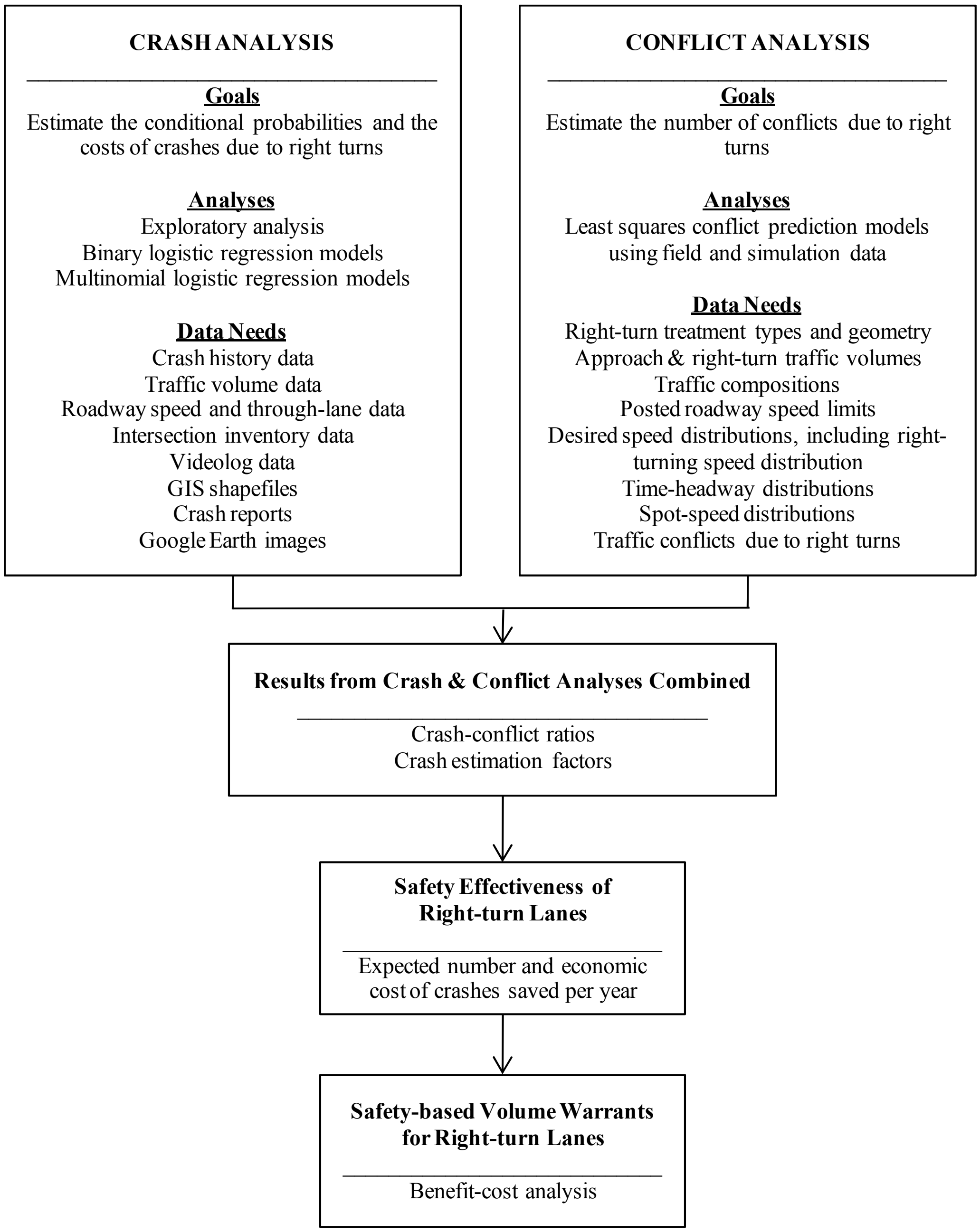


Figure 3.3. Methodology.

Finally, the safety-based volume warrant guidelines for right-turn lanes on uncontrolled approaches at unsignalized intersections and driveways on two-lane roadways were developed by using a benefit-cost approach. The cost used was the total cost of constructing a right-turn lane. The benefits considered were the expected safety benefits in terms of a fewer number of crashes due to right turns resulting from the provision of a right-turn lane. The warrants guidelines, developed separately for uncontrolled intersection approaches and driveway approaches, indicate the minimum number of right turns during design hour for which the expected safety benefits that can be achieved by providing a right-turn lane exceed its construction cost.

CHAPTER 4. CRASH ANALYSIS

The various types of crash analyses performed using the crash history and other relevant data are presented in this chapter. The goals of these analyses were to estimate the conditional probabilities and the costs associated with a crash caused by a right-turning vehicle.

4.1 Data collection

The crash history data, though very extensive and very well annotated with the codes explained by a data dictionary, were found to be inadequate to determine the safety impacts of right-turn lanes. An extensive data collection effort involving multiple data sources was, therefore, required, particularly to correctly identify the context within which a crash took place. This exercise also identified some data errors and highlighted the difficulties one faces when using archived data.

4.1.1 Crash history data

The statewide historical data of traffic crashes, reported on Minnesota's trunk highways over a period of five years from 2000 to 2002 and from 2004 to 2005, were obtained from Mn/DOT in a spreadsheet format. Because of some errors in 2003 crash history data, the Mn/DOT recommended not to use 2003 crash data in the analysis. The important attributes of crash history data were: crash location identifiers in terms of route identifiers and location measures (true miles/reference posts) along routes; the time, date, day, month and year a crash occurred; crash injury severity (property-damage-only, possible-injury, non-incapacitating-injury, incapacitating-injury or fatal crashes); number of vehicles involved in crash; relationship to junction (T, Y, four-legged, driveway/alley related, etc.); roadway posted speed limit; diagram of crash (rear-end, sideswipe, left-turn, right-angle, right-turn, head-on, or single-vehicle crash); action taken by vehicle (right-/left-/U-turning, changing lanes, overtaking, going straight ahead, etc.); and information related to environment (weather/light/road surface condition) and driver-vehicle unit (vehicle type, driver's physical condition/age/sex).

4.1.2 Traffic volume data

Traffic volume is one of the important factors representing exposure measure in traffic crash analysis. In order to determine the nature of the relationship between traffic volume and crash occurrence, the traffic volume data in spreadsheet formats for the same time periods as the crash history data were obtained from Mn/DOT. The traffic volume data attributes were: route identifiers, annual average daily traffic (both directions), average daily traffic of heavy commercial vehicles (both directions), data year, and the beginning and end points in terms of true miles or reference posts of road sections for which the traffic volumes were applicable.

4.1.3 Roadway speed and through-lane data

The roadway speed and through-lane data observed for the same time periods as the crash history data were obtained from Mn/DOT in spreadsheet formats. The important data attributes were: route identifiers; general road environment (rural, urban, suburban); road design type (freeway, expressway, conventional); median type (divided, not divided, barrier, curb); roadway posted speed limit; number of through lanes; and the beginning and end points of road sections in terms of true miles or reference posts for which the data were applicable. The roadway speed and through-lane data were particularly required to identify two-lane trunk highways, and also to verify the posted speed limits of roadways that already existed in the crash history data.

4.1.4 Intersection inventory data

Intersection inventory data, also obtained from Mn/DOT in spreadsheet formats, provided intersection related information, such as the type of intersection control (no control, yield sign, two-way stop, all-way stop, signal); number of intersecting legs; roadway lighting; general road environment; specific road environment (central business district, school crossing, industrial/residential/agricultural/forested/recreational area); including the location information of intersections in terms of route identifiers, reference posts/true miles and cross road descriptions. The intersection inventory data included a total of 7,893 records of intersections on Minnesota's trunk highways.

4.1.5 Crash reports

A total of 1,791 crash reports in hard copies, prepared and 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 objectives of collecting crash reports were threefold: to understand the sequence of events that led to a crash involving at least one vehicle making a right turn; to determine whether the crash was indeed caused by a right-turning vehicle; and to identify whether the right-turning vehicle was moving on to a cross road from a major road approach, or vice versa. Each of these crash reports, examined manually, would generally include a sketch showing vehicle positions, including a description of the events that led to the crash.

4.1.6 Videolog data

Videolog data, maintained by Mn/DOT, provided high-fidelity road images. The videolog data for the same time periods as the crash history data were accessed to investigate the road intersection geometry at crash locations, particularly to identify right-turn treatments. Only those crash locations that involved at least one vehicle making a right turn were examined using the videolog data, which coincidentally proved to be the only data source available to identify the right-turn treatment types at statewide crash locations.

4.1.7 Google Earth™ data

It was found that the crash reports, a critical data component in this study, sometimes referred the streets involved in a crash by street names, while the crash history data identified the streets by route identifiers, which are basically coded highway numbers. Although the intersection inventory data provided the names of cross roads, not all crashes, however, occurred at/around intersections; many of these crashes also occurred at/around alleys/driveways – the locations not included in the intersection inventory data. The relevance of Google Earth™ images as a data source was, therefore, found in resolving the ambiguities that sometimes arose with the identification of streets involved in a crash, because the Google Earth™ images are generally well annotated. In localized areas with high-fidelity image coverage, these images also helped verify the right-turn treatment types at crash locations.

4.1.8 GIS data

GIS data in the form of shapefiles of Minnesota's state boundary, district boundary, county boundary and road network were obtained from Mn/DOT websites. The GIS shapefiles provided an alternative source for roadway information, besides providing a platform to import crash locations, intersection locations, traffic volumes, roadway speed and through-lane data for rapid visualization of the spatial contexts and crash patterns, and also for determining the spatial proximities of crash locations with respect to intersection and driveway locations. The coordinate information obtained from GIS of data points representing crash locations or intersections was very useful in quickly retrieving the Google Earth™ images of these locations.

4.2 Data conflation

The data related to crash history, traffic volumes, roadway speeds and through lanes, intersection inventories, crash reports, videolog images, GIS shapefiles, and Google Earth™ images were all required to be tied to a common location to obtain a consistent set of data, and thus the need for data conflation. Based on the common route identifiers and the location measures in terms of true miles or reference posts along the routes, the data related to crash history, traffic volumes, roadway speeds and through lanes, and intersection inventories were conflated by writing simple VBA programs in MS Excel. The conflated data were used to create input files for subsequent statistical analyses. The conflated data were also brought into the GIS environment as route events by using ArcGIS software.

The crash reports, the videolog data and the Google Earth™ images, on the other hand, were manually examined crash by crash basis through a painstaking process to identify the right-turn treatment type at a crash location and to determine the directions of right-turn movements, as mentioned earlier, for about 1,800 crashes involving at least one vehicle making a right turn. The correct crash report in hard copy for a crash record in the spreadsheet was identified based on the common accident number, whereas the correct videolog image of a crash location was accessed by using the common route identifier and location measure. The correct Google Earth™ image of a crash location was retrieved by using the latitude-longitude coordinates obtained from either videolog image or GIS application.

4.3 Data reduction

Data reduction means reducing the dimensionality of the data by creating fewer variables that are some combinations of the original variables to facilitate the analysis and interpretation of results. However, in this dissertation, the terms 'data reduction' are used to mean the process of identifying the relevant data records, consistent with the study contexts (i.e., two-lane roadways, uncontrolled approaches to intersections or driveways), and, more importantly, to format the data to make them amenable for further statistical analysis. The terms 'formatting the data' were used to mean categorizing a variable observed on a qualitative or a quantitative scale into fewer categories, as discussed in the subsequent sections of this chapter, in order to make it amenable for statistical analysis and for easier interpretation.

The crash records determined relevant in this study were identified by scrutinizing whether a crash record met the data requirements, which were specified to include the following criteria: the crash involved two or more vehicles, the crash was classified as intersection/driveway/alley crash, the crash occurred at unsignalized intersection/driveway on a two-lane roadway, and the crash record contained location information. Any crash record that did not meet the data requirements was eliminated from the dataset.

A crash involving at least one vehicle making a right turn was identified based on the 'diagram of crash' and the 'action by vehicle' attributes of a crash record. A crash record with its 'diagram of crash' attribute coded with the value 'right-turn crash' was identified as involving a right-turn maneuver by at least one of the vehicles involved in the crash. Similarly, a crash record with its 'action by vehicle' attribute for a vehicle coded with the value 'vehicle making a right turn' was identified as involving right-turning maneuver by that vehicle. Therefore, the crash involving at least one vehicle making a right turn was identified by a crash record that had its 'diagram of crash' attribute coded with the value 'right-turn crash' and/or its 'action by vehicle' attribute coded with the value 'vehicle making a right turn'.

4.4 The final data

The original five-year historical data of statewide traffic crashes, reported on Minnesota's trunk highways, obtained from Mn/DOT contained a total of 22,211 crash history records. After screening these records through the criteria for data requirements and data consistencies, a total of 10,235 crashes were found to be relevant for this study. A total of 865 crashes (8.5%) were found to be involving at least one vehicle making a right turn, out of which 469 crashes were caused by right-turning vehicles moving on to cross roadways from major roadways, 355 crashes were caused by right-turning vehicles moving on to major roadways from cross roadways, whereas the movement directions and the roles of right-turning vehicles in 41 crashes that involved at least one right-turning vehicle could not be identified. Out of 469 crashes caused by vehicles making right turns from major roadways, a total of 34 crashes were caused due to false left-turn indications, i.e., vehicles indicated for left turns, also proceeded to take left turns sometimes, but took right turns instead.

The relevant and finally reduced data were divided into three separate datasets: (i) a total of 10,235 crashes that included all relevant crashes (referred to as 'All crashes'), (ii) a total of 435 crashes that were caused by vehicles making right turns from major roadways at unsignalized intersections/driveways (referred to as 'RT crashes'), and (iii) a total of 355 crashes that were also caused by right-turning vehicles, but the vehicles were making right turns from cross roadways on to major roadways (referred to as 'To-case crashes'). It needs to be noted that the attributes, such as traffic volume, posted roadway speed limit, number of lanes, as well as the route identifiers associated with crashes were major-roadway specific, i.e., these attributes did not pertain to cross roadways. The 'To-case crashes' were therefore not analyzed in this study. In other words, the crash analyses presented in this chapter were based on 'All crashes' and 'RT crashes' datasets. Figure 4.1 presents the locations of 'All crashes', whereas Figure 4.2 shows the locations of 'RT crashes' and 'To-case crashes'.

4.5 Exploratory analysis

The goal of exploratory analysis was to understand the nature and extents of crashes caused by vehicles making right turns from major roadways (RT crashes), and compare those with all the relevant crashes when viewed together (All crashes). This exercise was expected to help identify potential explanatory and outcome factors for subsequent regression model formulations. Most of the variables in the data were observed on a qualitative scale; if not, the quantitative variables were converted into the qualitative variables. The number of categories of a qualitative variable was kept as minimum, within the range of meaningful interpretation, as possible to avoid complete or quasicomplete separations in the data.

4.5.1 Variables related to time, day, month and year

The crash trends and crash shares by the variables related to time of day, day of week, month of year, and year are presented in Figure 4.3. The variation in the number of crashes over different years in both crash datasets was found to be minimum (Figure 4.3 a). The crash patterns by month of year are presented in Figure 4.3 (b). 'All crashes' and 'RT crashes' followed the same trends – the crash frequencies start to decrease from the highs in December and January to reach the lows in March and April, after which these trends climb up to reach the highs again in June and July followed by the lows in September and October before reaching the highs in December and January to complete a cycle. The crash patterns by date of month, shown in Figure 4.3 (c), do not reveal any clear trends.

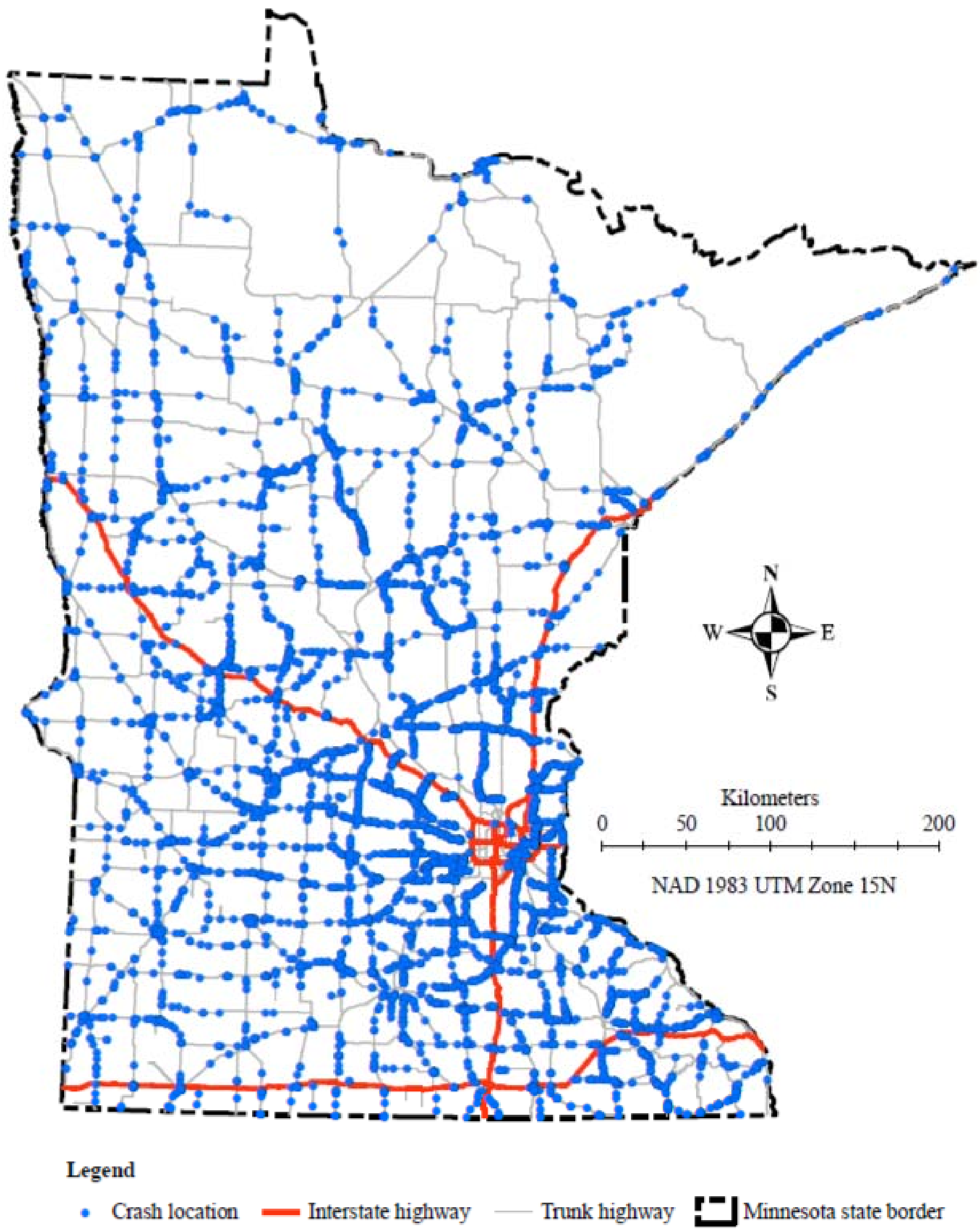


Figure 4.1. All relevant crashes on Minnesota's two-lane trunk highways.

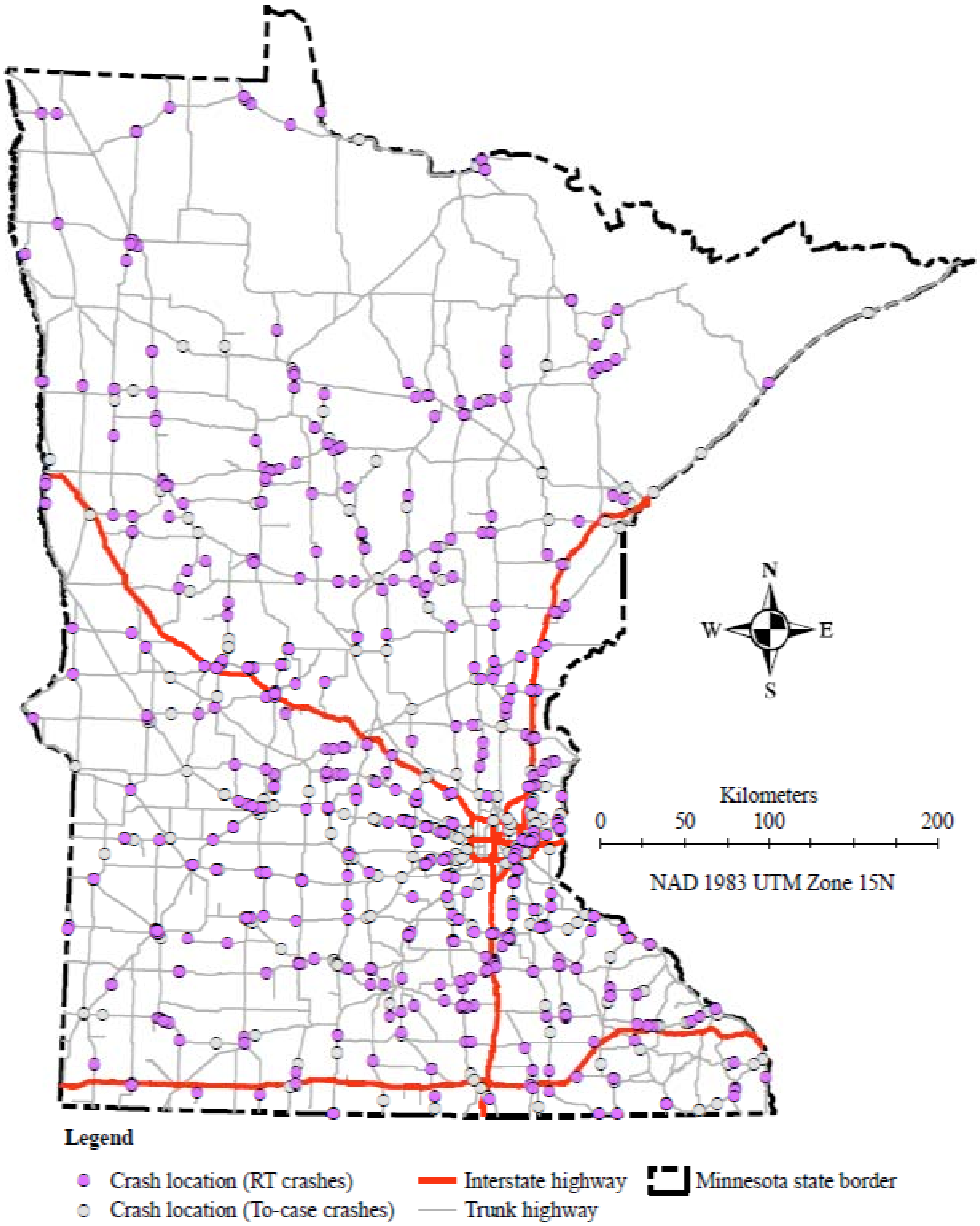


Figure 4.2. Crashes that involved vehicles making right turns on two-lane trunk highways.

Traffic volume varies over the days of week and may impact the crash frequencies accordingly. The crash trends by day of week, shown in Figure 4.3 (d), indicate that the Fridays are relatively more dangerous than the other days of week. Both datasets followed the same trends. The days of week were also categorized in terms of weekdays and weekends. Monday through Thursday were categorized as weekdays, while the remaining days were considered weekends. The crash shares by weekdays versus weekends revealed that about 60% of the crashes from both datasets took place during the weekdays (Figure 4.3 e).

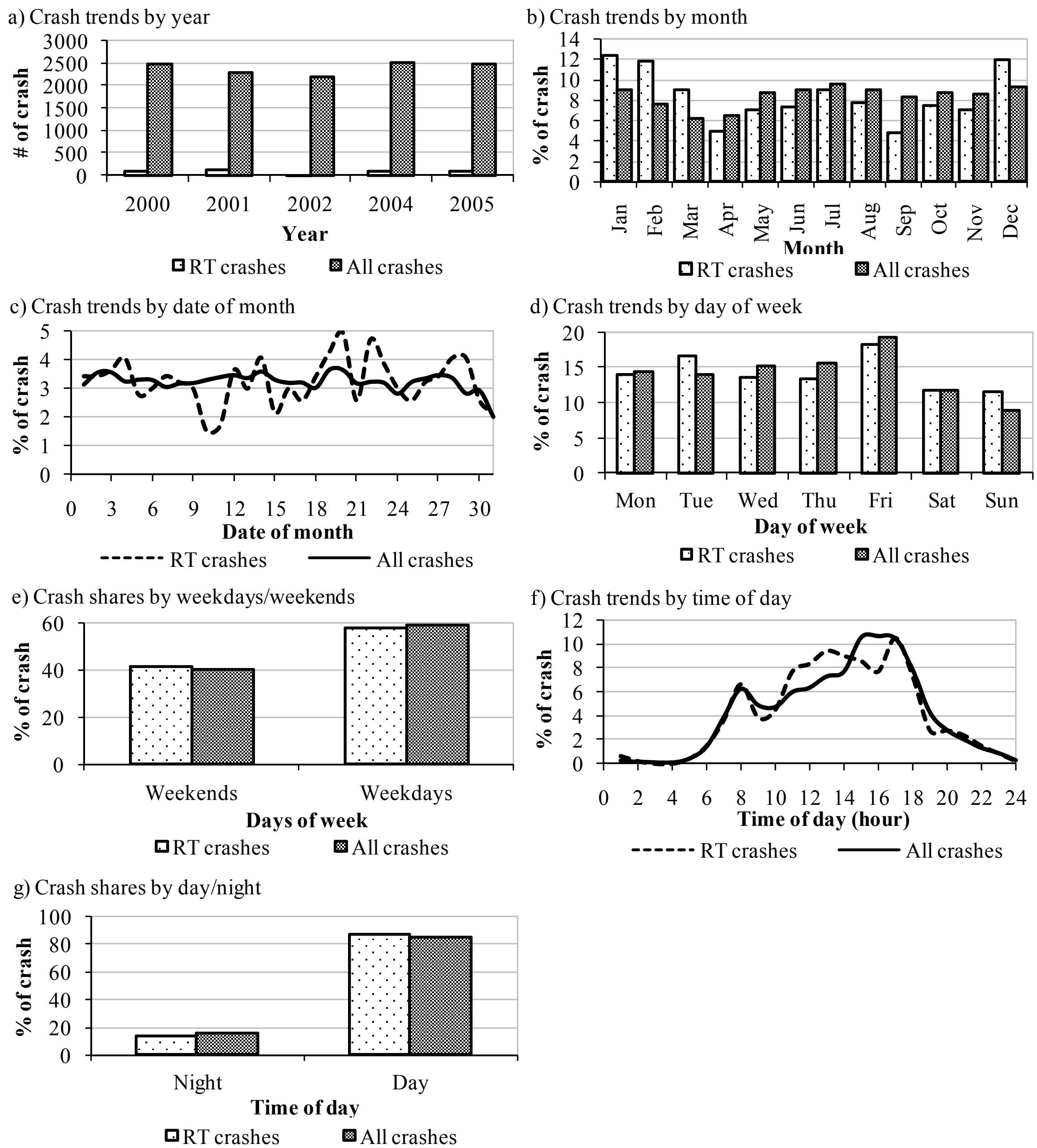


Figure 4.3. Crash trends by time, day, month and year.

Traffic volume also varies considerably over the time of day. Therefore, the crash trends are also expected to vary over the period of day. Figure 4.3 (f) shows that in this case also both datasets followed the same trends; the crash frequencies peaked during the afternoon peak hours (2:00 PM to 6:00 PM). It seems that the drivers, most of who would be heading back from workplaces, are more prone to inattention or error during the afternoon rush hours than during the morning rush hours. The time of day was also categorized into two classes – daytime crash and nighttime crash. The time period from 7:00 AM to 6:00 PM was considered daytime, whereas any time beyond this range was considered nighttime. Figure 4.3 (g) shows the crash shares by daytime versus nighttime. About 85% of the crashes from both datasets took place during daytime, which underscores the significant differences between the daytime and the nighttime traffic volumes.

4.5.2 Variables related to traffic and roadway characteristics

The crash trends by traffic and roadway characteristics are presented in Figure 4.4. It is to be noted that the traffic volume data obtained from Mn/DOT include total volume in terms of annual average daily traffic (AADT) for both directions. The crash trends by AADT are presented in Figure 4.4 (a), which reveals that more crashes occurred at lower AADT, the volumes less than 10,000 vehicles per day (vpd). The traffic volume was converted into a categorical variable and was categorized in terms of ‘low’ and ‘high’ – low, if AADT less than 10,000 vpd; and high, otherwise.

The daily traffic of heavy commercial vehicles (HCV) expressed as a percentage of AADT was considered a variable. The crash trends by percent HCV, presented in Figure 4.4 (b), revealed that both datasets followed the same trends. Most crashes occurred at 10% HCV. The percent HCV was also categorized in terms of ‘low’, if less than 10%; and ‘high’, otherwise.

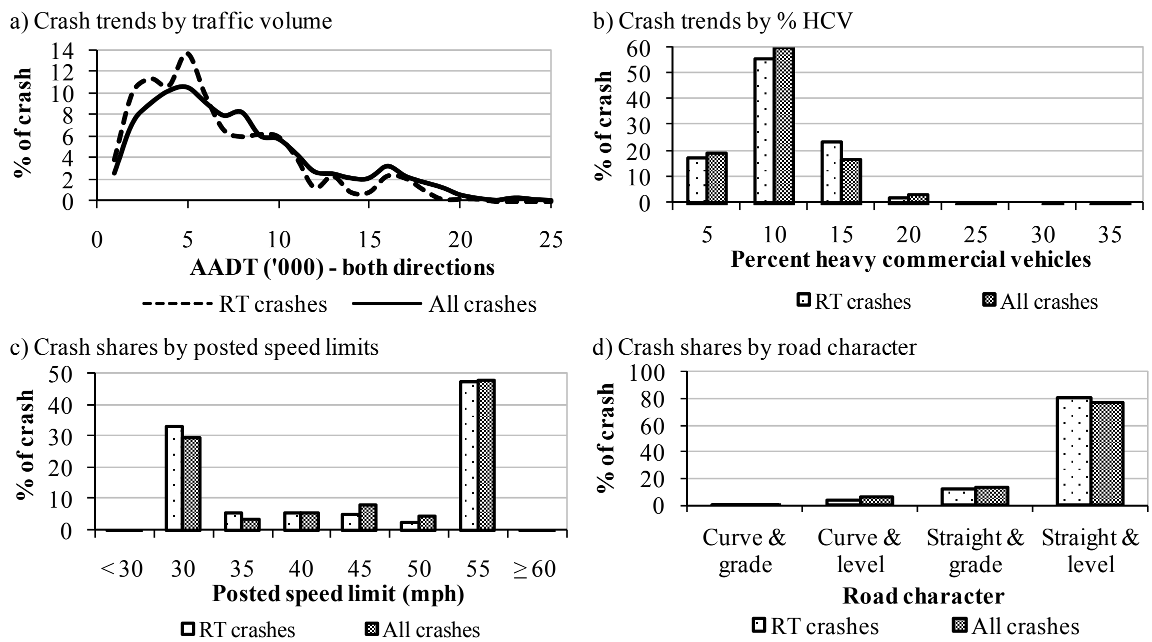


Figure 4.4. Crash trends by traffic and roadway characteristics.

The crash shares by posted speed limit of roadway are shown in Figure 4.4 (c). Most crashes (about 80%) took place at either 30 mph or 55 mph posted speed limit. This is possibly due to the fact that roadways usually have posted speed limits of 30 mph in urban and 55 mph in rural environments. The posted speed limit was classified as 'low', if speed less than or equal to 40 mph; and 'high', otherwise.

The road character at a crash location was also of interest. The variable was analyzed with four levels – straight & level, straight & grade, curve & level, and curve & grade. The 'straight & grade' category included those road characters classified in the data as straight and grade, straight at hillcrest, and straight in sag. Similarly, the 'curve & grade' category included curve and grade, curve at hillcrest, and curve in sag. The crash shares by road characters at crash locations, presented in Figure 4.4 (d), reveal that the crash frequencies at 'straight & level' category were far more (about 80%) compared to any other road character categories.

4.5.3 Variables related to environment and intersection characteristics

The crash shares by the variables related to road environment and intersection characteristics are presented in Figure 4.5. The light condition at the time of crash was categorized into three classes – daylight, some light and no light conditions. The light conditions at sunrise, sunset and dark but street lights on were considered 'some light' condition, whereas dark with no street lights was considered 'no light' condition. Both datasets were found to follow the same trends (Figure 4.5 a) with respect to light condition at the time of crash. Most crashes (80%) occurred in the daylight condition.

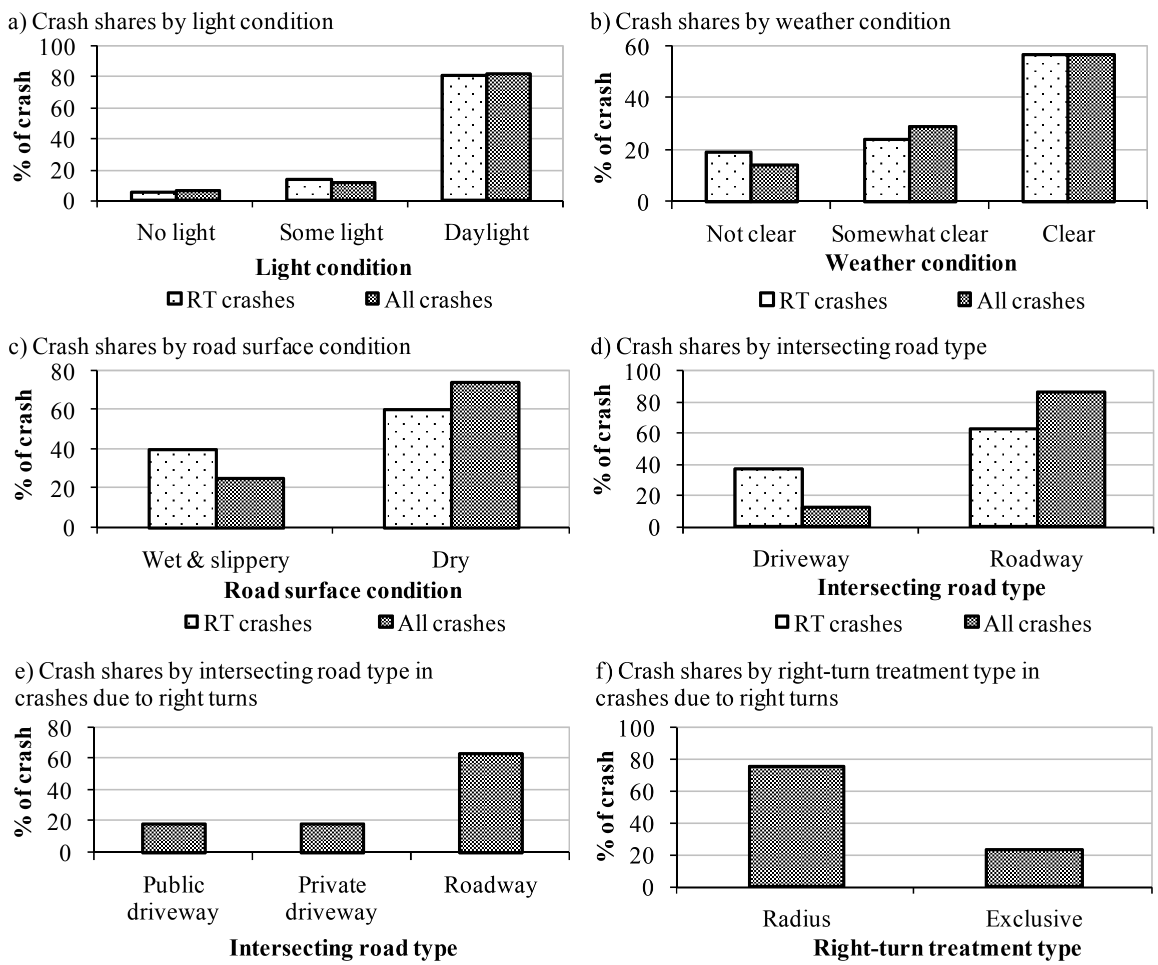


Figure 4.5. Crash trends by environment and intersection characteristics.

Weather condition at the time of crash was analyzed with three levels – clear, somewhat clear, and not clear. Cloudy weather condition was classified as 'somewhat clear' condition; whereas rain, snow, sleet, hail, freezing rain, fog, smog, smoke, blowing sand, dust, or snow, and severe cross winds were considered 'not clear' condition. The crash shares by weather condition, shown in Figure 4.5 (b), shows that most crashes (more than 50%) occurred during clear weather condition.

Road surface condition is considered to be an important factor affecting crash occurrences. The road surface condition at the time of crash was classified into two levels – dry, and wet & slippery. The wet, slushy, watery (standing or moving), muddy, or oily surfaces, including the surfaces covered with debris, snow, ice or packed snow were considered a 'wet & slippery' surface condition. Figure 4.5 (c) shows the crash shares by road surface condition. Most crashes (60% in case of 'RT crashes' and 75% in case of 'All crashes') occurred on dry road surface.

The intersection characteristic in terms of intersecting road type was distinguished as either roadway or driveway. Figure 4.5 (d) presents the crash shares by the type of intersecting road. It was observed that considerably more crashes (about 40%) due to vehicles making right turns from major roadways occurred at driveways compared to the driveway crashes (15%) when all relevant crashes were viewed together. In case of crashes due to vehicles making right turns from major roadways, the type of driveway was further categorized in terms of "private" driveway or "public" driveway. The low-volume driveways serving independent residential houses, including private field approaches, where only a few vehicles are expected to make right turns a day were considered private driveways. The high-volume driveways, with comparatively higher right-turn volumes, such as those serving commercial places or business units, or public places, such as churches, cemeteries, recreational places, etc. were considered public driveways. The shares of private driveways versus public driveways in crashes caused by vehicles making right turns were found to be the same (about 20%) as shown in Figure 4.5 (e).

The right-turn treatment type at a crash location was identified only in case of crashes that occurred due to vehicles making right turns. Not a single crash in the available crash history data was found to occur at a roadway approach with a taper right-turn treatment. Therefore, the right-turn treatment type was considered with two classes – radius right-turn treatment (shared right-turn movement) and full width right-turn lane treatment (exclusive right-turn movement). Figure 4.5 (f) presents the crash shares by right-turn treatment type – about 80% of the crashes due to vehicles making right turns occurred at radius right-turn treatments, while slightly more than 20% of the crashes occurred at exclusive right-turn lane treatments.

4.5.4 Variables related to road users

The crash history records identified up to two contributing factors for each driver-vehicle unit involved in a crash. The contributing factors listed for the first two vehicles were reclassified into four separate independent variables – driver error, driver inattention, vehicular defects, and obscured visibility. Each of these variables was analyzed with two levels – yes and no. For example, if a defective headlight on any of the first two vehicles involved in a crash was identified as contributing to the crash, then the variable 'vehicular defects' would be entered with a value 'yes', otherwise the value 'no' would be entered.

The following instances were considered a case of 'driver error' – failure to yield right of way, illegal or unsafe speed, following too closely, disregard of traffic control device, driving left of roadway center (not passing), improper passing or overtaking, improper or unsafe lane use, improper turn, no signal or improper signal, over-correcting, driver inexperience, and failure to use lights. Figure 4.6 (a) presents the crash shares by driver error. In about 70% of the crashes, the driver error was identified as one of the contributing factors leading to the crash.

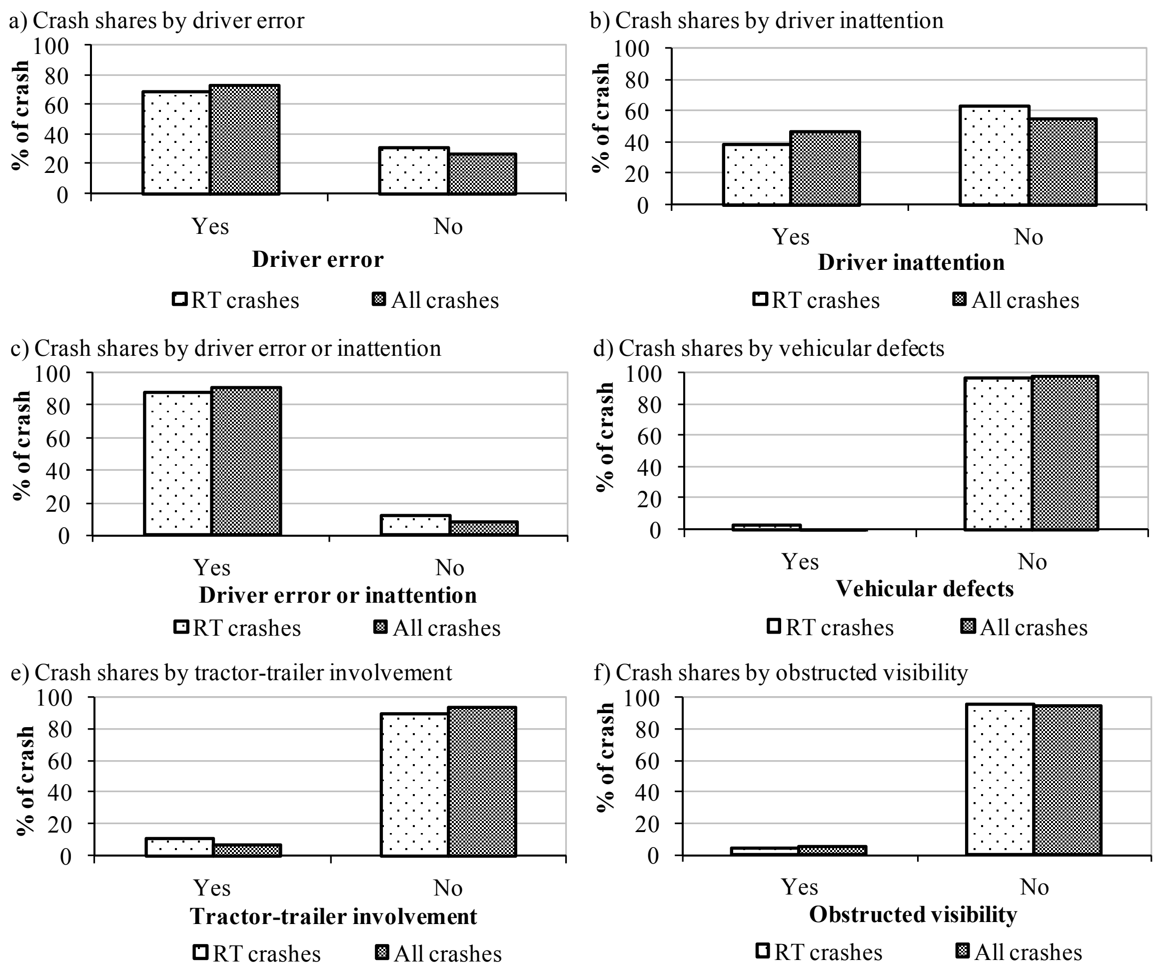


Figure 4.6. Crash shares by variables related to road users.

The variable ‘driver inattention’ identified whether one or more of the following causes were recorded as contributing to a crash – driver inattention or distraction, and driver on car phone, mobile phone, citizens’ band (CB), or two-way radio. The crash shares, shown in Figure 4.6 (b), indicate that driver inattention was identified as a contributing factor in about 40% of the crashes caused by vehicles making right turns. When all relevant crashes were combined together, the instances of driver inattention were identified in about 50% of the crashes.

An additional variable termed as ‘driver error or driver inattention’ was also created by combining ‘driver error’ and ‘driver inattention’ variables. Although driver inattention connotes carelessness rather than an error, and forms a variable by itself, it may also be thought of as an instance of error or, at least, an instance related to driver error. Combining the related variables facilitates analysis and interpretation. The driver error or inattention was found to be identified as one of the contributing factors in about 90% of the crashes (Figure 4.6 c).

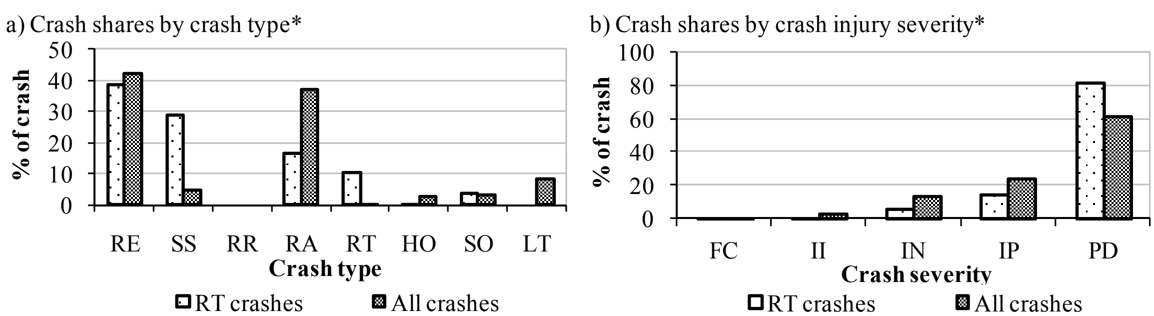
The variable ‘vehicular defects’ identified one or more of the following vehicle deficiencies found contributing to a crash – defective brakes, defective tire or tire failure, defective lights, inadequate windshield glass, and oversize or overweight vehicle. It was found that vehicular defects contributed to less than 5% of crashes (Figure 4.6 d).

The significance of the involvement of tractor-trailer combinations in crashes was analyzed by a variable termed ‘tractor-trailer involvement’ with two levels – yes and no. The value ‘yes’ for a crash meant that one or more tractor-trailer combinations were involved in that crash. The crash shares by tractor-trailer involvement, shown in Figure 4.6 (e), indicate that tractor-trailers were involved in 10% of the crashes caused by right-right turning vehicles; the corresponding number was slightly more than 5% when all relevant crashes were combined together.

The variable ‘obscured visibility’ identified one or more of the following instances of vision obstructions that were mentioned as contributing to a crash – obscured visibility due to windshield glass, sun or headlights, and vision obstructions due to other vehicles, buildings, or roadside features, such as cut slopes, sign posts, trees, overgrown shrubs, snow piles, etc. The obscured visibility was identified as one of the contributing factors in about 5% of the crashes (Figure 4.6 f).

4.5.5 Crash types and crash injury severities

The crash shares by crash types are shown in Figure 4.7 (a). In case of crashes due to vehicles making right turns, the most common crash type was the rear-end type (39%), followed by the same-direction-sideswipe type (29%), the right-angle type (17%), and the right-turn type (11%). In other words, these four crash types, namely, rear-end, same-direction-sideswipe, right-angle and right-turn crashes, together constituted 96% of all crashes caused by vehicles making right turns from major roadways. On the other hand, when all relevant crashes were combined together, the most common crash type was the rear-end type (42%), followed by the right-angle type (37%). The same-direction-sideswipe crashes constituted only about 5% of all relevant crashes.



* Notes:
Crash type: RE – Rear-end crash, SS – Same-direction-sideswipe crash, RR – Ran-off-road (single vehicle) crash, RA – Right-angle crash, RT – Right-turn crash, HO – Head-on crash, SO – Opposite-direction-sideswipe crash, LT – Left-turn crash.

Crash injury severity: FC – Fatal crash, II – Injury (incapacitating) crash, IN – Injury (non-incapacitating) crash, IP – Injury (possible) crash, PD – Property-damage-only crash.

Figure 4.7. Crash shares by crash type and crash injury severity.

The crash shares by crash injury severity are shown in Figure 4.7 (b). The property-damage-only crash severity type was found to be the leading severity type accounting for as much as 80% of the crashes caused by vehicles making right turns, and 60% of the crashes when all the relevant crashes were viewed together. This indicates that the crashes caused by vehicles making right turns tend to be less severe. In fact, only one fatal crash and two incapacitating injury crashes were found to be caused by vehicles making right turns.

4.6 Binary logistic regression models

The objectives of binary logistic regression models were: to estimate the probabilities of a crash caused by a right-turning vehicle from a major roadway given that a crash occurred, and to estimate the probabilities of a crash resulting in a particular crash type given that the crash was caused by a right-turning vehicle from a major roadway. The exploratory analysis provided a starting point to achieve these objectives by identifying potentially significant independent variables as well as appropriate outcome factors to include in such models.

4.6.1 Independent variables

A total of eighteen explanatory factors, presented in Table 4.1, were considered relevant for binary logistic regression model developments. The different levels within each of these factors considered for model developments are also presented. Each of these factors was explained and explored earlier in the exploratory analysis section. The variables ‘date of month’ and ‘month of year’ were not included in the analysis as contributing factors. Similarly, the crash injury severity was considered an outcome factor rather than an explanatory factor.

Table 4.1. Independent variable pool for binary logistic regression models

Sl.	Variable	Description	Levels	# of Levels
1	AADTC	Traffic volume	High (if > 10,000 vpd), Low (if otherwise)	2
2	HCVPR	Percent heavy commercial vehicles	High (if > 10%), Low (if otherwise)	2
3	SPEED	Posted speed limit of roadway	High (if > 40 mph), Low (if otherwise)	2
4	TTCMB	Tractor-trailer involvement	Yes, No	2
5	DTIME	Time of day	Night (6:00 PM – 7:00 AM), Day (if otherwise)	2
6	DTYPE	Day of week	Weekends(Fri. – Sun.), Weekdays (if otherwise)	2
7	LIGHT	Light condition	No light, Some light, Daylight	3
8	WETHR	Weather condition	Not clear, Somewhat clear, Clear	3
9	SURFC	Road surface condition	Wet & slippery, Dry	2
10	JUNCT	Type of intersecting road	Driveway, Roadway	2
11	RDCHR	Road character	Curve & grade, Curve & level, Straight & grade, Straight & level	4
12	DRERR	Driver error	Yes, No	2
13	INATT	Driver inattention	Yes, No	2
14	DRENI	Driver error or driver inattention	Yes, No	2
15	VHDEF	Vehicular defects	Yes, No	2
16	VISON	Obscured visibility	Yes, No	2
17	RTTRT	Right-turn treatment type*	Radius, Exclusive	2
18	DRWAY	Driveway type*	Public driveway, Private driveway, Roadway	3

* Identified only in cases of crashes caused by vehicles making right turns.

4.6.2 Model formulation

A total of five binary logistic regression models were developed. The Model 1 was formulated to estimate the probabilities of a crash being caused by a right-turning vehicle from a major roadway given that a crash occurred. The Model 2 through Model 5 each sought to determine the probabilities of a crash being resulted in a particular crash type given that the crash was caused due to a right-turning vehicle from a major roadway. Four crash types, namely, rear-end, same-direction-sideswipe, right-angle, and right-turn, together constituted about 96% of all crashes caused by vehicles making right turns from major roadways. Therefore, the probabilities of only these four dominant crash types were determined. The Model 2 dealt with the probabilities of a rear-end crash, while the Model 3 dealt with those of a same-direction-sideswipe crash. Similarly, the Model 4 dealt with the probabilities of a right-angle crash, whereas the Model 5 dealt with those of a right-turn crash type.

The goal of model formulation was to associate each of five binary logistic regression models with as many significant explanatory factors as possible with the available data. Therefore, the Model 1 was formulated as a function of sixteen relevant explanatory factors (Variable 1 through Variable 16 presented in Table 4.1), whereas the Model 2 through Model 5 were formulated as functions of eighteen explanatory factors (Variable 1 through Variable 18) as described below:

$$\pi_i = \frac{e^{(\alpha_i + \beta_i^{'}.x_j)}}{1 + e^{(\alpha_i + \beta_i^{'}.x_j)}}; \quad i = 1, \text{ for } j = 1; \quad i = 2,3,4,5, \text{ for } j = 2; \qquad (4.1)$$

where x_1 is the vector of sixteen explanatory factors (AADTC, HCVPR, SPEED, TTCMB, DTIME, DTYPE, LIGHT, WETHR, SURFC, JUNCT, RDCHR, DRERR, INATT, DRENI, VHDEF, VISON) and their two-way interactions considered for Model 1 development; x_2 is the vector of eighteen explanatory factors (AADTC, HCVPR, SPEED, TTCMB, DTIME, DTYPE, LIGHT, WETHR, SURFC, JUNCT, RDCHR, DRERR, INATT, DRENI, VHDEF, VISON, RTTRT, DRWAY) and their two-way interactions considered for the development of Model 2 through Model 5; π_1 is the probability that the crash was caused due to a right-turning vehicle from a major roadway, given that a crash occurred (Model 1); π_2 is the probability that a rear-end crash occurred, given that the crash was caused due to a right-turning vehicle from a major roadway (Model 2); π_3 is the probability that a same-direction-sideswipe crash occurred, given that the crash was caused due to a right-turning vehicle from a major roadway (Model 3); π_4 is the probability that a right-angle crash occurred, given that the crash was caused due to a right-turning vehicle from a major roadway (Model 4); π_5 is the probability that a right-turn crash occurred, given that the crash was caused due to a right-turning vehicle from a major roadway

(Model 5); α_i is intercept parameter for the i^{th} binary logistic regression model; and β_i is the vector of slope parameters for the i^{th} binary logistic regression model.

4.6.3 Variable selection

A potential explanatory factor for each of five binary logistic regression models was identified first by carrying out univariable analyses. The results of univariable analyses are presented in Appendix A. The contingency tables, presented in Appendix B, were then prepared to identify whether complete or quasicomplete separations existed in the data for the variables selected through univariable analyses. The traffic volume, the posted roadway speed limit and the right-turn treatment type were considered important explanatory factors, and, hence, these factors were selected for the development of final models irrespective of the results of univariable analyses.

Two-way interactions between some of the explanatory factors considered relevant were also included in the final model development processes. The finally selected explanatory factors for the development of five individual binary logistic regression models are presented below:

π_1 = f(AADTC, DRENI, DRERR, DTIME, HCVPR, INATT, JUNCT, LIGHT, RDCHR, SPEED, SURFC, TTCMB, VHDEF, WETHR); (4.2a)

π_2 = f(AADTC, DRENI, DRERR, HCVPR, INATT, JUNCT, SPEED, SURFC, VHDEF, RTTRT, DRWAY); (4.2b)

π_3 = f(AADTC, DRENI, DRERR, INATT, SPEED, SURFC, RTTRT); (4.2c)

π_4 = f(AADTC, DRENI, DTIME, INATT, SPEED, SURFC, VISON, RTTRT); (4.2d)

π_5 = f(AADTC, DRENI, DTIME, INATT, SPEED, SURFC, WETHR, RTTRT); (4.2e)

$$f(.) = \frac{e^{(\alpha_i + \beta_i^{'}.x_i)}}{1 + e^{(\alpha_i + \beta_i^{'}.x_i)}}; \quad i = 1,2,3,4,5; \tag{4.2f}$$

where α_i and β_i are the regression parameters as described earlier; and x_i is the vector of finally selected explanatory factors shown above, including their two-way interactions as applicable, for the i^{th} binary logistic regression model.

4.6.4 Results and discussion

The parameter estimates and the odds ratios for significant explanatory factors, as well as the goodness-of-fit test statistics for the fitted binary logistic regression models are presented in Appendix C. The final individual models in the form of equations of significant explanatory factors are provided below:

$$\ln [\pi_1/(1-\pi_1)] = -3.5497 - 0.3704.(AADTC) + 0.3474.(HCVPR) + 1.6747.(JUNCT) - 0.2177.(SPEED) + 1.1554.(SURFC) + 0.4746.(TTCMB) + 0.993.(VHDEF) - 0.3803.(WETHR_1) - 0.4521.(WETHR_2) - 0.5614.(JUNCT).(SURFC); \tag{4.3a}$$

$$\ln [\pi_2/(1- \pi_2)] = -3.0069 + 1.167.(INATT) + 0.8889.(SPEED) + 1.3468.(RTTRT) + 0.8052.(DRWAY_1) + 0.3688.(DRWAY_2); \tag{4.3b}$$

$$\ln [\pi_3/(1- \pi_3)] = -1.8146 + 1.0381.(DRERR) - 0.5421.(SURFC); \tag{4.3c}$$

$$\ln [\pi_4/(1- \pi_4)] = -1.9655 + 1.872.(VISON) + 0.7731.(SURFC); \tag{4.3d}$$

$$\ln [\pi_5/(1- \pi_5)] = -1.6487 - 1.5057.(AADTC) - 1.1424.(SPEED); \tag{4.3e}$$

where AADTC is traffic volume (1 if high, 0 otherwise); HCVPR is percent heavy commercial vehicles (1 if high, 0 otherwise); JUNCT is the type of intersecting road (1 if driveway, 0 otherwise); SPEED is the posted speed limit of roadway (1 if high, 0 otherwise); SURFC is road surface condition (1 if wet & slippery, 0 otherwise); TTCMB is tractor-trailer involvement in a crash (1 if yes, 0 otherwise); VHDEF is vehicular defects (1 if yes, 0 otherwise); $WETHR_1$ is weather condition (1 if not clear, 0 otherwise); $WETHR_2$ is weather condition (1 if somewhat clear, 0 otherwise); INATT is driver inattention (1 if yes, 0 otherwise); RTTRT is right-turn treatment type (1 if radius, 0 otherwise); $DRWAY_1$ is driveway type (1 if public driveway, 0 otherwise); $DRWAY_2$ is driveway type (1 if private driveway, 0 otherwise); DRERR is driver error (1 if yes, 0 otherwise); and VISON is obstructed visibility (1 if yes, 0 otherwise).

The goodness-of-fit test statistics, presented in Appendix C, revealed that each of five binary logistic regression models fitted the data well at 95% confidence level. Assuming no vehicular defects, the probabilities of a crash being caused by a right-turning vehicle from a major roadway approach on to an intersecting roadway or a driveway on a two-lane roadway, given that a crash had occurred, can be estimated using Equation 4.3a. A total of twelve scenarios (Table 4.2), six for intersecting roadway and six for intersecting driveway, were considered for various traffic volume and posted roadway speed limit combinations for the determination of the probabilities of such crash.

Table 4.2. Scenarios to estimate the probability of a crash due to a right-turning vehicle

Scenario	**Explanatory Factors**					
	HCVPR	**JUNCT**	**SURFC**	**TTCMB**	**VHDEF**	**WETHR**
I1	Low	Roadway	Dry	No	No	Clear
I2	High	Roadway	Dry	No	No	Clear
I3	High	Roadway	Wet & slippery	No	No	Clear
I4	High	Roadway	Wet & slippery	Yes	No	Clear
I5	High	Roadway	Wet & slippery	Yes	No	Not clear
I6	High	Roadway	Wet & slippery	Yes	No	Somewhat clear
D1	Low	Driveway	Dry	No	No	Clear
D2	High	Driveway	Dry	No	No	Clear
D3	High	Driveway	Wet & slippery	No	No	Clear
D4	High	Driveway	Wet & slippery	Yes	No	Clear
D5	High	Driveway	Wet & slippery	Yes	No	Not clear
D6	High	Driveway	Wet & slippery	Yes	No	Somewhat clear

Given that a crash had occurred, the probabilities of a crash being caused due to a right-turning vehicle, presented in Table 4.3, at an intersecting driveway were found to be considerably higher (2.3 to 5 times) than those at an intersecting roadway depending on the traffic volume and posted roadway speed categories. The probabilities of such crash at an intersecting roadway were found to vary from 1.6% at 'high' posted roadway speed and 'high' traffic volume under Scenario I1 to 17.2% at 'low' posted roadway speed and 'low' traffic volume under Scenario I4. In case of an intersecting driveway, the probabilities of a crash being caused due to a right-turning vehicle were found to vary from 7.8% at 'high' posted roadway speed and 'high' traffic volume under Scenario D1 to 38.7% at 'low' posted roadway speed and 'low' traffic volume under Scenario D4. These findings were considered important, because they seem to indicate the necessity of developing different set of warrant guidelines for right-turn lanes at intersection approaches and driveway approaches.

Table 4.3. Probabilities of a crash caused by a right-turning vehicle

Speed Cat.	Traffic Vol. Cat.	Scenario											
		I1	**I2**	**I3**	**I4**	**I5**	**I6**	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**
High	High	.016	.022	.067	.103	.073	.068	.078	.108	.179	.260	.194	.183
High	Low	.023	.032	.094	.143	.102	.096	.110	.149	.240	.337	.258	.244
Low	High	.019	.027	.082	.125	.089	.084	.096	.130	.213	.304	.230	.217
Low	Low	.028	.039	.114	.172	.124	.117	.133	.178	.282	.387	.302	.287

The probabilities of a rear-end crash type, given that the crash was caused by a right-turning vehicle from a major roadway, can be estimated using Equation 4.3b. Assuming that driver inattention also contributed to the crash, the estimated probabilities at different combinations of roadway speed and right-turn treatment type at an intersection approach and a driveway approach are presented in Table 4.4. The terms 'driveway approach' used in this dissertation, henceforth, pertain to the 'public' driveway approach, which was found significant in rear-end crashes (p-value = 0.005). The 'private' driveway was found not significant (p-value = 0.220) (Appendix C). Given that the crash was caused by a vehicle making a right turn from a major roadway, the probabilities of crash being a rear-end type were found to vary between 13.7 and 59.8% in case the crash occurred at an intersection approach and between 26.2 and 76.9% in case the crash occurred at a driveway approach, depending on right-turn treatment type and posted roadway speed limit category. The relative risks of a rear-end crash at an intersection approach with a radius right-turn treatment were found to be 2.8 and 2.1 times higher compared to those with an exclusive right-turn lane at 'low' and 'high' posted roadway speed respectively. The corresponding values of rear-end crash risks at a driveway approach with a radius right-turn treatment were 2.2 and 1.7 times higher. The relative risk, in this case, is defined as the ratio of the probability of a rear-end crash at a radius right-turn treatment to that at an exclusive right-turn lane.

Table 4.4. Probabilities and relative risks of a rear-end crash type

Approach Type	Speed Category	Right-turn Treatment Type	Ln(Odds)	Probability of a Rear-end Crash	Relative Risk
Intersection	Low	Radius	-0.493	0.379	2.766
	Low	Exclusive	-1.84	0.137	
	High	Radius	0.396	0.598	2.145
	High	Exclusive	-0.951	0.279	
Driveway	Low	Radius	0.312	0.577	2.202
	Low	Exclusive	-1.035	0.262	
	High	Radius	1.201	0.769	1.658
	High	Exclusive	-0.146	0.464	

The probabilities of a rear-end or a same-direction-sideswipe (RE/SS) crash, given that the crash was caused by a right-turning vehicle, can be estimated using Equations 4.3b and 4.3c. Assuming that driver error or driver inattention also contributed to the crash that was caused by a vehicle making a right turn, the probabilities of the crash being an RE/SS crash were estimated at different combinations of posted roadway speed limit category and right-turn treatment type at both intersection approach and driveway approach under dry pavement condition (Table 4.5). It was found that the probabilities of the crash being RE/SS type varied from 45.2 to 91.3% in case of an intersection approach and from 57.7 to 99.9% in case of a driveway approach, depending on the right-turn treatment type and the posted speed limit. The relative risks of an RE/SS crash at a radius right-turn treatment were found to be 1.5 times higher compared to those at an exclusive right-turn lane in case of an intersection approach, and 1.3 and 1.6 times higher in case of a driveway approach at 'high' and 'low' speed limit respectively.

Table 4.5. Probabilities and relative risks of an RE/SS crash type

Approach Type	Speed Category	Right-turn Treatment Type	Probability of an RE/SS Crash	Relative Risk
Intersection	Low	Radius	0.694	1.535
	Low	Exclusive	0.452	
	High	Radius	0.913	1.537
	High	Exclusive	0.594	
Driveway	Low	Radius	0.892	1.546
	Low	Exclusive	0.577	
	High	Radius	0.999	1.284
	High	Exclusive	0.779	

The relative risks of an RE/SS crash at a driveway approach compared to those at an intersection approach, given that the crash occurred due to a right-turning vehicle from a major roadway, can be estimated using the probabilities presented in Table 4.5. These relative risks (Table 4.6) at a driveway approach were found to be 1.1 to 1.3 times higher compared to those at an intersection approach, depending on the posted roadway speed category and the right-turn treatment type. These risk estimates can be used to determine whether a set of warrant guidelines different from the one for intersection approaches is required for right-turn lanes at driveway approaches.

Table 4.6. Relative risks of an RE/SS crash at driveway v. intersection approach

Speed Category	Right-turn Treatment Type	Relative Risk
Low	Radius	1.286
Low	Exclusive	1.277
High	Radius	1.096
High	Exclusive	1.311

4.7 Multinomial logistic regression model

While the cost of a traffic crash may not truly be estimable because of the direct and the indirect economic and social costs involved with it, several agencies, notwithstanding, routinely estimate the economic costs of a traffic crash by injury severity to quantify the implications of traffic crashes on the national and state economies. Table 4.7 presents the recommended economic costs in Minnesota of a traffic crash by injury severity for the state fiscal year 2009, obtained from Mn/DOT website. However, in the benefit-cost analysis usually performed to justify a targeted roadway/intersection improvement, the expected cost of a traffic crash is usually of interest rather than the cost by injury severity that varies from one crash to another depending on various related factors.

Table 4.7. Economic cost of a traffic crash by injury severity

Severity	Cost ($)
Fatal	6,800,000
Injury (incapacitating)	390,000
Injury (non-incapacitating)	121,000
Injury (possible)	75,000
Property damage only	12,000

Source: OIM (2009).

The goal of the multinomial logistic regression model, referred to as the Model 6, was to estimate the probabilities of various crash injury severities in a crash caused by a right-turning vehicle. Such probability estimates could then be used as weights to the economic cost of a crash injury severity (Table 4.7) to estimate the expected economic cost of a crash caused by a right-turning vehicle. The model was developed based on the crash dataset that included only those crashes that were caused by vehicles making right turns from major roadways (RT crashes).

4.7.1 Independent variables

A total of six explanatory factors from the available data were considered potential contributing factors in influencing the level of crash injury severity in a crash caused by a right-turning vehicle. Five of these explanatory factors, presented earlier in Table 4.1, were: traffic volume (AADTC), posted speed limit (SPEED), road surface condition (SURFC), intersecting road type (DRWAY), and right-turn treatment type (RTTRT). The sixth variable – crash type (CRASH) – was categorized into five classes: rear-end, same-direction-sideswipe, right-angle, right-turn, and 'other' crash. The head-on, opposite-direction-sideswipe and 'unidentified' crash types were combined together into 'other' crash type to prevent separations in the data. The contingency tables of crash injury severities versus these six explanatory factors considered for Model 6 are presented in Appendix B.

4.7.2 Model formulation

The outcome variable in the multinomial logistic regression model was the crash injury severity, which was categorized with three levels: injury, possible-injury and property-damage-only crash severity. Since only one fatal crash and two incapacitating-injury crashes were found to be caused by vehicles making right turns from major roadways in the five year period (i.e., fatalities and incapacitating injuries were not likely crash injury severities in the crashes due to right turns), these two crash severity types were combined together with the non-incapacitating injury type as 'injury' crashes, which were considered the baseline injury severity. The model was formulated in order to assess the appropriateness as an ordinal-response model as follows:

$$\ln\left(\frac{\gamma_i}{1-\gamma_i}\right) = \alpha_i + \beta'.x; \; \text{i = property-damage-only, possible-injury, injury (ordered);} \quad (4.4a)$$

$$p_1 + p_2 + p_3 = 1; \quad (4.4b)$$

where γ_i is $P(Y \leq i\,|x)$, the cumulative probability that the response falls in the i^{th} crash injury severity or below; p_1 is the probability that a property-damage-only crash occurred, given that the crash was caused by a right-turning vehicle from a major roadway; p_2 is the probability that a possible-injury crash occurred, given that the crash was caused by a right-turning vehicle from a major roadway; p_3 is the probability that an injury crash occurred, given that the crash was caused by a right-turning vehicle from a major roadway; α_i is the i^{th} intercept parameter of the ordinal-response multinomial logistic regression model; β is the vector of slope parameters of the ordinal-response multinomial logistic regression model; and x is the vector of six explanatory factors (AADTC, SPEED, SURFC, DRWAY, RTTRT, CRASH) and their two-way interactions.

4.7.3 Results and discussion

It was found that the ordinal-response multinomial logistic regression model fitted the data well. The score test results (p-value = 0.7667, chi-square = 1.1428, degrees of freedom = 3) revealed that the proportional odds assumption was reasonable. The parameter estimates for significant explanatory factors and the goodness-of-fit test statistics are presented in Appendix C. The goodness-of-fit test statistics indicate that the model fitted the data well at 95% confidence level. Three explanatory factors found significant in crash injury severity were: posted speed limit, right-turn treatment type and road surface condition. Based on the fitted model, the probabilities of various injury severities in crashes caused by right-turning vehicles can be estimated using the relationships provided below:

$$\ln\left(\frac{p_1}{1-p_1}\right) = 2.5829 - 1.1972.(SPEED) - 0.7360.(RTTRT) + 0.5345.(SURFC); \quad (4.5a)$$

$$\ln\left(\frac{p_1+p_2}{p_3}\right) = 4.1061 - 1.1972.(SPEED) - 0.7360.(RTTRT) + 0.5345.(SURFC); \quad (4.5b)$$

$$p_1 + p_2 + p_3 = 1; \quad (4.5c)$$

where SPEED is posted roadway speed limit (1 if high, 0 otherwise); RTTRT is right-turn treatment type (1 if radius, 0 otherwise); and SURFC is road surface condition (1 if wet & slippery, 0 otherwise).

Assuming dry road surface condition, the probabilities of various crash injury severities were estimated at different combinations of posted roadway speed limits and right-turn treatment types, as presented in Table 4.8. The probability of a crash resulting in property damage only was found to be higher at exclusive right-turn lanes compared to that at radius right-turn treatments, and at 'low' speed approaches compared to that at 'high' speed approaches. The probability of a crash resulting in injury or possible injury was found to be higher at radius right-turn treatments compared to that at exclusive right-turn lanes, and at 'high' speed approaches compared to that at 'low' speed approaches.

Table 4.8. Estimated probability of crash severity

Crash Injury Severity Type	**Probability**			
	Speed Category - Right-turn Treatment Type			
	High-Radius	**High-Exclusive**	**Low-Radius**	**Low-Exclusive**
Property damage only	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**

* Injury (non-incapacitating).

The expected economic cost of a crash due to a right-turning vehicle from a major roadway was estimated as a weighted average cost based on the estimated probabilities of various crash injury severities. For a given combination of posted roadway speed category and right-turn treatment type, the expected cost per crash can be estimated using the following relationship:

$$c_{lk} = \sum_{s} p_{lks} . u_{s}; \qquad \sum_{s} p_{lks} = 1.00; \tag{4.6}$$

l = high, low; k = radius, exclusive; s = property-damage-only, possible-injury, injury;

where c_{lk} is the expected economic cost of a crash caused by a right-turning vehicle at an approach with the k^{th} right-turn treatment type operating under the l^{th} speed category; p_{lks} is the estimated probability of the s^{th} crash injury severity, given that the crash was caused by a right-turning vehicle, at an approach with the k^{th} right-turn treatment type operating under the l^{th} speed category; and u_s is the unit economic cost of the s^{th} crash injury severity (Table 4.7).

The estimated costs, presented in Table 4.9, reflect the varying nature of crash injury severity. The estimated cost per crash was found to be higher at a radius right-turn treatment compared to that at an exclusive right-turn lane and at a 'high' speed approach compared to that at a 'low' speed approach. In other words, more severe crashes are expected at radius right-turn treatments than at exclusive right-turn lanes and at 'high' speed approaches than at 'low' speed approaches.

Table 4.9. Economic cost of a crash caused by a right-turning vehicle

Speed Category	Right-turn Treatment Type	Cost/crash ($)
High	Radius	38,314
High	Exclusive	26,985
Low	Radius	22,112
Low	Exclusive	17,171

4.8 Summary

This chapter presented various crash analyses that were carried out based on the five-year historical data of statewide traffic crashes reported on Minnesota's two-lane trunk highways, as well as other relevant data, most of which were obtained from Mn/DOT. The chapter also highlighted the efforts that were required for data collection and for data preparation for subsequent analyses.

Exploratory analyses were performed first to understand the nature and the extents of crashes caused by vehicles making right turns from major roadways (RT crashes) vis-à-vis the nature and the extents of crashes when all the relevant crashes were viewed together (All crashes). Some findings were intuitive, whereas others were not. It was found that in both datasets the majorities of crashes were rear-end type (40%), took place during weekdays (60%) and during daytime (85%), and were predominantly caused by driver error or inattention (90%). The most notable differences found between two datasets were in terms of crashes taking place at driveways (40% in case of 'RT crashes' versus 15% in case of 'All crashes'), in terms of same-direction-sideswipe crashes (29% in case of 'RT crashes' versus 5% in case of 'All crashes'), and in terms of crash injury severities. The crashes caused by vehicles making right turns were found to be less severe, mostly leading to property damage only with no apparent injury. It was also found that four dominant crash types, namely, rear-end, same-direction-sideswipe, right-angle and right-turn crashes, together constituted about 96% of all crashes caused by vehicles making right turns from major roadways.

Based on the exploratory analysis results, a total of five individual binary logistic regression models were developed to estimate the probabilities of a crash due to a right-turning vehicle from a major roadway given that a crash had occurred, and the probabilities of each of four dominant crash types given that the crash was caused by a right-turning vehicle from a major roadway. The probabilities of a crash occurring at an intersection approach due to a right-turning vehicle given that a crash had already occurred were found to vary from 1.6 to 17.2%, whereas in case of a driveway approach these probabilities varied from 7.8 to 38.7%, depending on the factors related to road and environment conditions and driver-vehicle units. The rear-end crashes were found to be significantly associated with the right-turn treatment type; the relative risks of a rear-end crash at a radius right-turn treatment were 1.7 to 2.8 times higher compared to those at an exclusive right-turn lane depending on the posted roadway speed category and the approach type. These findings were statistically significant and challenge the assumptions in the past studies that right-turn lane eliminates rear-end crashes. Similarly, the risks of a rear-end or a same-direction-sideswipe (RE/SS) crash at a radius right-turn treatment were 1.3 to 1.5 times higher compared to those at an exclusive right-turn lane. As far as approach types were concerned, the risks of a rear-end or a same-direction-sideswipe crash at a driveway approach were found to be 1.1 to 1.3 times higher compared to those at an intersection approach, depending on the posted roadway speed category and the right-turn treatment type. This highlighted the need and the relevance of exploring further to determine whether a set of warrant guidelines different from those for intersection approaches is required for driveway approaches for right-turn lanes.

In addition to five individual binary logistic regression models, an ordinal-response multivariable multinomial logistic regression model was fitted to estimate the probabilities of various crash injury severity levels in a crash caused by a right-turning vehicle from a major roadway. The probabilities of an injury or a possible-injury crash were found to be higher at a radius right-turn treatment compared to those at an exclusive right-turn lane, and at a ‘high’ speed approach compared to those at a ‘low’ speed approach. The property-damage-only crash, on the other hand, was found to be most likely to occur at an exclusive right-turn lane than a radius right-turn treatment, and at a ‘low’ speed approach than a ‘high’ speed approach. The expected economic cost of a crash due to a right-turning vehicle from a major roadway was estimated as a weighted average cost based on the probabilities of likely crash injury severities. The estimated costs reflect the nature of crash injury severities expected to vary from one crash to another. The expected cost per crash was found to be higher at a ‘high’ speed approach compared to that at a ‘low’ speed approach, and at a radius right-turn treatment compared to that at an exclusive right-turn lane.

Finally, it is important to mention here that a key piece of data which could help tremendously in determining the safety impacts of right-turn lanes was the information regarding the right-turn treatment type in the intersection inventory data file. The Mn/DOT still has to develop an intersection inventory database with such attribute. Another key piece of data that could really make the analysis more meaningful was the information related to the right-turning traffic volumes, which was not obtainable from any of the data sources discussed in this chapter. Therefore, in order to incorporate the effects of right-turning traffic volumes on the safety effectiveness of right-turn lanes, it was necessary to carry out the conflict analyses through the use of traffic conflicts technique as discussed in the next chapter.

CHAPTER 5. CONFLICT ANALYSIS

This chapter presents the conflict analyses that were carried out through the use of traffic conflicts technique (TCT). The goal of the analyses, which were based on the data obtained from both field surveys as well as conflict simulations, was to develop least squares conflict prediction models to determine the effects of right-turn volumes in the safety effectiveness of right-turn lanes. A wide range of posted roadway speed limits, traffic volumes and percent right turns was considered in the analysis, because these were the most important variables in the formulation of right-turn lane warrant guidelines.

5.1 Conflict analysis through field surveys

The field surveys of the conflicts due to vehicles making right turns were conducted at various locations in Minnesota. The conflict analyses based on the data obtained from these field surveys are presented in the sections that follow.

5.1.1 Design of experiment for field data collection

The goal of the design of experiment was to develop a least squares conflict prediction model using a balanced dataset. The dependent variable in the model was the conflicts due to right turns, measured in terms of the number of conflicts per thousand entering vehicles (TEV).

The crash analyses presented in Chapter 4 revealed that the rear-end crashes caused by vehicles making right turns from uncontrolled approaches of major roadways were significantly associated with the right-turn treatment type, the posted roadway speed limit, driver inattention and the type of intersecting road (driveway or roadway). The same-direction-sideswipe crashes, on the other hand, were significantly associated with driver error and the road surface condition. The right-turn volumes were an important factor that was not available in the crash analysis. Since the conflicts due to right turns were considered the surrogate measures for rear-end or same-direction-sideswipe (RE/SS) crashes caused by vehicles making right turns, it was important to take into account the variations in the conflict data caused by right-turn treatment types, posted roadway speed limits and right-turn volumes. The other variables found significant in RE/SS crashes, such as driver error, driver inattention, road surface condition and intersecting road type were considered not relevant in the design of experiment.

Consequently, the experiment for conflict data collection was designed as 2^k factorial design, where k = 3 (right-turn treatment type, posted roadway speed limit and percent right turns), resulting into eight treatment combinations. The levels of treatment factors considered were as follows: right-turn treatment type – exclusive and radius, posted roadway speed limit – high (if speed more than 40 mph) and low (otherwise), and percent right turns – high (if right-turn volume more than 5% of the approach volume) and low (otherwise). Each treatment combination (cell), shown in Table 5.1, was replicated three times, resulting in a total of twenty-four independent observations.

Table 5.1. Design of experiment

Posted Speed Limit*	**Right-turn Treatment Type**	**Percent Right Turns**	
		Low (≤ 5%)	**High (> 5%)**
Low	Radius	Cell 1	Cell 5
Low	Exclusive	Cell 2	Cell 6
High	Radius	Cell 3	Cell 7
High	Exclusive	Cell 4	Cell 8

* Low, if posted speed ≤ 40 mph; high, otherwise.

5.1.2 Field sites identification

The experiment designed above for field data collection posed one major problem – it could not be estimated with a certainty beforehand that whether the percent right turns at a survey location would fall into a 'low' or a 'high' category. The fact that the percent right turns would be known only after the data have been collected made it difficult to obtain an appropriate sample of intersection approaches to be surveyed under each cell. Nonetheless, it was considered relevant to conduct conflict surveys at those intersection approaches also, where crashes due to vehicles making right turns actually occurred.

Location selection for the purpose of field data collection was, therefore, done as follows. First, the two-lane unsignalized intersection inventory dataset obtained from Mn/DOT was divided into two subsets: the subset consisting of intersections where at least one crash due to a right-turning vehicle from a major roadway approach occurred (referred to as 'crash locations'), and the subset consisting of intersections where a crash due to a right-turning vehicle from a major roadway approach did not occur (referred to as 'non-crash locations'). Secondly, an equal number of data collection sites from both 'crash locations' and 'non-crash locations' were selected at random. Finally, each of these randomly selected sites was physically visited to make sure that conditions had not changed over years, and also to assess the appropriateness of sites for field surveys. The field data were collected in 2007 at the locations thus selected. However, the desired replicates for all of the treatment combinations could not be obtained during the allocated time at the survey locations selected based on the above site selection approach. It was, therefore, decided during the second phase of field data collection, carried out in 2008, to locate the intersection location through observation first to find the desired treatment combination and replicate the observation at the same location over several days. The survey locations where the field data were finally collected are shown in Figure 5.1. The particular intersection approaches where the field surveys were conducted are identified in Table 5.2. The selected photographs of study sites are presented in Appendix D.

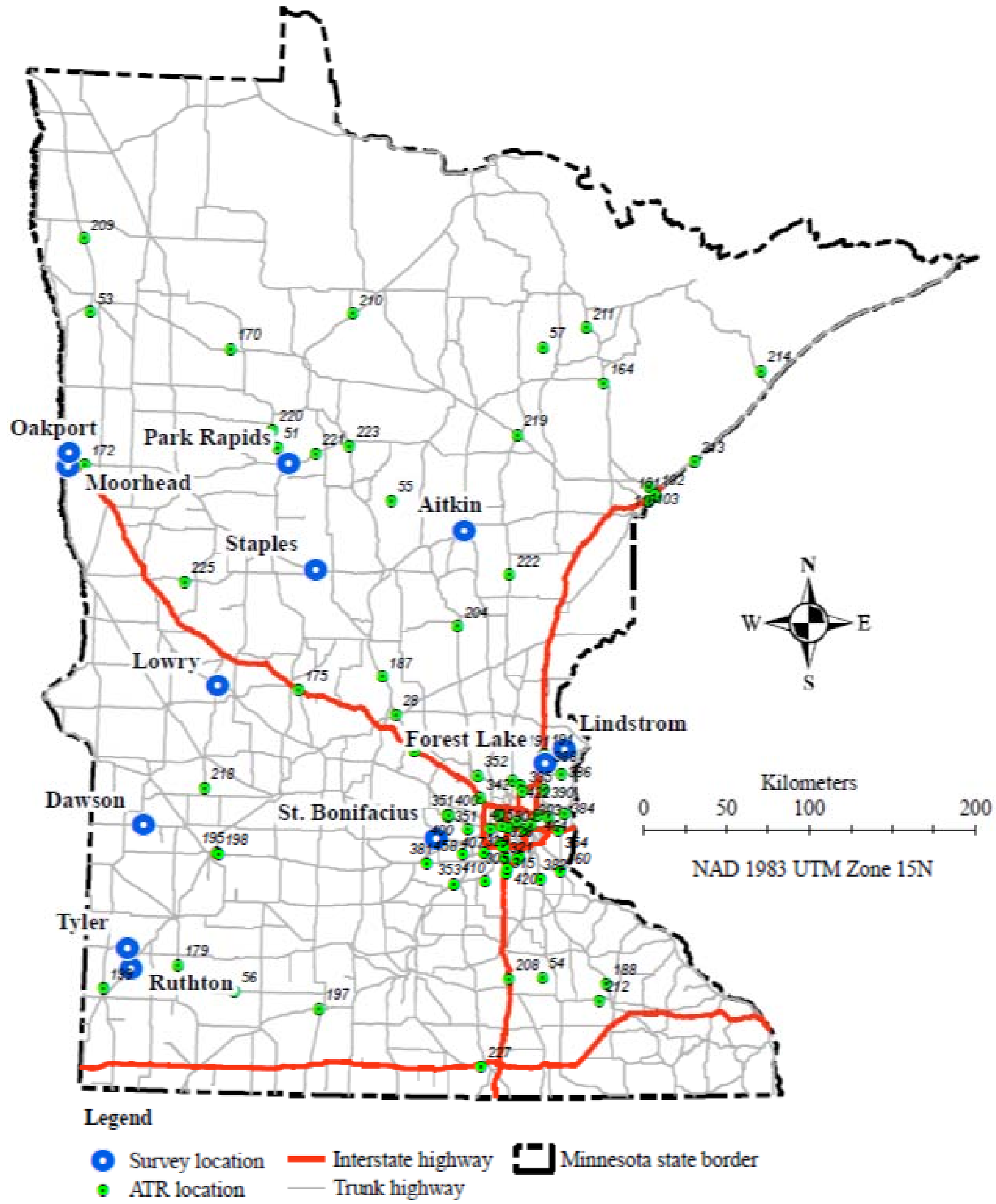


Figure 5.1. Field survey locations.

5.1.3 Field data collection

The field data were collected in the summers of 2007 and 2008. The various field data collected include the following: intersection geometry (type, number of intersecting legs, skew angles, pavement widths, turn lanes), right-turn treatment type (including right-turn pocket length and right-turn taper length in case of exclusive right-turn lane treatment), posted speed limit on the study approach, approach traffic volume, right-turn traffic volume, and the number of conflicts due to right turns during a continuous four-hour observation period. The four-hour observed conflicts, including traffic volumes, at study sites are summarized in Table 5.3.

Table 5.2. Field site identifications

Site Code	City / Nearest City	Intersection Description	Study Approach	Int. Type	Right-turn Treatment	Speed (mph)
C1R1	Staples	US-10/12th St. NE	US-10 West	+	Radius	30
C1R2	Dawson	US-212/4th St.	US-212 East	+	Radius	30
C1R3	Moorhead	12th Ave. S/15th St. S	12th Ave. S. West	T	Radius	30
C2L1	Moorhead	20th St. S/MSCTC Drive	20th St. S North	T	Exclusive	30
C2L2	Moorhead	20th St. S/MSCTC Drive*	20th St. S North	T	Exclusive	30
C2L3	Moorhead	20th St. S/MSCTC Drive*	20th St. S North	T	Exclusive	30
C3R1	Oakport	Oakport St. N/43rd Ave. N	Oakport St. N South	T	Radius	45
C3R2	Oakport	Oakport St. N/Old Trail	Oakport St. N North	T	Radius	45
C3R3	Aitkin	MNTH-210/CR-54 & CR-56	MNTH-210 West	+	Radius	55
C4L1	Park Rapids	MNTH-34/CR-4	MNTH-34 East	T	Exclusive	55
C4L2	Forest Lake	US-61/250th St.	US-61 North	+	Exclusive	55
C4L3	Forest Lake	US-61/250th St.*	US-61 North	+	Exclusive	55
C5R1	Moorhead	12th Ave. S/32nd St. Circle S	12th Ave. S West	T	Radius	30
C5R2	Moorhead	12th Ave. S/32nd St. Circle S*	12th Ave. S West	T	Radius	30
C5R3	Staples	US-10/12th St. NE	US-10 East	+	Radius	30
C6L1	Tyler	US-14/CR-8	US-14 East	T	Exclusive	35
C6L2	Moorhead	20th St. S/20th Ave. S	20th St. S North	T	Exclusive	30
C6L3	Lindstrom	MNTH-8/Akerson St.	MNTH-8 West	+	Exclusive	30
C7R1	Moorhead	28th Ave. N. (CR-18)/34th St. N	28th Ave. N West	T	Radius	55
C7R2	Moorhead	28th Ave. N. (CR-18)/34th St. N*	28th Ave. N West	T	Radius	55
C7R3	Moorhead	28th Ave. N. (CR-18)/40th St. N	28th Ave. N West	+	Radius	55
C8L1	Forest Lake	US-61/250th St.	US-61 South	+	Exclusive	55
C8L2	St. Bonifacius	MNTH-7/CR-10	MNTH-7 West	+	Exclusive	55
C8L3	Moorhead	US-75/46th Ave. S.	US-75 North	T	Exclusive	55

* Replicated.

5.1.4 Conflict prediction model development using field data

The least squares conflict prediction model using the field data was developed based on twenty-four independent observations that include three replicates for each of eight cells discussed earlier. The dependent variable was the number of conflicts due to right turns per TEV observed during a four-hour continuous observation period. The independent variables were: right-turn treatment type, posted speed limit, approach volume (peak hour), through volume (peak hour) and percent right turns (four-hour total). Stepwise regressions were carried out first to identify the significant independent variables, including interaction and higher order terms. After removing the insignificant variables from the model-building process, the conflict prediction model finally fitted was as follows:

$RTC_f = 4.37 - 2.97.(RTT) + 1.65.(RTP) + 5.61.(SPD) - 0.931.(RTT).(RTP)$,

$[S = 6.2625, R^2 = 87.60\%, \text{Adj. } R^2 = 85.00\%, \text{Pred. } R^2 = 80.88\%]$ (5.1)

where RTC_f is the number of conflicts due to right turns including associated secondary conflicts per TEV; RTP is percent right turns; RTT is right-turn treatment type (1 if exclusive, 0 if radius); and SPD is posted speed limit (1 if 'high', 0 if 'low').

Table 5.3. Four-hour observed conflicts at study sites

Site Code	Right-turn Treatment	Right-turn Volume	Through Volume	Total Approach Volume	Percent Right Turns	Observed Conflicts Number	Observed Conflicts Per TEV
C1R1	Radius	10	1180	1190	0.84	5	4.20
C1R2	Radius	11	502	513	2.14	2	3.90
C1R3	Radius	8	364	372	2.15	0	0.00
C2L1	Exclusive	48	1639	1687	2.85	11	6.52
C2L2	Exclusive	43	1526	1569	2.74	5	3.19
C2L3	Exclusive	32	1664	1696	1.89	0	0.00
C3R1	Radius	8	197	205	3.90	4	19.51
C3R2	Radius	7	268	275	2.55	4	14.55
C3R3	Radius	7	551	558	1.25	5	8.96
C4L1	Exclusive	44	903	947	4.65	10	10.56
C4L2	Exclusive	41	1681	1722	2.38	14	8.13
C4L3	Exclusive	26	1480	1506	1.73	2	1.33
C5R1	Radius	80	823	903	8.86	30	33.22
C5R2	Radius	80	934	1014	7.89	28	27.61
C5R3	Radius	73	917	990	7.37	12	12.12
C6L1	Exclusive	36	212	248	14.52	2	8.06
C6L2	Exclusive	155	2158	2313	6.70	17	7.35
C6L3	Exclusive	193	2359	2552	7.56	17	6.66
C7R1	Radius	115	251	366	31.42	23	62.84
C7R2	Radius	111	260	371	29.92	20	53.91
C7R3	Radius	46	340	386	11.92	12	31.09
C8L1	Exclusive	97	927	1024	9.47	24	23.44
C8L2	Exclusive	126	898	1024	12.30	21	20.51
C8L3	Exclusive	129	472	601	21.46	11	18.30

The parameter estimates and the residual plots of fitted conflict prediction model are presented in Appendix E. The predicted conflicts due to right turns per TEV at radius and exclusive right-turn lane treatments at different posted roadway speed limit categories and percent right turns are shown in Figure 5.2 (a). The predicted number of conflicts due to right turns per TEV that can be saved (or eliminated) at intersection approaches with radius treatments by providing exclusive right-turn lane treatments are presented in Figure 5.2 (b). These conflict savings were determined by subtracting the number of predicted conflicts at intersection approaches with right-turn lanes from that with radius right-turn treatments at the same combinations of percent right turns and posted speed limit.

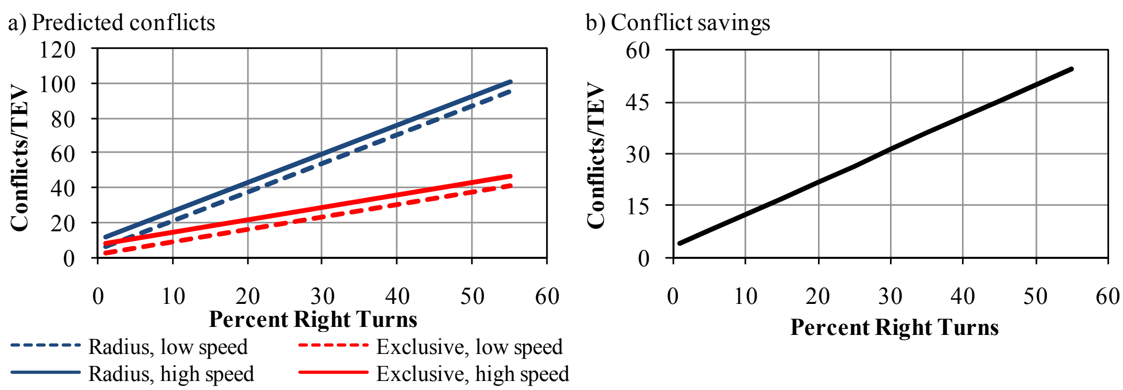


Figure 5.2. Estimates and savings of conflicts due to right turns based on the field data.

The sensitivity of the fitted conflict prediction model based on the field data is presented in Figure 5.3. The fitted model was insensitive to approach traffic volume (Figures 5.3c and 5.3d). It also lacked the variability in the predicted number of conflicts with respect to posted roadway speed limits (Figures 5.3a, 5.3b, 5.3e and 5.3f).

5.2 Conflict analysis through simulation

The simulations of conflicts due to right turns were carried out using VISSIM traffic simulators. The purpose of conflict simulations was to obtain greater variation in the conflict data that was found to be not easily obtainable through field surveys. As with the field data, the ultimate goal was to develop better least squares conflict prediction models.

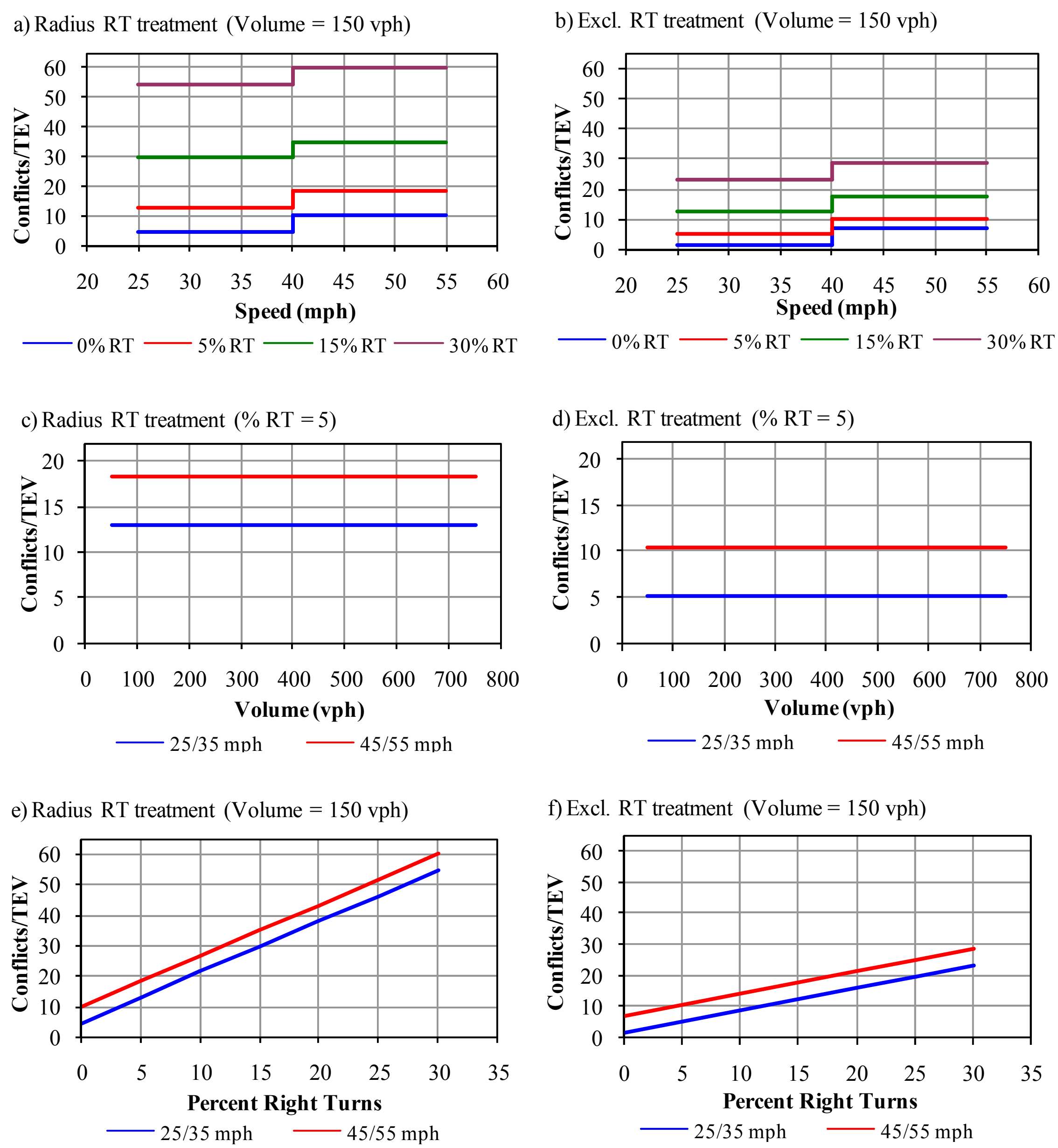


Figure 5.3. Sensitivity of the conflict prediction model fitted using the field data.

5.2.1 Car-following logic in VISSIM traffic simulation model

It is well known that the car-following behavior is directly associated with the risk of rear-end collisions. It greatly influences the distribution of available time or space gaps between vehicles at any point of interest in a traffic stream, and, therefore, is of particular interest in traffic safety studies. Car-following behaviors are simulated in traffic simulators by using car-following models that determine the mobility of following vehicles according to a set of rules in order to avoid contacts with the lead vehicles. In VISSIM, these behaviors are simulated based on the psycho-physical driver behavior model developed in Wiedemann and Reiter (1992). Two separate car-following models exist: Wiedemann 99 and Wiedemann 74. The Wiedemann 99 car-following model is suitable for interurban traffic, while the Wiedemann 74 model is suitable for urban traffic. In this study, the Wiedemann 74 car-following model was used for the simulation of conflicts due to right turns.

The performance of Wiedemann 74 car-following model has been compared with the models used in other traffic simulators as well as independently validated (Fellendorf and Vortisch 2001; Olstam and Tapani 2004; Panwai and Dia 2005). This model is an improved version of Wiedemann's 1974 car-following model, which, in general, is simple and effective, and was thoroughly validated using extensive field data (Wiedemann and Reiter 1992). The basic concept of Wiedemann's 1974 car-following model is that the driver of a faster moving vehicle adjusts his/her speed relative to a slower moving lead vehicle in an iterative process of acceleration and deceleration. First, he/she starts to decelerate as he/she reaches his/her individual perception threshold to a slower moving lead vehicle. However, he/she cannot exactly determine the speed of the lead vehicle; so, his/her speed falls below that of the lead vehicle until he/she starts to slightly accelerate again after reaching another perception threshold. The various thresholds, the distances and the associated driving behavior for one vehicle-driver unit and one actual speed level are presented in Figure 5.4. The horizontal axis represents the speed difference with the positive values characterizing a closing process, i.e. the speed of current vehicle is higher than the speed of lead vehicle. The vertical axis represents the distance to lead vehicle.

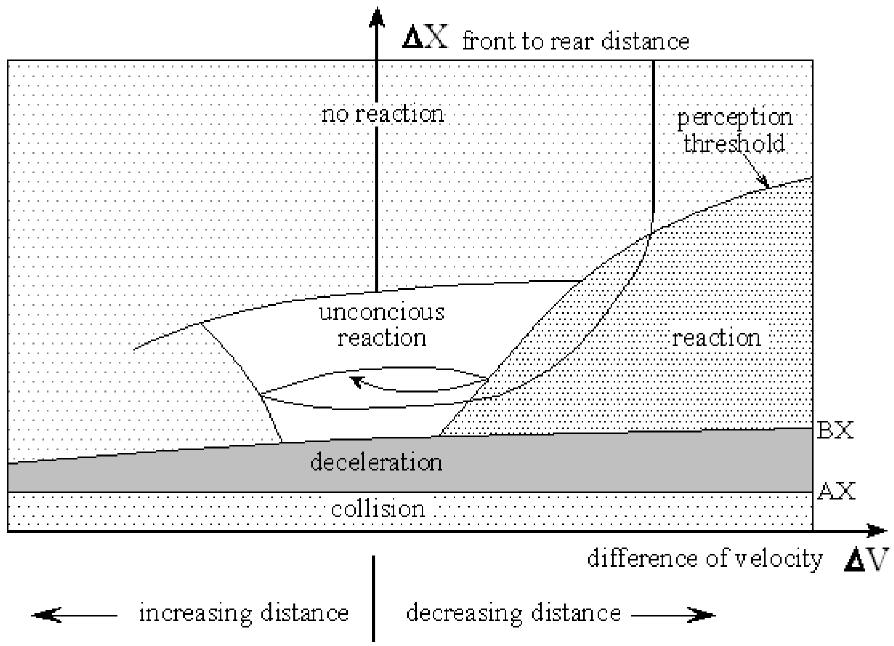


Figure 5.4. Wiedemann 1974 car-following logic.
Source: PTV (2007).

It is important that the car-following models are calibrated accurately in the simulations of traffic movements for safety assessments. Close replications of time headway distributions measured at various points in relation to the traffic stream of interest are especially important for a given condition of traffic volume and traffic composition (Archer 2005). Equally important are the close replications of observed speed distributions at various points on the traffic stream of interest, since they directly influence the time headway distributions. However, it has been recommended to keep the number of calibration parameters as low as possible if the parameterization used allows for the models to be well calibrated with respect to all proposed applications (Olstam and Tapani 2004).

One added advantage of using Wiedemann 74 car-following model is that it allows the model calibration by using a few calibration parameters. The model provides for the computation of desired minimum following distance between two vehicles travelling in a pair by using the relationships shown below (PTV 2007), in which BX_{add} and BX_{mult} are the car-following model parameters that are available for calibrations:

$$d = AX + BX; \tag{5.2a}$$

$$BX = (BX_{add} + BX_{mult}.z).\sqrt{v}; \tag{5.2b}$$

where d is desired minimum following distance between two vehicles; AX is average standstill distance (the average desired distance between stopped vehicles) with a fixed variation of ± 1m; BX is desired safety distance; BX_{add} is the additive part of desired safety distance; BX_{mult} is the multiplicative part of desired safety distance; z is a value of range [0, 1], which is normally distributed around 0.5 with a standard deviation of 0.15, depending on the safety need of a driver; and v is vehicle speed (m/s).

5.2.2 Design of experiment for VISSIM model calibrations

The purpose of the design of experiment in conflict simulations was to calibrate several VISSIM models to represent different traffic conditions. Unlike the experiment that was designed to obtain a balanced set of field data of conflicts due to right turns as discussed earlier, the emphasis in this case was on the collection of calibration data, especially the time headway distributions in the traffic stream of interest. The reason was that the same-direction conflicts are influenced by time headway distributions, which, in turn, are highly influenced by traffic volumes and speeds. Hence, the experiment for collecting field data for VISSIM model calibrations was designed with three factors – approach traffic volume, posted roadway speed limit and right-turn treatment type. The factor levels were as follows: approach traffic volume – low (volume ≤ 250 vph), medium (volume between 251 and 500 vph) and high (otherwise); posted roadway speed limits – low (speed ≤ 40 mph), and high (otherwise); and right-turn treatment type – radius and exclusive lane. The experiment designed resulted in twelve individual cells as shown in Table 5.4.

Table 5.4. Design of experiment for VISSIM model calibrations

Posted Speed Limit	**Traffic Volume**	**Right-turn Treatment Type**	
		Radius	**Exclusive**
Low	Low	Cell 1S	Cell 1E
Low	Medium	Cell 2S	Cell 2E
Low	High	Cell 3S	Cell 3E
High	Low	Cell 4S	Cell 4E
High	Medium	Cell 5S	Cell 5E
High	High	Cell 6S	Cell 6E

5.2.3 Data collection for VISSIM model developments and calibrations

The field data collected as inputs for VISSIM model layouts and initial model developments were: right-turn treatment type (including right-turn pocket and taper lengths if exclusive right-turn lane), posted roadway speed limit, approach traffic volume and composition, right-turn volume, and desired speed distribution, including the right-turn speed distribution. The traffic volume and composition were collected using traffic data collectors (TDC-12's), while the speed data were collected using Laser/Radar guns.

The input data collected for VISSIM model developments corresponding to each cell are presented in Table 5.5. The speed range shown is the range of desired speeds obtained as free-flow spot speeds. The individual desired speed distributions corresponding to each of these speed ranges are presented in Figure 5.5. The observed right-turn speed distribution (speed range 7-23 mph), based on a total of 180 right-turn spot speed observations collected at several intersection locations, is presented in Figure 5.5 (j).

Table 5.5. VISSIM model inputs

Cell	Location (Intersection)	Approach	Posted Speed (mph)	Speed Range (mph)	App. Vol. (vph)	Percent Trucks	Percent Right Turns
1S	Dawson (US-212/4th St.)	US-212 West	30	23-37	125	14.9	1.5
2S	Staples (US-10/12th St. NE)	US-10 West	30	22-38	303	19.5	3.1
3S(A)	Moorhead (20th St. S/16th Ave. S)	20th St. S North	30	22-38	413	19.5	1.5
4S	Moorhead (28th Ave. N /34th St. N)	28th Ave. N West	55	40-65	128	12.6	30.3
5S(B)	Forest Lake (US-61/240th St.)	US-61 North	55	44-63	504	4.9	0.3
6S	Forest Lake (US-61/240th St.)	US-61 North	55	44-63	504	4.9	0.3
1E	Tyler (US-14/CR-8)	US-14 East	35	25-43	80	22.7	11.8
2E(C)	Moorhead (20th St. S/MSCTC Dr.)	20th St. S North	30	28-43	393	4.4	2.7
3E	Lindstrom (MNTH-8/Akerson St.)	MNTH-8 West	30	28-43	784	4.4	5.7
4E	Park Rapids (MNTH-34/CR-4)	MNTH-34 East	55	48-64	247	13.9	5.0
5E	Forest Lake (US-61/250th St.)	US-61 North	55	46-62	358	7.1	2.0
6E	Forest Lake (US-61/250th St.)	US-61 South	55	49-60	681	3.3	19.0

(A) Speed distribution/percent trucks taken from Cell 2S. (B) Inputs same as Cell 6S.
(C) Speed distribution/percent trucks taken from Cell 3E.

In addition to the model input data, the field data collected for VISSIM model calibrations include time headway distributions and spot-speed distributions at various points in the traffic stream of interest. The locations of these points are shown in Figure 5.6. The locations as well as the type of data collected at these points are also specified in Table 5.6. The point X in Figure 5.6 was chosen at a distance sufficiently away from the location of the intersection under survey, so as to obtain an intersection-influence-free spot speed, or a desired speed. The point Y represents the location of conflict observer.

The time headway and the spot-speed data were collected within the four-hour period of conflict observations. The time headway data were collected by using TDC-12's at points A, B or C simultaneously in a time-synchronized manner by two or three observers, as applicable, for a minimum time period of two hours.

On the other hand, the collection of spot-speed data, collected by using Laser/Radar guns, required two observers; one to direct the Laser/Radar gun towards the traffic and the other to record the observed spot speed. A minimum of eighty spot-speed observations were collected at each of these points (A, B, X or C). Whenever possible, every care was taken by the spot-speed and the conflict observers to remain hidden from the sights of the drivers on the study approach or be inconspicuous as much as possible in order to avoid undue influence on the driving behavior.

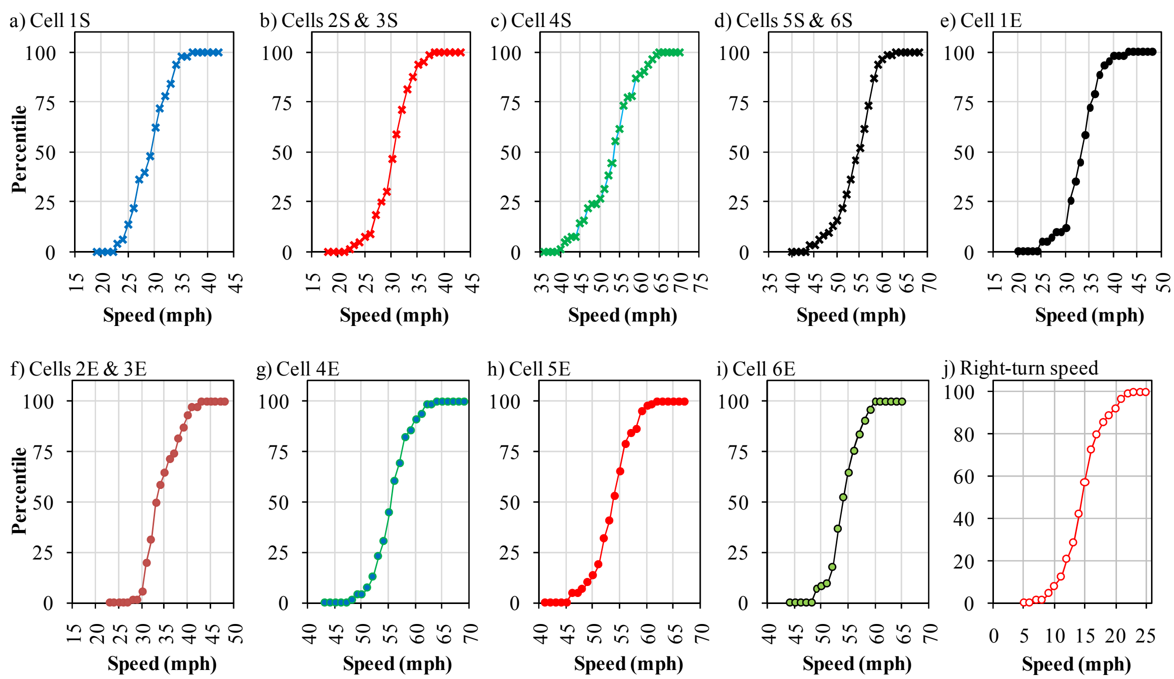


Figure 5.5. Observed desired speed distributions.

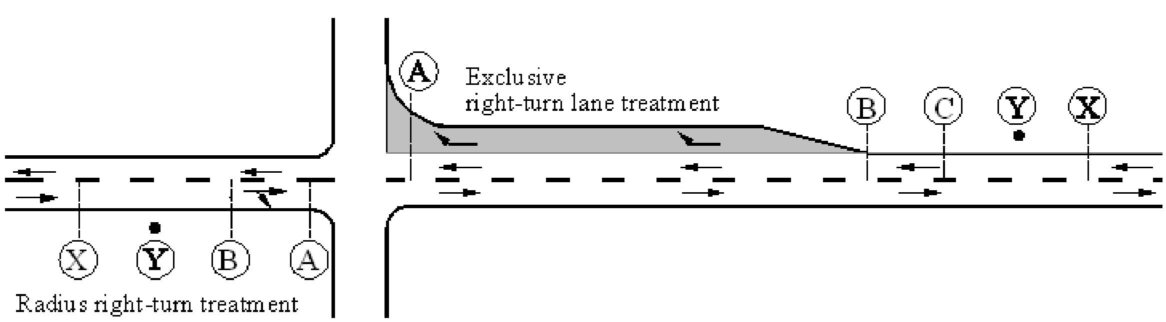


Figure 5.6. Time headway and spot-speed data points in the traffic stream of interest.

Table 5.6. Specifications of time headway and spot-speed data collection points

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

5.2.4 Warm-up period of VISSIM models

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

In this study, a simple road network consisting of one intersection of two-lane roadways was required to simulate the conflicts caused by vehicles making right turns from a major road approach onto a cross road. A total of twelve individual road networks were developed corresponding to each of the twelve cells. Each road network consisted of one intersection that had a 1000 ft long major road approach and a 500 ft long cross street. These lengths were considered sufficient to simulate the conflicts on the study approach, since the maximum length of exclusive right-turn lane, including the taper length, at survey locations was found to be 465 ft. The selected lengths were also adequate to incorporate the desired speed distributions that were observed at a minimum distance of 800 ft upstream of the stop bar. Screenshots of VISSIM simulation models consisting of a typical road network with and without a right-turn lane on the major road approach are presented in Figure 5.7.

a) Radius right-turn treatment on the study approach b) Exclusive right-turn lane treatment on the study approach

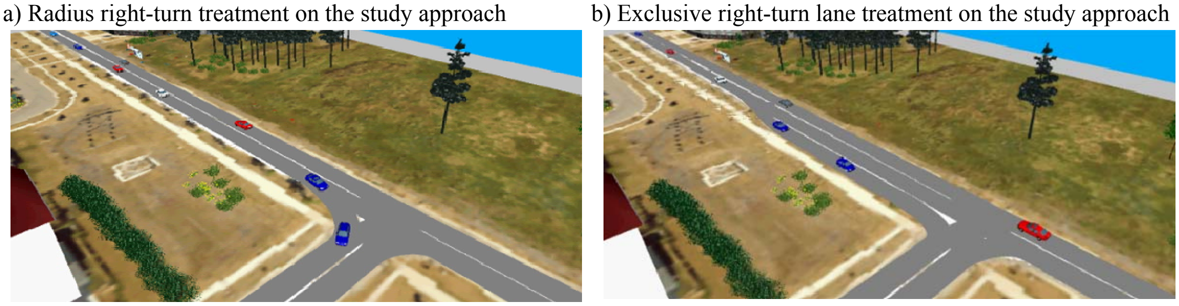


Figure 5.7. Screenshots of typical layout of VISSIM models.

Traffic volumes in VISSIM simulation models are defined in terms of the number of vehicles per hour (vph). Vehicles enter the system based on a Poisson distribution. Considering that the first vehicle enters the system at time zero with a speed of 12.5 mph (18.33 ft/sec), which was the lowest value of desired speed used in this study (Section 5.2.8), it takes the vehicle only 54.55 seconds to travel the 1000 ft long study approach. Therefore, a warm-up period of fifteen minutes chosen for convenience in this study was considered more than sufficient. The simulation outputs corresponding to the first fifteen minutes of simulations during the warm-up periods were not processed for further analysis in this study.

5.2.5 VISSIM model calibrations

Each of the twelve cells (factor level combinations) designed for VISSIM simulation model calibrations represented a particular combination of traffic volume, posted roadway speed limit and right-turn treatment type. Taken one cell at a time, this approach facilitated model calibrations in terms of the ease with which the effects of traffic volume, posted roadway speed limit and right-turn treatment type could be controlled. Collectively, these cells also allowed the simulations of conflicts due to right turns at a wide range of conditions.

Each of the twelve VISSIM models, corresponding to each of the twelve cells, was calibrated for the conditions observed during field surveys at the study approaches identified in Table 5.5 by the cells these approaches represent. The calibration exercises involved adjusting the values of BX_{add} and BX_{mult} in Equation 5.2b to find an appropriate combination of these values that replicated both spot-speed and time headway distributions observed at various points in the traffic stream of interest. Close replications were desired as the conflicts due to right turns are primarily influenced by the vehicle speeds and the time headways between the vehicles.

The calibration exercise turned out to be an endeavor, especially because close replications were sought simultaneously at multiple points (A, B, or C) in the traffic stream of interest. The values of calibration parameters finally found appropriate for the conditions observed during field surveys are summarized in Table 5.7. The comparisons of simulated spot-speed and time headway distributions, obtained from the VISSIM models considered sufficiently calibrated, versus the distributions of spot speeds and time headways observed at points A, B, or C during field surveys are presented in Appendix F.

Table 5.7. VISSIM model calibration parameters

Cell	Location (Intersection)	Approach	BX_{add}	BX_{mult}
1S	Dawson (US-212/4th St.)	US-212 West	1.0	15.0
2S	Staples (US-10/12th St. NE)	US-10 West	0.1	7.0
3S	Moorhead (20th St. S/16th Ave. S)	20th St. S North	1.0	5.0
4S	Moorhead (28th Ave. N /34th St. N)	28th Ave. N West	1.0	3.0
5S	Forest Lake (US-61/240th St.)	US-61 North	2.0	5.0
6S	Forest Lake (US-61/240th St.)	US-61 North	2.0	5.0
1E	Tyler (US-14/CR-8)	US-14 East	1.5	3.0
2E	Moorhead (20th St. S/MSCTC Dr.)	20th St. S North	1.0	6.5
3E	Lindstrom (MNTH-8/Akerson St.)	MNTH-8 West	0.5	6.5
4E	Park Rapids (MNTH-34/CR-4)	MNTH-34 East	1.5	5.0
5E	Forest Lake (US-61/250th St.)	US-61 North	2.5	15.0
6E	Forest Lake (US-61/250th St.)	US-61 South	0.1	15.0

5.2.6 Number of simulation repetitions per scenario

Random seeds are used in VISSIM simulation models to generate vehicles, select their routes and determine their behaviors as they move through the network. As such, the results from individual simulation runs (repetitions), each simulating the same field condition, can vary significantly. To estimate the true mean of a performance measure with a certain level of confidence, it is necessary to carry out several simulation runs, using different random seed for each run. The required number of repetitions is estimated by an iterative process based on the sample standard deviation and the desired length of the confidence interval of a performance measure at a desired confidence level, which is the probability that the true mean lies within the target interval. The analyst sets the desired confidence level (generally 95%) and decides on the acceptable length of confidence interval, depending on the purpose of simulations. At least four repetitions are recommended for the initial estimate of standard deviation, which is then used to estimate the required number of repetitions to obtain statistically valid results (Dowling et al. 2004).

The initial estimate of the number of repetitions is revisited and revised as the additional repetitions are performed and the sample standard deviation is revised.

If X_j is the estimator of the measure of performance from the j^{th} repetition, then given the conditions of repetitions, the sequence X_1, X_2, … X_N are independent and identically distributed (iid) random variables. Based on these iid random variables, the 100(1-α)% confidence interval (C.I.) for the expected value of X is estimated using the relationships shown below (Winston 2004):

$$100(1 - \alpha)\%\ \text{C.I.} = \overline{X} \pm t_{\alpha/2,\,N-1} \cdot \sqrt{\frac{S^2}{N}}; \tag{5.3a}$$

$$\overline{X} = \sum_{i=1}^{N} \frac{X_i}{N}, \quad i = 1,2,\ldots,N; \tag{5.3b}$$

$$S^2 = \sum_{i=1}^{N} \frac{(X_i - \overline{X})^2}{N-1}, \quad i = 1,2,\ldots,N; \tag{5.3c}$$

where $\overline{X}$ is sample mean used as the best estimate of performance measure; $t_{\alpha/2,N-1}$ is the number such that for a t-distribution with N-1 degrees of freedom, $P(t_{N-1} \geq t_{(\alpha,N-1)}) = \alpha$; S is sample standard deviation; and N is the number of repetitions.

The performance measure in this study was the number of conflicts due to right turns. The minimum number of repetitions required to obtain statistically valid results from simulations was determined by examining the confidence interval of the number of four-hour conflicts due to right turns at 95% confidence level. A total of twelve scenarios (Scenarios A through L), each representing a particular combination of right-turn treatment type, posted speed limit and approach volume at 10% right turns, were considered for this purpose as shown in Table 5.8.

Table 5.8. Scenarios to determine the number of simulation repetitions

Right-turn Trt. Type	App. Vol. (vph)	% Right Turns	Speed (mph)	Scenario	Right-turn Trt. Type	App. Vol. (vph)	% Right Turns	Speed (mph)	Scenario
Radius	100	10	35	A	Exclusive	100	10	35	G
Radius	100	10	55	B	Exclusive	100	10	55	H
Radius	500	10	35	C	Exclusive	500	10	35	I
Radius	500	10	55	D	Exclusive	500	10	55	J
Radius	750	10	35	E	Exclusive	750	10	35	K
Radius	750	10	55	F	Exclusive	750	10	55	L

The estimated 95% confidence intervals of the number of four-hour simulated conflicts due to right turns at four, ten, fifteen and twenty simulation repetitions are presented in Table 5.9. As expected, the confidence interval becomes narrower as the number of repetitions increases; e.g. the confidence interval of the number of four-hour conflicts under 'Scenario D' converges from ±45.2 conflicts from the sample mean at four repetitions to ±19.8 conflicts at ten, ±13.5 conflicts at fifteen and ±11.7 conflicts at twenty repetitions. The confidence intervals obtained at twenty simulation repetitions per scenario were considered reasonable. Therefore, the conflict simulations for each scenario in this study were carried out with twenty repetitions.

5.2.7 VISSIM model validations

The validations of calibrated VISSIM simulation models were carried out by comparing the number of four-hour simulated conflicts due to right turns with the number of four-hour conflicts observed during the continuous four-hour observation periods at study sites earlier listed in Table 5.2. Additional sites were also selected for such comparisons. The additional sites are identified in Table 5.10. The observed numbers of four-hour conflicts at additional sites are presented in Table 5.11.

Table 5.9. 95% C.I. of four-hour conflicts at different number of repetitions

N	Scenario	Four-hour Conflicts			N	Scenario	Four-hour Conflicts		
		$\bar{X}$	S	95% C.I.			$\bar{X}$	S	95% C.I.
4	A	5.8	2.2	5.8 ± 3.5	10	A	6.0	2.1	6.0 ± 1.5
4	B	8.5	3.1	8.5 ± 4.9	10	B	9.4	3.4	9.4 ± 2.4
4	C	184.8	22.2	184.8 ± 35.3	10	C	189.8	23.3	189.8 ± 16.6
4	D	258.3	28.4	258.3 ± 45.2	10	D	265.1	27.7	265.1 ± 19.8
4	E	391.3	30.6	391.3 ± 48.6	10	E	388.2	23.7	388.2 ± 16.9
4	F	504.8	27.9	504.8 ± 44.4	10	F	501.9	23.2	501.9 ± 16.6
4	G	1.8	0.5	1.8 ± 0.7	10	G	1.8	1.1	1.8 ± 0.8
4	H	1.8	1.0	1.8 ± 1.5	10	H	1.8	1.1	1.8 ± 0.8
4	I	45.3	10.2	45.3 ± 16.1	10	I	46.1	7.9	46.1 ± 5.6
4	J	62.5	9.3	62.5 ± 14.7	10	J	63.9	7.9	63.9 ± 5.6
4	K	100	10.2	100.0 ± 16.1	10	K	100.6	10.4	100.6 ± 7.4
4	L	131.8	11.2	131.8 ± 17.8	10	L	131.6	11.1	131.6 ± 7.9
15	A	5.9	2.0	5.9 ± 1.1	20	A	7.1	2.9	7.1 ± 1.3
15	B	9.0	2.9	9.0 ± 1.5	20	B	10.5	3.8	10.5 ± 1.7
15	C	190.9	20.6	190.9 ± 11.3	20	C	192.1	20.3	192.1 ± 9.4
15	D	263.8	24.4	263.8 ± 13.5	20	D	263.9	25	263.9 ± 11.7
15	E	386.9	28.2	386.9 ± 15.6	20	E	391.1	29.3	391.1 ± 13.7
15	F	494.1	31.5	494.1 ± 17.4	20	F	497.6	31.6	497.6 ± 14.8
15	G	1.9	1.4	1.9 ± 0.7	20	G	2.4	1.6	2.4 ± 0.7
15	H	1.9	1.5	1.8 ± 0.8	20	H	2.6	1.9	2.6 ± 0.9
15	I	45.9	6.6	45.9 ± 3.6	20	I	46.3	6.2	46.3 ± 2.8
15	J	62.7	7.0	62.7 ± 3.8	20	J	63.6	7.1	63.6 ± 3.3
15	K	99.9	9.6	99.9 ± 5.3	20	K	101.8	10.8	101.8 ± 5.0
15	L	131.3	11.4	131.3 ± 6.2	20	L	133	12.1	133.0 ± 5.6

Table 5.10. Additional field sites identification

Site Code	City / Nearest City	Intersection Description	Study Approach	Int. Type	Right-turn Treatment	Speed (mph)
AL1	Moorhead	20th St. S/20th Ave. S	20th St. S North	T	Exclusive	30
AL2	Moorhead	20th St. S/24th Ave. S	20th St. S North	T	Exclusive	30
AL3	Ruthton	MNTH-23/CR-10	MNTH-23 North	+	Exclusive	55
AS1	Moorhead	28th Ave. N /34th St. N*	28th Ave. N West	T	Radius	55
AS2	Moorhead	20th St. S/16th Ave. S	20th St. S North	T	Radius	30
AS3	Staples	US-10/11th St. NE	US-10 West	+	Radius	30
AS4	Dawson	US-212/4th St.	US-212 West	+	Radius	30
AS5	Moorhead	28th Ave. N/40th St. N*	28th Ave. N West	+	Radius	55

* Replicated.

The appropriate VISSIM model to simulate the conflicts due to right turns at a particular study approach was identified by the cell that characterized the approach. The simulated and the observed four-hour conflicts at study sites are presented in Table 5.12. The simulated conflicts presented are the average of twenty repetitions. To test the difference between the means of observed and simulated conflicts, matched-pairs t-tests were carried out. Small p-values in these tests reject the null hypothesis that the population means are equal; e.g. the null hypothesis is rejected if p-value is less than 0.05 at 95% confidence level. Three separate tests were conducted; one for radius right-turn treatment, one for exclusive lane treatment and one using all observations. The test results, presented in Table 5.13, show the lack of evidence to reject the null hypothesis in each test; in other words, it was concluded that the means of simulated and observed four-hour conflicts were equal.

Table 5.11. Observed four-hour conflicts at additional study sites

Site Code	Right-turn Treatment	RT Vol.	Thru Vol.	Total Vol.	% RT	Observed Conflicts	
						Number	Per TEV
AL1	Exclusive	79	1551	1630	4.85	13	7.98
AL2	Exclusive	134	1557	1691	7.92	11	6.51
AL3	Exclusive	22	407	429	5.13	1	2.33
AS1	Radius	100	250	350	28.57	15	42.86
AS2	Radius	25	1626	1651	1.51	24	14.54
AS3	Radius	20	1258	1278	1.56	18	14.08
AS4	Radius	2	560	562	0.36	0	0.00
AS5	Radius	33	136	169	19.53	3	17.75

However, a matched-pairs t-test requires that the differences in matched pairs are normally distributed. The tests for the normality of differences were carried out based on Anderson-Darling test. In this test also, a small p-value rejects the null hypothesis that the distribution is normal. The results of the normality tests, shown in Table 5.14, indicate that the differences in simulated and observed four-hour conflicts were normally distributed. Hence, the matched-pairs t-tests carried out to validate the VISSIM models were appropriate.

Table 5.12. Simulated and observed conflicts at study sites

Side Code	Right-turn Treatment	Speed (mph)	Volume (vph)	% RT	Conflicts (per TEV)	
					Observed	Simulated
C1R1	Radius	30	298	0.84	4.2	4.1
C1R2	Radius	30	128	2.14	3.9	3.8
C1R3	Radius	30	93	2.15	0.0	3.8
C2L1	Exclusive	30	422	2.85	6.5	4.6
C2L2	Exclusive	30	392	2.74	3.2	3.7
C2L3	Exclusive	30	424	1.89	0.0	2.5
C3R1	Radius	45	103	3.90	19.5	13.1
C3R2	Radius	45	92	2.55	14.5	9.2
C3R3	Radius	55	140	1.25	9.0	7.1
C4L1	Exclusive	55	237	4.65	10.6	8.3
C4L2	Exclusive	55	431	2.38	8.1	6.7
C4L3	Exclusive	55	377	1.73	1.3	5.1
C5R1	Radius	30	226	8.86	33.2	33.6
C5R2	Radius	30	254	7.89	27.6	31.9
C5R3	Radius	30	220	7.37	12.1	27.6
C6L1	Exclusive	35	62	14.52	8.1	3.9
C6L2	Exclusive	30	578	6.70	7.3	12.9
C6L3	Exclusive	30	638	7.56	6.7	14.8
C7R1	Radius	55	92	31.42	62.8	63.8
C7R2	Radius	55	93	29.92	53.9	60.7
C7R3	Radius	55	97	11.92	31.1	33.8
C8L1	Exclusive	55	256	9.47	23.4	17.4
C8L2	Exclusive	55	256	12.30	20.5	21.4
C8L3	Exclusive	55	150	21.46	18.3	18.3
AL1	Exclusive	30	408	4.85	8.0	6.6
AL2	Exclusive	30	423	7.92	6.5	10.5
AL3	Exclusive	55	107	5.13	2.3	4.1
AS1	Radius	55	78	28.57	42.9	48.2
AS2	Radius	30	413	1.51	14.5	11.2
AS3	Radius	30	320	1.56	14.1	7.4
AS4	Radius	30	141	0.36	0.0	0.8
AS5	Radius	55	42	19.53	17.8	15.9

Table 5.13. Test for the difference between simulated and observed conflicts at study sites

Right-turn Treatment	N	Observed Conflicts			Simulated Conflicts			Test for Mean Difference		
		Mean	St. Dev.	SE Mean	Mean	St. Dev.	SE Mean	T-Value	P-Value	95% C.I.
Radius	17	21.24	18.42	4.47	22.12	20.31	4.93	-0.66	0.52	(-3.68, 1.92)
Exclusive	15	8.72	6.92	1.79	9.39	6.14	1.58	-0.69	0.50	(-2.75, 1.42)
Combined	32	15.38	15.40	2.72	16.15	16.48	2.91	-0.94	0.35	(-2.45, 0.90)

Table 5.14. Test for the normality of differences between simulated and observed conflicts

Right-turn Treatment	N	Difference of Means		Test for Normality	
		Mean	St. Dev.	AD*	P-Value
Radius	17	-0.88	5.45	0.34	0.45
Exclusive	15	-0.66	3.76	0.12	0.98
Combined	32	-0.78	4.66	0.34	0.48

* Anderson-Darling test statistic.

5.2.8 Conflict simulations

The sole purpose of the simulations of conflicts due to right turns was to obtain greater variations in the conflict data found to be not easily obtainable through field surveys. The conflict simulations were carried out by controlling the effects of four factors: approach traffic volume, percent right turns, posted roadway speed limit and right-turn treatment type. The various levels of these factors as well as the total number of factor-level combinations (scenarios) used in simulations are presented in Table 5.15.

Table 5.15. Factor-level combinations used in conflict simulations

Factor	**Factor Levels**							**# of Levels**
Approach Volume (vph)	50	100	200	300	500	600	750	7
Percent Right Turns (%)	1	5	10	20	30			5
Posted Speed Limit (mph)	25	30	35	45	55			5
Right-turn Treatment Type	Radius	Exclusive						2
Total number of factor-level combinations								**350**

The conflict simulations were carried out using the validated VISSIM models. Each of the 350 scenarios fell into one of the twelve cells. At twenty repetitions per scenario, a total of 7,000 simulations were required to be performed. Each repetition of simulation was performed for four hours and fifteen minutes, including the warm-up period.

It is to be noted that the speed inputs in VISSIM models are defined as a range of speed values in the form of a speed distribution. For each posted speed limit to be used in the simulation, it was, therefore, required first to define the corresponding desired speed distribution, which was determined based on the observed free-flow spot speeds collected at various study approaches with 30 or 55 mph posted speed limits. Such spot speeds, shown in Figure 5.8, were found to be symmetrical and bell-shaped.

The symmetrical and bell-shaped nature of the speed distribution allowed the determination of the desired speed distributions according to the ‘Empirical Rule’. The rule states that if the population is symmetrical and bell-shaped, approximately 68% of the observations fall within one standard deviation from the mean, 95% within two standard deviations from the mean, and about 100% within three standard deviations from the mean (McClave and Sincich, 2003). The distributions corresponding to low posted speed limits (25, 30 and 35 mph) were determined based on the free-flow spot-speed distribution observed at 30 mph posted speed limit, whereas the distributions corresponding to high posted speed limits (45 and 55 mph) were determined based on the distribution observed at 55 mph posted speed limit, as shown in Figure 5.8. The desired speed distributions corresponding to various posted speed limits used in the conflict simulations are presented as percentile speeds in Table 5.16, and in the form of graphs in Figure 5.9. The minimum desired speed was determined to be 12.5 mph at 25 mph posted speed limit, while the maximum desired speed derived was 69.9 mph at 55 mph posted speed limit.

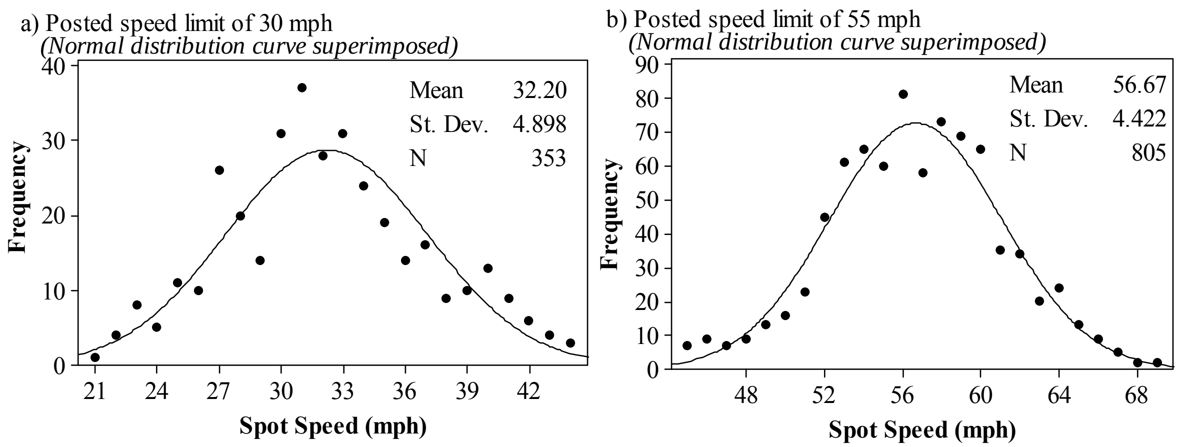
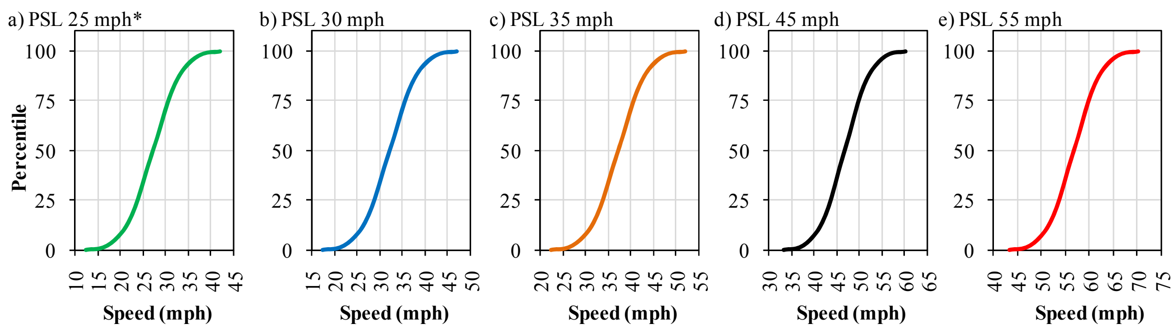


Figure 5.8. Observed spot-speed distributions at study approaches.

Table 5.16. Desired speed distribution based on the Empirical Rule

Posted Speed Limit (mph)	Shifted Mean Speed* (mph)	Desired Speed Distribution (Percentile Speed, mph)						
		0%	2.5%	16.0%	50.0%	84.0%	97.5%	100.0%
25	27.2	12.5	17.4	22.3	27.2	32.1	37.0	41.9
30	32.2	17.5	22.4	27.3	32.2	37.1	42.0	46.9
35	37.2	22.5	27.4	32.3	37.2	42.1	47.0	51.9
45	46.7	33.4	37.8	42.2	46.7	51.1	55.5	59.9
55	56.7	43.4	47.8	52.2	56.7	61.1	65.5	69.9

* Based on the observed shift of the mean spot speed from the posted speed limit.



* Note: PSL = Posted speed limit.

Figure 5.9. Desired speed distributions used in the conflict simulations.

5.2.9 Sensitivity analysis

The sensitivity analyses were carried out to understand the effects of four pertinent factors, namely, hourly approach traffic volume, posted roadway speed limit, percent right turns and right-turn treatment type, on the number of simulated conflicts due to right turns. The simulated conflicts were analyzed in terms of the total number of four-hour conflicts as well as the number of four-hour conflicts per TEV, both measures obtained as the average of twenty repetitions for each scenario. The nature of the relationships of these factors with the simulated conflicts presented in Figure 5.10 revealed that the posted speed limit, the percent right turns and the hourly approach volume all had positive effects on the number of conflicts due to right turns, i.e., the number of conflicts increased with an increase in the values of these variables. While the total number of four-hour conflicts was found to increase at an increasing rate with the increasing hourly approach volume, the number of conflicts per TEV appeared to increase at a decreasing rate. The number of simulated conflicts at approaches with radius right-turn treatments was found to be substantially higher than that at approaches with exclusive right-turn lanes.

The sensitivity analyses highlighted the need and the relevance of incorporating hourly approach traffic volume, posted roadway speed limit, percent right turns and right-turn treatment type as contributing factors in the prediction of conflicts caused by vehicles making right turns from a study approach on to a cross road. The least squares conflict prediction models using simulation data were, therefore, developed based on these variables as discussed in the next section.

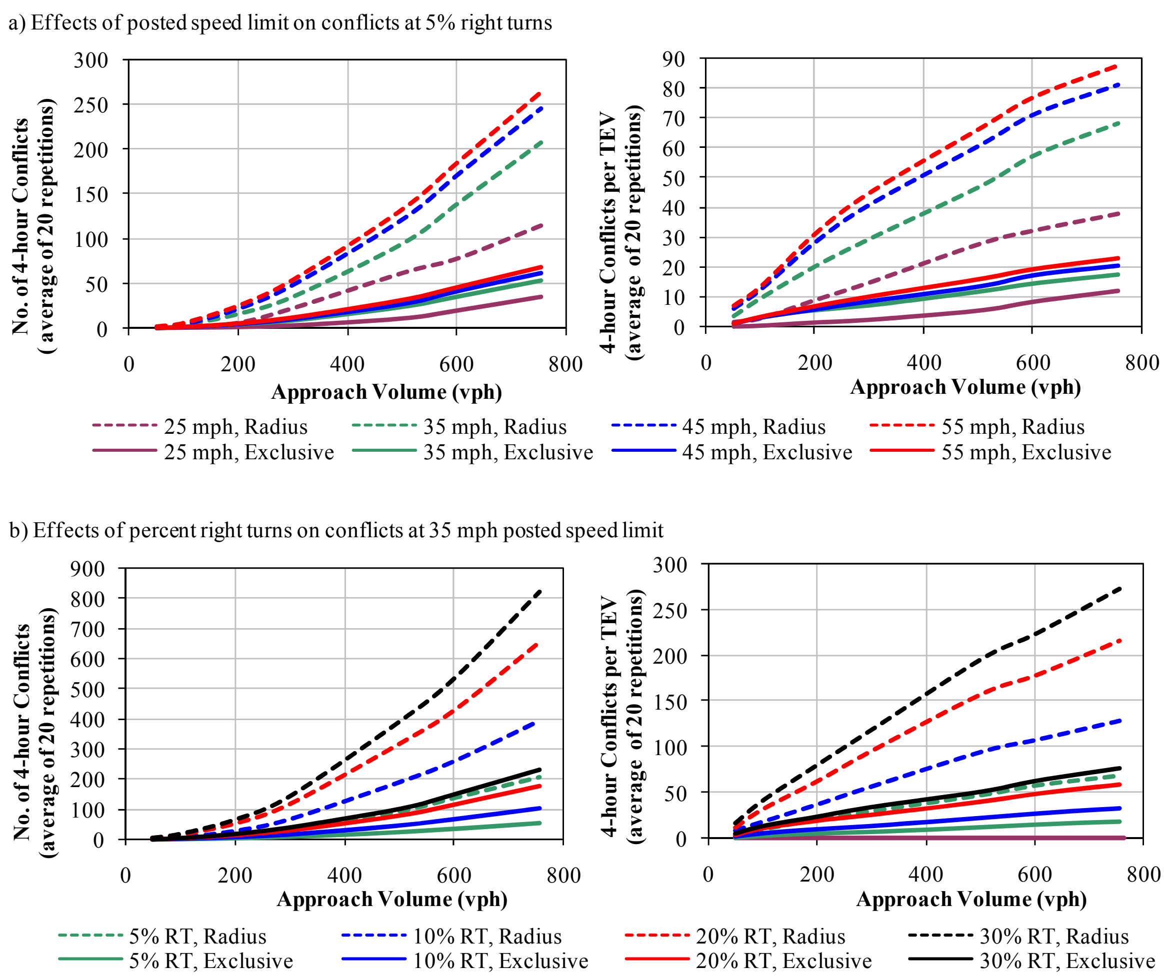


Figure 5.10. Effects of speed limit, approach volume and percent right turns on conflicts.

5.2.10 Conflict prediction model development using simulation data

The measure of conflicts due to right turns in terms of the number of conflicts per TEV was found to be an appropriate measure of the dependent variable in the least squares conflict prediction models developed based on four-hour conflict simulations. Moreover, instead of incorporating all pertinent variables together in a single model, it was found appropriate to develop two individual models to predict the conflicts at radius right-turn treatments and exclusive right-turn lanes separately. The parameter estimates and the residual plots, presented in Appendix E, indicate that the fitted models were appropriate. The fitted conflict prediction models are presented below:

RTC_R = - 1.540 + 0.0415.(SPD) + 1.2100.(RTP) + 0.00206.(VOL)

- 0.0357.(SPD).(RTP) - 0.000054.(SPD).(VOL) - 0.00563.(RTP).(VOL) + 0.00071.(SPD).(RTP).(VOL)

[S = 0.6877, R^2 = 99.80%, Adj. R^2 = 99.70%, Pred. R^2 = 99.62%] (5.4a)

RTC_L = - 0.544 + 0.016.(SPD) + 0.0581.(RTP) + 0.000737.(VOL)

- 0.00318.(SPD).(RTP) - 0.00002.(SPD).(VOL) + 0.000521.(RTP).(VOL)+ 0.000108.(SPD).(RTP).(VOL)

[S = 0.3707, R^2 = 99.60%, Adj. R^2 = 99.60%, Pred. R^2 = 99.47%] (5.4b)

where RTC_R is the number of conflicts due to right turns, including the associated secondary conflicts, per TEV at radius right-turn treatment, RTC_L is the number of conflicts due to right turns, including the associated secondary conflicts, per TEV at exclusive right-turn lane, SPD is posted speed limit (mph), RTP is percent right turns, and VOL is approach volume (vph).

5.3 Field model and simulation model comparison

The conflict prediction models fitted using the simulation data were compared with the model fitted using the field data. The model performances at approaches with radius and exclusive lane treatments are compared in Figure 5.11 and Figure 5.12 respectively. Unlike the model fitted using the field data, the conflict prediction models fitted using the simulation data were found to be sensitive to the changes in approach volumes, posted speed limits and percent right turns. The models based on the simulation data were therefore considered appropriate in this study to estimate the number of conflicts due to right turns.

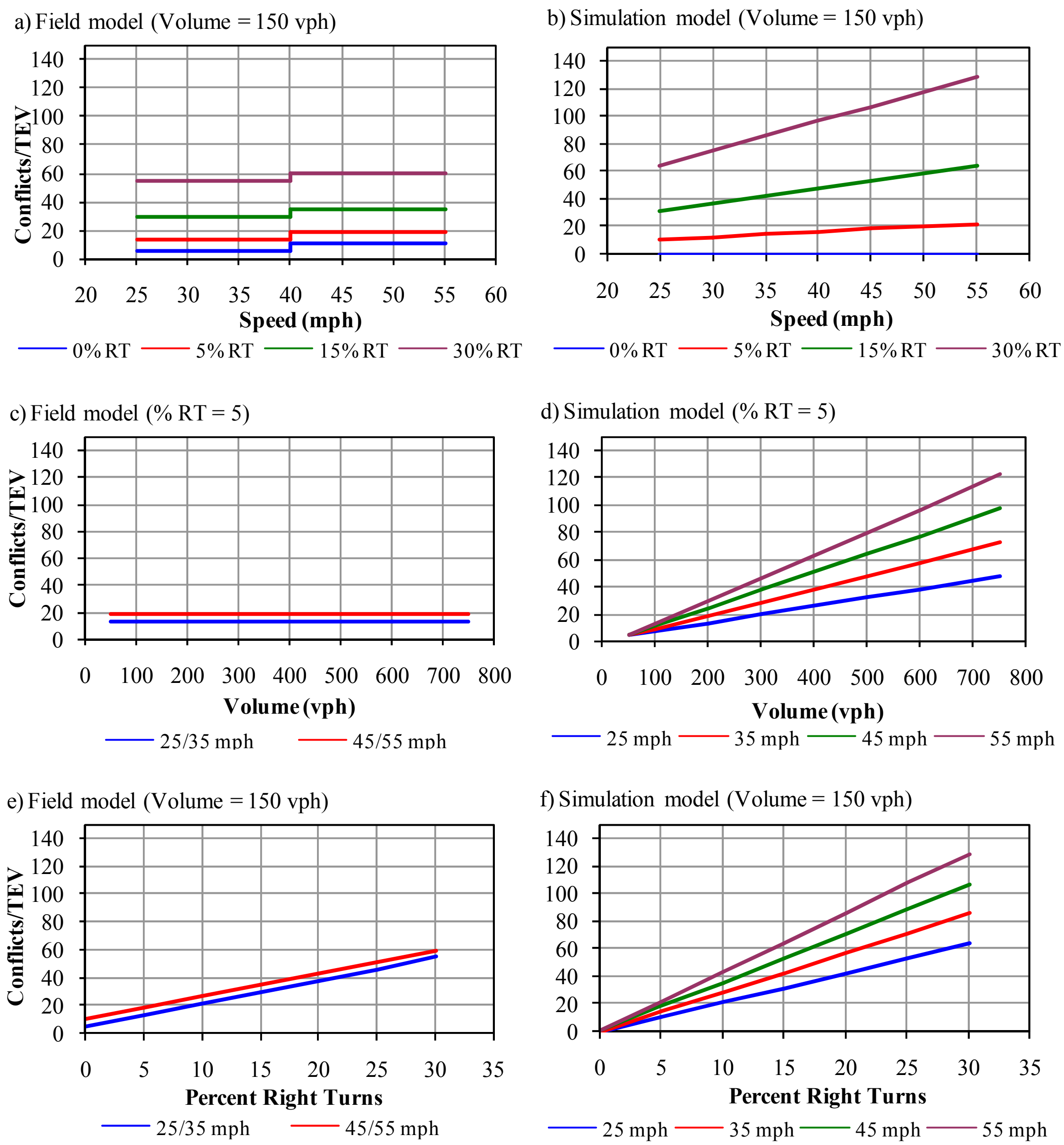


Figure 5.11. Model comparisons for approaches with radius right-turn treatments.

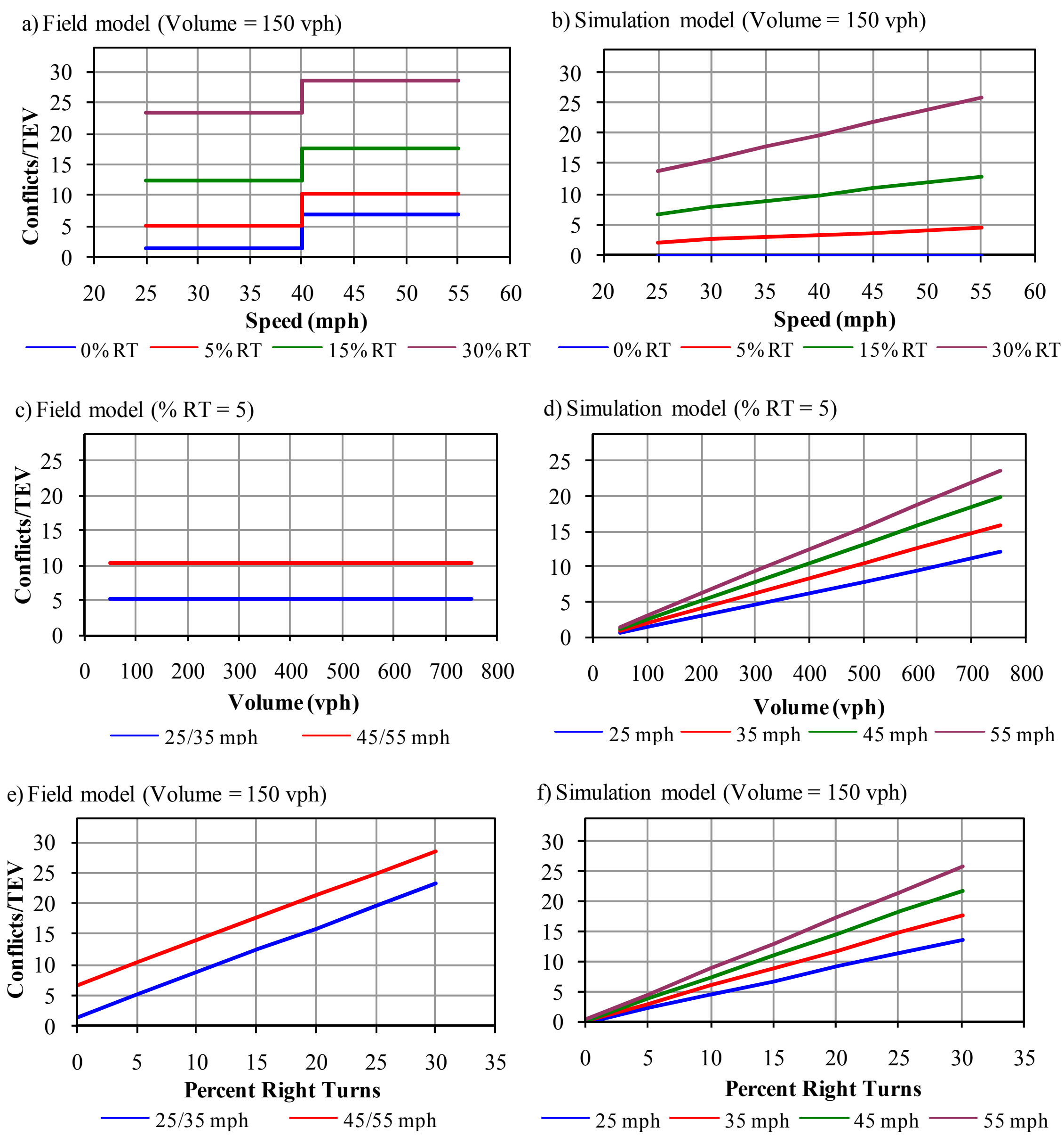


Figure 5.12. Model comparisons for approaches with exclusive right-turn lanes.

5.4 Validation of conflict prediction models

The foregoing provided the basis for selecting the least squares conflict prediction models that were fitted using the simulation data to predict the number of conflicts due to right turns. The appropriateness of the selected models was assessed by testing the equality of means between the predicted and the observed conflicts at various study sites. The number of predicted and observed conflicts per TEV at each study site is presented in Table 5.17.

Table 5.17. Predicted and observed conflicts at study sites

Side Code	Approach Vol. (vph)	Percent Right Turns	Right-turn Treatment	Speed (mph)	Conflicts per TEV	
					Observed	Predicted
C1R1	298	0.84	Radius	30	4.2	3.9
C1R2	128	2.14	Radius	30	3.9	4.4
C1R3	93	2.15	Radius	30	0.0	3.2
C3R1	103	3.90	Radius	45	19.5	9.3
C3R2	92	2.55	Radius	45	14.5	5.4
C3R3	140	1.25	Radius	55	9.0	5.5
C5R1	226	8.86	Radius	30	33.2	32.4
C5R2	254	7.89	Radius	30	27.6	32.3
C5R3	220	7.37	Radius	30	12.1	26.2
C7R1	92	31.42	Radius	55	62.8	73.1
C7R2	93	29.92	Radius	55	53.9	70.9
C7R3	97	11.92	Radius	55	31.1	30.1
AS1	78	28.57	Radius	55	42.9	53.4
AS2	413	1.51	Radius	30	14.5	9.9
AS3	320	1.56	Radius	30	14.1	7.9
AS4	141	0.36	Radius	30	0.0	0.6
AS5	42	19.53	Radius	55	17.8	13.6
C2L1	422	2.85	Exclusive	30	6.5	4.4
C2L2	392	2.74	Exclusive	30	3.2	3.9
C2L3	424	1.89	Exclusive	30	0.0	2.9
C4L1	237	4.65	Exclusive	55	10.6	6.8
C4L2	431	2.38	Exclusive	55	8.1	6.5
C4L3	377	1.73	Exclusive	55	1.3	4.2
C6L1	62	14.52	Exclusive	35	8.1	3.1
C6L2	578	6.70	Exclusive	30	7.3	14.3
C6L3	638	7.56	Exclusive	30	6.7	17.9
C8L1	256	9.47	Exclusive	55	23.4	14.8
C8L2	256	12.30	Exclusive	55	20.5	19.2
C8L3	150	21.46	Exclusive	55	18.3	18.6
AL1	408	4.85	Exclusive	30	8.0	7.2
AL2	423	7.92	Exclusive	30	6.5	12.3
AL3	107	5.13	Exclusive	55	2.3	3.3

Similar to the VISSIM model validation tests discussed earlier, the tests for the equality of means between the predicted and the observed conflicts carried out to validate the conflict prediction models were based on three separate matched-pairs t-tests. The results of these tests, presented in Table 5.18, indicate that there was not enough evidence to reject the null hypothesis that the population means were equal in each of these three cases. Similarly, the results of the normality tests, presented in Table 5.19, show that the differences between the observed and the predicted conflicts were normally distributed, which indicate the validity of the matched-pairs t-tests in the validations of the conflict prediction models. Hence, the application of the conflict prediction models developed in this study to predict the number of conflicts due to right turns per TEV was considered appropriate.

Table 5.18. Validation of the conflict prediction models fitted using the simulation data

Right-turn Treatment	N	Observed Conflicts			Predicted Conflicts			Test for Mean Difference		
		Mean	St. Dev.	SE Mean	Mean	St. Dev.	SE Mean	T-Value	P-Value	95% C.I.
Radius	17	21.24	18.42	4.47	22.46	23.52	5.70	-0.64	0.53	(-5.26, 2.82)
Exclusive	15	8.72	6.92	1.79	9.30	6.18	1.60	-0.45	0.66	(-3.32, 2.17)
Combined	32	15.38	15.40	2.72	16.29	18.64	3.29	-0.79	0.44	(-3.29, 1.45)

Table 5.19. Test for the normality of differences between predicted and observed conflicts

Right-turn Treatment	N	Difference of Means		Test for Normality	
		Mean	St. Dev.	AD*	P-Value
Radius	17	-1.22	7.86	0.40	0.33
Exclusive	15	-0.58	4.96	0.21	0.82
Combined	32	-0.92	6.57	0.54	0.15

* Anderson-Darling test statistic.

5.5 Conflict estimates

The number of conflicts due to right turns per TEV at various combinations of hourly approach traffic volume, posted roadway speed limit and percent right turns was estimated for radius and exclusive right-turn lane treatments separately by using the validated least squares conflict prediction models fitted using the simulation data. The conflict savings, in other words, the number of conflicts per TEV at intersection approaches without right-turn lanes that can be eliminated by providing right-turn lanes, were obtained by subtracting the number of conflicts per TEV estimated at approaches with right-turn lanes from that estimated at approaches with radius right-turn treatments at the same factor-level combinations. The estimated conflicts as well as the conflict savings at intersection approaches operating under 25, 35, 45, and 55 mph posted roadway speed limits are presented in Figure 5.13.

5.6 Summary

This chapter dealt with the conflict analysis. The goal was to quantify the safety effects of right-turn volumes, by developing least squares conflict prediction models, to pave a way for realizing the broader objective of making comprehensive assessments of the safety effectiveness of right-turn lanes at a wide range of conditions. The conflict analyses were carried out by using the field as well as the conflict simulation data. While the field data were obtained at locations spread throughout the State of Minnesota, the simulations of conflicts due to right turns were carried out using the VISSIM traffic simulators.

The purpose of conflict simulations, carried out in several steps, was to obtain greater variations in the conflict data found to be difficult to obtain through field surveys. First of all, a total of twelve VISSIM models were developed and calibrated for the field conditions, characterized by approach traffic volume and composition, percent right turns, right-turn treatment type, and desired speed distribution, including the right-turn speed distribution, to replicate the spot-speed and time headway distributions observed at selected study sites at various points in the traffic stream of interest. The calibrated VISSIM models were validated by comparing the number of simulated four-hour conflicts with the number of four-hour conflicts observed at various study sites by using matched-pairs t-tests. The validated VISSIM models were then used to perform a total of 7,000 conflict simulations, including twenty repetitions for each of the 350 scenarios used in the simulations. Each simulation was carried out for four hours, after a warm-up period of fifteen minutes.

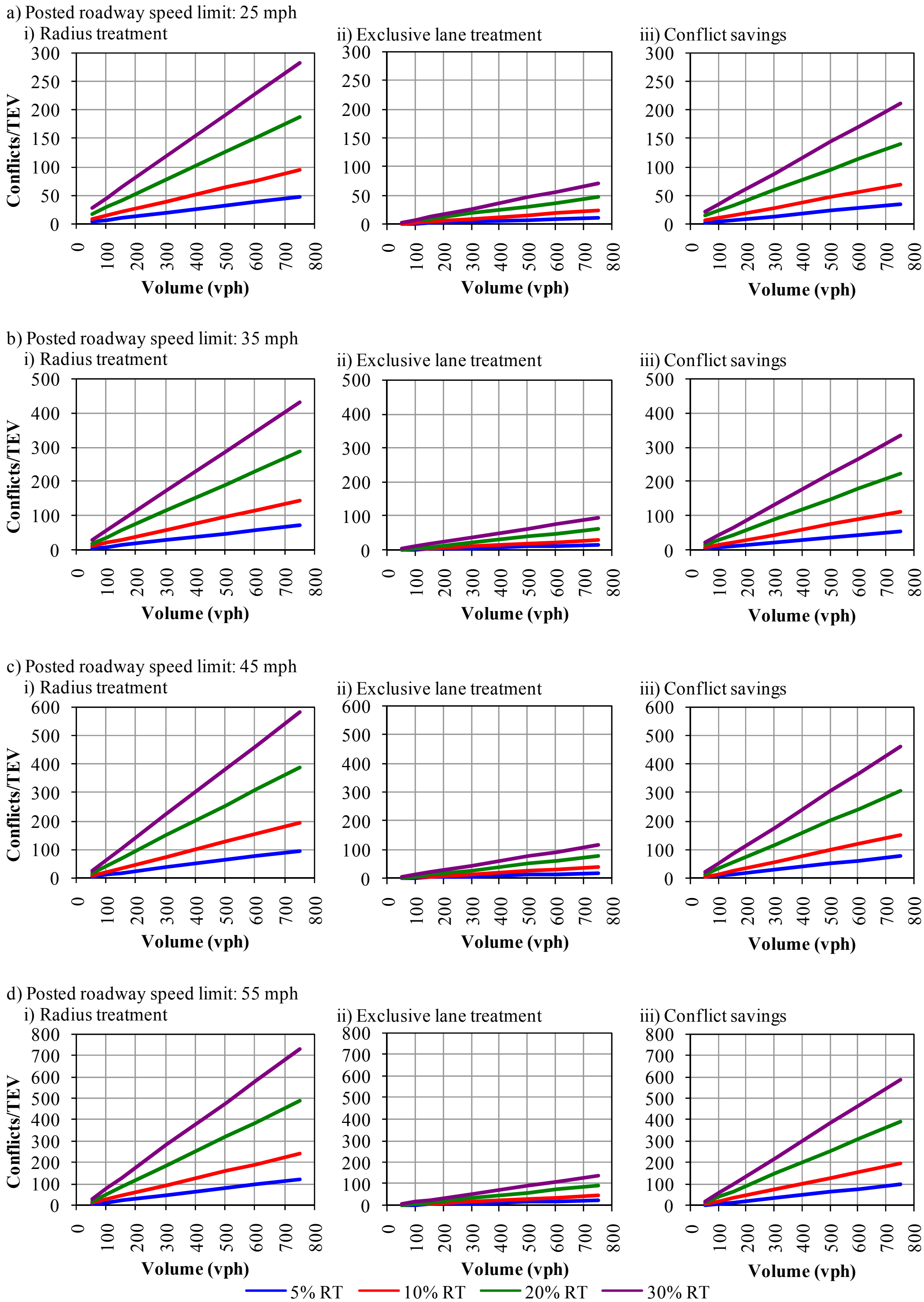


Figure 5.13. Conflict estimates and conflict savings.

Next, least squares conflict prediction models using the field data and the conflict simulation data were fitted separately. However, unlike the conflict prediction model fitted using the field data, the two separate models that were fitted using the simulation data to predict the conflicts separately at radius and exclusive right-turn lane treatments were found sensitive to the changes in approach traffic volume, posted roadway speed limit and percent right turns. Therefore, the models fitted using the simulation data were considered superior to the field model to predict the conflicts caused by right-turning vehicles.

The conflict prediction models fitted using the simulation data were then validated by comparing the number of predicted conflicts with the number of conflicts observed at various study sites. In this case also, matched-pairs t-tests were used to test the equality of population means. The conflict prediction models developed in this study were found to be appropriate for practical applications.

Finally, the number of conflicts due to right turns was estimated at a wide range of road conditions. It was found that a significant number of conflicts due to right turns at intersection approaches without right-turn lanes can be eliminated by providing right-turn lanes.

CHAPTER 6. SAFETY EFFECTIVENESS OF RIGHT-TURN LANES AND THEIR SAFETY-BASED VOLUME WARRANTS

The safety effectiveness of right-turn lanes and their safety-based volume warrants are presented in this chapter. The safety effectiveness was estimated in terms of the number and the cost of crashes that can be saved by providing right-turn lanes. The volume warrants were developed based on benefit-cost analysis.

6.1 Crash-conflict ratios

The terms 'crash-conflict ratio' (CCR) were defined earlier in this dissertation as the expected number of rear-end/same-direction-sideswipe (RE/SS) crashes caused by vehicles making right turns per conflict due to a right turn. The crash and conflict analyses revealed that the type of right-turn treatment was significant in the occurrence of crashes as well as conflicts. Accordingly, the CCRs were determined separately for radius and exclusive right-turn lane treatments.

Given the total number of crashes that occurred over a period of *n* years at an intersection approach, the expected number of RE/SS crashes caused by vehicles making right turns from that approach over the same time period can be estimated using Equations 4.3a, 4.3b and 4.3c, or Tables 4.3 and 4.5. The expected number of conflicts due to right turns from the same approach over the same *n* years can be estimated based on Equation 5.4a or 5.4b, depending on the right-turn treatment type. These estimates of crashes and conflicts can then be used to determine the site-specific CCR at that approach as below:

$$T_{kn} = 365.\sum_{j=1}^{n}\sum_{i=1}^{24}\left(\frac{RTC_{ik}}{1000}.\frac{AADT_j}{2}.r_i\right); \qquad (6.1a)$$

$$Q_{klm} = N.p_{1,lm}.p_{2,kl}; \quad (6.1b)$$

$$CCR_{klm} = \frac{Q_{klm}}{T_{kn}}; \quad (6.1c)$$

k = radius, exclusive; l = high, low; m = high, low;

where T_{kn} is the expected number of conflicts due to right turns at an approach with the kth right-turn treatment type over a period of *n* years; RTC_{ik} is the expected number of hourly conflicts per TEV due to right turns during the ith hour of day at an approach with the kth right-turn treatment type (Equation 5.4a or 5.4b); $AADT_j$ is annual average daily traffic in the jth year (vpd); r_i is the portion of AADT during the ith hour of day; Q_{klm} is the expected number of RE/SS crashes caused by right-turning vehicles in *n* years at an approach with the kth right-turn treatment type operating under the lth speed category and the mth traffic volume category; N is the total number of approach crashes in *n* years; $p_{1,lm}$ is the probability of the crash being caused by a right-turning vehicle, given that a crash had occurred, at an approach operating under the lth speed category and the mth traffic volume category (Equation 4.3a or Table 4.3); $p_{2,kl}$ is the probability of an RE/SS crash, given that a right-turning vehicle caused the crash, at an approach with the kth right-turn treatment type operating under the lth speed category (Equations 4.3b and 4.3c, or Table 4.5); and CCR_{klm} is the expected site-specific CCR based on *n*-year crash and conflict estimates at an approach with the kth right-turn treatment type operating under the lth speed category and the mth traffic volume category.

The expected number of hourly conflicts per TEV due to right turns during the ith hour of day at an approach with the kth right-turn treatment type (RTC_{ik}) can be estimated by using hourly approach volumes in Equation 5.4a or 5.4b. The hourly approach volumes were estimated as equal to 50% of AADT factored by the hourly portions of AADT (r_i), which, in turn, were estimated based on one-year continuous traffic volume counts recorded by a total of eight automatic traffic recorders (ATRs) located around the field survey locations. The estimated hourly portions of AADT are presented in Table 6.1.

Table 6.1. Average hourly portions of AADT in Minnesota's trunk highways

Hour	Portion of AADT (r_i)	Hour	Portion of AADT (r_i)	Hour	Portion of AADT (r_i)
1:00	0.008	9:00	0.050	17:00	0.084
2:00	0.005	10:00	0.052	18:00	0.081
3:00	0.004	11:00	0.056	19:00	0.064
4:00	0.003	12:00	0.061	20:00	0.047
5:00	0.005	13:00	0.064	21:00	0.038
6:00	0.016	14:00	0.063	22:00	0.031
7:00	0.036	15:00	0.067	23:00	0.021
8:00	0.054	16:00	0.077	0:00	0.012

A total of twenty intersection approaches, ten each for radius and exclusive right-turn lane treatments, were selected to determine the mean CCRs by right-turn treatment types. The expected site-specific CCRs, based on five-year crash and five-year conflict estimates, are presented in Table 6.2. The estimated numbers of five-year RE/SS crashes (Q_{klm}) and five-year conflicts (T_{kn}) are also provided. The probabilities of a crash being caused by a right-turning vehicle ($p_{1,lm}$) used in these estimates were those estimated for Scenario I1 in Table 4.3, whereas the probabilities of an RE/SS crash ($p_{2,kl}$) used were those as provided in Table 4.5 for an intersection approach. The total numbers of approach crashes (N) at these locations in five years were obtained from the crash history data, whereas the AADTs were obtained from the traffic volume data. The percent right turns observed during the period of field observations at these locations were assumed to be applicable over the entire five-year period. The estimated mean CCRs based on the site-specific CCRs are presented in Table 6.3. The expected mean CCR at an approach with a radius right-turn treatment was two times higher than at an approach with an exclusive right-turn lane. This indicates a more severe nature of conflicts due to right turns at an approach with a radius right-turn treatment.

Table 6.2. Site-specific crash-conflict ratios

Location (Intersection)	Study App.	% RT	Speed (mph)	N (#)	AADT (vpd)	T (#)	Q (#)	CCR (x 10^{-6})
Radius right-turn treatment								
1) Aitkin (TH-210/CR-54 & CR-56)	TH-210, SB	0.6	55	0	4,285	11,055	0.000	0.000
2) Aitkin (TH-210/CR-54 & CR-56)	TH-210, NB	1.9	55	1	4,285	28,363	0.022	0.772
3) Dawson (US-212/4th St.)	US-212, WB	2.1	30	1	4,497	18,255	0.020	1.103
4) Dawson (US-212/4th St.)	US-212, EB	0.4	30	1	4,497	2,755	0.020	7.309
5) Forest Lake (US-61/240th St.)	US-61, NB	0.4	55	0	12,648	52,084	0.000	0.000
6) Lowry (TH-55/CR-114)	TH-55, WB	48.0	30	0	1,603	60,602	0.000	0.000
7) Staples (US-10/11th St. NE)	US-10, EB	1.5	30	6	10,800	74,974	0.083	1.111
8) Staples (US-10/12th St. NE)	US-10, WB	7.3	30	1	10,800	362,219	0.014	0.038
9) Staples (US-10/12th St. NE)	US-10, EB	0.8	30	5	10,800	40,759	0.069	1.703
10) Staples (US-10/SW-DQ Drives)	US-10, EB	0.2	30	2	10,800	8,086	0.028	3.434
Exclusive right-turn lane treatment								
1) Forest Lake (US-61/250th St.)	US-61, SB	2.6	55	5	10,265	47,085	0.048	1.009
2) Forest Lake (US-61/250th St.)	US-61, NB	14.3	55	5	10,265	244,037	0.048	0.195
3) Lindstrom (TH-8/Akerson St.)	TH-8, EB	8.0	30	0	17,068	229,629	0.000	0.000
4) Moorhead (US-75/46th Ave. S)	US-75, SB	21.8	55	1	4,166	56,589	0.014	0.252
5) Park Rapids (TH-34/CR-4)	TH-34, WB	4.6	55	0	10,521	84,962	0.000	0.000
6) Ruthton (TH-23/CR-10)	TH-23, SB	3.5	55	2	3,309	6,114	0.029	4.661
7) Ruthton (TH-23/CR-10)	TH-23, NB	2.2	55	0	3,309	4,370	0.000	0.000
8) St. Bonifacius (TH-7/CR-10)	TH-7, WB	15.7	55	7	8,455	180,439	0.100	0.553
9) St. Bonifacius (TH-7/CR-10)	TH-7, EB	12.1	55	9	8,455	139,448	0.128	0.920
10) Tyler (US-14/CR-8)	US-14, WB	14.7	35	0	1,754	3,959	0.000	0.000

Table 6.3. Mean crash-conflict ratios

Right-turn Treatment	Sample Size	Mean CCR (x 10^{-6})	St. Dev.	SE Mean	85% C.I.
Radius	10	1.547	2.291	0.724	(0.407, 2.687)
Exclusive	10	0.759	1.424	0.450	(0.050, 1.467)

6.2 Crash estimation factors and their usefulness in estimating crashes

The CCRs estimated in the preceding section determined the relationships between RE/SS crashes caused by right-turning vehicles and conflicts due to right turns. The crash estimation factors (CEFs), on the other hand, were determined in order to estimate the number of crashes caused by right-turning vehicles by taking into account all crash types, including RE/SS crashes. The relationships presented below determine CEFs and the number of all types of crashes caused by right-turning vehicles:

$$CEF_{kl} = CCR_k / p_{2,kl}; \tag{6.2a}$$

$$A_{nkl} = CEF_{kl} . T_{kn}; \tag{6.2b}$$

where CEF_{kl} is the expected CEF for an approach with the k^{th} right-turn treatment type operating under the l^{th} speed category; CCR_k is estimated mean CCR for an approach with the k^{th} right-turn treatment type (Table 6.3); and A_{nkl} is the expected number of all types of crashes caused by right-turning vehicles over a period of *n* years at an approach with the k^{th} right-turn treatment type operating under the l^{th} speed category.

The CEFs determined under different posted speed limit categories at intersection approaches with radius and exclusive right-turn lane treatments are presented in Table 6.4. The probabilities of RE/SS crashes ($p_{2,kl}$) used were those presented in Table 4.5.

Table 6.4. Crash estimation factors

Speed	Right-turn Treatment	CEF
Low	Radius	2.228 x 10^{-6}
Low	Exclusive	1.679 x 10^{-6}
High	Radius	1.695 x 10^{-6}
High	Exclusive	1.278 x 10^{-6}

The trustworthiness of CEFs in estimating the number of all crash types caused by right-turning vehicles was assessed by comparing the average number of crashes per year estimated based on the number of reported crashes with that based on estimated conflicts factored by a CEF. The goal was to see whether the estimated conflicts factored by a CEF were a reasonable estimate of the number of crashes caused by right-turning vehicles. A total of twenty-eight intersection approaches (twenty-four with exclusive lane treatment and four with radius treatment), not previously used in the estimation of CCRs, were used for the assessment of CEFs. The percent right turns at these approaches, located in Minneapolis/St. Paul Metro area, were determined based on the survey of turning volume counts conducted by Mn/DOT over a six-hour day (6:00 - 9:00 AM, 3:00 - 6:00 PM) in different years (2006 - 08). The study approach locations and the average crash/year based on five-year estimated conflicts and five-year reported crashes are presented in Table 6.5.

The estimated average numbers of crashes per year by right-turn treatment type as well as when all observations were combined together are summarized in Table 6.6. It was found that the estimates of the number of crashes caused by right-turning vehicles based on conflicts factored by CEFs were reasonable – 0.040 crash/year based on conflicts versus 0.032 crash/year based on actual reported crashes at ‘high’ speed approach with exclusive right-turn lane, and 0.042 crash/year versus 0.040 crash/year respectively at ‘low’ speed approach with exclusive right-turn lane. In case of radius right-turn treatment, the estimate of 0.137 crash/year based on conflicts seemed to be slightly higher compared to 0.100 crash/year based on actual crashes. However, it needs to be noted that these estimates for radius right-turn treatment was based on small sample size. When all observations were viewed together, the estimates were 0.054 crash/year based on conflicts versus 0.043

crash/year based on actual crashes. In other words, the use of CEFs to determine the expected number of all types of crashes caused by right-turning vehicles was reasonable.

Table 6.5. Expected number of crashes per year caused by right-turning vehicles

Study Approach[(A)]	Cross Road	Right-turn Treatment Type	Post. Speed (mph)	AADT [(B)]	% RT	No. of Crashes/Year	
						Based on Conflicts	Based on Reported Crashes
TH-3 NB	170th St./CR-58	Exclusive	55	9,046	2.0	0.007	0.00
TH-3 SB	170th St./CR-58	Exclusive	55	9,046	15.1	0.051	0.00
TH-3 SB	CR-66 (Vermillion River Trail)	Exclusive	55	11,246	0.2	0.001	0.00
TH-3 NB	CR-66 (Vermillion River Trail)	Exclusive	55	11,246	17.7	0.093	0.00
TH-3 WB	TH-149	Exclusive	50	12,013	3.2	0.018	0.20
TH-5 WB	Minnewashta Pkwy (Victoria)	Exclusive	55	22,014	4.4	0.091	0.00
TH-8 WB	Pleasant Valley Rd./CR-26/82	Exclusive	55	11,376	0.7	0.004	0.00
TH-8 EB	Pleasant Valley Rd./CR-26/82	Exclusive	55	11,376	22.2	0.119	0.20
TH-12 WB	Budd Ave. (Maple Plain)	Exclusive	35	17,872	3.9	0.047	0.00
TH-12 EB	Budd Ave. (Maple Plain)	Exclusive	35	17,872	3.4	0.041	0.00
TH-12 WB	CR-83/Halgren Rd.	Exclusive	35	16,598	2.4	0.025	0.20
TH-12 EB	CR-83/Halgren Rd.	Exclusive	35	16,598	4.5	0.047	0.00
TH-47 NB	McKinley St. NW	Exclusive	45	17,574	2.2	0.025	0.00
TH-47 SB	McKinley St. NW	Exclusive	45	17,574	1.3	0.015	0.00
TH-97 WB	Hornsby St. NE	Radius	55	15,546	0.2	0.017	0.20
TH-97 EB	Hornsby St. NE	Exclusive	55	15,546	3.0	0.031	0.00
TH-149 SB	Wescott Rd.	Exclusive	55	9,468	25.8	0.095	0.00
TH-149 NB	Wescott Rd.	Exclusive	55	9,468	7.7	0.029	0.00
TH-12 EB	CR-90, Independence	Radius	35	17,872	6.7	0.485	0.20
TH-12 WB	CR-90, Independence	Exclusive	35	17,872	4.2	0.050	0.00
TH-13 NB	150th St.	Exclusive	45	15,939	4.1	0.037	0.20
TH-13 SB	150th St.	Exclusive	45	15,939	7.8	0.070	0.00
TH-55 EB	CR-42/CR-85	Exclusive	55	15,639	5.8	0.060	0.00
TH-55 WB	CR-42/CR-85	Exclusive	55	15,639	0.4	0.004	0.00
TH-212 EB	Kelly Ave.	Exclusive	55	9,936	0.5	0.002	0.00
TH-212 WB	Kelly Ave.	Exclusive	55	9,936	0.2	0.001	0.00
TH-284 NB	CR-153	Radius	55	3,675	2.3	0.008	0.00
TH-284 SB	CR-153	Radius	55	3,675	11.2	0.037	0.00

[(A)] NB – Northbound, SB – Southbound, EB – Eastbound, WB – Westbound. [(B)] AADT – Five-year average AADT.

Table 6.6. Comparison of expected crash/year based on conflicts and reported crashes

Right-turn Treatment	Speed Category	Sample Size	Expected Crash per Year					
			Based on Actual Crash			Based on Conflicts		
			Average	St. Dev.	St. Error	Average	St. Dev.	St. Error
Exclusive	High	19	0.032	0.075	0.017	0.040	0.038	0.009
Exclusive	Low	5	0.040	0.089	0.040	0.042	0.010	0.004
Radius	All	4	0.100	0.116	0.058	0.137	0.233	0.116
Combined	All	28	0.043	0.084	0.016	0.054	0.090	0.017

6.3 Safety effectiveness of right-turn lanes

The safety effectiveness of right-turn lanes was determined in terms of the number and the economic cost of crashes that the right-turn lanes are expected to save. The estimated conflicts due to right-turns factored by CEFs were the estimates of the expected number of crashes, including all crash types, caused by right-turning vehicles. The savings in the economic cost of crashes caused by right-turning vehicles were estimated based on the unit cost of crash presented in Table 4.9. The intersection and driveway approaches were analyzed separately.

6.3.1 Right-turn lanes at intersection approaches

The safety effectiveness of right-turn lanes at intersection approaches in terms of the number of crashes saved per year was determined by subtracting the annual number of crashes estimated at approaches with right-turn lanes from the number estimated at approaches without right-turn lanes at the same road condition. For a given combination of traffic volume (AADT), posted roadway speed limit and percent right-turns, the number of crashes per year caused by right-turning vehicles at intersection approaches with or without right-turn lanes was estimated by using the relationship below:

$$A_{int,k} = 365.\sum_{i=1}^{24}\left(\frac{RTC_{ik}}{1000}.\frac{AADT}{2}.r_i\right).CEF_{kl}; \qquad (6.3)$$

where $A_{int,k}$ is the expected number of crashes/year caused by right-turning vehicles at an intersection approach with the k^{th} right-turn treatment type; and AADT is annual average daily traffic (vpd).

The crash estimates and the crash savings per year at different road conditions are presented in Figure 6.1 for the posted roadway speed limits of 25, 35, 45 and 55 mph. It was found that the number of crashes saved per year by providing a right-turn lane was perceptible, especially at higher values of traffic volume, posted roadway speed limit and percent right turns. The crash savings or the numbers of crashes eliminated by providing a right-turn lane estimated in this study were also compared with the crash savings estimated based on the methodologies adopted by McCoy et al. (1993) and Hasan and Stokes (1996). These comparisons are presented in Appendix G.

On the other hand, the safety effectiveness of right-turn lanes at intersection approaches in terms of the economic cost of crashes saved per year was determined by subtracting the estimated annual economic cost of crashes caused by right-turning vehicles at approaches with right-turn lanes from the cost estimated at approaches without right-turn lanes at the same road condition. The cost of crashes at intersection approaches with and without right-turn lanes was estimated by using the relationship shown below:

$$C_{int,k} = A_{int,k}.c_{lk}; \quad (6.4)$$

where $C_{int,k}$ is the expected economic cost of crashes/year caused by right-turning vehicles at an intersection approach with the k^{th} right-turn treatment type; and c_{lk} is the expected economic cost of a crash caused by a right-turning vehicle at an approach with the k^{th} right-turn treatment type operating under the l^{th} speed category (Table 4.9).

The economic cost of crashes per year estimated at intersection approaches with radius and exclusive right-turn lane treatments, as well as the economic cost savings per year at intersection approaches with exclusive right-turn lanes are presented in Figure 6.2 for the posted roadway speed limits of 25, 35, 45 and 55 mph. It was found that a substantial amount of economic cost could be saved annually by providing approaches with right-turn lanes.

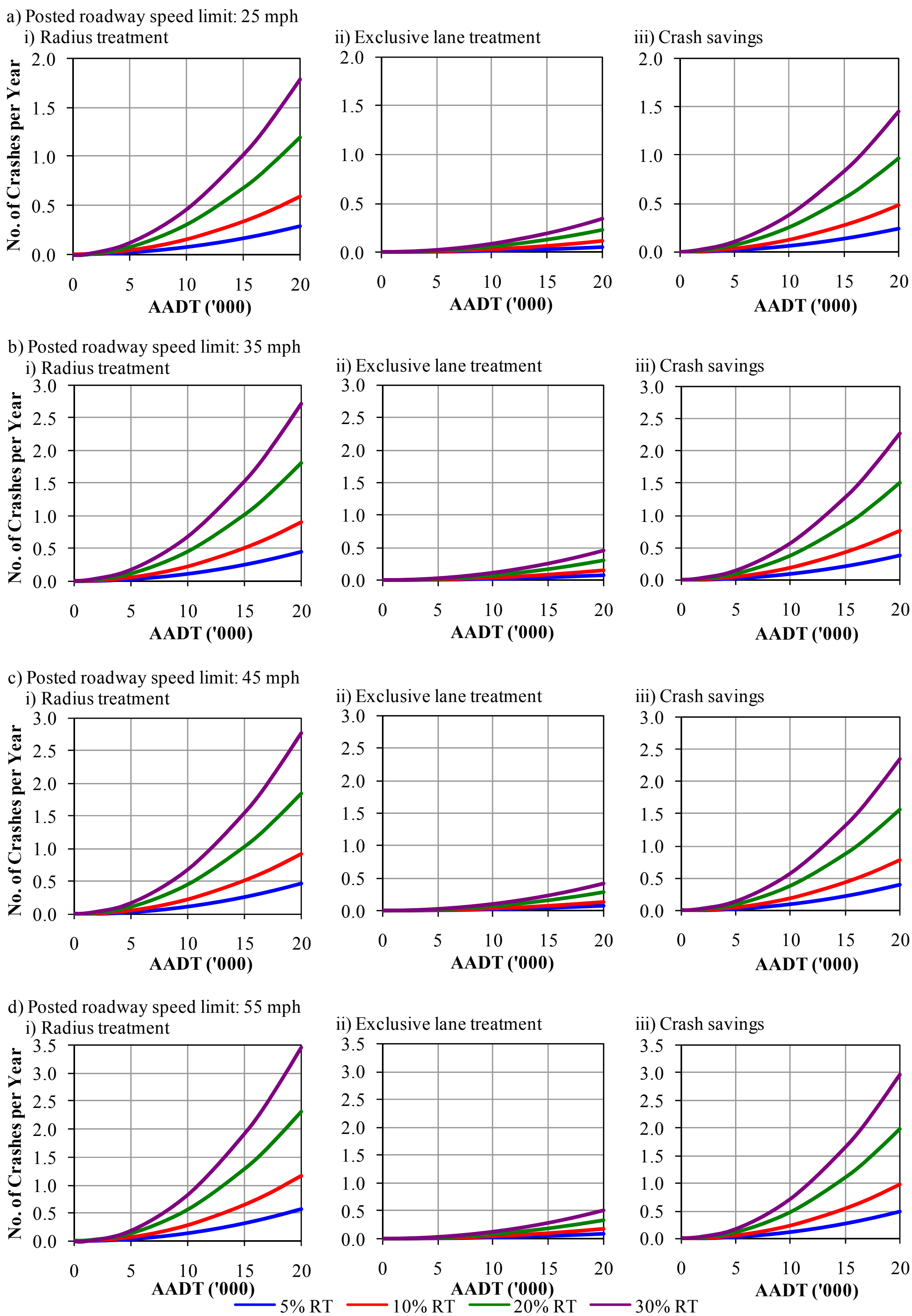


Figure 6.1. Crash estimates and crash savings at intersection approaches.

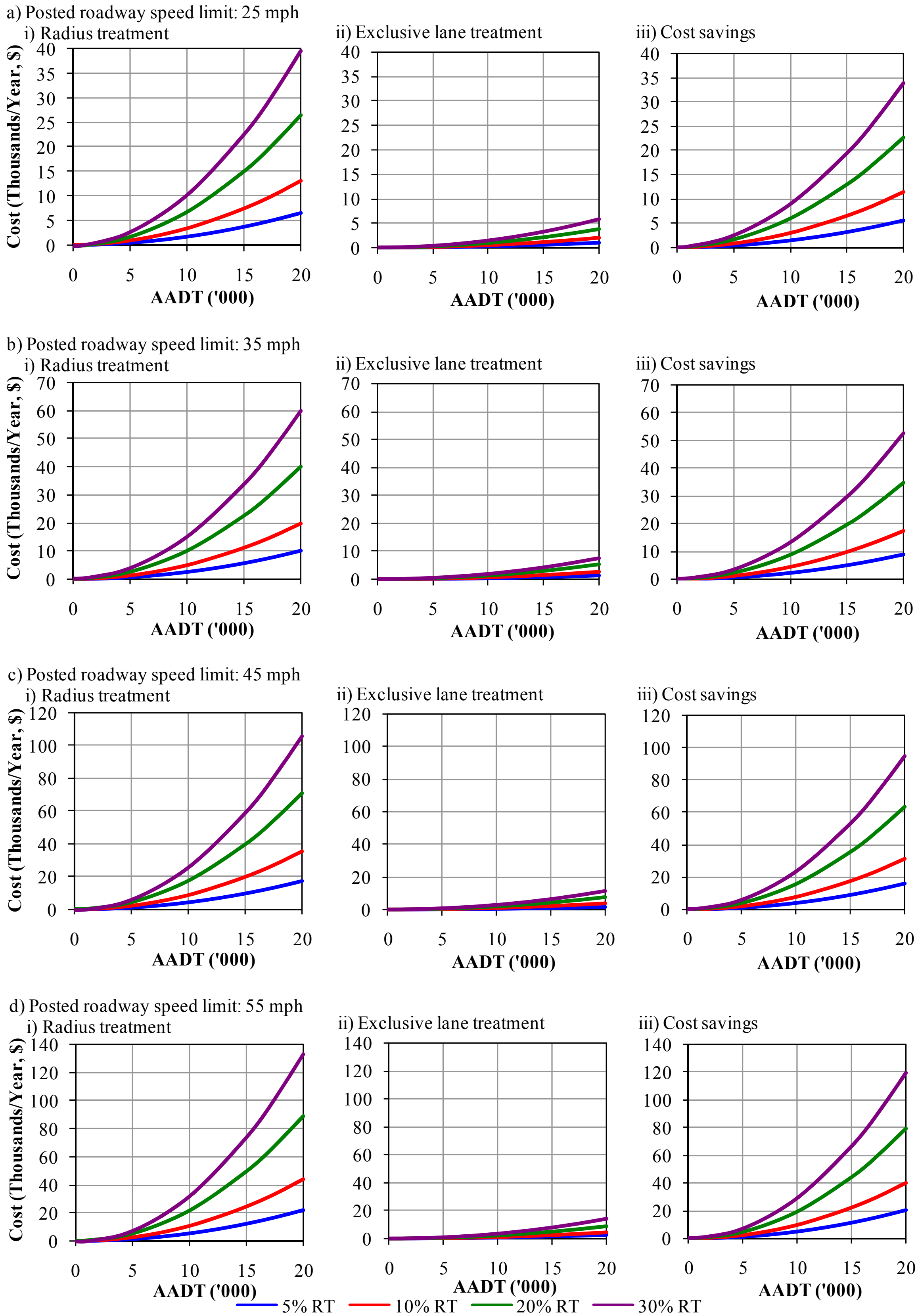


Figure 6.2. Cost estimates and cost savings at intersection approaches.

6.3.2 Right-turn lanes at driveway approaches

The safety effectiveness of right-turn lanes at driveway approaches in terms of the number of crashes saved per year was determined in the same manner as the safety effectiveness of right-turn lanes at intersection approaches. However, the annual number of crashes, including all crash types, caused by vehicles making right turns at driveway approaches with and without right-turn lanes was estimated by using the relationship shown below:

$$A_{dr,k} = 365.\sum_{i=1}^{24}\left(\frac{RTC_{ik}}{1000}.\frac{AADT}{2}.r_i\right).CEF_{kl}.RR_{dr,kl}; \tag{6.5}$$

where $A_{dr,k}$ is the expected number of crashes/year caused by right-turning vehicles at a driveway approach with the k^{th} right-turn treatment type; and $RR_{dr,kl}$ is the relative risk of an RE/SS crash caused by a right-turning vehicle at a driveway approach with the k^{th} right-turn treatment type operating under the l^{th} posted speed limit category compared to the risk at an intersection approach operating under the same road condition.

The relative risks of RE/SS crashes caused by right-turning vehicles at driveway approaches compared to the risks at intersection approaches were as provided in Table 4.6. The estimated numbers of crashes per year at driveway approaches with and without right-turn lanes, as well as the expected crash savings per year by providing right-turn lanes are presented in Figure 6.3 for the posted speed limits of 25, 35, 45 and 55 mph. It was found that the safety effectiveness of right-turn lanes at driveway approaches in terms of the number of crashes saved per year was comparatively higher than that estimated for intersection approaches.

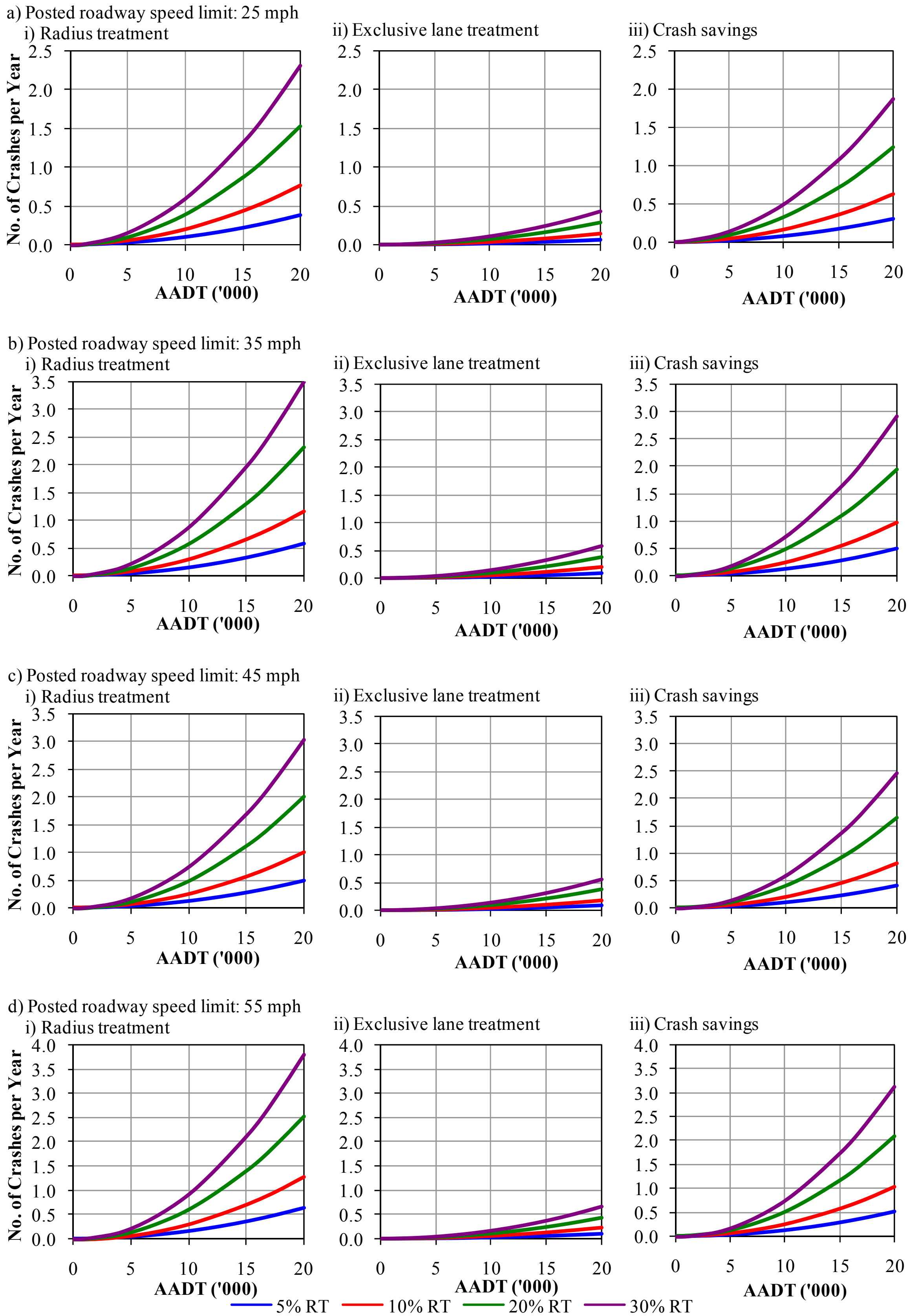


Figure 6.3. Crash estimates and crash savings at driveway approaches.

Similarly, the safety effectiveness of right-turn lanes at driveway approaches in terms of the economic cost of crashes saved per year was determined in the same manner as that for intersection approaches. However, the annual economic cost of crashes caused by right-turning vehicles at driveway approaches with and without right-turn lanes was estimated using the relationship shown below:

$$C_{dr,k} = A_{dr,k}.c_{lk}; \qquad (6.6)$$

where $C_{dr,k}$ is the expected economic cost/year of crashes due to right turns at driveway approaches with the k^{th} right-turn treatment type.

The estimated annual economic cost of crashes at driveway approaches at radius and exclusive right-turn lane treatments are presented in Figure 6.4 for the posted speed limits of 25, 35, 45 and 55 mph. The corresponding annual economic cost savings achievable by providing exclusive right-turn lanes at driveway approaches are also presented. Similar to the amount of cost savings estimated for intersection approaches, it was found that a substantial amount of economic cost of crashes could be saved by providing right-turn lanes at driveway approaches. However, it was also found that the annual economic cost savings achievable by providing right-turn lanes at driveway approaches were comparatively higher than those achievable by providing right-turn lanes at intersection approaches. These findings were considered significant, since they underscored the need of developing a separate set of warrant guidelines for right-turn lanes at driveway approaches. Hence, two separate sets of safety-based volume warrants for right-turn lanes, one set at intersection approaches and another set at driveway approaches, were developed in this dissertation.

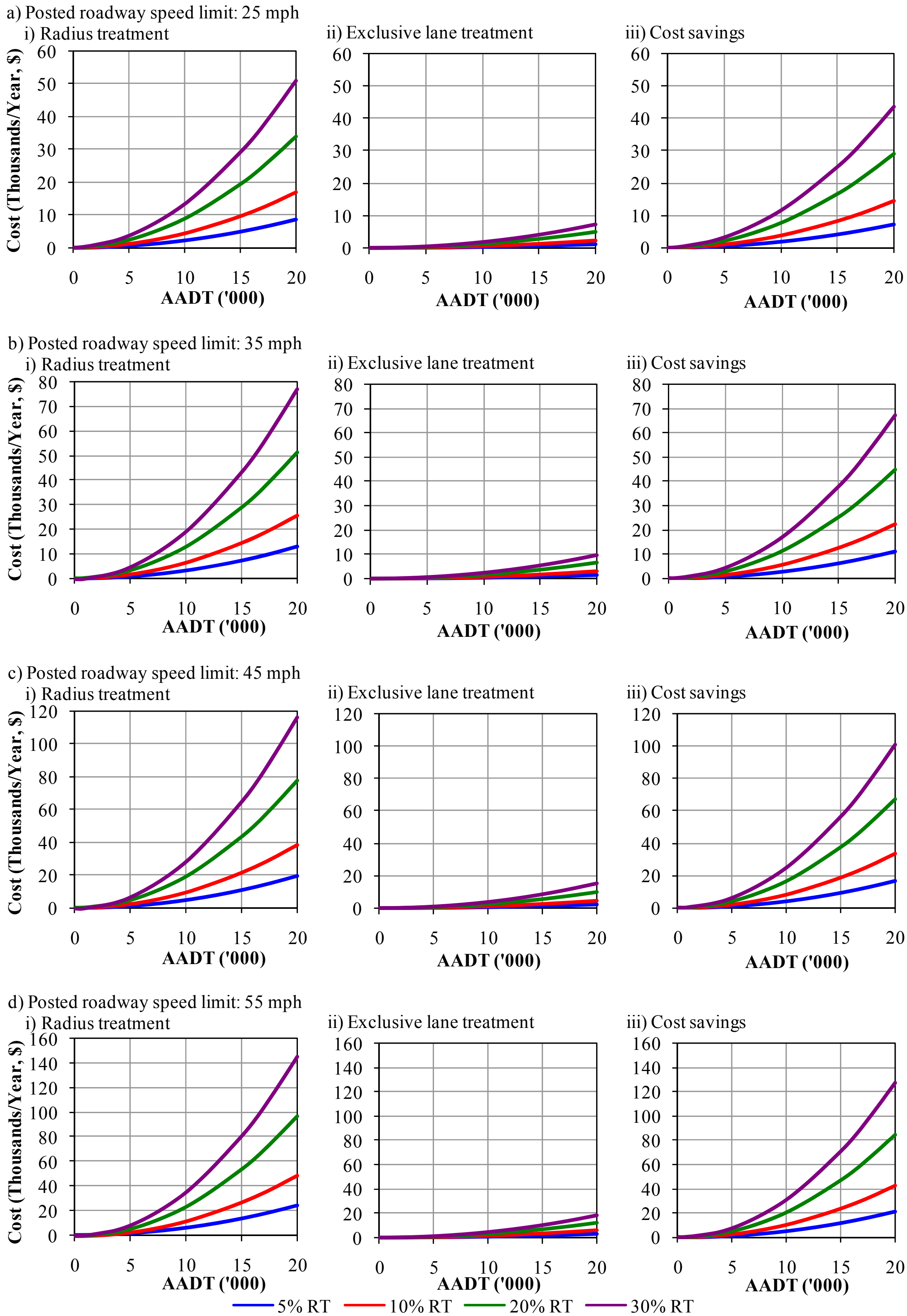


Figure 6.4. Cost estimates and cost savings at driveway approaches.

6.4 Safety-based volume warrants for right-turn lanes

The safety-based volume warrants for right-turn lanes were developed in terms of the minimum number of right turns during the design hour (RTDHV) that is required to justify their construction. The thresholds of the minimum number of RTDHV were established by performing benefit-cost analyses. The costs used in analyses were the right-turn lane construction costs, while the benefits were determined in terms of economic cost savings as a result of fewer crashes caused by vehicles making right turns at approaches with right-turn lanes compared to those at approaches without right-turn lanes.

However, to establish an RTDHV threshold, it was first required to determine a relationship between the directional design hour volume (DDHV) and directional annual average daily traffic (DAADT). This relationship was determined by fitting a least squares DDHV prediction model based on one-year continuous traffic volume counts recorded by eight ATRs located around the survey locations. The fitted model is provided below:

$$DDHV = -25.5 + 0.113.(DAADT),$$

$$[S = 134.1210,\ R^2 = 91.80\%,\ Adj.\ R^2 = 91.80\%,\ Pred.\ R^2 = 91.80\%] \quad (6.7)$$

where DDHV is directional design hour volume (vph), and DAADT is directional annual average daily traffic (vpd).

6.4.1 Right-turn lanes at intersection approaches

For a given DDHV, Equation 6.7 provided a relationship to find the corresponding DAADT, which was required to determine the hourly approach volumes in Equations 5.4a and 5.4b to estimate the hourly number of conflicts due to right turns per TEV at both radius and exclusive right-turn lane treatments for a given combination of posted roadway speed limit and percent right turns. The hourly conflicts were used to determine the expected number of conflicts in the design year. The estimated conflicts in the design year were multiplied by the CEFs and the costs of crashes to estimate the annual economic costs of crashes caused by vehicles making right turns at radius and exclusive right-turn lane treatments, as well as the annual economic cost savings (benefits) expected at exclusive right-turn lanes. Next, the total expected right-turn lane construction cost was annualized (costs).

The minimum number of RTDHV at which the expected safety benefits of exclusive right-turn lanes exceed their construction costs was then determined by solving the difference between benefits and costs, which was set equal to zero. The steps of establishing the minimum RTDHV thresholds are summarized below through a set of relationships:

$$DAADT = (25.5 + DDHV)/0.113; \tag{6.8a}$$

$$VOL_i = DAADT.r_i; \tag{6.8b}$$

$$RTP = (RTDHV/DDHV).100; \tag{6.8c}$$

$$\begin{aligned} RTC_{Ri} = {} & - 1.540 + 0.0415.(SPD) + 1.210.(RTP) + 0.00206.(VOL_i) \\ & - 0.0357.(SPD).(RTP) - 0.000054.(SPD).(VOL_i) - 0.00563.(RTP).(VOL_i) \\ & + 0.000710.(SPD).(RTP).(VOL_i); \end{aligned} \tag{6.8d}$$

$$\begin{aligned} RTC_{Li} = {} & - 0.544 + 0.0160.(SPD) + 0.058.(RTP) + 0.00074.(VOL_i) \\ & - 0.00318.(SPD).(RTP) - 0.000020.(SPD).(VOL_i) + 0.000521.(RTP).(VOL_i) \\ & + 0.000108.(SPD).(RTP).(VOL_i); \end{aligned} \tag{6.8e}$$

$$B_{l,int} = 365.\left[\sum_{i=1}^{24}\left(\frac{RTC_{Ri}}{1000}.VOL_i\right).CEF_{Rl}.c_{Rl} - \sum_{i=1}^{24}\left(\frac{RTC_{Li}}{1000}.VOL_i\right).CEF_{Ll}.c_{Ll}\right]; \tag{6.8f}$$

$$C_{RTL} = M_{RTL} \cdot \left(\frac{p.(1+p)^n}{(1+p)^n - 1} \right); \tag{6.8g}$$

$$B_{l,int} - C_{RTL} = 0; \tag{6.8h}$$

where VOL_i is the hourly approach volume during the i^{th} hour of day (vph); r_i is the portion of AADT during the i^{th} hour of day; RTP is percent right turns (%); RTDHV is the number of right turns during the design hour (vph); SPD is posted roadway speed limit (mph); RTC_{Ri} is the number of conflicts due to right turns per TEV during the i^{th} hour of day at an approach with a radius right-turn treatment (Equation 5.4a); RTC_{Li} is the number of conflicts due to right turns per TEV during the i^{th} hour of day at an approach with an exclusive right-turn lane treatment (Equation 5.4b); $B_{l,int}$ is the estimated benefits in terms of the economic cost of crashes caused by right-turning vehicles saved per year at an intersection approach with a right-turn lane operating under the l^{th} posted speed limit category ($); C_{RTL} is the annualized cost of constructing a right-turn lane ($); CEF_{Rl} is the crash estimation factor for radius right-turn treatment operating under the l^{th} posted speed limit category (Table 6.4); CEF_{Ll} is the crash estimation factor for exclusive right-turn lane treatment operating under the l^{th} posted speed limit category (Table 6.4); c_{Rl} is the estimated economic cost of a crash caused by a right-turning vehicle at an approach with a radius right-turn treatment operating under the l^{th} posted speed limit category ($) (Table 4.9); c_{Ll} is the estimated economic cost of a crash caused by a right-turning vehicle at an approach with an exclusive right-turn lane treatment operating under the l^{th} posted speed limit category ($) (Table 4.9); M_{RTL} is the total cost of constructing a right-turn lane ($); p is interest rate (decimals); and n is the service life of exclusive right-turn lanes (number of years).

The relationships presented above were solved using VBA programs in MS Excel software. The safety-based volume warrants for exclusive right-turn lanes at intersection approaches for DDHV ranging from 100 to 1,500 vph are presented graphically in Figure 6.5. The volume thresholds are also summarized in Table 6.7. The posted roadway speed limits considered for the development of warrant guidelines include 25, 35, 45 and 55 mph. The warrant guidelines indicate the minimum number of RTDHV corresponding to various combinations of DDHV and posted roadway speed limit at which the costs of constructing right-turn lanes are fully justified by the safety benefits they are expected to provide to the road users. Since the right-turn lane construction costs may vary significantly, depending on many such factors as intersection geometry, design, location, land availability, etc., a total of sixteen different cost scenarios ranging from $15,000 to $90,000 were considered for developing the warrant guidelines. These costs of constructing right-turn lanes were annualized based on a 3.1% interest rate (OIM, 2009), a 20-year service life and a zero salvage value.

The volume warrants for right-turn lanes at intersection approaches by taking into account their safety as well as operational benefits are presented in Appendix H. The expected annual savings in operational costs resulting from the reduction in delay and fuel consumption at approaches with right-turn lanes incorporated in these warrant guidelines were estimated based on Varma et al. (2008).

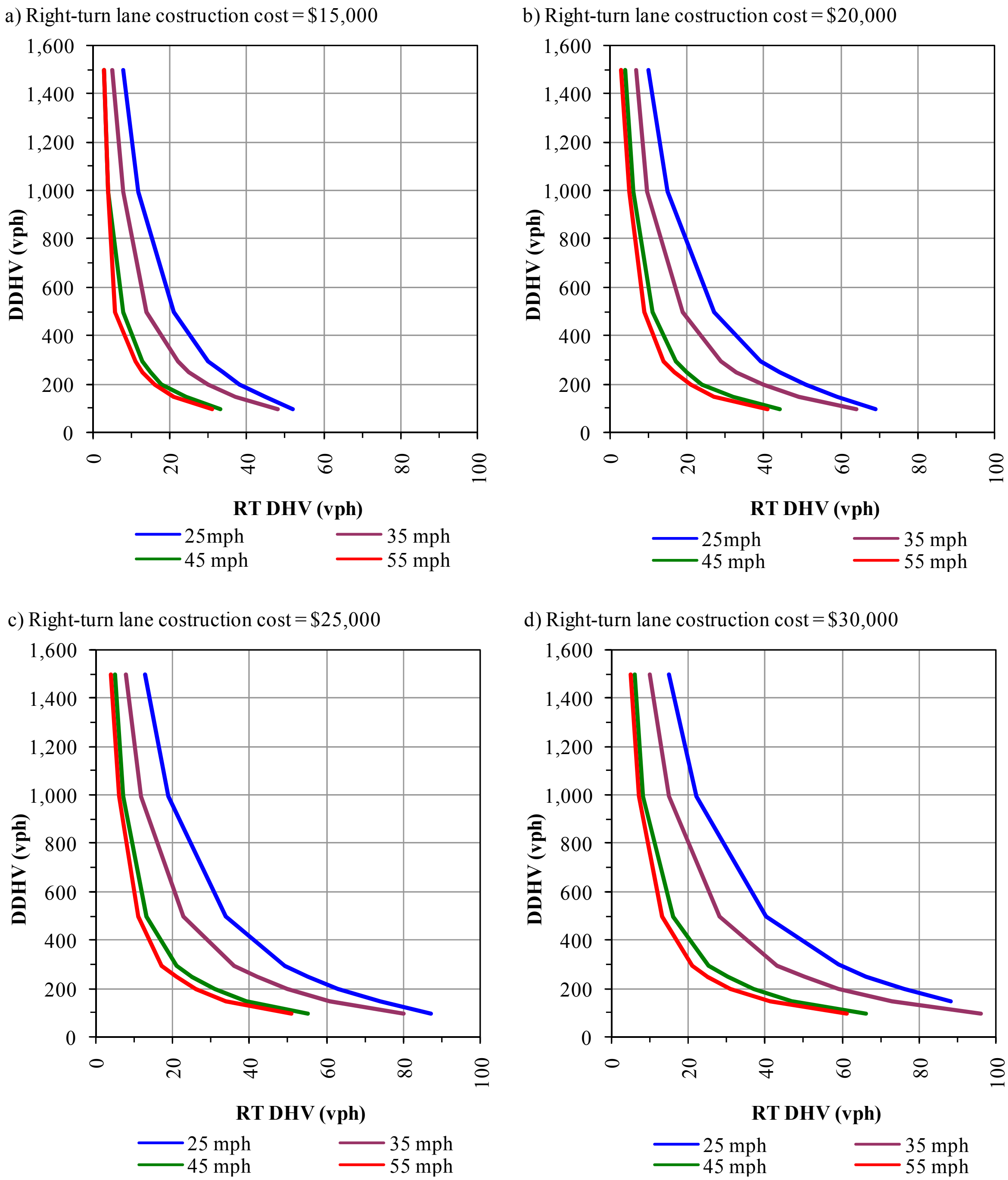


Figure 6.5. Safety-based volume warrants for right-turn lanes at intersection approaches.

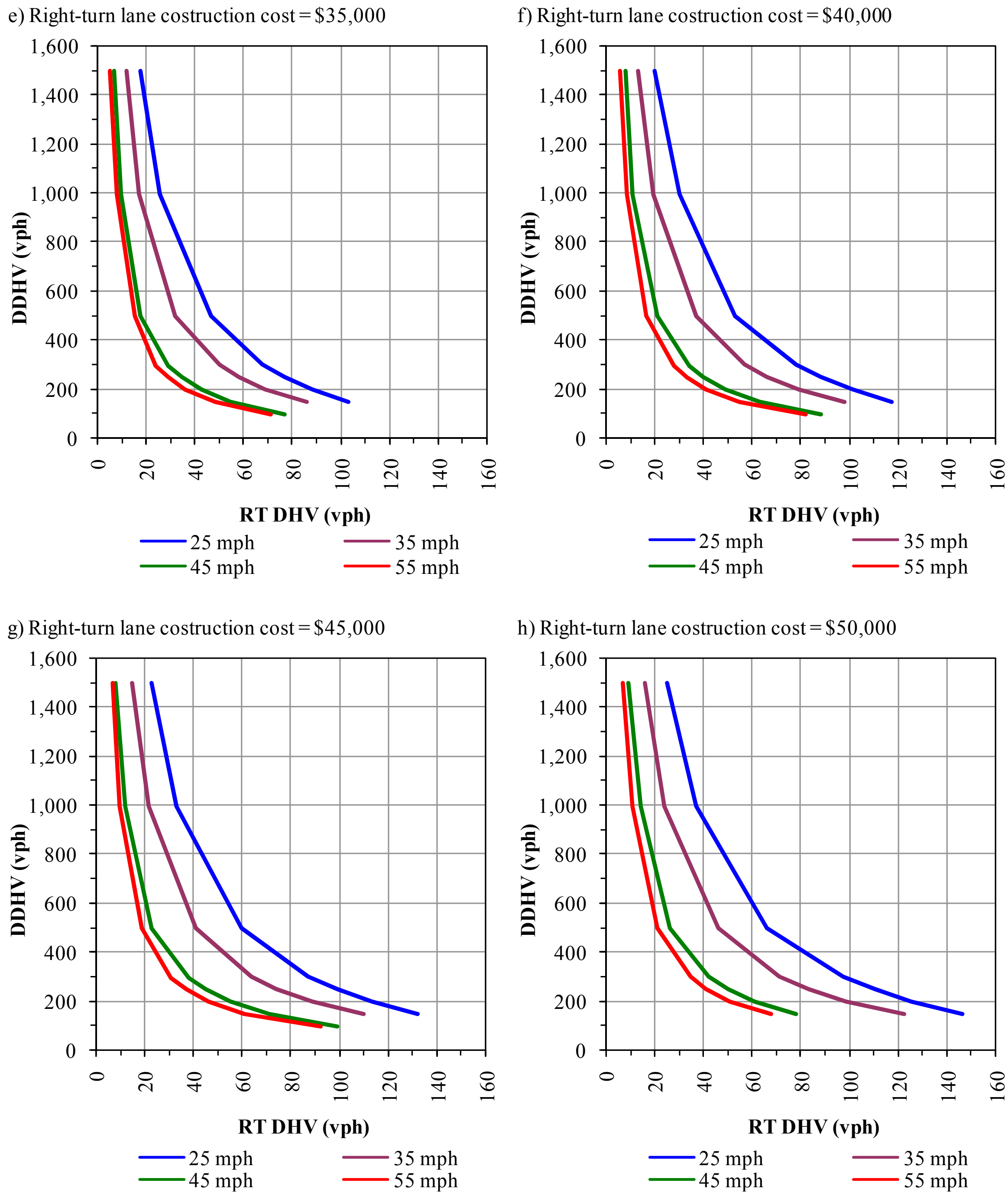


Figure 6.5. (Continued)

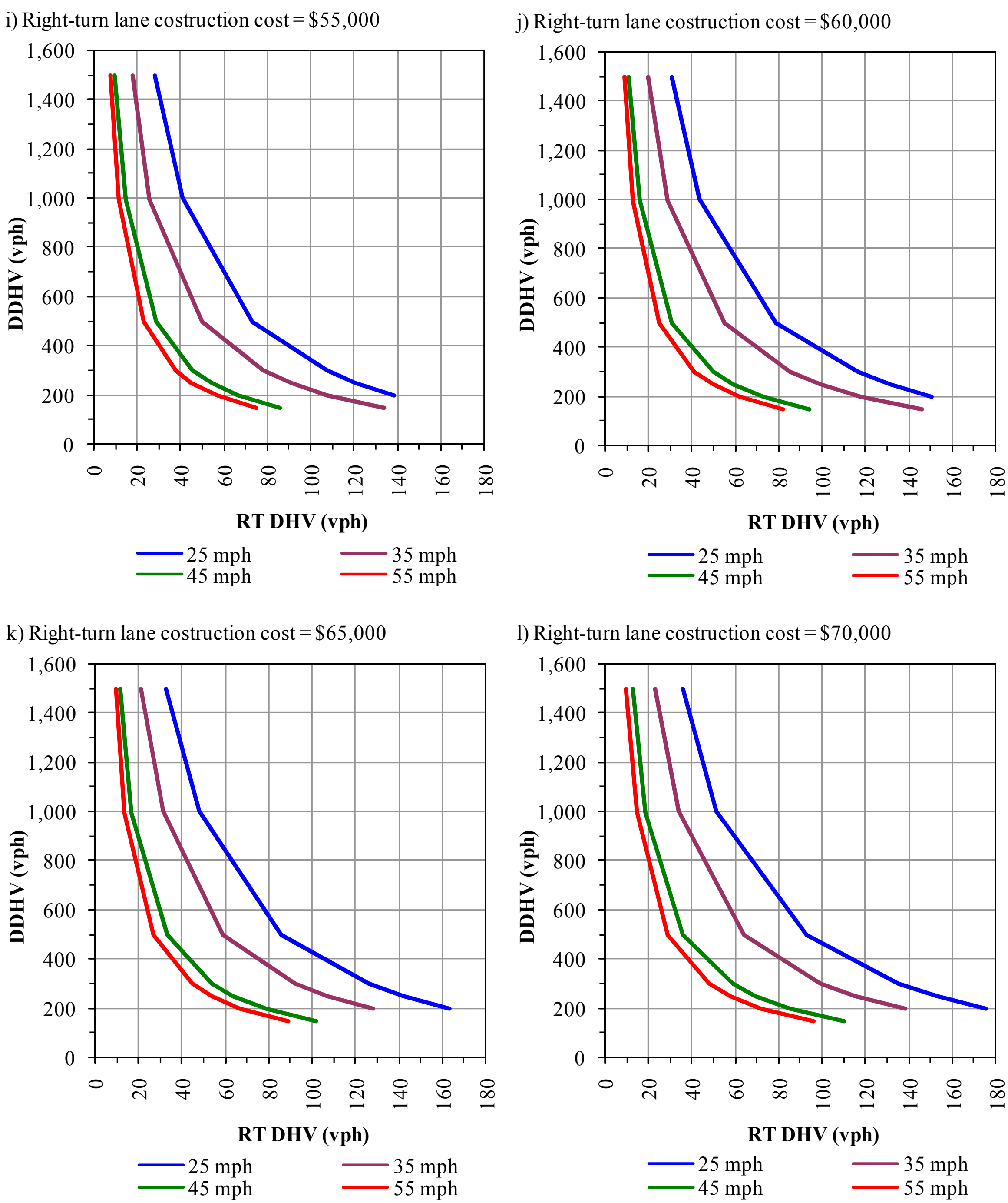


Figure 6.5. (Continued)

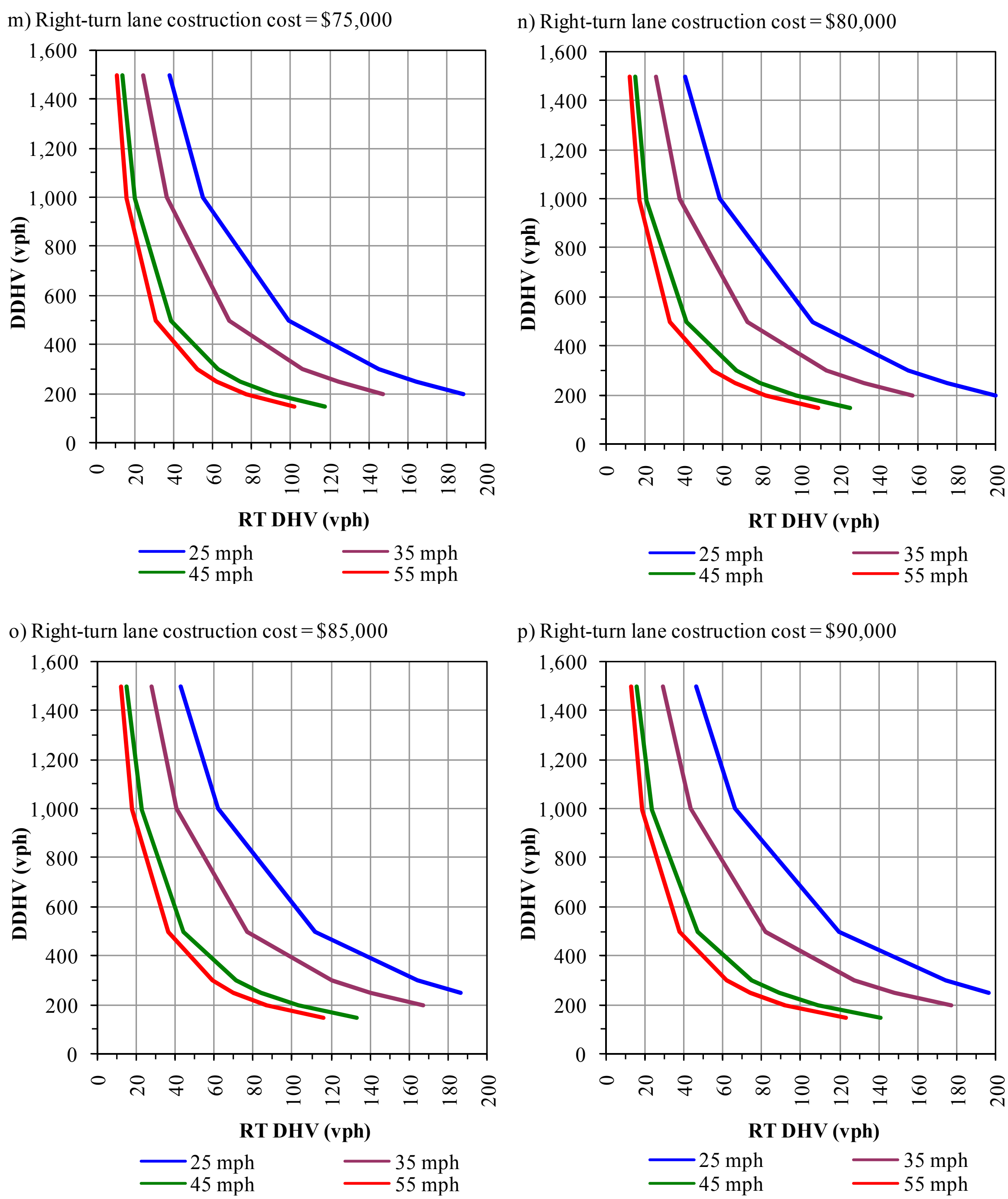


Figure 6.5. (Continued)

Table 6.7. Safety-based volume warrants for right-turn lanes at intersection approaches

Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	Right-turn Lane Cost = $15,000								Right-turn Lane Cost = $20,000							
	DDHV (vph)								DDHV (vph)							
	100	150	200	250	300	500	1,000	1,500	100	150	200	250	300	500	1,000	1,500
25	52	45	38	34	30	21	12	8	69	59	51	44	39	27	15	10
35	48	37	30	25	22	14	8	5	64	49	40	33	29	19	10	7
45	33	24	18	15	13	8	4	3	44	32	24	20	17	11	6	4
55	31	21	16	13	11	6	4	3	41	27	21	17	14	9	5	3
Speed (mph)	Right-turn Lane Cost = $25,000								Right-turn Lane Cost = $30,000							
25	87	74	63	55	49	34	19	13	NA*	88	76	66	59	40	22	15
35	80	61	50	42	36	23	12	8	96	73	59	50	43	28	15	10
45	55	39	31	25	21	13	7	5	66	47	37	30	25	16	8	6
55	51	34	26	21	17	11	6	4	61	41	31	25	21	13	7	5
Speed (mph)	Right-turn Lane Cost = $35,000								Right-turn Lane Cost = $40,000							
25	NA	103	88	77	68	47	26	18	NA	117	101	88	78	53	30	20
35	NA	86	69	58	50	32	17	12	NA	98	79	66	57	37	19	13
45	77	55	43	35	29	18	10	7	88	63	49	40	34	21	11	8
55	71	48	36	29	24	15	8	5	82	55	41	33	28	17	9	6
Speed (mph)	Right-turn Lane Cost = $45,000								Right-turn Lane Cost = $50,000							
25	NA	132	113	99	87	60	33	23	NA	146	125	110	97	66	37	25
35	NA	110	89	74	64	41	22	15	NA	122	98	83	71	46	24	16
45	99	71	55	45	38	23	12	8	NA	78	61	50	42	26	14	9
55	92	61	46	37	31	19	10	7	NA	68	51	41	35	21	11	7
Speed (mph)	Right-turn Lane Cost = $55,000								Right-turn Lane Cost = $60,000							
25	NA	NA	138	120	107	73	41	28	NA	NA	150	131	116	79	44	31
35	NA	134	108	91	78	50	26	18	NA	146	118	99	85	55	29	20
45	NA	86	67	55	46	29	15	10	NA	94	73	59	50	31	16	11
55	NA	75	57	45	38	23	12	8	NA	82	62	50	41	25	13	9
Speed (mph)	Right-turn Lane Cost = $65,000								Right-turn Lane Cost = $70,000							
25	NA	NA	163	142	126	86	48	33	NA	NA	175	153	135	93	51	36
35	NA	NA	128	107	92	59	31	21	NA	NA	138	115	99	64	34	23
45	NA	102	79	64	54	34	17	12	NA	110	85	69	59	36	19	13
55	NA	89	67	54	45	27	14	10	NA	96	72	58	48	29	15	10
Speed (mph)	Right-turn Lane Cost = $75,000								Right-turn Lane Cost = $80,000							
25	NA	NA	188	164	145	99	55	38	NA	NA	200	175	155	106	59	41
35	NA	NA	147	124	106	68	36	24	NA	NA	157	132	113	73	38	26
45	NA	117	91	74	63	39	20	14	NA	125	97	79	67	41	21	15
55	NA	102	77	62	52	31	16	11	NA	109	82	66	55	33	17	12
Speed (mph)	Right-turn Lane Cost = $85,000								Right-turn Lane Cost = $90,000							
25	NA	NA	NA	186	164	112	62	43	NA	NA	NA	196	174	119	66	46
35	NA	NA	167	140	120	77	41	28	NA	NA	177	148	127	82	43	29
45	NA	133	103	84	71	44	23	15	NA	141	109	89	75	47	24	16
55	NA	116	87	70	59	36	18	12	NA	123	92	74	62	38	19	13

* Not applicable.

6.4.2 Right-turn lanes at driveway approaches

The safety-based volume warrants for right-turn lanes at driveway approaches were developed in the same manner as the warrants for right-turn lanes at intersection approaches discussed above. The annual safety benefits in terms of annual economic cost savings expected at right-turn lanes provided at driveway approaches were, however, estimated by using the relationship shown below:

$$B_{l,dr} = 365.\left[\sum_{i=1}^{24}\left(\frac{RTC_{Ri}}{1000}.VOL_i\right).CEF_{Rl}.c_{Rl}.RR_{Rl}\right]$$

$$-365.\left[\sum_{i=1}^{24}\left(\frac{RTC_{Li}}{1000}.VOL_i\right).CEF_{Ll}.c_{Ll}.RR_{Ll}\right]; \qquad (6.9a)$$

$$B_{l,dr} - C_{RTL} = 0; \qquad (6.9b)$$

where $B_{l,dr}$ is the estimated benefits in terms of the economic cost of crashes caused by right-turning vehicles saved per year at a driveway approach with a right-turn lane operating under the l^{th} posted speed limit category ($); RR_{Rl} is the relative risk of an RE/SS crash caused by a right-turning vehicle at a driveway approach with a radius right-turn treatment operating under the l^{th} posted speed limit category compared to the risk at an intersection approach operating under the same road condition; and RR_{Ll} is the relative risk of an RE/SS crash caused by a right-turning vehicle at a driveway approach with an exclusive right-turn lane operating under the l^{th} posted speed limit category compared to the risk at an intersection approach operating under the same road condition.

The other variables that were required to develop the warrant guidelines were same as mentioned earlier. The safety-based volume warrants for right-turn lanes at driveway approaches are presented graphically in Figure 6.6 and are also summarized in Table 6.8. It was found that the minimum RTDHV thresholds required for justifying the construction of right-turn lanes at driveway approaches were lower compared to those required at intersection approaches. The volume warrants for right-turn lanes at driveway approaches based on their safety and operational benefits are presented in Appendix H.

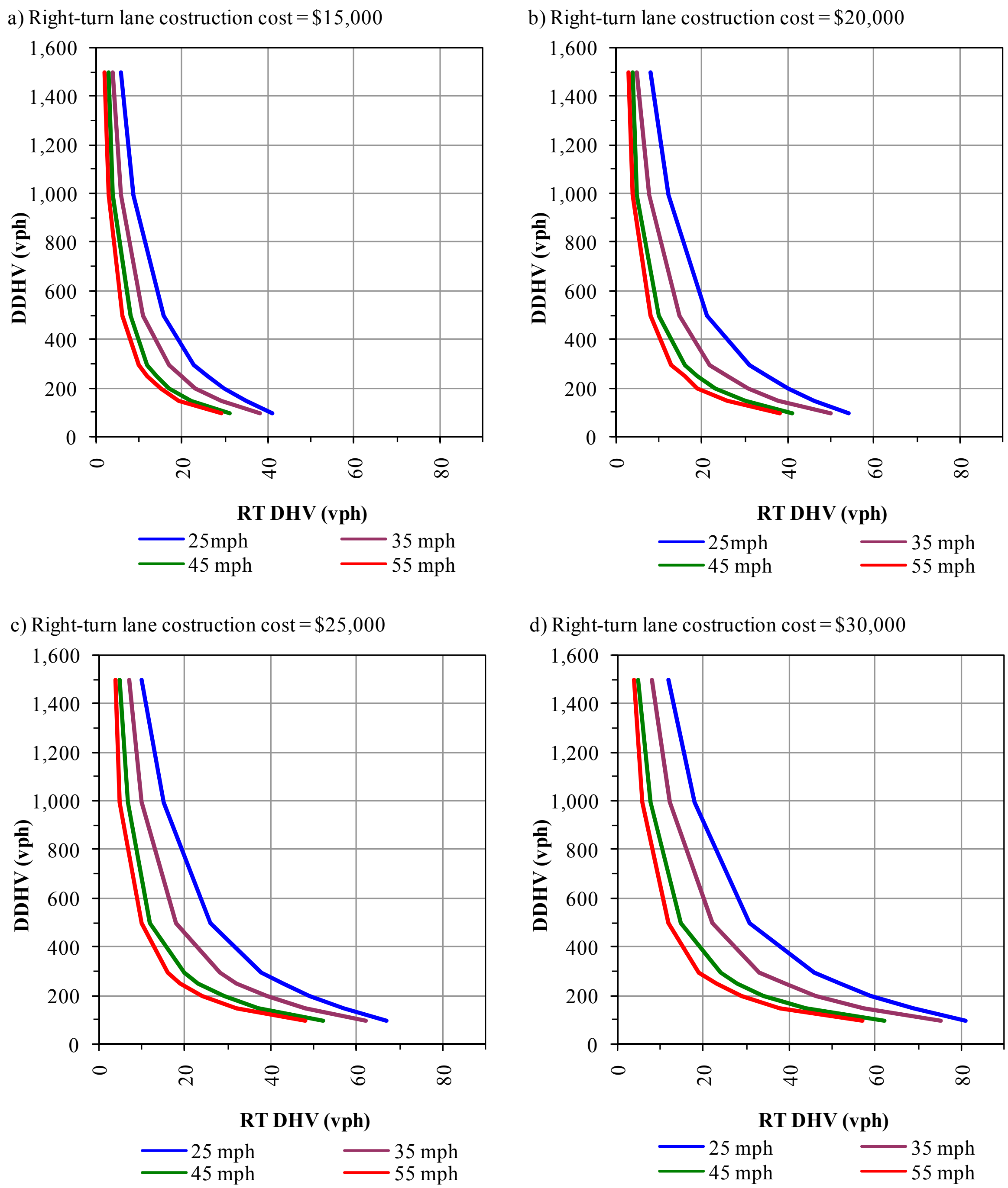


Figure 6.6. Safety-based volume warrants for right-turn lanes at driveway approaches.

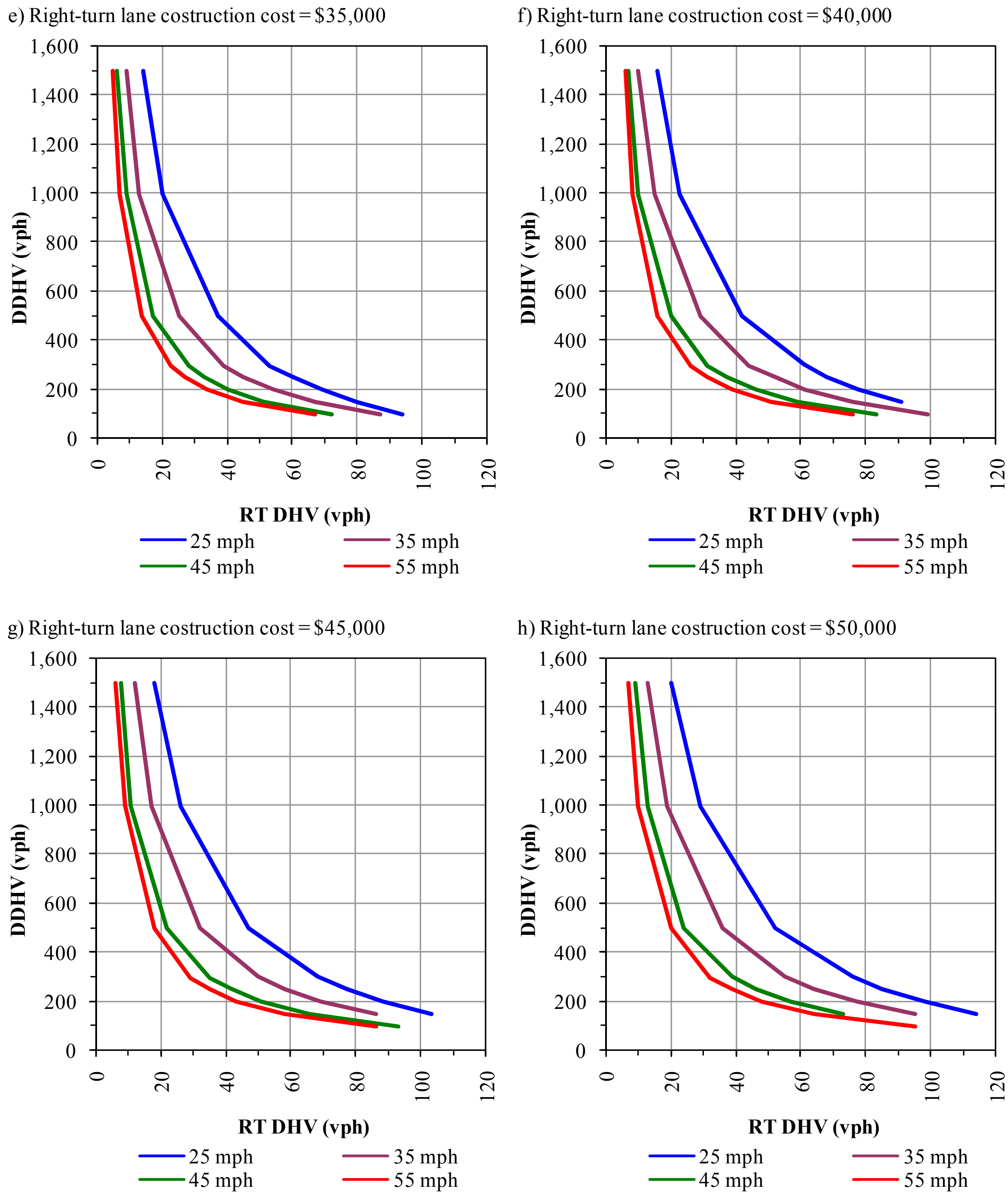


Figure 6.6. (Continued)

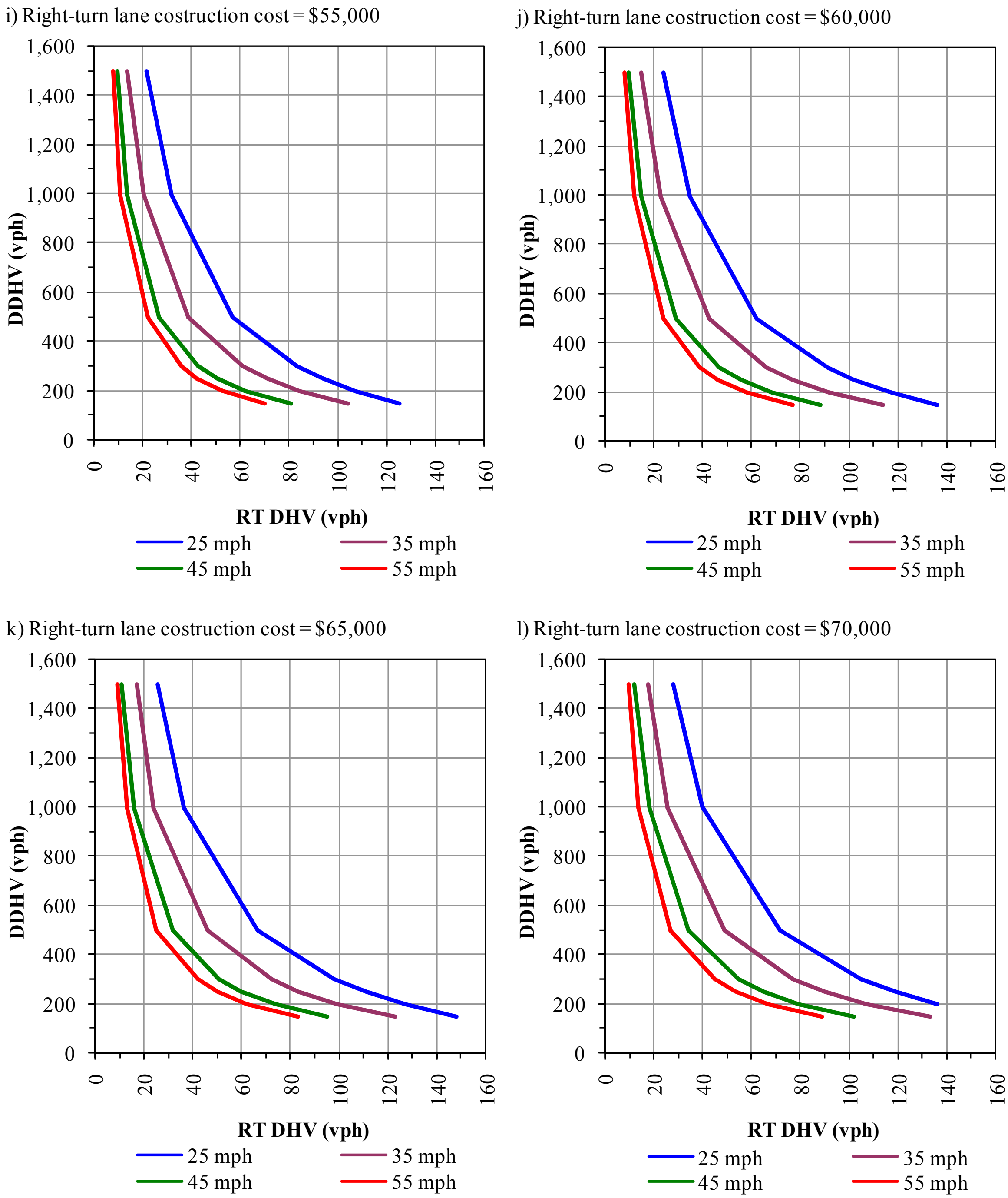
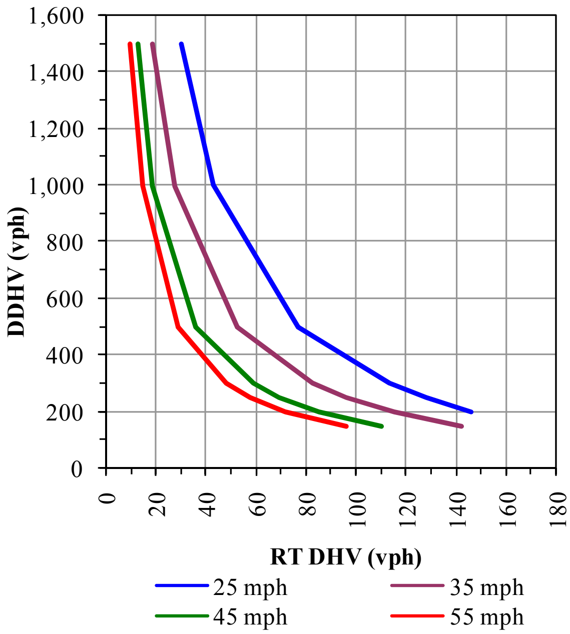
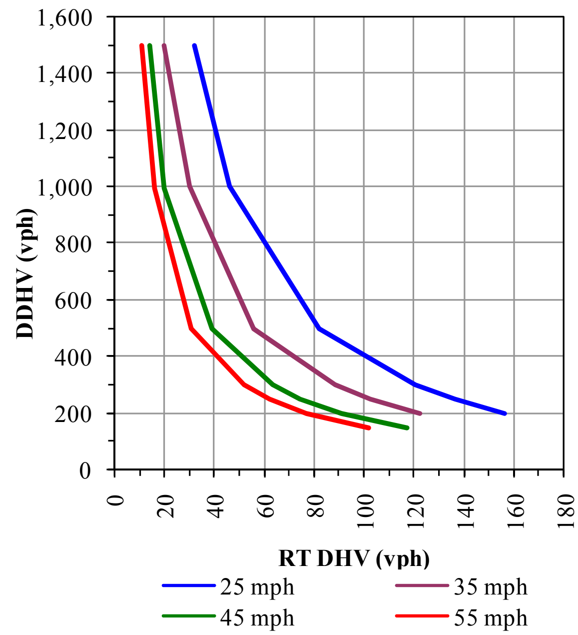


Figure 6.6. (Continued)

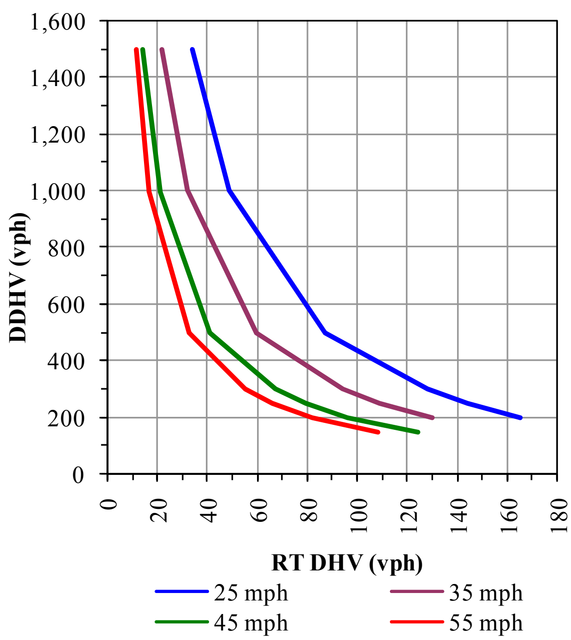
m) Right-turn lane costruction cost = $75,000



n) Right-turn lane costruction cost = $80,000



o) Right-turn lane costruction cost = $85,000



p) Right-turn lane costruction cost = $90,000

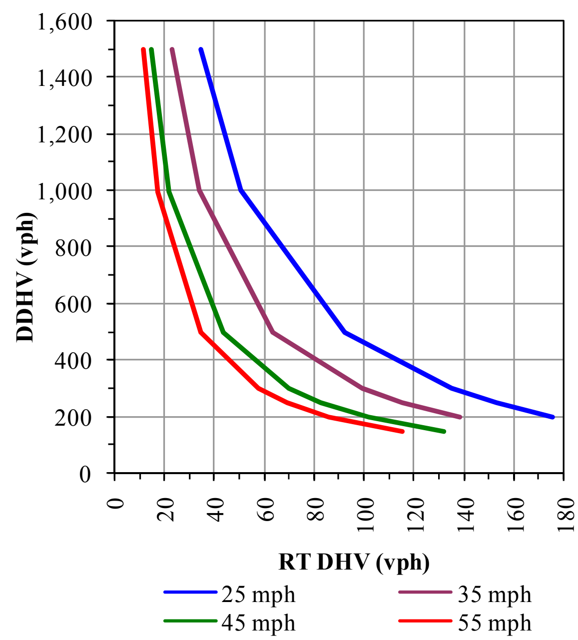


Figure 6.6. (Continued)

Table 6.8. Safety-based volume warrants for right-turn lanes at driveway approaches

Minimum Right-turn DHV (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	**Right-turn Lane Cost = $15,000**								**Right-turn Lane Cost = $20,000**							
	DDHV (vph)								**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
25	41	35	30	26	23	16	9	6	54	46	40	35	31	21	12	8
35	38	29	23	20	17	11	6	4	50	38	31	26	22	15	8	5
45	31	22	17	14	12	8	4	3	41	30	23	19	16	10	5	4
55	29	19	15	12	10	6	3	2	38	26	19	16	13	8	4	3
Speed (mph)	**Right-turn Lane Cost = $25,000**								**Right-turn Lane Cost = $30,000**							
25	67	57	49	43	38	26	15	10	81	69	59	52	46	31	18	12
35	62	48	39	32	28	18	10	7	75	57	46	39	33	22	12	8
45	52	37	29	23	20	12	7	5	62	44	34	28	24	15	8	5
55	48	32	24	19	16	10	5	4	57	38	29	23	19	12	6	4
Speed (mph)	**Right-turn Lane Cost = $35,000**								**Right-turn Lane Cost = $40,000**							
25	94	80	69	60	53	37	20	14	NA*	91	78	68	61	42	23	16
35	87	67	54	45	39	25	13	9	99	76	61	52	44	29	15	10
45	72	51	40	33	28	17	9	6	83	59	46	37	31	20	10	7
55	67	45	34	27	23	14	7	5	76	51	39	31	26	16	8	6
Speed (mph)	**Right-turn Lane Cost = $45,000**								**Right-turn Lane Cost = $50,000**							
25	NA	103	88	77	68	47	26	18	NA	114	98	85	76	52	29	20
35	NA	86	69	58	50	32	17	12	NA	95	77	64	55	36	19	13
45	93	66	51	42	35	22	11	8	NA	73	57	46	39	24	13	9
55	86	58	43	35	29	18	9	6	95	64	48	39	32	20	10	7
Speed (mph)	**Right-turn Lane Cost = $55,000**								**Right-turn Lane Cost = $60,000**							
25	NA	125	107	94	83	57	32	22	NA	136	117	102	91	62	35	24
35	NA	104	84	71	61	39	21	14	NA	114	92	77	66	43	23	15
45	NA	81	62	51	43	27	14	10	NA	88	68	56	47	29	15	10
55	NA	70	53	42	36	22	11	8	NA	77	58	46	39	24	12	8
Speed (mph)	**Right-turn Lane Cost = $65,000**								**Right-turn Lane Cost = $70,000**							
25	NA	148	127	111	98	67	37	26	NA	NA	136	119	105	72	40	28
35	NA	123	99	83	72	46	24	17	NA	133	107	90	77	49	26	18
45	NA	95	74	60	51	32	16	11	NA	102	79	65	55	34	18	12
55	NA	83	62	50	42	25	13	9	NA	89	67	54	45	27	14	10
Speed (mph)	**Right-turn Lane Cost = $75,000**								**Right-turn Lane Cost = $80,000**							
25	NA	NA	146	128	113	77	43	30	NA	NA	156	136	120	82	46	32
35	NA	142	115	96	83	53	28	19	NA	NA	122	102	88	56	30	20
45	NA	110	85	69	59	36	19	13	NA	117	91	74	63	39	20	14
55	NA	96	72	58	48	29	15	10	NA	102	77	62	52	31	16	11
Speed (mph)	**Right-turn Lane Cost = $85,000**								**Right-turn Lane Cost = $90,000**							
25	NA	NA	165	144	128	87	49	34	NA	NA	175	153	135	92	51	35
35	NA	NA	130	109	94	60	32	22	NA	NA	138	115	99	63	34	23
45	NA	124	96	79	67	41	21	14	NA	132	102	83	70	44	22	15
55	NA	108	82	66	55	33	17	12	NA	115	86	69	58	35	18	12

* Not applicable.

6.5 Summary

This chapter presented the safety effectiveness of right-turn lanes at unsignalized intersection and driveway approaches. The safety-based volume warrants for right-turn lanes at intersection and driveway approaches were then developed based on their safety effectiveness. The steps taken to achieve these goals are summarized below.

First, the relationships between RE/SS crashes caused by right-turning vehicles and conflicts due to right turns were determined through crash-conflict ratios (CCRs) that estimated the expected number of RE/SS crashes per conflict. The CCRs were derived based on five-year expected conflicts and crashes at twenty study approaches, ten with radius and ten with exclusive right-turn lane treatments. The mean CCR at approaches with radius right-turn treatments was found to be two times higher than the mean CCR at approaches with exclusive right-turn lanes. This indicated a more severe nature of conflicts due to right turns at an approach with a radius right-turn treatment.

Next, a total of four different crash estimation factors (CEFs), corresponding to four different combinations of right-turn treatment type and posted roadway speed limit, were determined based on the estimated mean CCRs and the estimated probabilities of RE/SS crashes. The goal was to estimate the number of all types of crashes, including RE/SS crashes, caused by right-turning vehicles. The trustworthiness of CEFs in estimating the number of all crash types was assessed by comparing the average number of crashes per year estimated based on the number of actual reported crashes at twenty-eight intersection approaches with the number based on the estimated conflicts factored by relevant CEFs. It was found that the estimated CEFs were appropriate in providing a reasonable estimate of the number of all types of crashes caused by vehicles making right turns.

The safety effectiveness of right-turn lanes at intersection approaches and driveway approaches were then determined separately in terms of the expected number and the expected economic cost of crashes saved per year at approaches provided with right-turn lanes. It was found that the annual safety benefits of right-turn lanes were perceptible. It was also found that the safety benefits of right-turn lanes at driveway approaches were comparatively higher than those at intersection approaches.

Finally, the safety-based volume warrants for right-turn lanes were developed through benefit-cost analyses. The warrant guidelines indicate the minimum number of right turns during the design hour (RTDHV) at which the expected safety benefits of right-turn lanes exceed their construction costs. Various combinations of directional design hour volume (DDHV) and posted roadway speed limit were considered for the development of warrant guidelines. The DDHVs considered range from 100 to 1,500 vph; whereas the posted roadway speed limits considered include 25, 35, 45 and 55 mph. Two separate sets of warrant guidelines for right-turns lanes were developed, one set for intersection approaches and the other set for driveway approaches. In each case, a total of sixteen right-turn lane construction cost scenarios were considered, ranging from $15,000 to $90,000. It was found that the warrant thresholds for right-turn lanes at driveway approaches were lower compared to those at intersection approaches.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The study used data from different sources, conducted many data conflations and reductions, and performed numerous analyses using innovative methodology, to develop relationships, models and findings related to the safety impacts and effectiveness of right-turn lanes, which improves the state of knowledge related to the impacts of right-turn movements and the related strategies in different contexts. The developed models were used to determine and recommend the safety-based volume thresholds for warranting right-turn lanes at approaches to intersections and driveways on two-lane roadways for a broad range of conditions, which enhances the state-of-practice. It must be emphasized that the conclusions made herein are relevant only for the contexts studied in this study. In the process of doing research, a variety of data, modeling and application related issues were encountered, which provide the basis for recommendations for further research as well as for implementation of the findings of this research in traffic engineering practice.

7.1 Conclusions

7.1.1 Crash analysis

The crash analyses were carried out based on the five-year statewide historical data of traffic crashes reported on Minnesota's two-lane trunk highways. Also required in the analysis, and obtained from multiple data sources, were various other types of archived data such as, traffic volume, speed, videolog, crash reports, etc. for the same time periods as the historical crash data. The data preparation involved data conflation and reduction, including manual examinations of crash reports and locations to obtain a set of data relevant and consistent with the study contexts. A total of 10,235 intersection/intersection-related crashes were identified to be relevant for the analysis. Out of total crashes, a total of

435 crashes were caused by vehicles making right turns from the uncontrolled major roadway approaches at unsignalized intersections and driveways, which were analyzed separately. Exploratory analyses identified the nature and the extent of crashes caused by right-turning vehicles. It also helped identify the potential outcome as well as the explanatory factors that provided bases for the development of six individual logistic regression models, including five binary logistic regression models and one multinomial logistic regression model. The key findings of crash analysis were:

- The crashes caused by right-turning vehicles tended to be less severe, in terms of bodily injury, mostly leading to property-damage-only crashes with no apparent injury.
- Four crash types, namely, rear-end, same-direction-sideswipe, right-angle and right-turn crash types, constituted as much as 96% of all crashes caused by vehicles making right turns from major roadways.
- The conditional probabilities of a crash caused by a right-turning vehicle, given that a crash had already occurred, were found to vary considerably depending on the contributing factors related to road and environment conditions and driver-vehicle units. For the scenarios identified in Table 7.1, such probabilities at an intersection approach were found to vary from 1.6 to 17.2%; in case of a driveway approach, the probabilities varied from 7.8 to 38.7% (Table 7.2).
- Given that the crash was caused by a right-turning vehicle, the probabilities of the crash being a rear-end type were found to vary from 13.7 to 46.4% at approaches with exclusive right-turn lanes and from 37.9 to 76.9% at approaches with radius right-turn treatments, depending on the posted roadway speed limit category and the

roadway approach type (driveway or intersection). These results indicate that the right-turn lanes are expected to reduce the occurrence of rear-end crashes (or crash risks) significantly, but these may not completely eliminate the rear-end crashes.

Table 7.1. Scenarios to estimate the probability of a crash due to a right-turning vehicle

Scenario	Explanatory Factors					
	HCVPR	JUNCT	SURFC	TTCMB	VHDEF	WETHR
I1	Low	Roadway	Dry	No	No	Clear
I2	High	Roadway	Dry	No	No	Clear
I3	High	Roadway	Wet & slippery	No	No	Clear
I4	High	Roadway	Wet & slippery	Yes	No	Clear
I5	High	Roadway	Wet & slippery	Yes	No	Not clear
I6	High	Roadway	Wet & slippery	Yes	No	Somewhat clear
D1	Low	Driveway	Dry	No	No	Clear
D2	High	Driveway	Dry	No	No	Clear
D3	High	Driveway	Wet & slippery	No	No	Clear
D4	High	Driveway	Wet & slippery	Yes	No	Clear
D5	High	Driveway	Wet & slippery	Yes	No	Not clear
D6	High	Driveway	Wet & slippery	Yes	No	Somewhat clear

Table 7.2. Probabilities of a crash caused by a right-turning vehicle

Speed Cat.	Traffic Vol. Cat.	Scenario (Table 7.1)											
		I1	I2	I3	I4	I5	I6	D1	D2	D3	D4	D5	D6
High	High	.016	.022	.067	.103	.073	.068	.078	.108	.179	.260	.194	.183
High	Low	.023	.032	.094	.143	.102	.096	.110	.149	.240	.337	.258	.244
Low	High	.019	.027	.082	.125	.089	.084	.096	.130	.213	.304	.230	.217
Low	Low	.028	.039	.114	.172	.124	.117	.133	.178	.282	.387	.302	.287

- The relative risks of a rear-end crash at an approach with a radius right-turn treatment were 1.7 to 2.8 times higher compared to those with an exclusive right-turn lane, depending on the posted roadway speed limit category and the roadway approach type (driveway or intersection).
- Given that a crash was caused by a right-turning vehicle, the probabilities of the crash being a rear-end/same-direction-sideswipe type were found to vary from 45.2 to 91.3% at intersection approaches and from 57.7 to 99.9% at driveway approaches, depending on right-turn treatment type and posted roadway speed limit.

- The relative risks of a rear-end or a same-direction-sideswipe crash at an approach with a radius right-turn treatment were 1.3 to 1.5 times higher compared to those with an exclusive right-turn lane, depending on the posted roadway speed limit category and the roadway approach type (driveway or intersection).
- The relative risks of a rear-end or a same-direction-sideswipe crash at a driveway approach were found to be 1.1 to 1.3 times higher compared to those at an intersection approach, depending on the posted roadway speed limit category and the right-turn treatment type. This indicated the possibility of developing warrant guidelines for right-turn lanes at driveway approaches separately from those at intersection approaches.
- The probabilities of an injury and a possible-injury crash were found to be higher at a radius right-turn treatment compared to those at an exclusive right-turn lane, and at a 'high' speed approach compared to that at a 'low' speed approach. On the other hand, the property-damage-only crash was most likely to occur at an exclusive right-turn lane than at a radius right-turn treatment, and at a 'low' speed approach than at a 'high' speed approach. These probabilities, presented again in Table 7.3 below, were used as crash severity weights to estimate the weighted average costs of crashes caused by vehicles making right turns.

Table 7.3. Estimated probability of crash severity

Crash Injury Severity Type	**Probability**			
	Speed Category - Right-turn Treatment Type			
	High-Radius	**High-Exclusive**	**Low-Radius**	**Low-Exclusive**
Property damage only	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**

* Injury (non-incapacitating).

- The expected economic cost of a crash caused by a right-turning vehicle was estimated as a weighted average cost using crash severity weights, so that it reflects the nature of crash injury severity expected to vary from one crash to another. The expected cost per crash was found to be higher at a 'high' speed approach compared to that at a 'low' speed approach, and at a radius right-turn treatment compared to that at an exclusive right-turn lane (Table 7.4).

Table 7.4. Economic cost of a crash caused by a right-turning vehicle

Speed Category	Right-turn Treatment Type	Cost/crash ($)
High	Radius	38,314
High	Exclusive	26,985
Low	Radius	22,112
Low	Exclusive	17,171

- The crash analyses helped estimate the conditional probabilities and the costs associated with a crash caused by a right-turning vehicle; however, the results from crash analyses alone were found insufficient to develop comprehensive warrant guidelines for right-turn lanes.

7.1.2 Conflict analysis

The conflict analyses were carried using the traffic conflicts technique. Least squares conflict prediction models were developed based on the field and the simulation data separately to predict the number of conflicts due to right turns, in an endeavor to quantify the effects of right-turn volumes, approach traffic volumes, posted roadway speed limits and right-turn treatment types on such conflicts. The conflict prediction model based on the field data was fitted using twenty-four independent four-hour observations of conflicts at locations spread throughout Minnesota. The models based on the simulation data, on the other hand, were fitted by using simulated conflicts obtained by performing

7,000 four-hour simulations, including twenty repetitions for each of the 350 scenarios. The conflict simulations were carried using a set of twelve individual calibrated and validated VISSIM traffic simulation models. The conflict prediction models based on the simulation data were validated by comparing the predicted conflicts with the ones observed at thirty-two study sites. These models were ultimately selected as the appropriate conflict prediction models, by virtue of their abilities to estimate the conflicts in a wide range of conditions, to predict the number of conflicts due to right turns. The key findings of conflict analysis were:

- The traffic conflicts technique provided a way to incorporate the right-turn volumes in the overall analysis in order that their effects on the safety-effectiveness of right-turn lanes were quantified, which was not possible through the crash analyses based on archived data that lacked information on right-turn volumes.
- The conflict simulations provided greater variations in the conflict data that were found to be difficult to obtain through field surveys.
- The conflicts due to right turns were found to increase with the increase in traffic volume, posted roadway speed limit and percent right turns.
- On an average, the number of conflicts per thousand entering vehicles at an approach volume of 750 vph was about nineteen times more than that at 50 vph. The number of conflicts at a posted roadway speed limit of 55 mph was two times more compared to that at 25 mph. The number of conflicts at 30% right turns was six times more compared to that at 5% right turns.
- It was found that a significant number of conflicts due to right turns can be reduced by providing roadway approaches with exclusive right-turn lanes, ranging from

75% conflict reduction at 5% right turns and 25 mph posted speed limit to 81% conflict reduction at 30% right turns and 55 mph posted speed limit at an approach volume of 750 vph. At an approach volume of 50 vph, the conflict reduction ranged from 77% at 30% right turns and 55 mph posted speed limit to 86% at 5% right turns and 25 mph posted speed limit. On an average, right-turn lanes reduced the number of conflicts at approaches without right-turn lanes by 80%.

7.1.3 Safety effectiveness of right-turn lanes

The crash-conflict ratios, which estimated the expected number of rear-end/same-direction-sideswipe crashes caused by right-turning vehicles per conflict due to a right turn, were determined based on the results obtained from crash and conflict analyses. These ratios were then used to derive crash estimation factors to estimate the number of all types of crashes, including rear-end/same-direction-sideswipe crashes, caused by vehicles making right turns. These relationships developed through an original and improved methodology provide for the determination of the safety effectiveness of right-turn lanes at a broad range of roadway and traffic conditions, considered necessary in the development of a comprehensive warrant guideline. The key findings were as follows:

- The crash-conflict ratio estimated at an approach with a radius right-turn treatment was found to be two times higher than the ratio estimated at an approach with an exclusive right-turn lane (Table 7.5). This indicates a more severe nature of conflicts due to right turns at an approach with a radius right-turn treatment.

Table 7.5. Mean crash-conflict ratios

Right-turn Treatment	Crash Conflict Ratio
Radius	1.547×10^{-6}
Exclusive	0.759×10^{-6}

- The crash estimation factors, presented in Table 7.6, provided reasonable estimates of the number of all types of crashes caused by right-turning vehicles.

Table 7.6. Crash estimation factors

Speed	Right-turn Treatment	Crash Estimation Factors
Low	Radius	2.228×10^{-6}
Low	Exclusive	1.679×10^{-6}
High	Radius	1.695×10^{-6}
High	Exclusive	1.278×10^{-6}

- The safety effectiveness of right-turn lanes at intersection approaches and driveway approaches were determined separately as a function of posted roadway speed limit, traffic volume and percent right turns. The safety benefits were quantified in terms of the number and the economic cost of crashes that the right-turn lanes were expected to save. These benefits were found to be perceptible.
- At intersection approaches, the right-turn lanes were expected to save from 0.06 crash ($1,500) per year at 25 mph speed limit to 0.12 crash ($4,800) per year at 55 mph speed limit at 5% right turns and a bi-directional AADT of 10,000 vpd. At 30% right turns, the corresponding savings were about six times as high.
- At driveway approaches, the right-turn lanes were expected to save from 0.08 crash ($1,900) per year at 25 mph speed limit to 0.13 crash ($5,100) per year at 55 mph speed limit at 5% right turns and a bi-directional AADT of 10,000 vpd. At 30% right turns, the corresponding savings were more than 6 times as high.

7.1.4 Safety-based volume warrants for right-turn lanes

The safety-based volume warrants for right-turn lanes, developed through benefit-cost analyses, indicate the minimum number of right turns during the design hour at which the expected safety benefits of right-turn lanes exceed their construction costs. The directional design hour volume considered for the development of warrant guidelines range from 100 to 1,500 vph; whereas the posted roadway speed limits considered were 25, 35, 45 and 55 mph. Two separate sets of warrant guidelines for right-turns lanes were developed, one for intersection approaches and one for driveway approaches. In each case, a total of sixteen right-turn lane construction cost scenarios were considered, ranging from $15,000 to $90,000. The warrant thresholds for right-turn lanes were found to be lower at driveway approaches compared to those at intersection approaches. Depending on roadway conditions, interest rate and construction costs, these thresholds ranged from 3 to 200 right turns per hour during the design hour at intersection approaches, and from 2 to 175 right turns at driveway approaches.

7.2 Recommendations

Volume warrant thresholds developed in this study are sensitive to the unit economic costs of traffic crashes by injury severity, presented in Table 4.7. Substantial revisions in the unit costs may translate into significant shifts in the volume thresholds for the warrants. In such cases, the safety-based volume warrants for right-turn lanes may be reworked based on the methodologies and the relationships presented in this dissertation.

7.2.1 Data related recommendations

Bulk of crash related data are found in the crash database maintained by the Department of Public Safety. Understanding of the crash databases is improved using videolog data, particularly with respect to crash location information and whether it took place at an intersection, or at a driveway, or at a midblock location. This can be a time consuming process, but it improves the quality of the data used for analyses. Different agencies might have crash related data in different databases; so, data conflation using GIS sometimes is an important exercise, which should not be underestimated. This exercise also allows in the determination of field locations to be used for data collection purposes for conflict study. In addition, crash reports should be examined to understand whether the right-turn movement was from major roadway or not and to further clarify the type of crash. Such detail and examination are important in getting accurate data for doing exploratory analysis and developing probabilities.

Field data collection should pay attention to removing bias by selecting field data location in a random manner, by choosing appropriate sample size, and should be influenced by the design of experiment and the needed replications. This will help gather adequate data and develop appropriate field-based models. Among the data to be collected are spot speeds at various locations, volume data for approach volume and right-turn volume, headway data and conflict data. The speed data and headway data are particularly useful for the calibration of simulation models. The data obtained from simulations should be based on average from a minimum number of runs for each condition or scenario, so that there is a better convergence. In this study, the minimum number of runs used was 20. However, it is recommended that each study determines this based on the confidence interval chosen.

The context studied did not find the impacts of left turns or cross traffic volume to be perceptible and were not used in the development of relationships or models. However, right-turn movements in contexts where there are substantial left-turn movements and where control is on all approaches, the left-turn volume and cross-traffic data as well as the pedestrian movement data should be collected and analyzed. All data collection was done for dry conditions. For wet conditions and the impact of wet conditions, additional data collection and analyses have to be carried out.

7.2.2 Modeling related recommendations

Special issues related to the design of experiments and replications should be carefully considered in determining the number of field data locations. In this study, six different conditions were studied with three replications in each. It was very challenging to acquire data for all cells, especially three replications for each cell. The decisions regarding the number of cells and replications must be made based on the availability of data locations and resources. Lack of attention to this consideration may result in poor field-data based conflict prediction models.

There are numerous issues related to the development of simulation models in order to understand and analyze the safety impacts of right turn movements in different contexts. The number of distinct model calibrations depends on the levels of traffic volume (three levels used in this study), speed (two levels) and right turn treatment type (two levels). Thus, a total of twelve different simulation model calibrations were done. The number of calibrations has to follow the design of experiment that is relevant and needed for the purpose of analysis. The calibrations involved fitting the distributions of spot speeds and time headways to the ones found in the field, using adjustments to multiplicative and additive parts of the VISSIM car-following model. This is an iterative process until a good fit is obtained, and requires a considerable post processing of data.

7.2.3 Use of safety-based volume thresholds provided in this dissertation

The charts and values developed for volume thresholds for determining the safety-based right-turn lane needs on two-lane roadways, where major roadway has no control, can be directly used and incorporated in the practice and are transferable to other states and communities with similar traffic and speed conditions. However, the assumption of interest rates and construction costs can be changed to better the thresholds and the decisions made. These values will be of special use for determining the right-turn lane needs on approaches to driveways because guidelines for that are absent.

7.2.4 Development of volume thresholds using safety and operational effectiveness

The volume thresholds can be improved by including operational effectiveness as well. In Appendix H, a procedure of incorporating the operational effectiveness, based on the work by Varma et al. (2008), is provided, which can serve as a guideline for further research and for the development of thresholds taking into account both safety and operational effectiveness.

7.2.5 Development of volume thresholds for other contexts of right-turn movements

Additional data collection and analyses are needed for developing volume-thresholds based warrants for other contexts having right-turn movements. In particular, the impacts of left-turns and cross traffic on the right-turn movements need to be explored for other contexts. Typically, in Minnesota, the right-turn lane lengths are taken as 480 feet, which was used in this study. The differing lengths of right-turn lane may impact operational effectiveness, and is another area to be researched further to develop warrants for right-turn lane.

REFERENCES

Agent, K. R. (1988). "Traffic control and accidents at rural high-speed intersections." *Transportation Research Record. 1160*, Transportation Research Board, Washington, D.C., 14-21.

Ale, G. B. (2007). *Analysis of right-turn related crashes and safety effectiveness of a right-turn lane*, Master's Thesis, North Dakota State University, Fargo, North Dakota.

Al-Ghamdi, A. S. (2002). "Using logistic regression to estimate the influence of accident factors on accident severity." *Accid. Anal Prev.* 34(6), 729-741.

Allison, P. D. (1999), *Logistic regression using the SAS® system: Theory and application*, SAS Institute Inc., Cary, NC.

Altman, M., Gill, J., and McDonald, M. P. (2004). *Numerical issues in statistical computing for the social scientist*, John Wiley and Sons, New York.

American Association of State Highway and Transportation Officials (AASHTO). (2004). *A policy on geometric design of highways and streets*, Washington, D.C.

Archer, J. (2005). *Indicators for traffic safety assessment and prediction and their application in micro-simulation modeling: A study of urban and suburban intersections*, Doctoral Dissertation, Royal Institute of Technology, Stockholm, Sweden.

Archer, J., and Kosonen, I. (2000). "The potential of micro-simulation modeling in relation to traffic safety assessment." *Proc., 12th European Simulation Symposium*, Hamburg, Germany.

Archer, J., and Young, W. (2009). "The application of a micro-simulation model to study the safety performance of a traffic signal incident-reduction function." *Proc., Transportation Research Board Annual Meeting* (CD-ROM), Transportation Research Board, Washington, D.C.

Aultman-Hall, L., and Padlo, P. (2004). "Factors affecting young driver safety." *Rep. No. JHR 04-298*, Connecticut Department of Transportation, Rocky Hill, Connecticut.

Bauer, K. M., and Harwood, D. W. (1996). “Statistical models of at-grade intersection accidents.” *Rep. No. FHWA-RD-96-125*, Federal Highway Administration, Washington, D.C.

Bauer, K. M., and Harwood, D. W. (2000). “Statistical models of at-grade intersection accidents – Addendum.” *Rep. No. FHWA-RD-99-094*, Federal Highway Administration, Washington, D.C.

Bedard, M., Guyatt, G. H., Stones, M. J., and Hirdes, J. P. (2002). “The independent contribution of driver, crash, and vehicle characteristics to driver fatalities.” *Accid. Anal Prev.* 34(6), 717-727.

Bloomberg, L., and Dale, J. (2000). “A comparison of the VISSIM and CORSIM traffic simulation models on a congested network.” *Transportation Research Record. 1727*, Transportation Research Board, Washington, D.C., 52-60.

Campbell, K. L., Joksch, H. C., and Green, P. E. (1996). “A bridging analysis for estimating the benefits of active safety technologies.” *Rep. No. UMTRI-96-18*, National Highway Traffic Safety Administration, Washington, D.C.

Chin, H-C., and Quek, S-T. (1997). “Measurement of traffic conflicts.” *Safety Science*, 26(3), 169-185.

Christian, W. J., Carroll, M., Meyer, K., Vitaz, T. W., and Franklin, G. A. (2003). “Motorcycle helmets and head injuries in Kentucky, 1995-2000.” *J. Ky. Med. Assoc.*, 101(1), 21-26.

Cottrell, B. H., Jr. (1981). “The development of criteria for the treatment of right-turn movements on rural roads.” *Rep. No. VHTRC 81-R45*, Virginia Highway and Transportation Research Council, Charlottesville, Virginia.

Crowe, E. C. (1990). “Traffic conflict values for three-leg, unsignalized intersections.” *Transportation Research Record. 1287*, Transportation Research Board, Washington, D.C., 185-194.

Cunto, F., and Saccomanno, F. F. (2008). “Calibration and validation of simulated vehicle safety performance at signalized intersections.” *Accid. Anal Prev.*, 40(3), 1171-1179.

Dissanayake, S., and Lu, J. (2002). “Analysis of severity of young driver crashes: Sequential binary logistic regression modeling.” *Transportation Research Record. 1784*, Transportation Research Board, Washington, D.C., 108-114.

Dixon, K. K., Hibbard, J. L., and Nyman, H. (1999). “Right-turn treatment for signalized intersections." *Proc., TRB Circular E-C019: Urban Street Symposium*, Transportation Research Board, Washington, D.C.

Donnell, E. T., and Mason, J. M., Jr. (2004). “Predicting the severity of median-related crashes in Pennsylvania by using logistic regression.” *Transportation Research Record. 1897*, Transportation Research Board, Washington, D.C., 55-63.

Dowling, R., Skabardonis, A., and Alexiadis, V. (2004). “Traffic analysis toolbox, Volume III: Guidelines for applying traffic microsimulation software.” *Rep. No. FHWA-HRT-04-040*, Federal Highway Administration, Washington, D.C. <http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol3/Vol3_Guidelines.pdf> (Jan. 16, 2007)

Eisele, W. L., and Frawley, W. E. (2004). “Estimating the impacts of access management with micro-simulation: Lessons learned.” *Proc., 6th National Conference on Access Management*, Kansas City, Missouri.

Eisele, W. L., and Toycen, C. M. (2005). “Identifying and quantifying operational and safety performance measures for access management: Micro-simulation results.” *Rep. No. SWUTC/05/167725-1*, Texas Transportation Institute, Texas A&M University System, College Station, Texas.

Fellendorf, M., and Vortisch, P. (2001). “Validation of the microscopic traffic flow model VISSIM in different real-world situations.” *Proc., Transportation Research Board Annual Meeting* (CD-ROM), Transportation Research Board, Washington, D.C.

Fitzpatrick, K., and Schneider, W. H., IV. (2005). “Turn speeds and crashes within right-turn lanes.” *Rep. No. FHWA/TX-05/0-4365-4*, Texas Transportation Institute, Texas A&M University System, College Station, Texas. <http://tti.tamu.edu/documents/0-4365-4.pdf> (Jan. 11, 2009)

Fitzpatrick, K., Schneider, W. H., IV, and Park, E. S. (2006). “Operation and safety of right-turn lane designs.” *Proc., Transportation Research Board Annual Meeting* (CD-ROM), Transportation Research Board, Washington, D.C.

Gettman, D., and Head, L. (2003). “Surrogate safety measures from traffic simulation models.” *Rep. No. FHWA-RD-03-050*, Turner-Fairbank Highway Research Center, Federal Highway Administration, McLean, Va.

Gettman, D., Pu, L., Sayed, T., and Shelby, S. (2008). “Surrogate safety assessment model and validation: Final report.” *Rep. No. FHWA-HRT-08-051*, Turner Fairbank Highway Research Center, Federal Highway Administration, McLean, Va.

Glauz, W. D., and Migletz, D. J. (1980). “Application of traffic conflict analysis at intersections.” *NCHRP Rep. No. 219*, Transportation Research Board, National Research Council, Washington, D.C.

Glauz, W. D., Bauer, K. M., and Migletz, D. J. (1985). "Expected traffic conflict rates and their use in predicting accidents." *Transportation Research Record. 1026*, Transportation Research Board, Washington, D.C., 1-12.

Gluck, J., Levinson, H. S., and Stover, V. (1999). “Impacts of access management techniques.” *NCHRP Rep. No. 420*, Transportation Research Board, Washington, D.C.

Hadi, M. A., and Thakkar, J. (2003). "Speed differential as a measure to evaluate the need for right-turn deceleration lanes at unsignalized intersections." *Transportation Research Record. 1847*, Transportation Research Board, Washington, D.C., 58-65.

Harwood, D.W., Bauer, K.M., Potts, I.B., Torbic, D .J., Richard, K.R., Kohlman- Rabbani, E.R., Hauer, E., and Elefteriadou, L. (2002). “Safety effectiveness of intersection left- and right-turn lanes.” *Rep. No. FHWA-RD-02-089*, Federal Highway Administration, McLean, Va.

Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A. (2000). “Prediction of the expected safety performance of rural two-lane highways.” *Rep. No. FHWA-RD-99-207*, Federal Highway Administration, Washington, D.C. <http://www.tfhrc.gov/safety/pubs/99207.pdf> (Jan. 14, 2007)

Hasan, T., and Stokes, R. W. (1996). “Guidelines for right-turn treatments at unsignalized intersections and driveways: Final report.” *Rep. No. K-TRAN: KSU-95-5*, Kansas State University, Manhattan, Kansas.

Hauer, E. (1997). *Observational before-after studies in road safety: Estimating the effect of highway and traffic engineering measures on road safety*, Pergamon Press, Elsevier Science Ltd., Oxford, United Kingdom.

Hauer, E., and Garder, P. (1986). "Research into the validity of traffic conflicts technique." *Accid. Anal Prev.*, 18(6), 471-481.

HCM. (2010). *Highway capacity manual*, Transportation Research Board, National Research Council, Washington, D.C.

Hochstein, J. L. (2006). "Safety effects of offset right-turn lanes at rural expressway intersections." *Proc., Transportation Scholars Conference*, Iowa State University, Center for Transportation Research and Education, Ames, IA. <http://www.ctre.iastate.edu/mtc/papers/index.htm> (Jan. 12, 2009)

Hosmer, D. W., Jr., and Lemeshow, S. (2000). *Applied logistic regression*, 2nd Ed., Wiley-Interscience, John Wiley & Sons, Inc., New York.

Hovey, P., and Chowdhury, M. (2005). "Development of crash reduction factors." *Rep. No. FHWA/OH-2005/12*, Ohio Department of Transportation, Columbus, Ohio. <http://www2.dot.state.oh.us/research/2005/Safety/14801-FR.pdf> (Jan. 19, 2009)

Huguenin, F., Torday, A., and Dumont, A-G. (2005). "Evaluation of traffic safety using microsimulation." *Proc., 5th Swiss Transport Research Conference*, Monte Verità, Ascona, Switzerland

Institute for Transport Studies (ITS). (2000). *SMARTEST*, University of Leeds, GB. <http://www.its.leeds.ac.uk/projects/smartest/finrep.PDF> (Dec. 31, 2008)

Iyaz, S. (1997). *Validation and improvement of rear-end traffic conflict model for safety evaluation of coordinated signal systems*, Master's Thesis, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia.

Joksch, H. C., and Kostyniuk, L. P. (1997). "Modeling intersection crash counts and traffic volume: Final report." *Rep. No. FHWA-RD-98-096*, Federal Highway Administration, Georgetown Pike, McLean, Virginia.

Katamine, N. M. (2000a). "Various volume definitions with conflicts at unsignalized intersections." *J. Transp. Eng.*, 126(1), 27-34.

Katamine, N. M. (2000b). “Nature and frequency of secondary conflicts at unsignalized intersections.” *J. Transp. Eng.*, 126(2), 129-133.

Kaub, A. R., Kaub, J. A. (2000). “Predicting annual intersection accidents with conflict opportunities.” *Proc.*, *Transportation Research E-circular E-C019*, Urban Street Symposium, Dallas, Texas, June 28–30, 1999, H-2/1-12. <http://onlinepubs.trb.org/Onlinepubs/circulars/ec019/ec019.pdf> (Feb. 27, 2009)

Kim, D-G., Washington, S., and Oh, J. (2006). "Modeling crash types: New insights into the effects of covariates on crashes at rural intersections." *J. Transp. Eng.*, 132(4), 282-292.

Kim, S. (2006). *Simultaneous calibration of a microscopic traffic simulation model and OD matrix*, Doctoral Dissertation, Texas A&M University. <http://txspace.tamu.edu/handle/1969.1/4409> (Jan. 9, 2008)

Ladrón de Guevara, F., Washington, S. P., and Oh, J. (2004). “Forecasting crashes at the planning level: Simultaneous negative binomial crash model applied in Tucson, Arizona.” *Transportation Research Record. 1897*, Transportation Research Board, Washington, D.C., 191-199

Lu, J., Dissanayake, S., Castillo, N., and Williams, K. (2001). *Safety evaluation of right turns followed by U-turns as an alternative to direct left turns - Conflict analysis*, Department of Civil and Environmental Engineering, University of South Florida, Tampa, Florida.

Mauro, R., and Cattani, M. (2004). “Model to evaluate potential accident rate at roundabouts.” *J. Transp. Eng.*, 130(5), 602-609.

McCoy, P. T., Ataullah, S., and Bonneson, J. A. (1993). “Guidelines for right-turn lanes on urban highways: Final report.” *Research Rep. No. TRP-02-28-92*, Department of Civil Engineering, University of Nebraska, Lincoln.

McCoy, P. T., and Bonneson, J. A. (1996). “Volume warrant for free right-turn lanes at unsignalized intersections on rural two-lane highways.” *Transportation Research Record. 1523*, Transportation Research Board, Washington, D.C., 83-90

McCoy, P. T., Hoppe, W. J., and Dvorak, D. V. (1984). “Cost-effectiveness evaluation of turning lanes on uncontrolled approaches of rural intersections: Final report.”

Research Rep. No. TRP-02-15-84, Department of Civil Engineering, University of Nebraska, Lincoln.

McGee, H., Taori, S., and Persaud, B. N. (2003). "Crash experience warrant for traffic signals." *NCHRP Rep. No. 491*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. <http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_491.pdf> (Jan. 14, 2009)

McNutt, L. A., Holcomb, J. P., and Carlson, B. E. (2000). "Logistic regression analysis: When the odds ratio does not work – an example using intimate partner data." *J. Interpers Violence,* 15(10), 1050-1059.

Mendenhall, W., and Sincich, T. (2003). *A second course in Statistics – Regression analysis*, 6th Ed., Pearson-Prentice Hall, Upper Saddle River, NJ.

Mounce, J. M. (1983). "Influence of arterial access control and driveway design on energy conservation." *Transportation Research Record. 901,* Transportation Research Board, Washington, D.C., 42-46.

Muchuruza, V. (2006). *Simulation of traffic crashes using cell based microsimulation*, Doctoral Dissertation, Florida State University, FAMU-FSU college of Engineering, Florida.

National Highway Traffic Safety Administration (NHTSA). (2006). *Traffic safety facts 2005 - A compilation of motor vehicle crash data from the fatality analysis reporting system and the general estimates system*, National Center for Statistics and Analysis, U.S. Department of Transportation, Washington, DC. < http://www-nrd.nhtsa.dot.gov/Pubs/TSF2005.PDF> (Jan. 4, 2008)

National Highway Traffic Safety Administration (NHTSA). (2007). *Traffic safety facts 2006 - A compilation of motor vehicle crash data from the fatality analysis reporting system and the general estimates system*, National Center for Statistics and Analysis, U.S. Department of Transportation, Washington, DC. < http://www-nrd.nhtsa.dot.gov/Pubs/TSF2006FE.PDF> (Jan. 4, 2008)

Neuman, T. R. (1985). "Intersection channelization design guide." *NCHRP Rep. No. 279*, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C.

Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Kohlman-Rabbani, E. R. (2003). "Guidance for implementation of the AASHTO strategic highway safety plan, Vol. 5: A guide for addressing unsignalized intersection collisions." *NCHRP Rep. No. 500*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. <http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_500v5.pdf> (Jan. 12, 2009)

Office of Investment Management (OIM). (2009). "Benefit-cost analysis for transportation projects." Minnesota Department of Transportation, Saint Paul, MN. <http://www.oim.dot.state.mn.us/EASS/index.html> (Feb. 17, 2009)

Oh, J., Washington, S., and Choi, K. (2004). "Development of accident prediction models for rural highway intersections." *Transportation Research Record. 1897*, Transportation Research Board, Washington, D.C., 18-27.

Olstam, J. J., and Tapani, A. (2004). *Comparison of car-following models*, VTI meddelande 960A, Swedish National Road and Transport Research Institute, Linkoping, Sweden.

Pant, P. D., Park, Y., Neti, S. V., and Hossain, A. B. (1999). "Comparative study of rural stop controlled and beacon-controlled intersections." *Transportation Research Record. 1692*, Transportation Research Board, Washington, D.C., 164-172.

Panwai, S., and Dia, H. (2005). "Comparative evaluation of microscopic car following behavior." *IEEE Transactions on Intelligent Transportation Systems*, 6(3), 314-325.

Parker, M. R., Jr., and Zegeer, C. V. (1988). "Traffic conflict techniques for safety and operations – Engineer's guide." *Rep. No. FHWA-IP-88-026*, Federal Highway Administration, Washington, D.C.

Parker, M. R., Jr., and Zegeer, C. V. (1989). "Traffic conflict techniques for safety and operations – Observers manual." *Rep. No. FHWA-IP-88-027*, Federal Highway Administration, Washington, D.C.

Perkins, S. R., and Harris, J. I. (1968). "Traffic conflict characteristics: Accident potential at intersections." *Highway Research Record. 225*, Highway Research Board, Washington, D.C., 35-43.

Planung Transport Verkehr AG (PTV). (2007). *VISSIM 4.30 User Manual*, Stumpfstraße 1, Karlsruhe, Germany.

Quddus, M. A., Wang, C., and Ison, S. G. (2009). "The impact of road traffic congestion on crash severity using ordered response models." *Proc., Transportation Research Board Annual Meeting* (CD-ROM), Transportation Research Board, Washington, D.C.

Rao, V. T., and Rengaraju, V. R. (1997). "Probabilistic model for conflicts at urban uncontrolled intersection." *J. Transp. Eng.*, 123(1), 81-84.

Rao, V. T., and Rengaraju, V. R. (1998). "Modeling conflicts of heterogeneous traffic at urban uncontrolled intersections." *J. Transp. Eng.*, 124(1), 23-34.

Ratrout, N. T., Al-Ofi, K. A., and Iyaz, S. (2004). "Validation and improvement of a rear-end conflict prediction model." *Transportation Research Record. 1897*, Transportation Research Board, Washington, D.C., 206-210.

Sadegh, A., Mehta, J., and Smith, M. (1991). "Conflicts at traffic circles in New Jersey." *Transportation Research Record. 1327*, Transportation Research Board, Washington, D.C., 54-61.

Salman, N. K., and Al-Maita, K. J. (1995). "Safety evaluation at three-leg, unsignalized intersections by traffic conflict technique." *Transportation Research Record. 1485*, Transportation Research Board, Washington, D.C., 177-185

SAS. (2008). *Help and documentation*, SAS® 9.2, SAS Institute Inc., Cary, NC.

Sohn, S. Y., and Shin, H. (2001). "Pattern recognition for road traffic accident severity in Korea." *Ergonomics*, 44(1), 107-117.

Solomon, D. (1964). *Accidents on main rural highways related to speed, driver, and vehicle*, U.S. Department of Commerce, Bureau of Public Roads, Washington, DC.

Tarko, A. P., and Songchitruksa, P. (2005). "Estimating the frequency of crashes as extreme traffic events." *Proc., Transportation Research Board Annual Meeting* (CD-ROM), Transportation Research Board, Washington, D.C.

Tarrall, M. B., and Dixon, K. K. (1998). "Conflict analysis for double left-turn lanes with protected-plus-permitted signal phases." *Transportation Research Record. 1635*, Transportation Research Board, Washington, D.C., 105-112.

Tiwari, G., Mohan, D., and Fazio, J. (1998). "Conflict analysis for prediction of fatal crash locations in mixed traffic streams." *Accid. Anal Prev.*, 30(2), 207-215.

Thomas, G. B., and Smith, D. J. (2001). *Effectiveness of roadway safety improvements, Final report*, Center for Transportation Research and Education, Iowa State University, Ames, IA. <http://ntl.bts.gov/lib/19000/19100/19185/PB2002104907.pdf> (Jan. 19, 2009)

Varma, A., Ale, G. B., Gyawali, S., Chevuri, P., and Hagel, S. (2008). "Warrants for right-turn lanes/treatments on two-lane roads." *Rep. No. MN/RC 2008-25*, Minnesota Department of Transportation, St. Paul, Minnesota.

Vogt, A. (1999). "Crash models for rural intersections: Four-lane by two-lane stop-controlled and two-lane by two-lane signalized." *Rep. No. FHWA-RD-99-128*, Federal Highway Administration, McLean, Va.

Vogt, A., and Bared, J. (1998). "Accident models for two-lane rural segments and intersections." *Transportation Research Record. 1635,* Transportation Research Board, Washington, D.C., 18-29.

Walker, J., (1996). "Methodology application – Logistic regression using the CODES data." *Contract No. OPM 91-2973*, Department of Transportation, National Highway Traffic Safety Administration, Washington, D.C.

Wang, X., and Abdel-Aty, M. (2006). "Temporal and spatial analyses of rear-end crashes at signalized intersections." *Accid. Anal Prev.*, 38(6), 1137-1150.

Wang, X., and Abdel-Aty, M. (2008). "Analysis of left-turn crash injury severity by conflicting pattern using partial proportional odds models." *Accid. Anal Prev.*, 40(5), 1674–1682.

Washington, S., Leonard, J., Manning, D. G., Roberts, C., Williams, B., Bacchus, A. R., Devanhalli, A., Ogle, J., and Melcher, D. (2002). "Scientific approaches to transportation research, Vol. 1 and Vol. 2." *NCHRP Rep. No. 20-45*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. <http://onlinepubs.trb.org/Onlinepubs/nchrp/cd-22/start.htm> (Jan. 17, 2009)

Weerasuriya, S. A., and Pietrzyk, M. C. (1998). "Development of expected conflict value tables for unsignalized three-legged intersections." *Transportation Research Record. 1635*, Transportation Research Board, Washington, D.C., 121-126.

Wiedemann, R., and Reiter, U. (1992). *Microscopic traffic simulation – The simulation system MISSION*, Karlsruhe University, Germany.

Winston, W. L. (2004). *Operations research: Applications and algorithms*, 4^{th} Ed., Brooks/Cole, Belmont, CA.

Yan, X., Radwan, E., and Abdel-Aty, M. (2005). "Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model." *Accid. Anal Prev.,* 37(6), 983-995.

Yang, J. (2008). "Risk-based volume warrants for free right-turn lanes on two-lane roadways." *J. Transp. Eng.*, 134(4), 155-162.

Ye, X., Pendyala, R. M., Washington, S. P., Konduri, K., and Oh, J. (2009). "A simultaneous equations model of crash frequency by collision type for rural intersections." *Safety Science*, 47(3), 443-452.

Zhang, J., Lindsay, J., Clarke, K., Robbins, G., and Mao, Y. (2000). "Factors affecting the severity of motor vehicle traffic crashes involving elderly drivers in Ontario." *Accid. Anal Prev.*, 32(1), 117-125.

APPENDIX A. UNIVARIABLE LOGISTIC REGRESSION MODELS

Univariable analyses were carried out to shortlist potential explanatory factors for five individual binary logistic regression models developed in this study. Hosmer and Lemeshow (2000) suggested that any explanatory factor with p-value less than 0.25 from the univariable test is a candidate for the multivariable model along with all variables considered important.

This appendix presents the results of such univariable analyses. The traffic volume, the posted roadway speed limit, and the right-turn treatment type were considered important explanatory factors; hence, these factors were considered for the development of final models irrespective of the results of univariable analyses.

Table A.1. Univariable logistic regression results for Model 1

Explanatory Factor				**Estimate**	**Standard Error**	**Wald Chi-Square**	**p-Value**
AADTC	High	v.	Low	-0.737	0.129	32.682	<.0001
DRENI	Yes	v.	No	-0.383	0.146	6.887	0.009
DRERR	Yes	v.	No	-0.195	0.102	3.670	0.055
DTIME	Night	v.	Day	-0.286	0.136	4.409	0.036
DTYPE*	Weekends	v.	Weekdays	0.049	0.095	0.267	0.605
HCVPR	High	v.	Low	0.330	0.107	9.582	0.002
INATT	Yes	v.	No	-0.297	0.097	9.455	0.002
JUNCT	Driveway	v.	Roadway	1.440	0.100	206.126	<.0001
LIGHT	No light	v.	Daylight	-0.479	0.217	4.857	0.028
	Some light	v.	Daylight	0.158	0.139	1.291	0.256
RDCHR	Curve & grade	v.	Straight & level	-0.295	0.286	1.066	0.302
	Curve & level	v.	Straight & level	-0.461	0.238	3.758	0.053
	Straight & grade	v.	Straight & level	-0.233	0.147	2.522	0.112
SPEED	High	v.	Low	-0.321	0.095	11.389	0.001
SURFC	Wet & slippery	v.	Dry	0.640	0.097	43.665	<.0001
TTCMB	Yes	v.	No	0.407	0.153	7.060	0.008
VHDEF	Yes	v.	No	0.760	0.263	8.330	0.004
VISON*	Yes	v.	No	-0.093	0.244	0.145	0.704
WETHR	Not clear	v.	Clear	0.307	0.125	6.038	0.014
	Somewhat clear	v.	Clear	-0.210	0.115	3.368	0.067

* Not selected for further analysis.

Table A.2. Univariable logistic regression results for Model 2

Explanatory Factor				Estimate	Standard Error	Wald Chi-Square	p-Value
AADTC	High	v.	Low	0.150	0.276	0.296	0.587
DRENI	Yes	v.	No	0.518	0.327	2.514	0.113
DRERR	Yes	v.	No	-0.439	0.212	4.304	0.038
DTIME*	Night	v.	Day	-0.003	0.291	0.000	0.992
DTYPE*	Weekends	v.	Weekdays	0.133	0.204	0.428	0.513
HCVPR	High	v.	Low	-0.296	0.233	1.616	0.204
INATT	Yes	v.	No	1.323	0.212	38.936	<.0001
JUNCT	Driveway	v.	Roadway	0.929	0.208	19.938	<.0001
LIGHT*	No light	v.	Daylight	0.613	0.461	1.767	0.184
	Some light	v.	Daylight	-0.338	0.307	1.215	0.270
RDCHR*	Curve & grade	v.	Straight & level	0.057	0.637	0.008	0.929
	Curve & level	v.	Straight & level	-0.259	0.544	0.227	0.634
	Straight & grade	v.	Straight & level	-0.166	0.322	0.267	0.606
SPEED	High	v.	Low	0.723	0.209	11.935	0.001
SURFC	Wet & slippery	v.	Dry	-0.345	0.209	2.734	0.098
TTCMB*	Yes	v.	No	-0.322	0.344	0.875	0.350
VHDEF	Yes	v.	No	0.930	0.514	3.267	0.071
VISON*	Yes	v.	No	-0.634	0.576	1.212	0.271
WETHR*	Not clear	v.	Clear	-0.233	0.270	0.743	0.389
	Somewhat clear	v.	Clear	0.140	0.244	0.331	0.565
RTTRT	Radius	v.	Exclusive	1.401	0.309	20.519	<.0001
DRWAY	Pub. driveway	v.	Roadway	0.892	0.259	11.896	0.001
	Pvt. driveway	v.	Roadway	1.036	0.263	15.520	<.0001

* Not selected for further analysis.

Table A.3. Univariable logistic regression results for Model 3

Explanatory Factor				Estimate	Standard Error	Wald Chi-Square	p-Value
AADTC	High	v.	Low	-0.280	0.342	0.669	0.413
DRENI	Yes	v.	No	1.413	0.533	7.036	0.008
DRERR	Yes	v.	No	0.994	0.290	11.722	0.001
DTIME*	Night	v.	Day	-0.152	0.345	0.195	0.659
DTYPE*	Weekends	v.	Weekdays	-0.246	0.238	1.065	0.302
HCVPR*	High	v.	Low	0.026	0.261	0.010	0.920
INATT	Yes	v.	No	-0.465	0.247	3.554	0.059
JUNCT*	Driveway	v.	Roadway	-0.188	0.242	0.603	0.438
LIGHT*	No light	v.	Daylight	-1.728	1.034	2.794	0.095
	Some light	v.	Daylight	0.005	0.330	0.000	0.987
RDCHR*	Curve & grade	v.	Straight & level	-0.246	0.792	0.096	0.756
	Curve & level	v.	Straight & level	0.652	0.524	1.551	0.213
	Straight & grade	v.	Straight & level	-0.580	0.427	1.846	0.174
SPEED	High	v.	Low	-0.104	0.233	0.199	0.655
SURFC	Wet & slippery	v.	Dry	-0.456	0.245	3.469	0.063
TTCMB*	Yes	v.	No	0.389	0.350	1.232	0.267
VHDEF*	Yes	v.	No	-0.692	0.765	0.817	0.366
VISON*	Yes	v.	No	-0.831	0.759	1.199	0.274
WETHR*	Not clear	v.	Clear	-0.138	0.305	0.204	0.651
	Somewhat clear	v.	Clear	-0.269	0.297	0.821	0.365
RTTRT	Radius	v.	Exclusive	-0.267	0.268	0.995	0.318
DRWAY*	Pub driveway	v.	Roadway	-0.015	0.298	0.002	0.961
	Pvt. driveway	v.	Roadway	-0.335	0.328	1.046	0.307

* Not selected for further analysis.

Table A.4. Univariable logistic regression results for Model 4

Explanatory Factor				Estimate	Standard Error	Wald Chi-Square	p-Value
AADTC	High	v.	Low	0.420	0.344	1.485	0.223
DRENI	Yes	v.	No	-0.688	0.351	3.839	0.050
DRERR*	Yes	v.	No	-0.024	0.289	0.007	0.933
DTIME	Night	v.	Day	0.439	0.356	1.524	0.217
DTYPE*	Weekends	v.	Weekdays	0.016	0.275	0.003	0.955
HCVPR*	High	v.	Low	0.255	0.295	0.749	0.387
INATT	Yes	v.	No	-0.418	0.290	2.069	0.150
JUNCT*	Driveway	v.	Roadway	0.075	0.279	0.072	0.788
LIGHT*	No light	v.	Daylight	0.129	0.646	0.040	0.842
	Some light	v.	Daylight	0.457	0.358	1.625	0.202
RDCHR*	Curve & grade	v.	Straight & level	-13.216	551.800	0.001	0.981
	Curve & level	v.	Straight & level	-0.964	1.042	0.855	0.355
	Straight & grade	v.	Straight & level	0.630	0.364	2.990	0.084
SPEED	High	v.	Low	-0.053	0.277	0.037	0.848
SURFC	Wet & slippery	v.	Dry	0.392	0.274	2.052	0.152
TTCMB*	Yes	v.	No	-0.362	0.495	0.536	0.464
VHDEF*	Yes	v.	No	-0.957	1.042	0.844	0.358
VISON	Yes	v.	No	0.867	0.545	2.534	0.111
WETHR*	Not clear	v.	Clear	-0.017	0.362	0.002	0.963
	Somewhat clear	v.	Clear	0.207	0.324	0.407	0.523
RTTRT	Radius	v.	Exclusive	-0.471	0.302	2.426	0.119
DRWAY*	Pub driveway	v.	Roadway	-0.337	0.393	0.736	0.391
	Pvt. driveway	v.	Roadway	0.317	0.335	0.896	0.344

* Not selected for further analysis.

Table A.5. Univariable logistic regression results for Model 5

Explanatory Factor				Estimate	Standard Error	Wald Chi-Square	p-Value
AADTC	High	v.	Low	-1.326	0.738	3.227	0.072
DRENI	Yes	v.	No	-0.765	0.409	3.497	0.062
DRERR*	Yes	v.	No	0.019	0.354	0.003	0.958
DTIME	Night	v.	Day	-1.205	0.739	2.658	0.103
DTYPE*	Weekends	v.	Weekdays	0.111	0.334	0.110	0.740
HCVPR*	High	v.	Low	0.403	0.351	1.321	0.251
INATT	Yes	v.	No	-1.655	0.489	11.468	0.001
JUNCT*	Driveway	v.	Roadway	-0.272	0.353	0.595	0.440
LIGHT*	No light	v.	Daylight	-0.779	1.041	0.559	0.455
	Some light	v.	Daylight	-0.796	0.618	1.660	0.198
RDCHR*	Curve & grade	v.	Straight & level	-0.013	1.065	0.000	0.991
	Curve & level	v.	Straight & level	-0.483	1.047	0.212	0.645
	Straight & grade	v.	Straight & level	0.071	0.506	0.020	0.889
SPEED	High	v.	Low	-0.962	0.353	7.445	0.006
SURFC	Wet & slippery	v.	Dry	0.687	0.339	4.103	0.043
TTCMB*	Yes	v.	No	0.210	0.506	0.172	0.678
VHDEF*	Yes	v.	No	-13.195	564.300	0.001	0.981
VISON*	Yes	v.	No	0.221	0.769	0.082	0.774
WETHR	Not clear	v.	Clear	0.427	0.368	1.347	0.246
	Somewhat clear	v.	Clear	-1.746	0.745	5.499	0.019
RTTRT	Radius	v.	Exclusive	0.002	0.397	0.000	0.996
DRWAY*	Pub driveway	v.	Roadway	-0.050	0.423	0.014	0.906
	Pvt. driveway	v.	Roadway	-0.507	0.504	1.009	0.315

* Not selected for further analysis.

APPENDIX B. CONTINGENCY TABLES

Contingency tables were prepared to examine whether complete or quasicomplete separations existed in the data used to develop a total of six individual logistic regression models in this study. This appendix presents the contingency tables of the outcome variable (Y) versus the levels of the explanatory factors considered for the development of each of these six individual models.

Table B.1. Contingency table for the explanatory factors included in Model 1

Explanatory Factor	**Crash was caused by a right-turning vehicle from a major roadway (Y)**		**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**
Percent heavy commercial vehicles (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**
Intersecting road type (JUNCT)				
Driveway	1,207	175	1,382	13.5
Roadway	8,559	294	8,853	86.5
Total	**9,766**	**469**	**10,235**	**100.00**
Light condition (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**

Table B.1. (Continued)

Explanatory Factor	Crash was caused by a right-turning vehicle from a major roadway (Y)		Grand Total	
	No	**Yes**	**# of event**	**%**
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 condition (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 involvement (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 condition (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. ** Out 469 crashes, 34 crashes were caused by false left-turn indications.

Table B.2. Contingency table for the explanatory factors included in Model 2

Explanatory Factor	Rear-end crash was caused by a right-turning vehicle from a major roadway (Y)		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**
Percent heavy commercial vehicles (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**
Intersecting road type (JUNCT)				
Driveway	87	79	166	38.2
Roadway	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 condition (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**
Right-turn treatment type (RTTRT)				
Radius	201	136	337	77.5
Exclusive	84	14	98	22.5
Total	**285**	**150**	**435**	**100.0**
Driveway type (DRWAY)				
Pub. driveway	45	39	84	19.3
Pvt. driveway	40	40	80	18.4
Roadway	200	71	271	62.3
Total	**285**	**150**	**435**	**100.0**

* Not included in the analysis.

Table B.3. Contingency table for the explanatory factors included in Model 3

Explanatory Factor	**Same-direction-sideswipe crash was caused by a right-turning vehicle from a major roadway (Y)**		**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 condition (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 type (RTTRT)				
Radius	267	70	337	77.5
Exclusive	73	25	98	22.5
Total	**340**	**95**	**435**	**100.0**

* Not included in the analysis.

Table B.4. Contingency table for the explanatory factors included in Model 4

Explanatory Factor	Right-angle crash was caused by a right-turning vehicle from a major roadway (Y)		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 condition (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 type (RTTRT)				
Radius	293	44	337	77.5
Exclusive	79	19	98	22.5
Total	**372**	**63**	**435**	**100.0**

* Not included in the analysis.

Table B.5. Contingency table for the explanatory factors included in Model 5

Explanatory Factor	Right-turn crash was caused by a right-turning vehicle from a major roadway (Y)		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 condition (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 condition (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 type (RTTRT)				
Radius	306	31	337	77.5
Exclusive	89	9	98	22.5
Total	**395**	**40**	**435**	**100.0**

* Not included in the analysis.

Table B.6. Contingency table for the explanatory factors included in Model 6

Explanatory Factor	Crash Injury Severity (Y)			Total Events
	Injury	**Possible Injury**	**Property Damage only**	
Traffic volume (AADTC)				
High	4	9	60	73
Low	20	56	318	394
*Not identified**	-	-	*2*	*2*
Total	**24**	**65**	**380**	**469**
Posted speed limit (SPEED)				
High	19	47	190	256
Low	5	17	186	208
*Not identified**	-	*1*	*4*	*5*
Total	**24**	**65**	**380**	**469**
Intersecting road type (DRWAY)				
Pub. driveway	6	10	70	86
Pvt. driveway	5	21	61	87
Roadway	13	34	249	296
Total	**24**	**65**	**380**	**469**
Right-turn treatment type (RTTRT)				
Radius	20	54	282	356
Exclusive	4	11	96	111
*Not identified**	-	-	*2*	*2*
Total	**24**	**65**	**380**	**469**
Road surface condition (SURFC)				
Wet & slippery	4	20	160	184
Dry	20	45	217	282
*Not identified**	-	-	*3*	*3*
Total	**24**	**65**	**380**	**469**
Type of crash (CRASH)				
Rear end	8	39	107	154
Same-direction sideswipe	4	10	100	114
Right angle	4	6	57	67
Right turn	2	2	38	42
Other	6	8	78	92
Total	**24**	**65**	**380**	**469**

* Not included in the analysis.

APPENDIX C. PARAMETER ESTIMATES, ODDS RATIOS AND GOODNESS-OF-FIT TEST STATISTICS FOR LOGISTIC REGRESSION MODELS

The parameter estimates for significant explanatory factors and the goodness-of-fit test statistics for the logistic regression models developed in this study are presented in this appendix. The odds ratios for significant explanatory factors are also provided, and may be used to quickly estimate the relative risks. It, however, needs to be noted that when the occurrence of desired outcome event is more than 10% (i.e., 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).

C.1 Binary logistic regression models

The parameter estimates and the odds ratios for significant explanatory factors for each of five individual binary logistic regression models are presented in Table C.1. The goodness-of-fit test statistics for each of these models, presented in Table C.2, indicate that each of the models fitted the data well at 95% confidence level.

As mentioned in Chapter 4, the Model 1 modeled the probabilities of a crash being caused by a right-turning vehicle from a major roadway, given that a crash had occurred. A total of eight explanatory factors found significant were: traffic volume, percent heavy commercial vehicles, intersecting road type, posted speed limit of roadway, road surface condition, tractor-trailer involvement, vehicular defects, and weather condition. The explanatory factor 'intersecting road type' was found to interact with the 'road surface

Table C.1. Binary logistic regression model estimations and odds ratios for significant explanatory factors

Explanatory Factor				Estimate	Standard Error	Wald Chi-Square	P-Value	Odds Ratio	95% Wald Confidence Limits	
Model 1										
Intercept				-3.550	0.110	1051.716	<.0001	-	-	-
AADTC	High	v.	Low	-0.370	0.137	7.345	0.007	0.690	0.528	0.903
HCVPR	High	v.	Low	0.347	0.117	8.868	0.003	1.415	1.126	1.779
JUNCT	Drwy	v.	Rdwy	1.675	0.129	169.553	<.0001	-	-	-
SPEED	High	v.	Low	-0.218	0.101	4.623	0.032	0.804	0.660	0.981
SURFC	WS	v.	Dry	1.155	0.151	58.580	<.0001	-	-	-
TTCMB	Yes	v.	No	0.475	0.164	8.369	0.004	1.607	1.165	2.217
VHDEF	Yes	v.	No	0.993	0.281	12.457	0.000	2.699	1.555	4.685
WETHR	NC	v.	Clear	-0.380	0.170	5.022	0.025	0.684	0.490	0.953
	SC	v.	Clear	-0.452	0.128	12.472	0.000	0.636	0.495	0.818
(JUNCT) *(SURFC)	Drwy * WS			-0.561	0.220	6.486	0.011	-	-	-
Model 2										
Intercept				-3.007	0.382	61.916	<.0001	-	-	-
INATT	Yes	v.	No	1.167	0.227	26.537	<.0001	3.212	2.061	5.008
SPEED	High	v.	Low	0.889	0.243	13.347	0.000	2.432	1.510	3.919
RTTRT	Radius	v.	Excl	1.347	0.347	15.100	0.000	3.845	1.949	7.584
DRWAY	Pub. drwy	v.	Rdwy	0.805	0.287	7.885	0.005	2.237	1.275	3.925
	Pvt. drwy	v.	Rdwy	0.369	0.301	1.505	0.220	1.446	0.802	2.607
Model 3										
Intercept				-1.815	0.269	45.439	<.0001	-	-	-
DRERR	Yes	v.	No	1.038	0.293	12.581	0.000	2.824	1.591	5.011
SURFC	WS	v.	Dry	-0.542	0.252	4.647	0.031	0.582	0.355	0.952
Model 4										
Intercept				-1.966	0.206	91.107	<.0001	-	-	-
VISON	Yes	v.	No	1.872	0.736	6.469	0.011	6.501	1.536	27.510
SURFC	WS	v.	Dry	0.773	0.293	6.973	0.008	2.166	1.220	3.845
Model 5										
Intercept				-1.649	0.216	58.432	<.0001	-	-	-
AADTC	High	v.	Low	-1.506	0.744	4.092	0.043	0.222	0.052	0.954
SPEED	High	v.	Low	-1.142	0.365	9.805	0.002	0.319	0.156	0.652

Note: WS – Wet & slippery, NC – Not clear, SC – Somewhat clear, Drwy – Driveway, Rdwy – Roadway, Excl – Exclusive.

condition' significantly. The heavy commercial vehicles, the tractor-trailer involvement, and the vehicular defects all contributed to the crashes due to right turns. The relative risks of such crashes were 42% higher at 'high' percent heavy commercial vehicles, 61% higher when the tractor-trailers were involved, and 2.7 times higher with the vehicular defects. On the other hand, the relative risks of crashes due to right turns were about 45% higher at 'low' traffic volumes compared to those at 'high' traffic volumes, about 25% higher at 'low' posted speed limits compared to those at 'high' posted speed limits, and 46% and 57% higher at 'clear' weather condition compared to those at 'not clear' and 'somewhat clear' weather conditions respectively. The reasons for these are the higher crash exposure at 'clear' weather condition as well as 'low' traffic volume conditions since there are more 'clear' days in a year and the two-lane roadways typically serve 'low' traffic volumes.

Table C.2. Goodness-of-fit test statistics for binary logistic regression models

Model	Criterion	Chi-Square	Value	DF*	Value/DF	P-Value
1	Deviance	-	958.122	1506	0.636	1.000
	Pearson	-	1484.958	1506	0.986	0.645
	Hosmer and Lemeshow	4.200	-	8	-	0.839
2	Deviance	-	176.275	147	1.199	0.050
	Pearson	-	154.412	147	1.050	0.321
	Hosmer and Lemeshow	3.368	-	6	-	0.761
3	Deviance	-	66.308	51	1.300	0.073
	Pearson	-	59.192	51	1.161	0.201
	Hosmer and Lemeshow	1.138	-	2	-	0.566
4	Deviance	-	20.713	26	0.797	0.757
	Pearson	-	20.593	26	0.792	0.763
5	Deviance	-	18.254	13	1.404	0.148
	Pearson	-	23.279	13	1.791	0.038
	Hosmer and Lemeshow	1.793	-	2	-	0.408

* Degrees of freedom.

The Model 2 estimated the probabilities of a rear-end crash, given that the crash was caused by a right-turning vehicle from a major roadway. Four explanatory factors turned out to be significant: the posted speed limit of a roadway, the right-turn treatment type, the driver inattention, and the type of intersecting roadway. The odds of a rear-end crash occurring with an inattentive driver were found to be 3.2 times higher compared to those when the driver was attentive. Similarly, the odds of a rear-end crash occurring at a roadway with a ‘high’ posted speed limit were 2.4 times higher compared to those with a ‘low’ posted speed limit. The odds of a rear-end crash occurring at an intersection approach without a right-turn lane were 3.8 times higher compared to those with an exclusive right-turn lane. As far as the intersecting road types are concerned, only the ‘public’ driveways were found to significantly affect the rear-end crashes (p-value = 0.005); the odds of a rear-end crash occurring at a public driveway approach were 2.2 times higher compared to those at an intersection approach.

The Model 3 estimated the probabilities of a same-direction-sideswipe crash, given that the crash was caused by a right-turning vehicle from a major roadway. Two explanatory factors found significant include driver error and road surface condition. The odds of the occurrence of a same-direction-sideswipe crash due to driver error were 2.8 times higher compared to those when the driver committed no error. The odds of a same-direction-sideswipe crash occurring on dry road surface condition were about 72% higher compared to those on wet & slippery road surface condition. The reason for this seemingly counter-intuitive finding may again be attributed to the comparatively higher crash opportunities at dry road surface condition. It may also indicate to the drivers being more cautious when they find road surface condition to be wet and slippery.

The Model 4 estimated the probabilities of a right-angle crash, given that the crash was caused by a right-turning vehicle from a major roadway. Two explanatory factors found significant were the road surface condition and the obstructed visibility. The odds of the occurrence of a right-angle crash on wet & slippery road surface condition were 2.2 times higher compared those on dry road surface condition. The obstructed visibility, on the other hand, resulted in the odds of the occurrence of a right-angle crash being 6.5 times higher compared to those when the visibility was not obstructed.

The Model 5 estimated the probabilities of a right-turn crash, given that the crash was caused by a right-turning vehicle from a major roadway. The traffic volumes and the posted roadway speed limits were the two explanatory factors found significant. The odds of the occurrence of a right-turn crash at ‘low’ traffic volumes were 4.5 times higher compared to those at ‘high’ traffic volumes, whereas the odds at ‘low’ posted roadway speed were 3.1 times higher compared to those at ‘high’ posted roadway speed.

C.2 Multinomial logistic regression model

The multinomial logistic regression model, referred to as Model 6, developed in this study estimated the probabilities of a crash injury severity level in a crash caused by a right-turning vehicle from a major roadway. Ordinal-response model was found appropriate. The score test results (p-value = 0.7667, chi-square = 1.1428, degrees of freedom = 3) revealed that the assumption of proportional odds was reasonable.

The crash injury severity was analyzed with three levels: injury, possible injury, and property damage only. The ‘injury’ severity level was considered the reference level. Three explanatory factors turned out to be significant in determining the level of crash injury severity. These were: posted roadway speed limit, right-turn treatment type and road surface condition. The parameter estimates and the odds ratios for significant explanatory factors are presented in Table C.3. The goodness-of-fit test statistics, presented in Table C.4, indicate that the model fitted the data well.

Table C.3. Multinomial logistic regression model estimation and odds ratios for significant explanatory factors

Explanatory Factor				Estimate	Standard Error	Wald Chi-Square	P-Value	Odds Ratio	95% Wald Confidence Limits	
Int. 1	Property Damage			2.583	0.393	43.112	<.0001			
Int. 2	Possible Injury			4.106	0.437	88.127	<.0001			
SPEED	High	v.	Low	-1.197	0.275	19.028	<.0001	0.302	0.176	0.517
RTTRT	Radius	v.	Exclusive	-0.736	0.321	5.268	0.022	0.479	0.256	0.898
SURFC	Wet & slippery	v.	Dry	0.535	0.270	3.933	0.047	1.707	1.006	2.894

Note: Int. – intercept.

Table C.4. Goodness-of-fit test statistics for multinomial logistic regression model

Criterion	Value	DF	Value/DF	P-Value
Deviance	165.703	225	0.737	0.999
Pearson	206.112	225	0.916	0.812

APPENDIX D. SELECTED PHOTOGRAPHS OF STUDY SITES

a) US-212/4th St. intersection (+), Dawson, MN

Radius treatment, viewed from east approach.

b) US-61/250th St. intersection (+), Forest Lake, MN.

Exclusive lane treatment, north approach in view.

c) MNTH-210/CR-54 & 56 intersection (+), Aitkin, MN.

Radius treatment, east approach in view.

d) US-10/12th St. NE intersection (+), Staples, MN.

Radius treatment, viewed from west approach; also shows intersecting 11th St. NE and Subway-DQ driveways.

e) MNTH-23/CR-10 intersection (+), Ruthton, MN.

Exclusive lane treatment, viewed from south approach.

f) MNTH-34/CR-4 intersection (T), Park Rapids, MN.

Exclusive lane treatment, east approach in view.

Figure D.1. Selected pictures of survey locations.

g) MNTH-8/Akerson St. intersection (+), Lindstrom, MN.

Exclusive lane treatment, viewed from west approach.

h) US-75/46th Ave. S. intersection (T), Moorhead, MN.

Exclusive lane treatment, viewed from north approach.

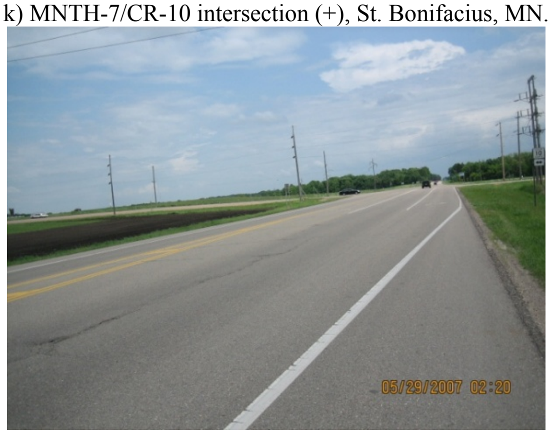
i) US-61/240th St. intersection (T), Forest Lake, MN.

Radius treatment, viewed from south approach.

j) MNTH-55/CR-114 intersection (T), Lowry, MN.

Radius treatment, west approach in view.

k) MNTH-7/CR-10 intersection (+), St. Bonifacius, MN.



Exclusive lane treatment, viewed from west approach.

l) US-14/CR-8 intersection (T), Tyler, MN.

Exclusive lane treatment, viewed from east approach.

Figure D.1. (Continued)

m) 28th Av. N/40th St. N int. (+), Moorhead, MN.

Radius treatment, viewed from west approach.

n) 20th St. S/14th Av. S int. (T), Moorhead, MN.

Radius treatment, viewed from north approach.

o) 28th Av. N/34th St. N int. (T), Moorhead, MN.

Radius treatment, viewed from west approach.

p) 20th St. S/16th Av. S int. (T), Moorhead, MN.

Radius treatment, viewed from north approach.

q) 12th Av. S/32 St. Cir. S int. (T), Moorhead, MN.

Radius treatment, viewed from west approach.

r) 20th St. S/20th Av. S int. (T), Moorhead, MN.

Exclusive lane treatment, viewed from north approach.

Figure D.1. (Continued)

s) 20th St. S/24th Av. S int. (T), Moorhead, MN.

Exclusive lane treatment, viewed from north approach.

t) Oakport St. N/43rd Av. N int. (T), Oakport, MN.

Radius treatment, viewed from south approach.

u) 20th St. S/MSCTC Drive int. (T), Moorhead, MN.

Exclusive lane treatment, viewed from north approach.

v) Oakport St. N/Old Trail int. (T), Oakport, MN.

Radius treatment, viewed from north approach.

Figure D.1. (Continued)

APPENDIX E. PARAMETER ESTIMATES AND RESIDUAL PLOTS OF CONFLICT PREDICTION MODELS

E.1 Conflict prediction model using the field data

The conflict prediction model developed using the field data was presented in Equation 5.1. The parameter estimates and the residual plots, presented in Table E.1 and Figure E.1 respectively, reveal that the model fitted the data well.

Table E.1. Parameter estimates of the conflict prediction model fitted with the field data

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	4.372	2.615	1.670	0.111
(RTT)	-2.970	3.812	-0.780	0.446
(RTP)	1.652	0.188	8.770	0.000
(SPD)	5.606	2.707	2.070	0.052
(RTT).(RTP)	-0.931	0.356	-2.610	0.017

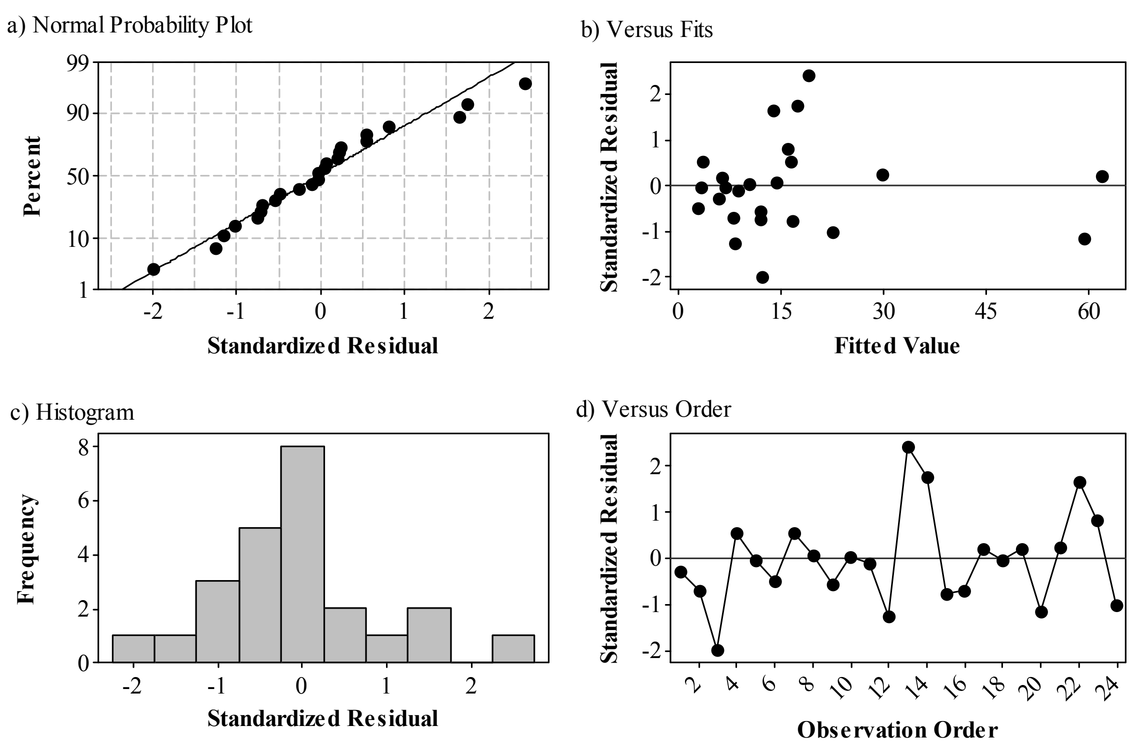


Figure E.1. Residual plots of conflicts due to right turns predicted using the field data.

E.2 Conflict prediction model using the simulation data

E.2.1 Radius right-turn treatment

The conflict prediction model developed using the simulation data for radius right-turn treatment was presented in Equation 5.4a. The parameter estimates (Table E.2) and the residual plots (Figure E.2) show that the model fitted the data well.

Table E.2. Parameter estimates of the conflict prediction model for radius right-turn treatment fitted with the simulation data

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	-1.543600	0.537600	-2.870	0.005
(SPD)	0.041460	0.013320	3.110	0.003
(RTP)	1.212200	0.148900	8.140	0.000
(VOL)	0.002056	0.001327	1.550	0.126
(SPD).(RTP)	-0.035735	0.002947	-12.130	0.000
(SPD).(VOL)	-0.000054	0.000034	-1.590	0.117
(RTP).(VOL)	-0.005631	0.000653	-8.630	0.000
(SPD).(RTP).(VOL)	0.000710	0.000019	37.330	0.000

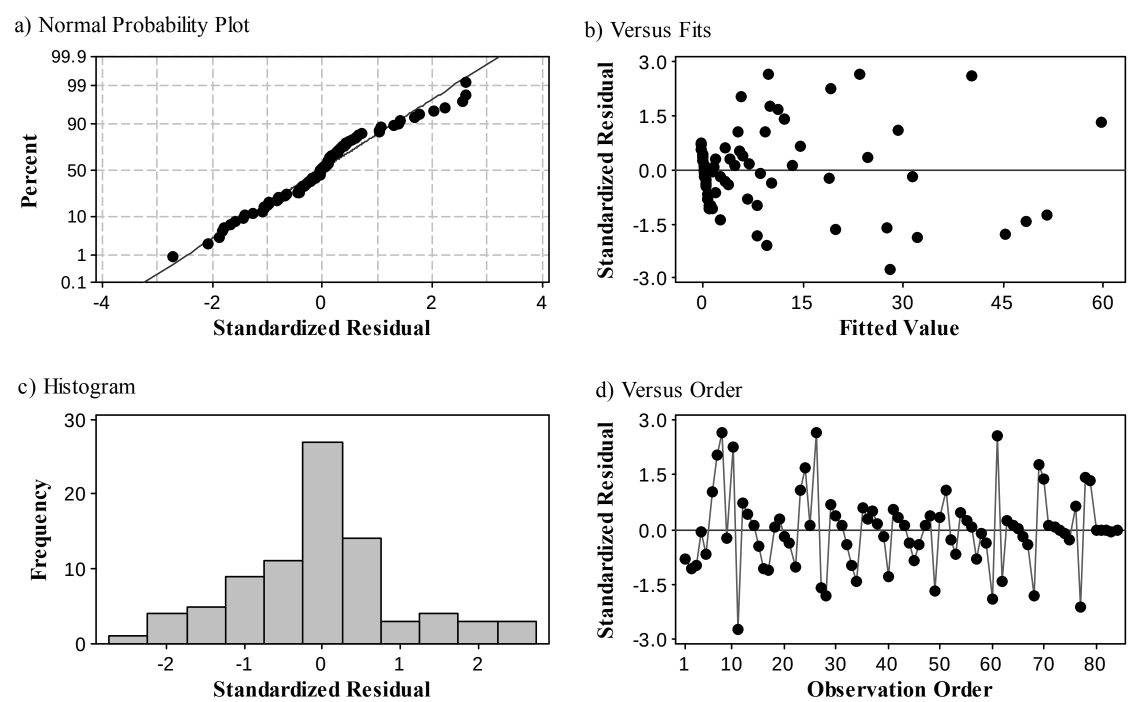


Figure E.2. Residual plots of conflicts due to right turns predicted at radius right-turn treatment using the simulation data.

E.2.2 Exclusive right-turn lane treatment

The conflict prediction model developed using the simulation data for exclusive right-turn lane treatment was shown in Equation 5.4b. The parameter estimates (Table E.3) and the residual plots (Figure E.3) show that the model fitted the data well.

Table E.3. Parameter estimates of the conflict prediction model for exclusive right-turn lane treatment fitted with the simulation data

Predictor	β Coefficient	Std. Error of Coefficient	T-Statistic	P-Value
Intercept	-0.544200	0.283900	-1.920	0.058
(SPD)	0.015982	0.007040	2.270	0.025
(RTP)	0.058140	0.051120	1.140	0.258
(VOL)	0.000737	0.000706	1.040	0.299
(SPD).(RTP)	-0.003184	0.001114	-2.860	0.005
(SPD).(VOL)	-0.000020	0.000018	-1.100	0.274
(RTP).(VOL)	0.000521	0.000198	2.630	0.010
(SPD).(RTP).(VOL)	0.000108	0.000004	24.240	0.000

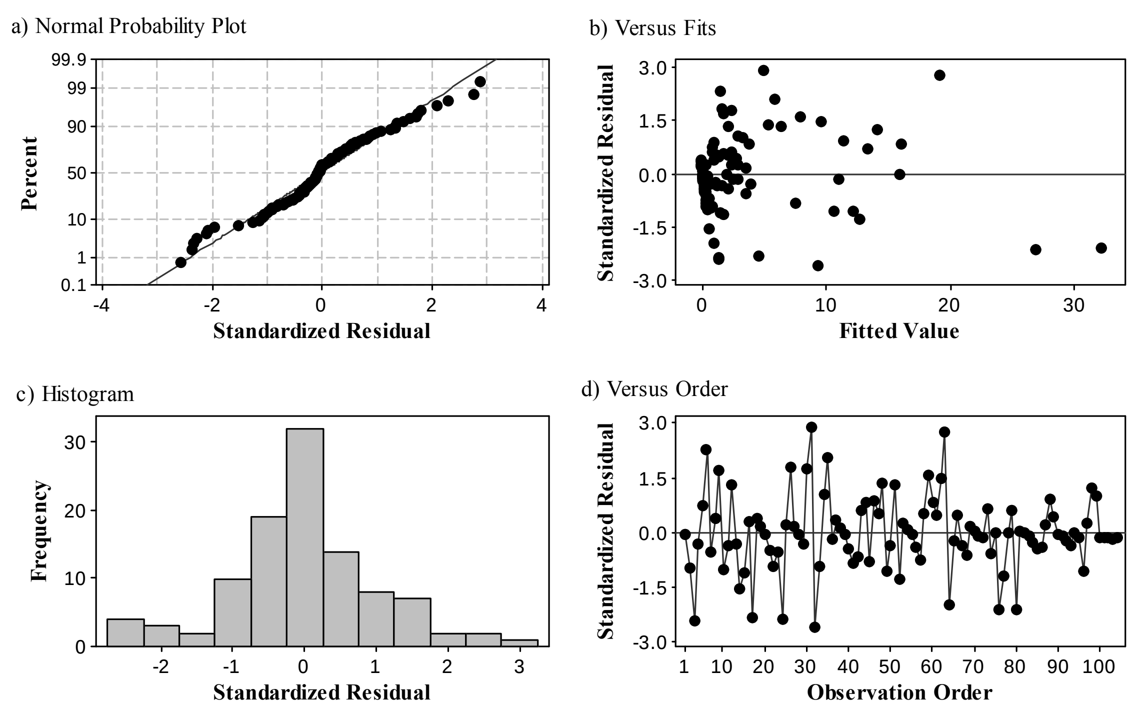


Figure E.3. Residual plots of conflicts due to right turns predicted at exclusive right-turn lane treatment using the simulation data.

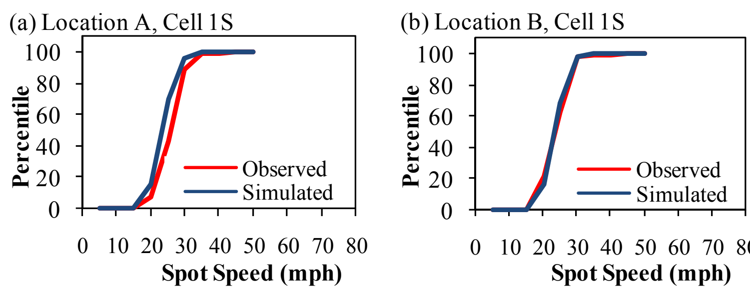
APPENDIX F. VISSIM MODEL CALIBRATIONS

A total of twelve individual VISSIM models were developed corresponding to twelve cells. Six cells (Cell 1S through Cell 6S) were used to calibrate six VISSIM models for the simulations of conflicts due to right turns at an approach with a radius right-turn treatment. The remaining six cells (Cell 1E through Cell 6E) were used to calibrate the rest of the VISSIM models for conflict simulations at an approach with an exclusive right-turn lane. The VISSIM model calibrations involved finding appropriate combinations of BX_{add} and BX_{mult} in Equation 5.2b for the condition observed at a study approach to replicate the observed spot-speed and time headway distributions at various locations (points) in the traffic stream of interest on that approach.

This appendix presents the observed and the simulated distributions of spot speeds and time headways. The simulated distributions presented are those obtained from the VISSIM models considered sufficiently calibrated. The spot-speed and the time headway distributions at study approaches with right-turn lanes were observed at three locations (A, B, and C) and at approaches without right-turn lanes at two locations (A and B). The observed and the simulated distributions presented correspond to these locations.

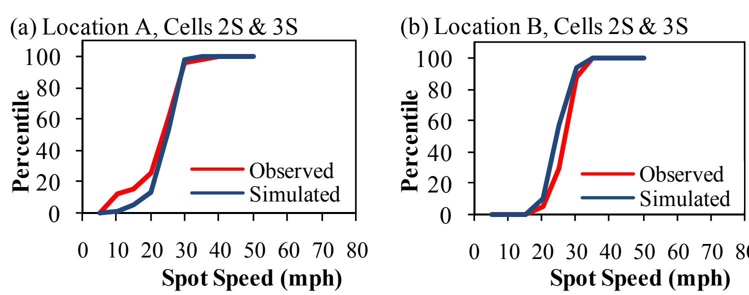
F.1 Spot-speed distributions

The observed and the simulated spot-speed distributions at study approaches with radius right-turn treatments are presented in Figure F.1 through Figure F.4. The desired speed distribution at the study approach corresponding to Cell 3S (low speed, high traffic volume) was considered same as that observed at the study approach corresponding to Cell 2S (low speed, medium traffic volume). Similarly, same calibration parameters were used for the conditions represented by Cell 5S (high speed, medium traffic volume) and Cell 6S (high speed, high traffic volume).



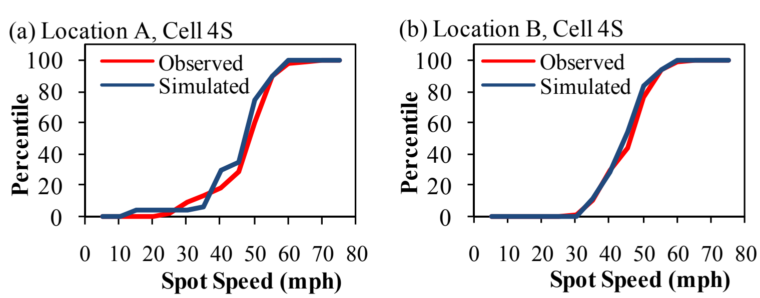
Location: US-212 West Approach at US-212/4th St., Dawson; Posted speed: 30 mph; Volume: 125 vph.

Figure F.1. Spot-speed distributions corresponding to Cell 1S.



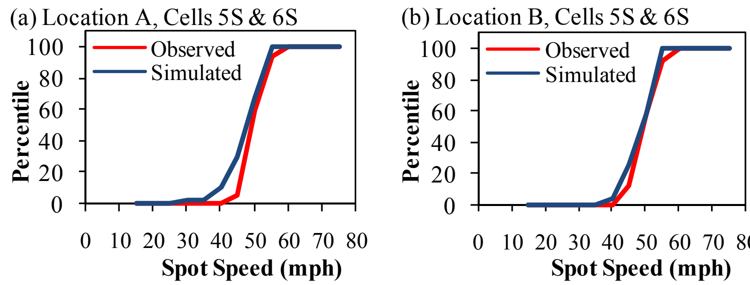
Location: US-10 West Approach at US-10/12th St. NE, Staples; Posted speed: 30 mph; Volume: 303 vph.

Figure F.2. Spot-speed distributions corresponding to Cells 2S & 3S.



Location: 28th Ave. N West Approach at 28th Ave. N /34th St. N, Moorhead; Posted speed: 55 mph; Volume: 128 vph.

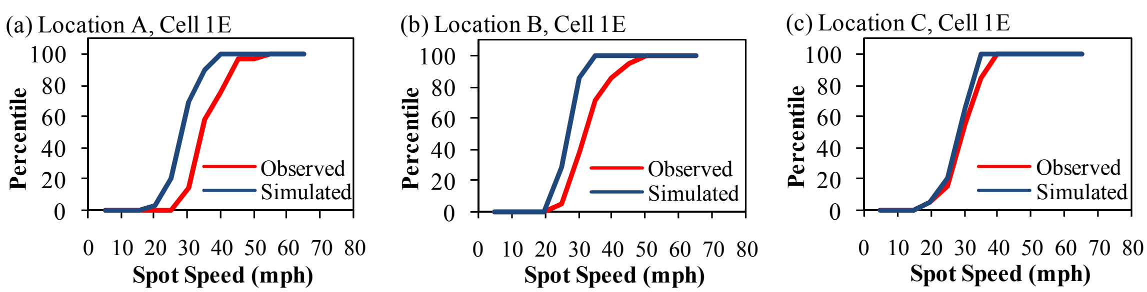
Figure F.3. Spot-speed distributions corresponding to Cell 4S.



Location: US-61 North Approach at US-61/240th St., Forest Lake; Posted speed: 55 mph; Volume: 504 vph.

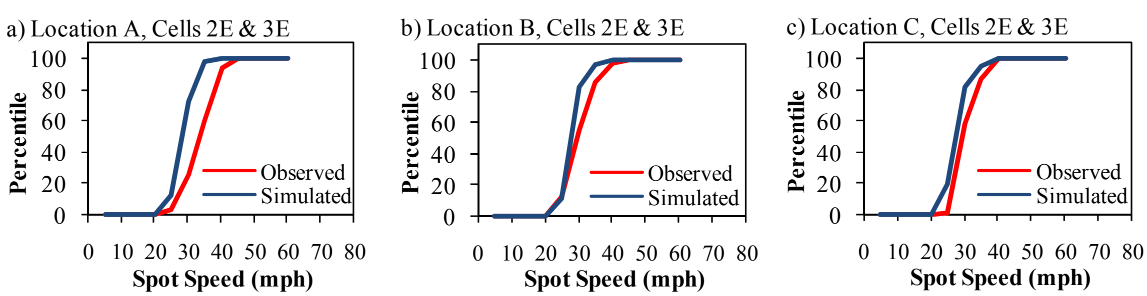
Figure F.4. Spot-speed distributions corresponding to Cells 5S & 6S.

The observed and the simulated spot-speed distributions at study approaches with right-turn lanes are presented in Figure F.5 through Figure F.9. The desired speed at the study approach corresponding to Cell 2E (low speed, medium volume) was considered same as that observed at the approach corresponding to Cell 3E (low speed, high volume).



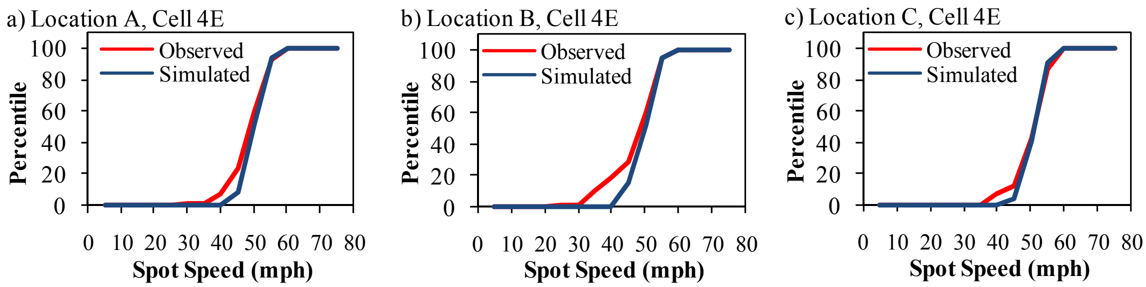
Location: US-14 East Approach at US-14/CR-8, Tyler; Posted speed: 35 mph; Volume: 80 vph.

Figure F.5. Spot-speed distributions corresponding to Cell 1E.



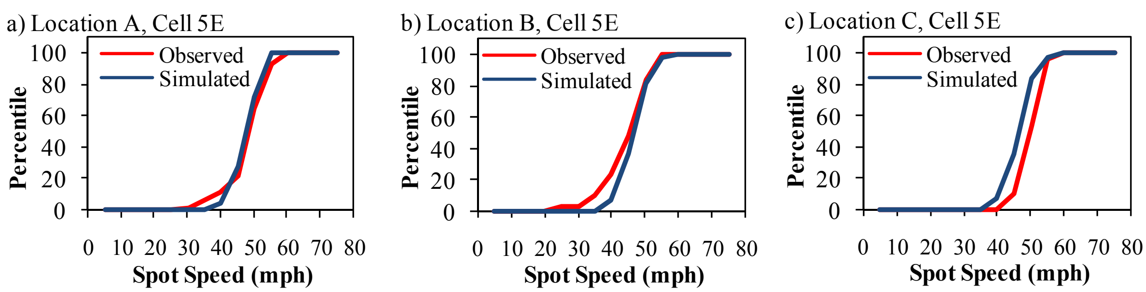
Location: MNTH-8 West Approach at MNTH-8/Akerson St., Lindstrom; Speed: 30 mph; Volume: 766 vph.

Figure F.6. Spot-speed distributions corresponding to Cells 2E & 3E.



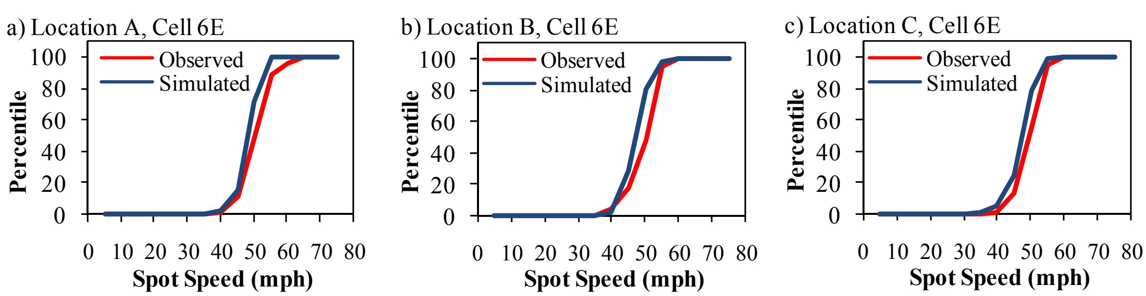
Location: MNTH-34 East Approach at MNTH-34/CR-4, Park Rapids; Speed: 55 mph; Volume: 247 vph.

Figure F.7. Spot-speed distributions corresponding to Cell 4E.



Location: US-61 North Approach at US-61/250th St., Forest Lake; Speed: 55 mph; Volume: 358 vph.

Figure F.8. Spot-speed distributions corresponding to Cell 5E.



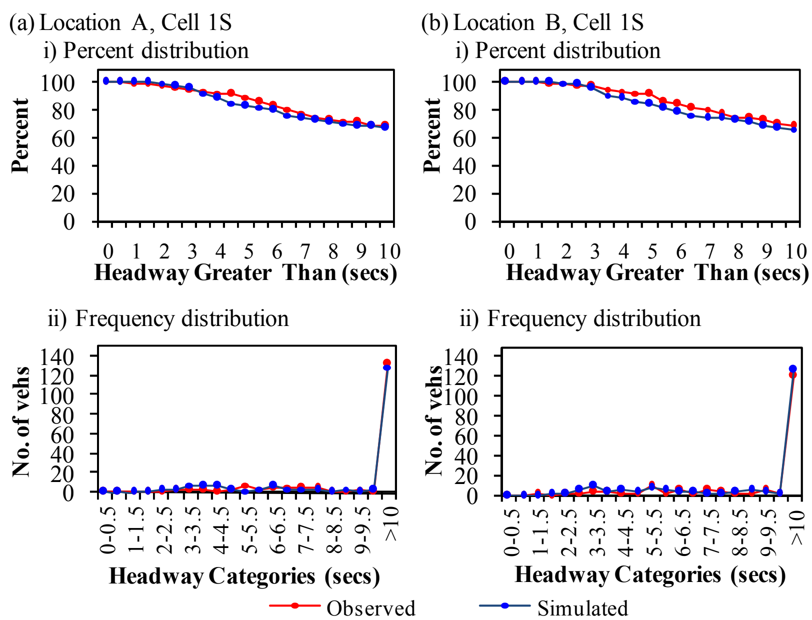
Location: US-61 South Approach at US-61/250th St., Forest Lake; Speed: 55 mph; Volume: 681 vph.

Figure F.9. Spot-speed distributions corresponding to Cell 6E.

F.2 Time headway distributions

A close replication of observed time headway distribution was the most critical component of VISSIM model calibration. The exercise turned out to be a time-consuming process, especially because close replications were sought simultaneously at multiple points in the traffic stream of interest. The time headway distribution at a location is presented in terms of both percent distribution and frequency distribution.

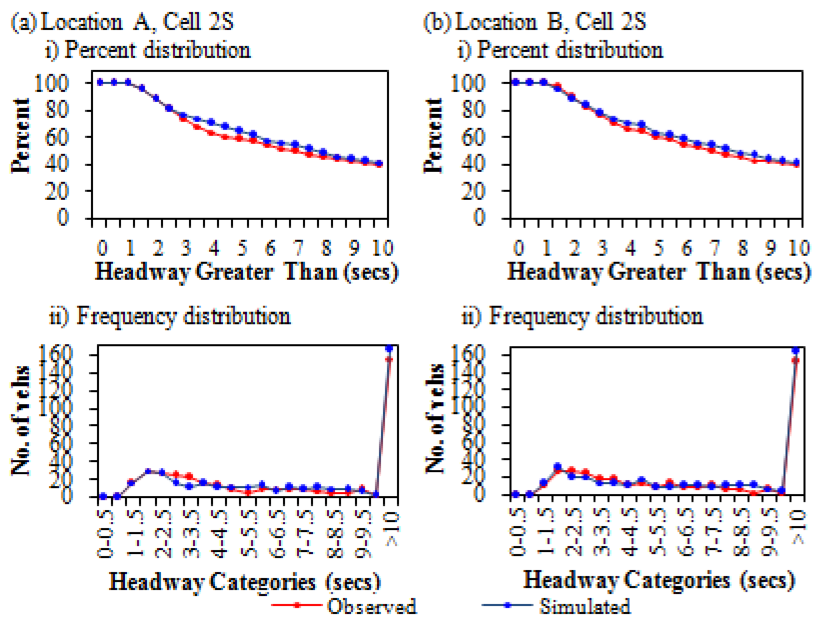
The observed and the simulated time headway distributions at study approaches with radius right-turn treatments are presented in Figure F.10 through Figure F.14. For the VISSIM model corresponding to Cell 3S (low speed, high volume), only the time headway distribution observed at Location A on the study approach was replicated.



Location: US-212 West Approach at US-212/4th St., Dawson; Posted speed: 30 mph; Volume: 125 vph.

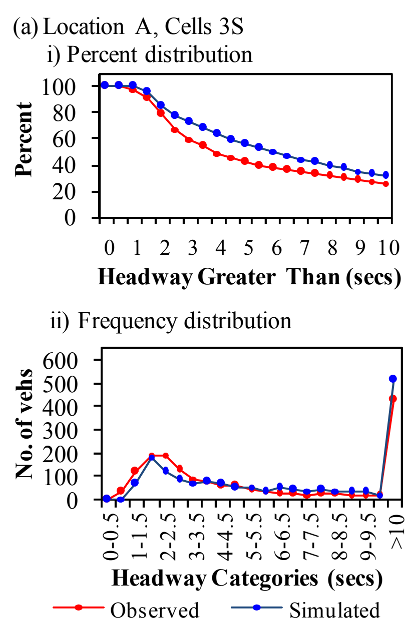
Figure F.10. Time headway distributions corresponding to Cell 1S.

The observed and the simulated time headway distributions at study approaches with exclusive right-turn lane treatments are presented in Figure F.15 through Figure F.20. For the VISSIM model corresponding to Cell 2E (low speed, medium volume), only the time headway distribution observed at Location A on the study approach was replicated.



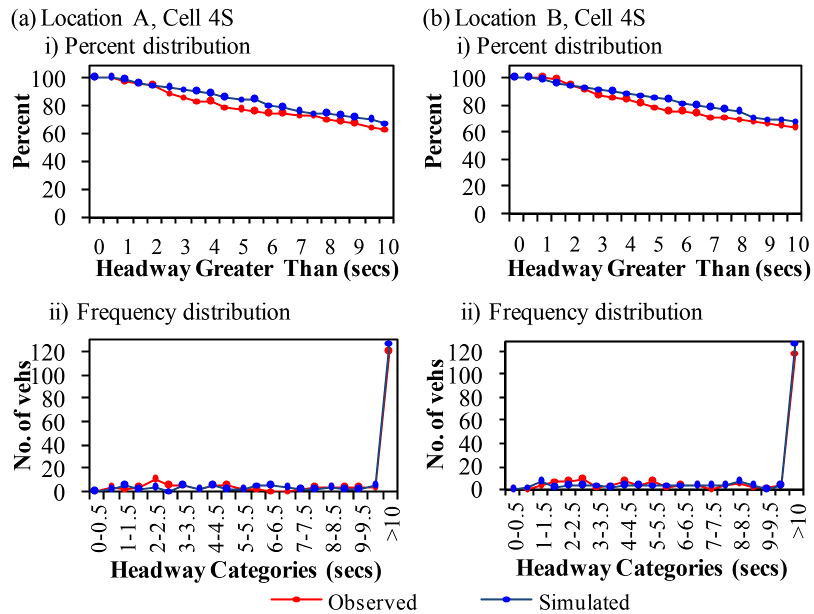
Location: US-10 West Approach at US-10/12th St. NE, Staples; Posted speed: 30 mph; Volume: 303 vph.

Figure F.11. Time headway distributions corresponding to Cell 2S.



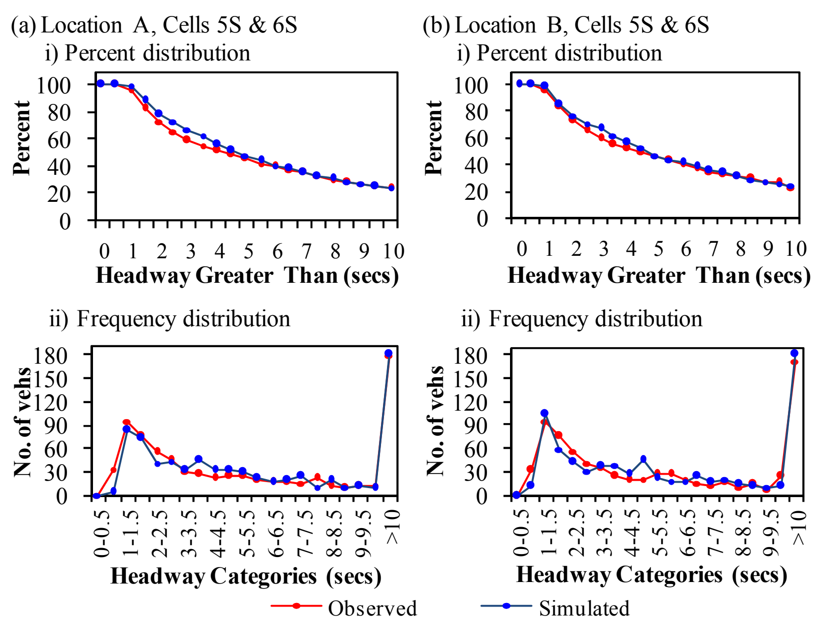
Location: 20th St. S North Approach at 20th St. S/16th Ave. S, Moorhead; Posted speed: 30 mph; Volume: 413 vph.

Figure F.12. Time headway distributions corresponding to Cell 3S.



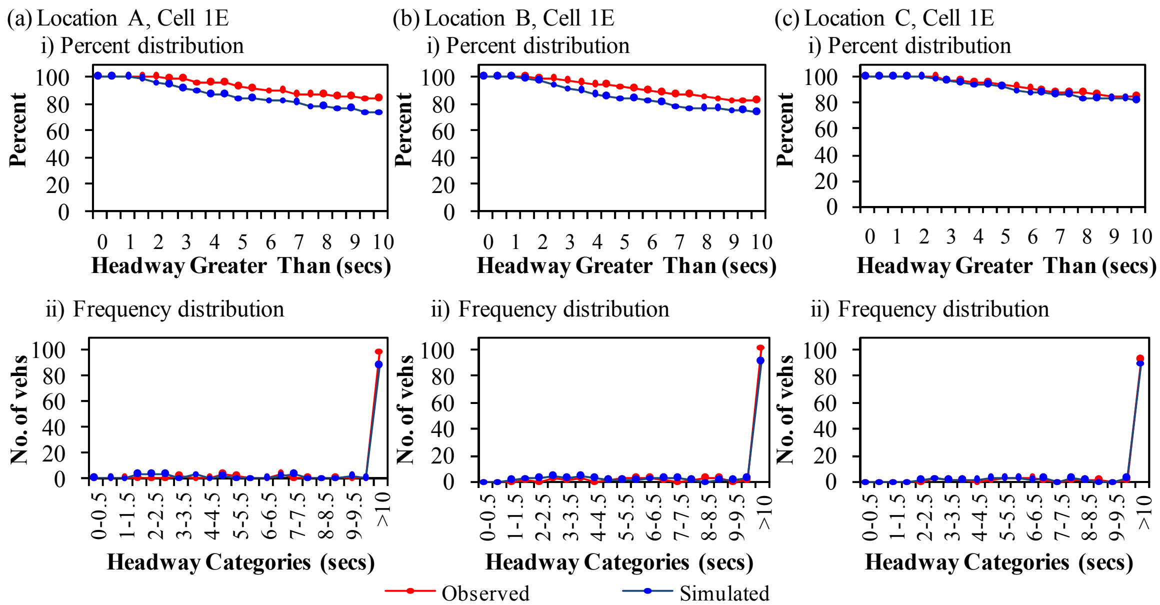
Location: 28th Ave. N West Approach at 28th Ave. N /34th St. N, Moorhead; Posted speed: 55 mph; Volume: 128 vph.

Figure F.13. Time headway distributions corresponding to Cell 4S.



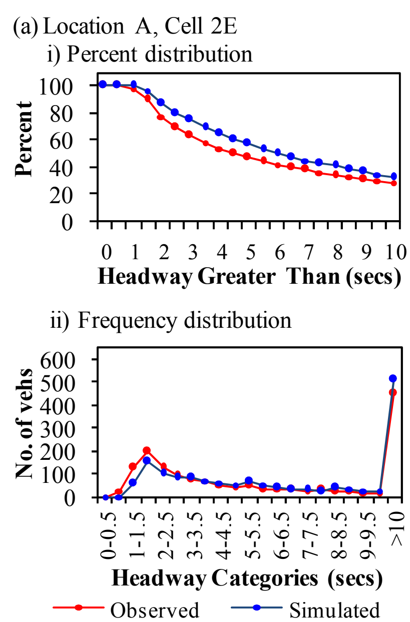
Location: US-61 North Approach at US-61/240th St., Forest Lake; Posted speed: 55 mph; Volume: 504 vph.

Figure F.14. Time headway distributions corresponding to Cells 5S & 6S.



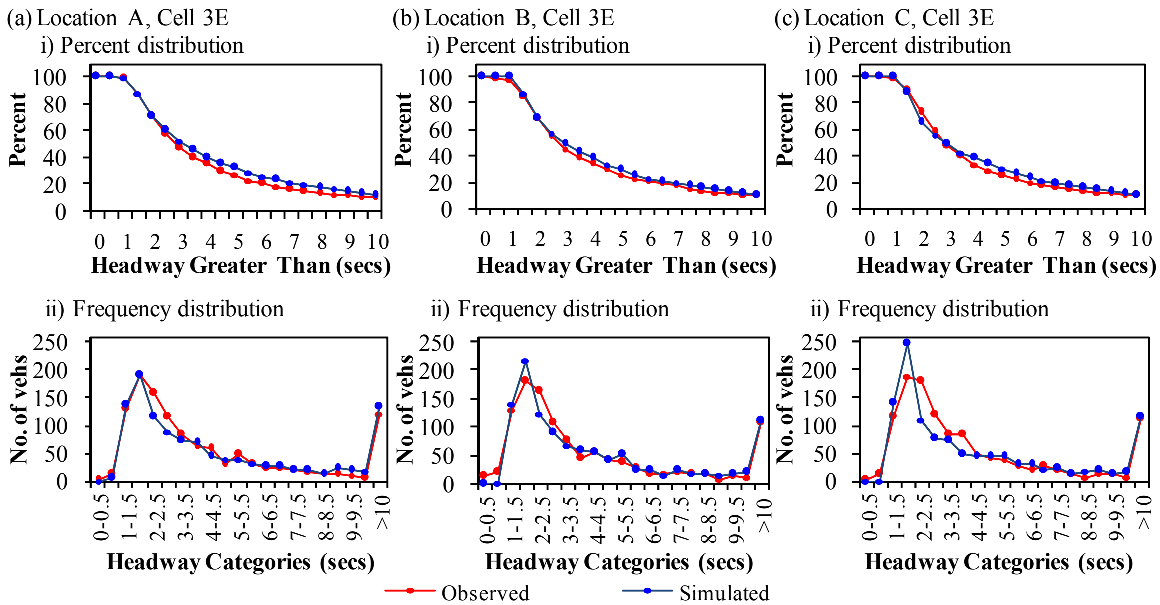
Location: US-14 East Approach at US-14/CR-8, Tyler; Posted speed: 35 mph; Volume: 80 vph.

Figure F.15. Time headway distributions corresponding to Cell 1E.



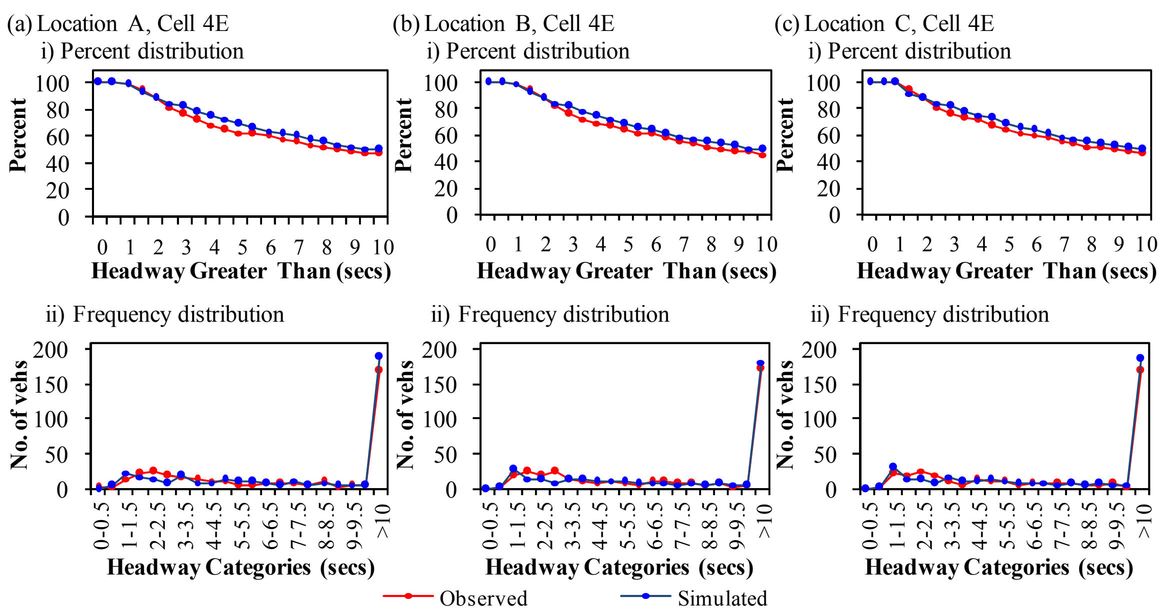
Location: 20th St. S North Approach at 20th St. S/MSCTC Drive, Moorhead; Speed: 30 mph; Volume 393 vph.

Figure F.16. Time headway distributions corresponding to Cell 2E.



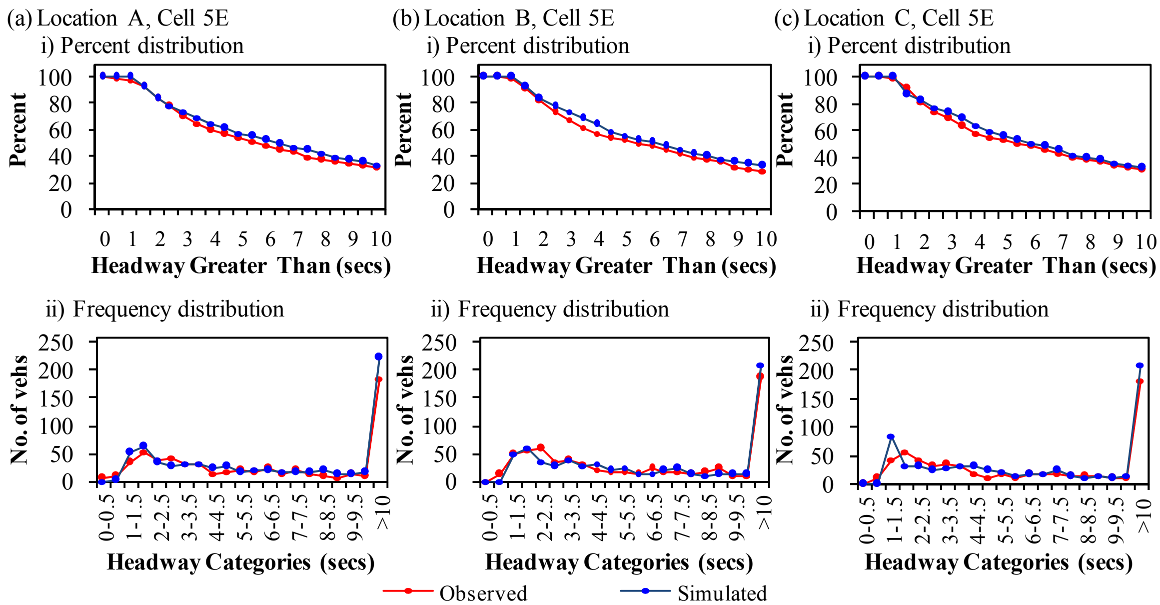
Location: MNTH-8 West Approach at MNTH-8/Akerson St., Lindstrom; Speed: 30 mph; Volume: 766 vph.

Figure F.17. Time headway distributions corresponding to Cell 3E.



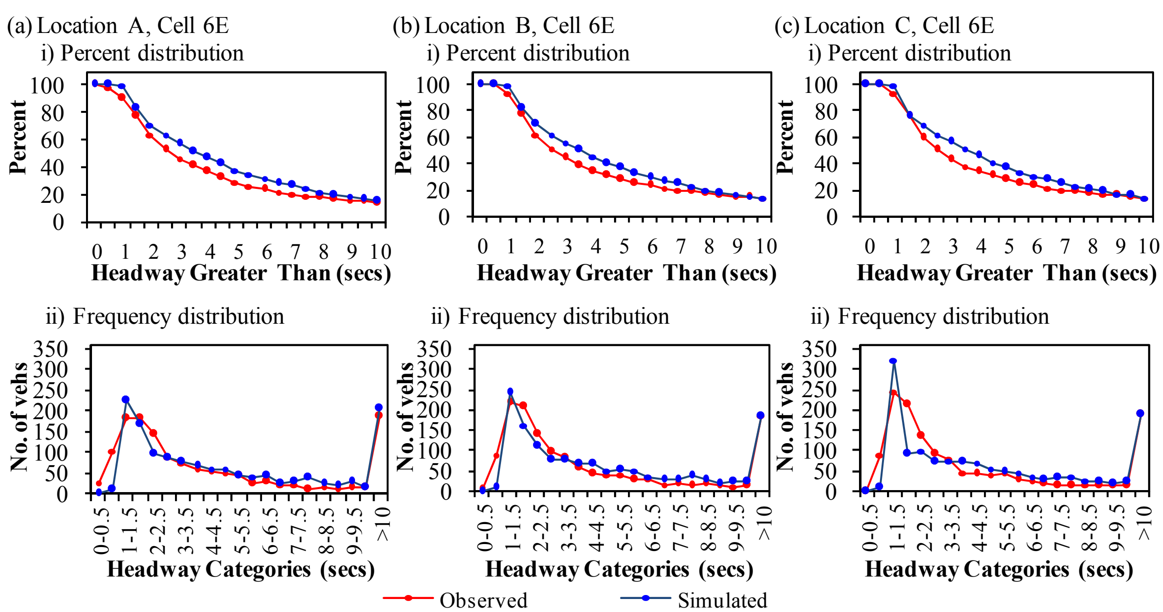
Location: MNTH-34 East Approach at MNTH-34/CR-4, Park Rapids; Speed: 55 mph; Volume: 247 vph.

Figure F.18. Time headway distributions corresponding to Cell 4E.



Location: US-61 North Approach at US-61/250th St., Forest Lake; Speed: 55 mph; Volume: 358 vph.

Figure F.19. Time headway distributions corresponding to Cell 5E.



Location: US-61 South Approach at US-61/250th St., Forest Lake; Speed: 55 mph; Volume: 681 vph.

Figure F.20. Time headway distributions corresponding to Cell 6E.

APPENDIX G. COMPARISONS OF EXPECTED CRASH SAVINGS AT RIGHT-TURN LANES WITH OTHER STUDIES

McCoy et al. (1993) determined the safety effectiveness of right-turn lanes using speed differentials as the surrogate safety measure. The relationship shown below was formulated to estimate the number of crashes saved per year by providing right-turn lanes:

$$A = (P_D I_D + P_N I_N).\frac{AADT}{2x10^8}.P_{RT}.\frac{L}{5280}.365, \tag{G.1}$$

where A is the number of accidents saved per year by providing right-turn lanes, P_D is the portion of daytime traffic, I_D is daytime accident involvement rate (accidents per 100 MVM), P_N is the portion of nighttime traffic, I_N is nighttime accident involvement rate (accidents per 100 MVM), AADT is annual average daily traffic (vpd), P_{RT} is the portion of right-turning vehicles, and L is right-turn deceleration distance (ft).

The portion of daytime traffic was estimated at 0.76, while the portion of nighttime traffic was estimated at 0.24 based on the traffic counts found at the continuous traffic counting stations on urban arterial sections of the state highway system in Nebraska. The daytime and the nighttime accident involvement rates were determined based on the relationship between speed differentials and crashes presented in Figure 2.2. The speed differentials were estimated as the differences between the average speeds of right-turning vehicles shown in Table G.1 and the average roadway speeds (Table G.2) determined using Equation G.2. The right-turn deceleration distances used were as provided in Table G.1

$$S_{avg} = P_{RT}.S_{RT} + (1 - P_{RT}).S_R, \tag{G.2}$$

where S_{avg} is average roadway speed (mph), P_{RT} is the portion of right-turning vehicles, S_{RT} is the average speed of right-turning vehicles (mph), and S_R is roadway speed (mph).

Table G.1. Average speeds and deceleration distances of right-turning vehicles

Roadway Speed (mph)	Average Speed of Right-turning Vehicles (mph)	Deceleration Distance of Right-turning Vehicles (ft)
25	20	185
35	25	295
45	30	405
55	35	540

Source: McCoy et al. (1993).

Table G.2. Average roadway speeds (mph)

Roadway Speed (mph)	Percent Right Turns						
	0	5	15	25	35	45	55
25	25.00	24.75	24.25	23.75	23.25	22.75	22.25
35	35.00	34.50	33.50	32.50	31.50	30.50	29.50
45	45.00	44.25	42.75	41.25	39.75	38.25	36.75
55	55.00	54.00	52.00	50.00	48.00	46.00	44.00

Hasan and Stokes (1996) used the same relationship (Equation G.1) formulated by McCoy et al. (1993) to determine the number of crashes saved per year by providing right-turn lanes. However, the right-turn deceleration distances they used were as presented in Table G.3, which were determined analytically by using the relationship shown below:

$$L = \frac{1}{2a}.(u^2 - u_T^2), \qquad \text{(G.3)}$$

where L is right-turn deceleration distance (ft), a is the deceleration rate of a right-turning vehicle (assumed to be 3 ft/sec^2), u is the operating speed of the roadway (ft/sec), and u_T is right-turn speed (assumed to be 22 ft/sec or 15 mph).

Table G.3. Deceleration distances of right-turning vehicles

Roadway Speed (mph)	Deceleration Distance of Right-turning Vehicles (ft)
40	493
45	645
50	816
55	1,004
60	1,210
65	1,434

Source: Hasan and Stokes (1996).

The estimates of crash savings, in terms of the number of crashes saved per year, by providing exclusive right-turn lanes at intersection approaches based on the methodologies adopted by McCoy et al. (1993) and Hasan and Stokes (1996) were compared with the crash savings estimated in this study. These comparisons of annual crash savings are presented in Figure G.1 for the posted roadway speed limits of 25, 35, 45 and 55 mph. At higher traffic volumes (AADT more than 5,000 vpd), the crash saving estimates obtained based on the methodologies adopted by McCoy et al. (1993) and Hasan and Stokes (1996) were found to be substantially lower than those estimated in this study, more so at lower posted roadway speed limits (25 & 35 mph). At lower traffic volumes (AADT less than 5,000 vpd) and higher speed limits (45 & 55 mph), the crash savings estimated in this study were found to be slightly lower.

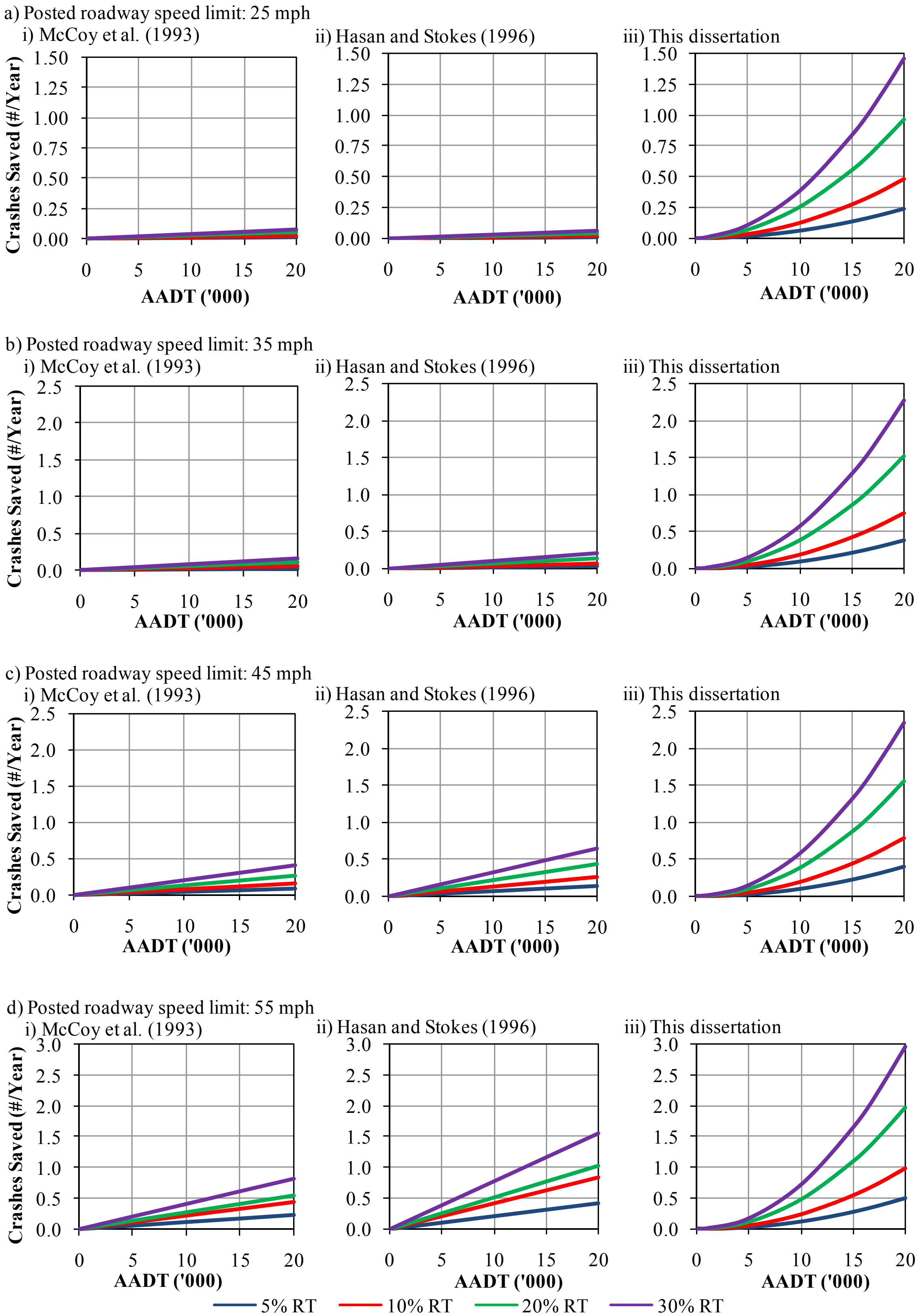


Figure G.1. Crash saving comparisons at intersection approaches.

APPENDIX H. VOLUME WARRANTS FOR RIGHT-TURN LANES BASED ON THEIR SAFETY AND OPERATIONAL EFFECTIVENESS

This appendix presents the volume warrants for right-turn lanes on two-lane roadway approaches with no control at unsignalized intersections and driveways. The warrant guidelines, developed through benefit-cost analyses, take into account both the safety and the operational benefits of providing right-turn lanes. The safety benefits considered in the guidelines were as determined in this study, whereas the operational benefits considered were as determined by Varma et al. (2008). The costs considered were the costs of constructing right-turn lanes.

In addition to the impacts on traffic safety, the vehicles slowing to make right turns also cause adverse operational impacts in terms of delay and extra fuel consumption by causing the following through vehicles to slow down as well. Varma et al. (2008) showed that exclusive right-turn lanes for right-turning vehicles alleviate these operational problems and proposed the relationships presented below to estimate the delay and the extra fuel consumption caused by right-turning vehicles:

$$DL\text{-}SPT = 0.912 - 0.0197.(SR) + 0.0102.(VRT) + 0.00228.(V) - 0.0116.(VRT).(RT); \quad (H.1a)$$

$$FUEL = - 0.150 + 0.00361.(SR) + 0.000889.(VRT) + 0.00440.(V) - 0.000263.(VRT).(RT); \quad (H.1b)$$

where DL-SPT is delay per through vehicle (seconds); FUEL is fuel consumption (gallons per 15 minutes); SR is approach roadway speed (mph); V is approach volume (vehicles per 15 minutes); VRT is right-turn volume (vehicles per 15 minutes); and RT is right-turn treatment type (1 if exclusive right-turn lane, 0 if radius right-turn treatment).

The operational benefits of providing right-turn lanes were estimated at the delay cost of $13.42 per hour (OIM, 2009). For the fuel costs, a total of three scenarios were considered – $2, $3 and $4 per gallon.

H.1 Right-turn lanes at intersection approaches

The volume warrants for right-turn lanes at intersection approaches were developed for the DDHV ranging from 100 to 1,500 vph at four different posted roadway speed limits (25, 35, 45, and 55 mph). A total of sixteen different scenarios for the construction costs of right-turn lanes were considered, ranging from $15,000 to $90,000. The benefits considered were the expected safety and the expected operational benefits of providing right-turn lanes. The other relevant inputs and the methodology adopted for determining the minimum RTDHV thresholds to warrant a right-turn lane at an intersection approach were same as discussed in Chapter 6.

Keeping the annual safety and the annual delay savings same, the warrant guidelines for right-turn lanes at intersection approaches presented in Figure H.1/Table H.1 are based on the fuel cost of $2/gallon. On the other hand, the warrant guidelines presented in Figure H.2/Table H.2 and Figure H.3/Table H.3 are based on the fuel cost of $3 and $4 per gallon, respectively.

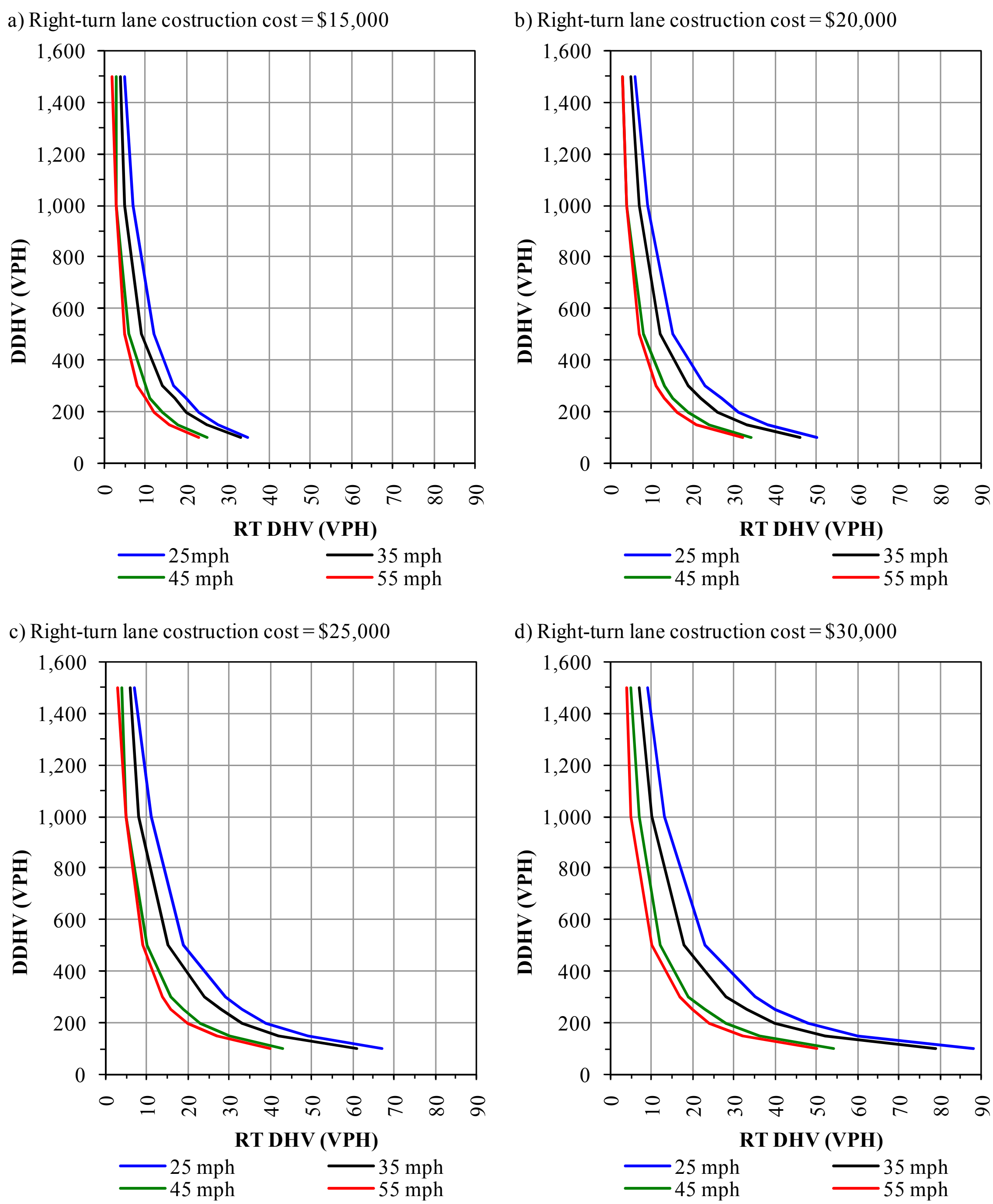


Figure H.1. Volume warrants for right-turn lanes at uncontrolled intersection approaches on two-lane roadways – fuel cost $2/gallon, delay cost $13.42/hour.

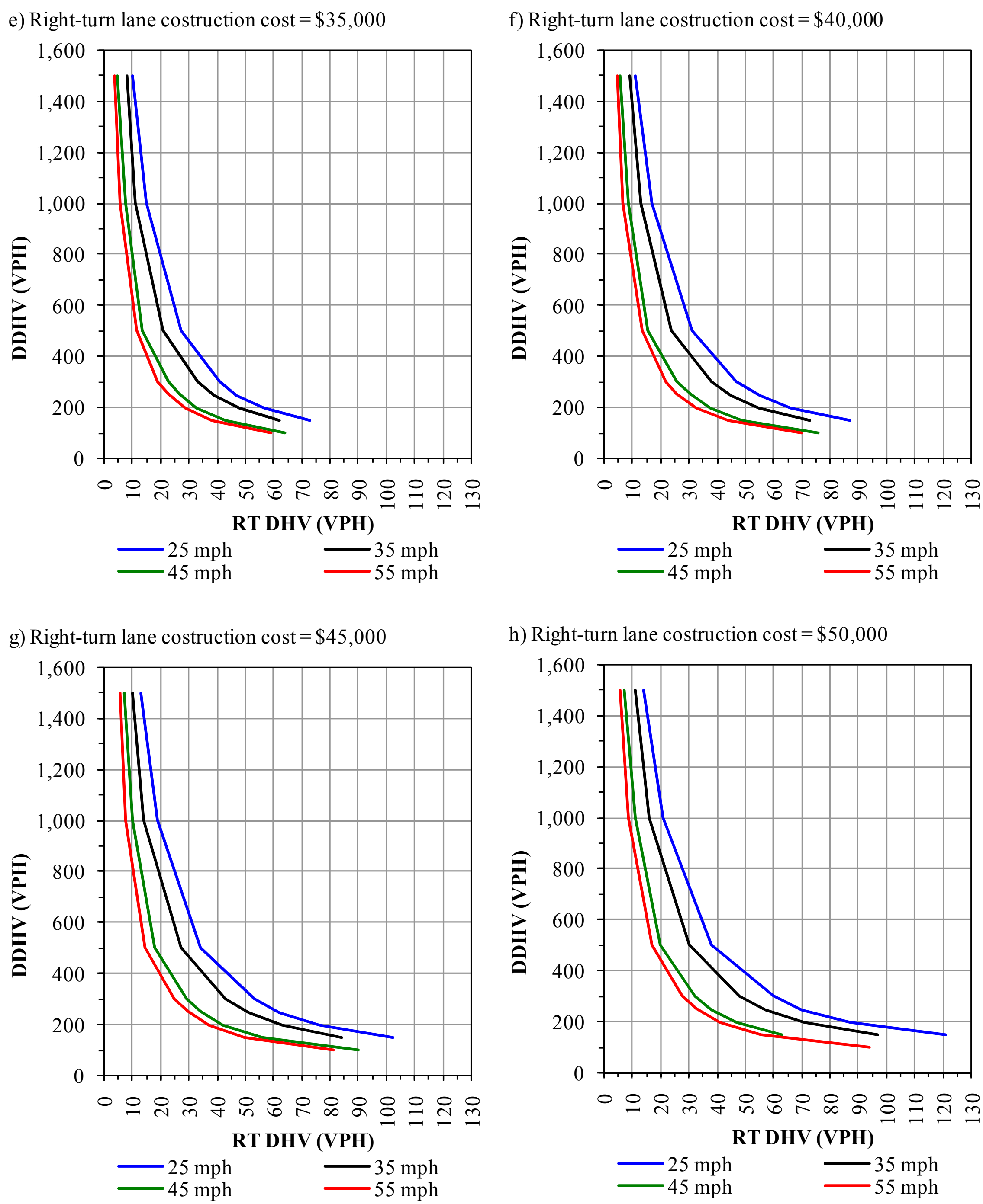
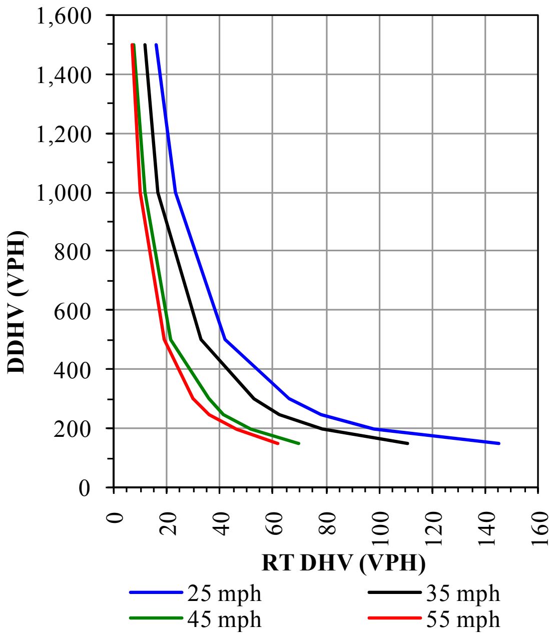
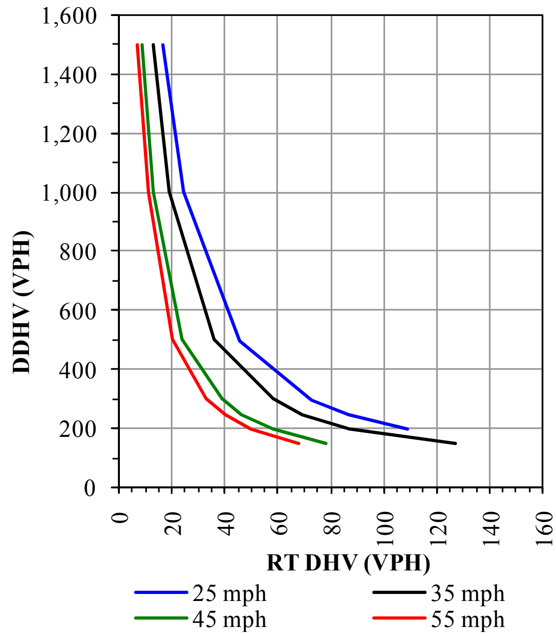


Figure H.1. (Continued)

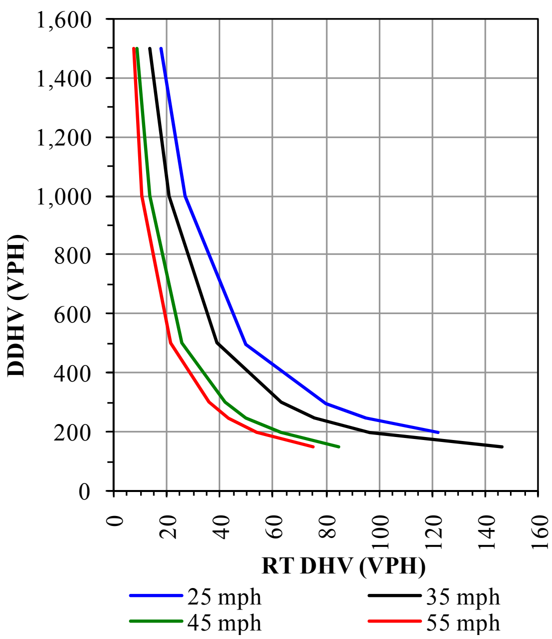
i) Right-turn lane costruction cost = $55,000



j) Right-turn lane costruction cost = $60,000



k) Right-turn lane costruction cost = $65,000



l) Right-turn lane costruction cost = $70,000

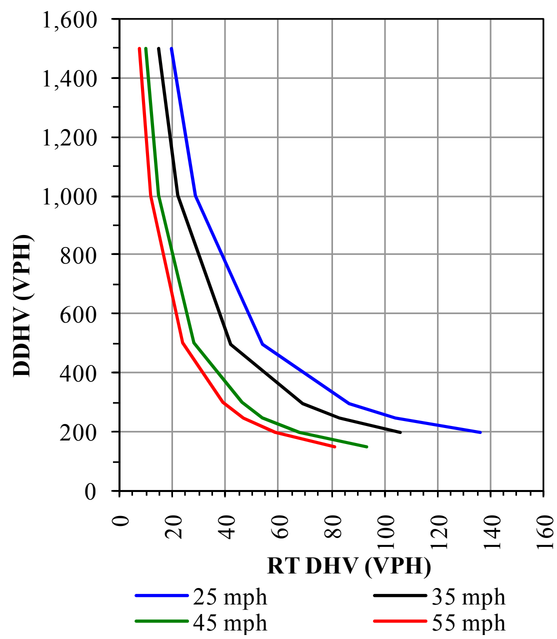
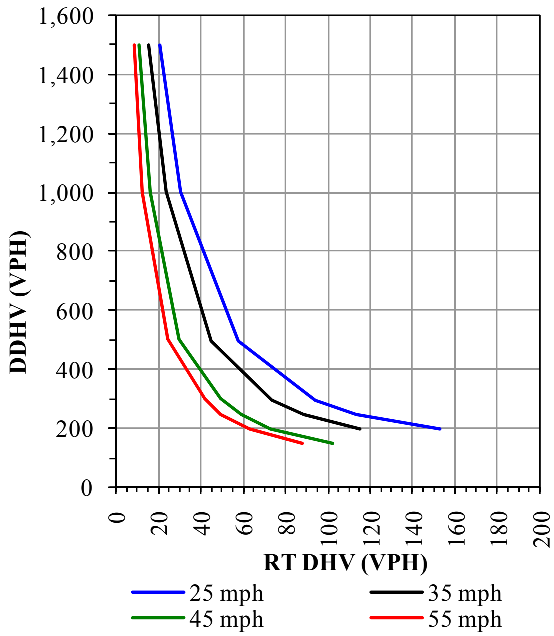
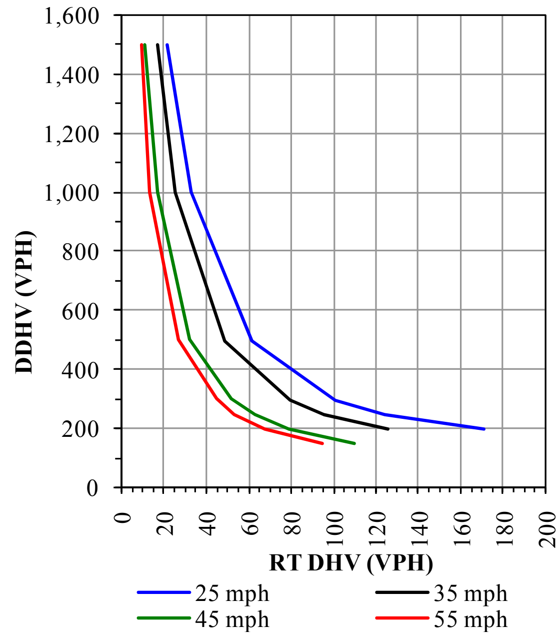


Figure H.1. (Continued)

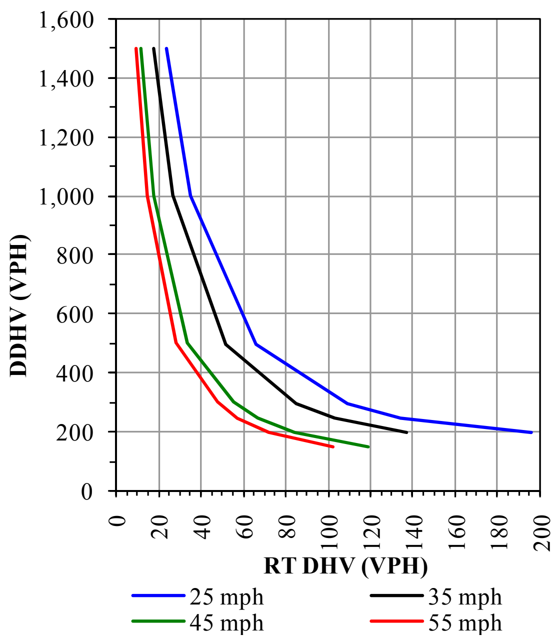
m) Right-turn lane costruction cost = $75,000



n) Right-turn lane costruction cost = $80,000



o) Right-turn lane costruction cost = $85,000



p) Right-turn lane costruction cost = $90,000

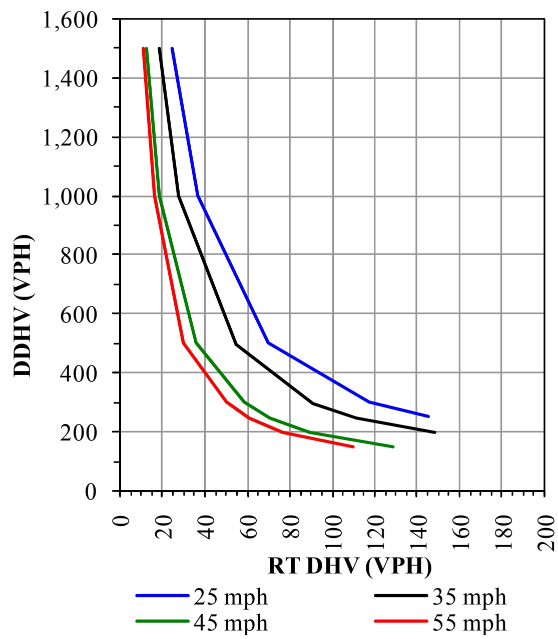


Figure H.1. (Continued)

Table H.1. Volume warrants for right-turn lanes at uncontrolled intersection approaches on two-lane roadways – fuel cost $2/gallon, delay cost $13.42/hour

Minimum Right-turn Design Hour Volume (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	Right-turn Lane Cost = $15,000								Right-turn Lane Cost = $20,000							
	DDHV (vph)								DDHV (vph)							
	100	150	200	250	300	500	1,000	1,500	100	150	200	250	300	500	1,000	1,500
25	35	28	23	20	17	12	7	5	50	38	31	27	23	15	9	6
35	33	25	20	17	14	9	5	4	46	33	26	22	19	12	7	5
45	25	18	14	11	10	6	3	3	34	24	19	15	13	8	4	3
55	23	16	12	10	8	5	3	2	32	21	16	13	11	7	4	3
Speed	**Right-turn Lane Cost = $25,000**								**Right-turn Lane Cost = $30,000**							
25	67	49	39	33	29	19	11	7	88	60	48	40	35	23	13	9
35	61	42	33	28	24	15	8	6	79	52	40	33	28	18	10	7
45	43	30	23	19	16	10	5	4	54	36	28	23	19	12	7	5
55	40	27	20	16	14	9	5	3	50	32	24	20	17	10	5	4
Speed	**Right-turn Lane Cost = $35,000**								**Right-turn Lane Cost = $40,000**							
25	NA*	73	57	47	41	27	15	10	NA	87	66	55	47	31	17	11
35	NA	62	48	39	33	21	11	8	NA	73	55	45	38	24	13	9
45	64	43	33	27	23	14	8	5	76	49	38	31	26	16	9	6
55	59	38	29	23	19	12	6	4	70	44	33	26	22	14	7	5
Speed	**Right-turn Lane Cost = $45,000**								**Right-turn Lane Cost = $50,000**							
25	NA	102	76	62	53	34	19	13	NA	121	87	70	60	38	21	14
35	NA	84	63	51	43	27	14	10	NA	97	71	57	48	30	16	11
45	90	56	42	34	29	18	10	7	NA	63	47	38	32	20	11	7
55	81	50	37	30	25	15	8	6	94	56	41	33	28	17	9	6
Speed	**Right-turn Lane Cost = $55,000**								**Right-turn Lane Cost = $60,000**							
25	NA	145	98	78	66	42	23	16	NA	NA	109	87	73	46	25	17
35	NA	111	79	63	53	33	17	12	NA	127	87	69	58	36	19	13
45	NA	70	52	42	36	22	12	8	NA	78	58	46	39	24	13	9
55	NA	62	46	36	30	19	10	7	NA	68	50	40	33	20	11	7
Speed	**Right-turn Lane Cost = $65,000**								**Right-turn Lane Cost = $70,000**							
25	NA	NA	122	95	80	50	27	18	NA	NA	136	104	87	54	29	20
35	NA	146	96	76	63	39	21	14	NA	NA	106	83	69	42	22	15
45	NA	85	63	50	42	26	14	9	NA	93	68	54	46	28	15	10
55	NA	75	54	43	36	22	11	8	NA	81	59	47	39	24	12	8
Speed	**Right-turn Lane Cost = $75,000**								**Right-turn Lane Cost = $80,000**							
25	NA	NA	153	114	94	58	31	21	NA	NA	171	124	101	62	33	22
35	NA	NA	115	89	74	45	24	16	NA	NA	126	96	80	49	25	17
45	NA	102	73	59	49	30	16	11	NA	110	79	63	52	32	17	11
55	NA	88	63	50	42	25	13	9	NA	95	68	54	45	27	14	10
Speed	**Right-turn Lane Cost = $85,000**								**Right-turn Lane Cost = $90,000**							
25	NA	NA	196	134	109	66	35	24	NA	NA	NA	145	117	70	37	25
35	NA	NA	137	103	85	52	27	18	NA	NA	148	111	91	55	28	19
45	NA	119	84	67	56	34	18	12	NA	129	90	71	59	36	19	13
55	NA	102	72	57	48	29	15	10	NA	110	77	61	50	30	16	11

* NA – Not applicable.

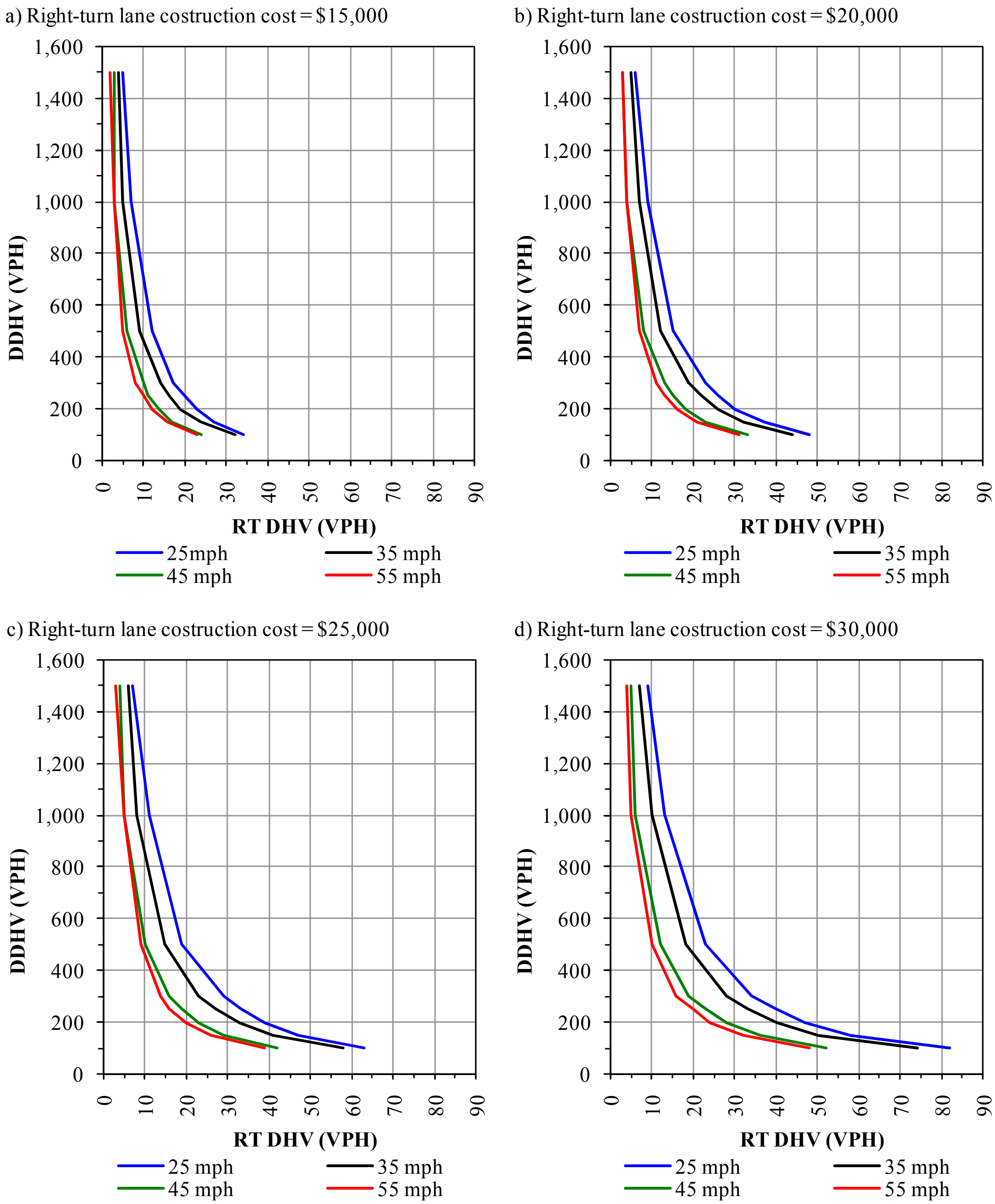


Figure H.2. Volume warrants for right-turn lanes at uncontrolled intersection approaches on two-lane roadways – fuel cost $3/gallon, delay cost $13.42/hour.

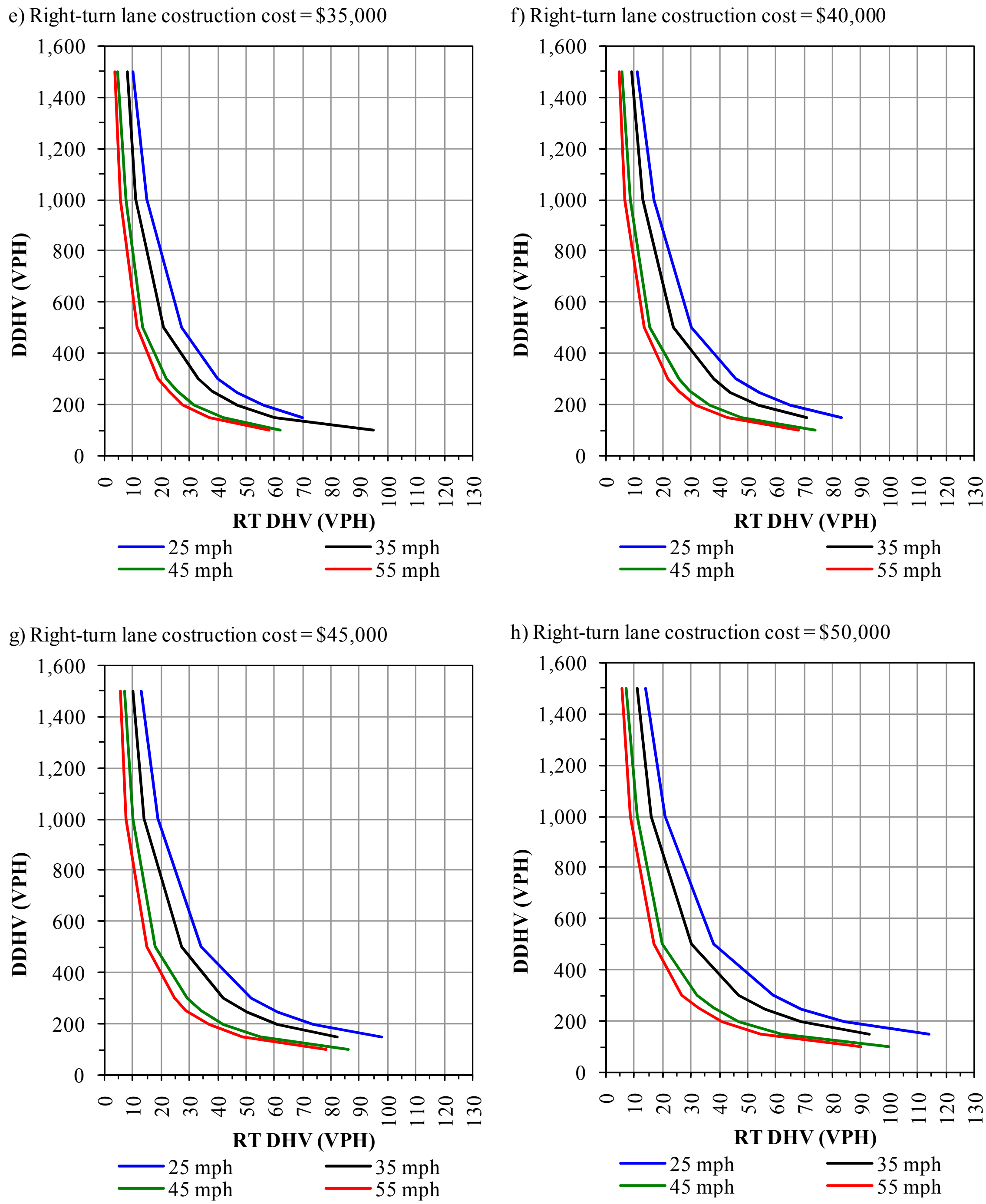


Figure H.2. (Continued)

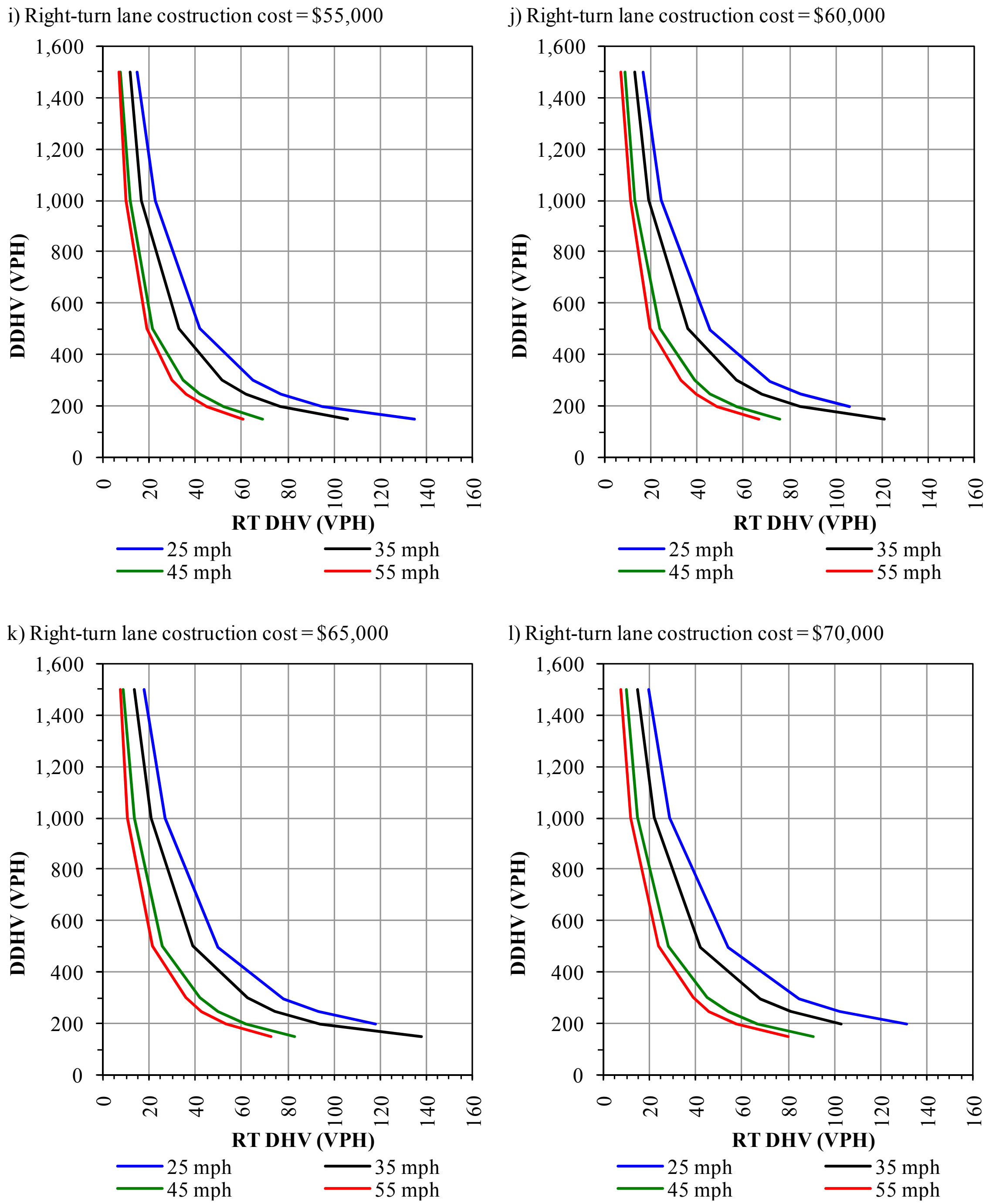


Figure H.2. (Continued)

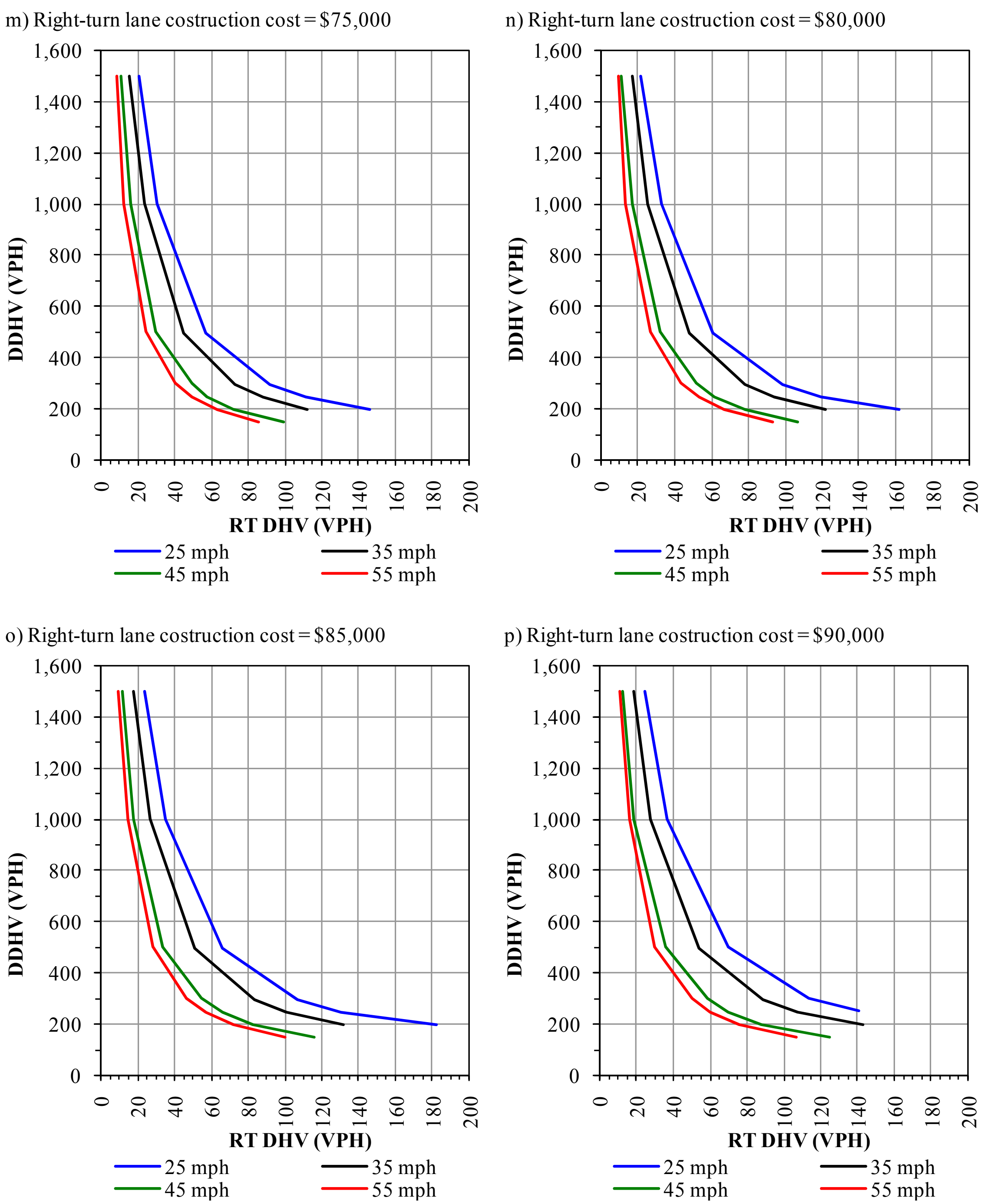


Figure H.2. (Continued)

Table H.2. Volume warrants for right-turn lanes at uncontrolled intersection approaches on two-lane roadways – fuel cost $3/gallon, delay cost $13.42/hour

Minimum Right-turn Design Hour Volume (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	**Right-turn Lane Cost = $15,000**								**Right-turn Lane Cost = $20,000**							
	DDHV (vph)								**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
25	34	27	23	20	17	12	7	5	48	37	30	26	23	15	9	6
35	32	24	19	16	14	9	5	4	44	32	26	22	19	12	7	5
45	24	17	14	11	10	6	3	3	33	23	18	15	13	8	4	3
55	23	16	12	10	8	5	3	2	31	21	16	13	11	7	4	3
Speed	**Right-turn Lane Cost = $25,000**								**Right-turn Lane Cost = $30,000**							
25	63	47	39	33	29	19	11	7	82	58	47	40	34	23	13	9
35	58	41	33	27	23	15	8	6	74	50	40	33	28	18	10	7
45	42	29	23	19	16	10	5	4	52	36	28	23	19	12	6	5
55	39	26	20	16	14	9	5	3	48	32	24	20	16	10	5	4
Speed	**Right-turn Lane Cost = $35,000**								**Right-turn Lane Cost = $40,000**							
25	NA*	70	56	47	40	27	15	10	NA	83	65	54	46	30	17	11
35	95	60	47	38	33	21	11	8	NA	71	54	44	38	24	13	9
45	62	42	32	26	22	14	8	5	74	48	37	30	26	16	9	6
55	58	37	28	23	19	12	6	4	68	43	32	26	22	14	7	5
Speed	**Right-turn Lane Cost = $45,000**								**Right-turn Lane Cost = $50,000**							
25	NA	98	74	61	52	34	19	13	NA	114	84	69	59	38	21	14
35	NA	82	61	50	42	27	14	10	NA	93	69	56	47	30	16	11
45	86	55	42	34	29	18	10	7	100	62	47	38	32	20	11	7
55	78	49	37	29	25	15	8	6	90	55	41	33	27	17	9	6
Speed	**Right-turn Lane Cost = $55,000**								**Right-turn Lane Cost = $60,000**							
25	NA	135	95	77	65	42	23	15	NA	NA	106	85	72	46	25	17
35	NA	106	77	62	52	33	17	12	NA	121	85	68	57	36	19	13
45	NA	69	52	42	35	22	12	8	NA	76	57	46	39	24	13	9
55	NA	61	45	36	30	19	10	7	NA	67	49	40	33	20	11	7
Speed	**Right-turn Lane Cost = $65,000**								**Right-turn Lane Cost = $70,000**							
25	NA	NA	118	93	78	50	27	18	NA	NA	131	102	85	54	29	20
35	NA	138	94	75	63	39	21	14	NA	NA	103	81	68	42	22	15
45	NA	83	62	50	42	26	14	9	NA	91	67	54	45	28	15	10
55	NA	73	54	43	36	22	11	8	NA	80	58	46	39	24	12	8
Speed	**Right-turn Lane Cost = $75,000**								**Right-turn Lane Cost = $80,000**							
25	NA	NA	146	111	92	57	31	21	NA	NA	162	120	99	61	33	22
35	NA	NA	112	88	73	45	24	16	NA	NA	122	94	78	48	25	17
45	NA	99	72	58	49	30	16	11	NA	107	78	62	52	32	17	11
55	NA	86	63	50	41	25	13	9	NA	93	67	53	44	27	14	10
Speed	**Right-turn Lane Cost = $85,000**								**Right-turn Lane Cost = $90,000**							
25	NA	NA	182	130	107	66	35	24	NA	NA	NA	141	114	70	37	25
35	NA	NA	132	101	84	51	27	18	NA	NA	143	108	89	54	28	19
45	NA	116	83	66	55	34	18	12	NA	125	88	70	59	36	19	13
55	NA	100	72	57	47	29	15	10	NA	107	76	60	50	30	16	11

* NA – Not applicable.

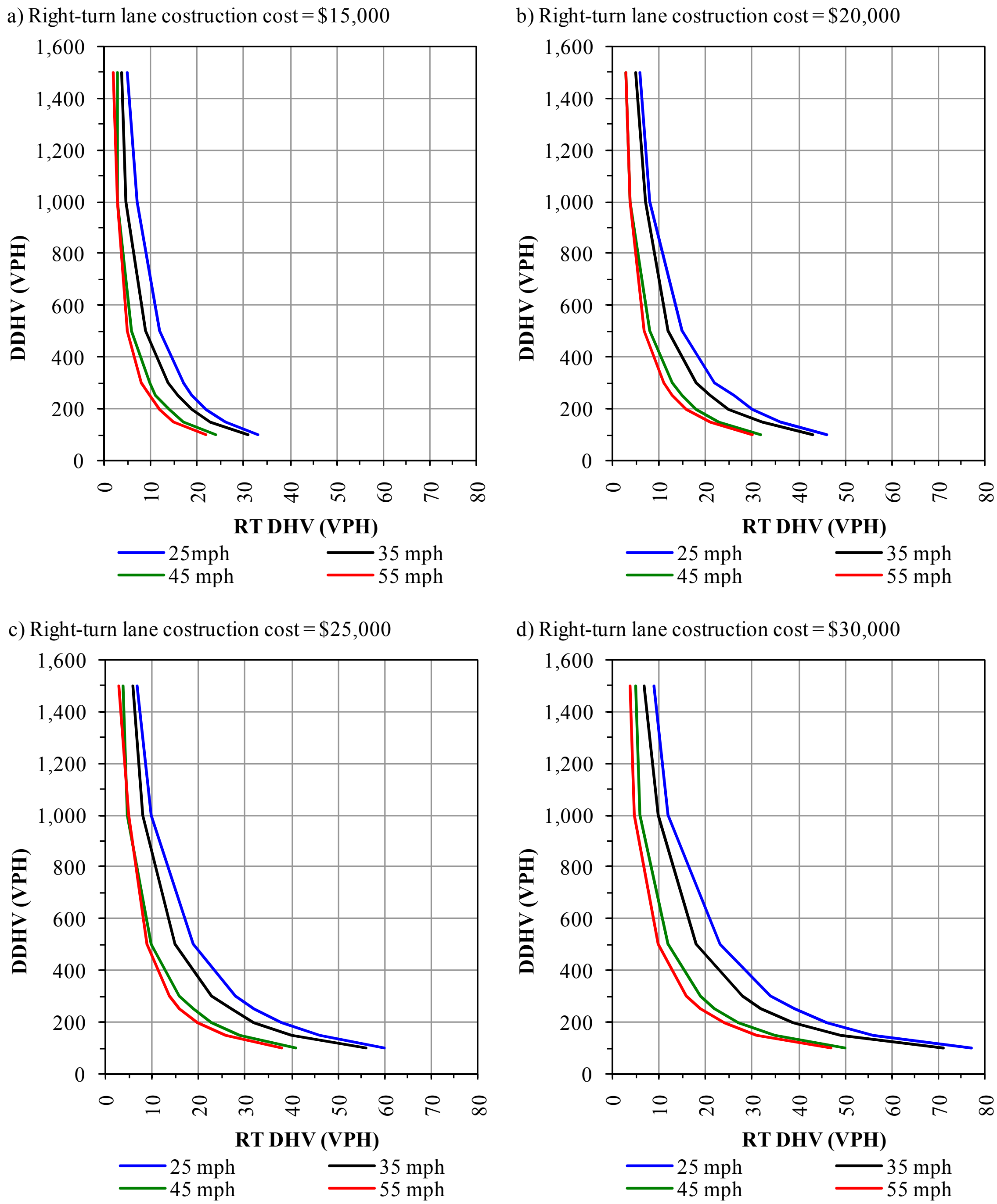


Figure H.3. Volume warrants for right-turn lanes at uncontrolled intersection approaches on two-lane roadways – fuel cost $4/gallon, delay cost $13.42/hour.

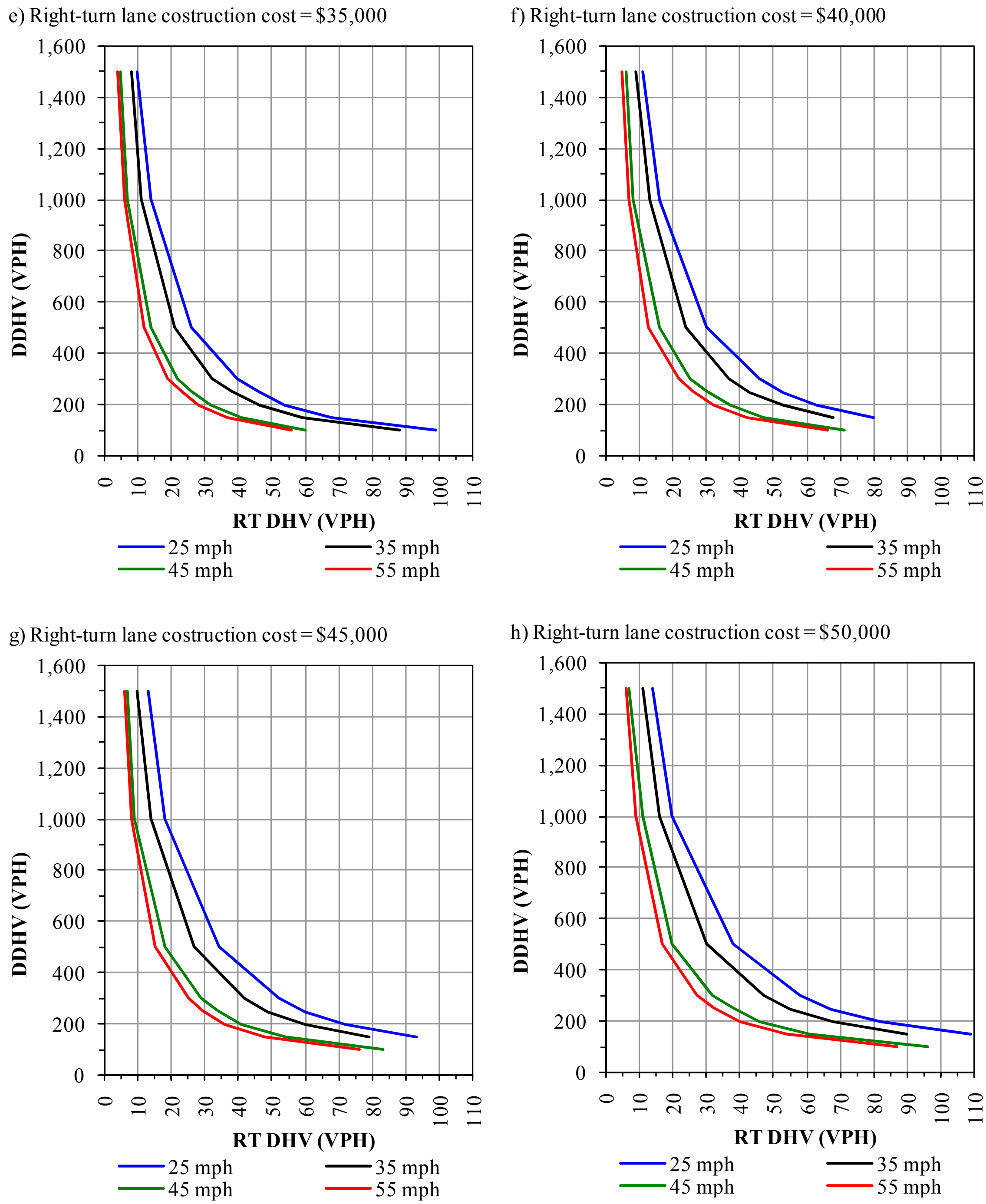
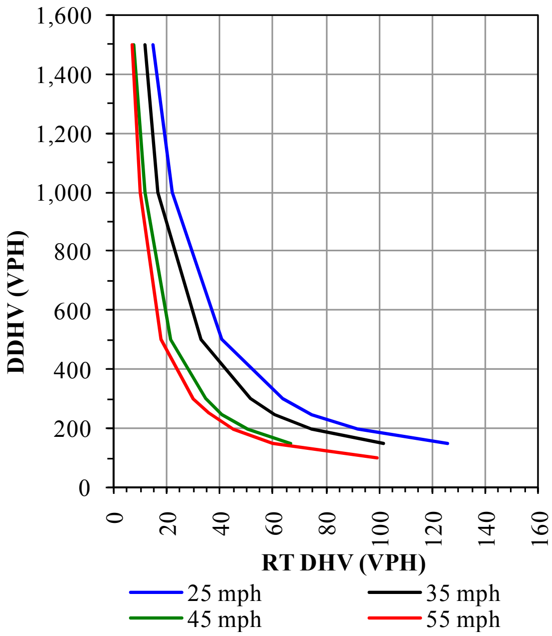
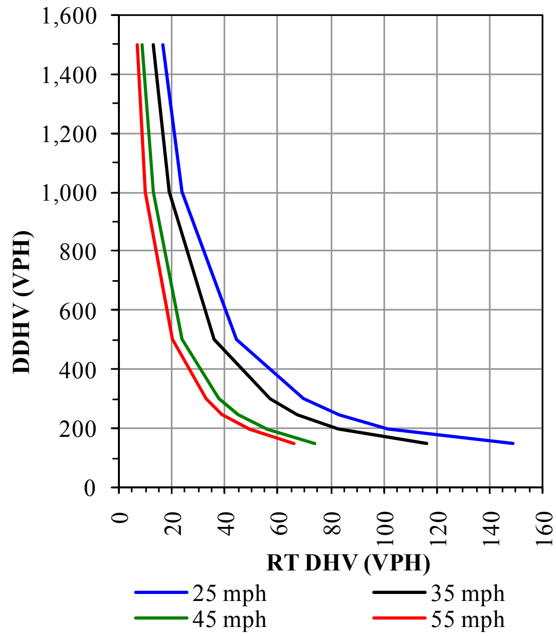


Figure H.3. (Continued)

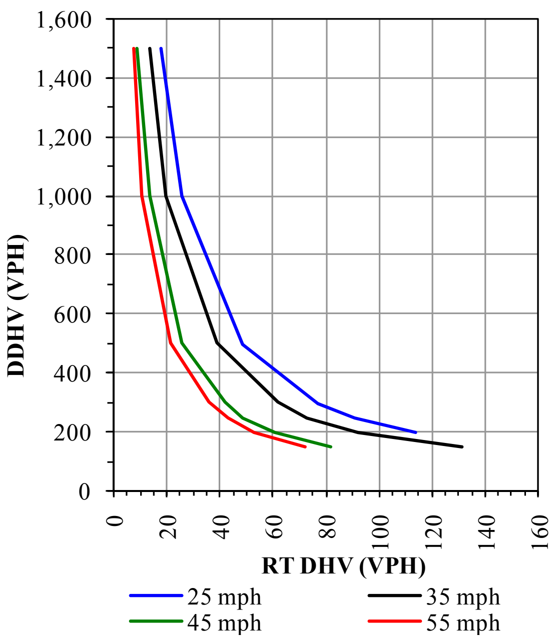
i) Right-turn lane costruction cost = $55,000



j) Right-turn lane costruction cost = $60,000



k) Right-turn lane costruction cost = $65,000



l) Right-turn lane costruction cost = $70,000

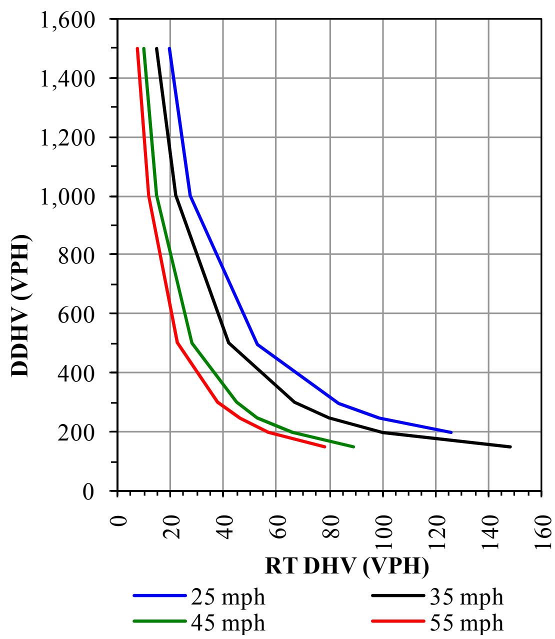
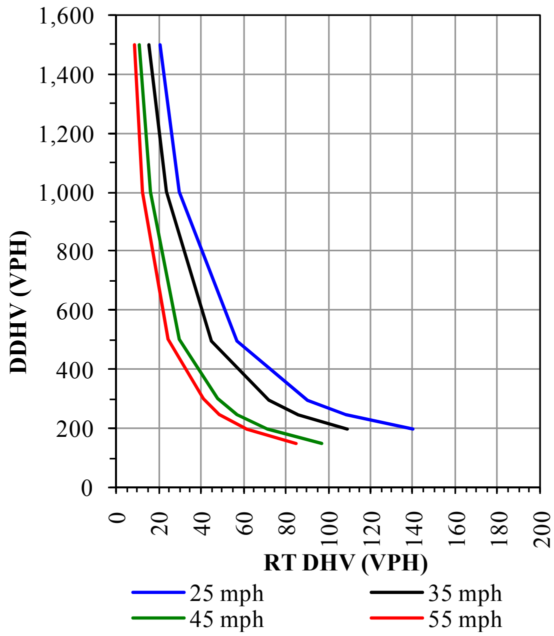
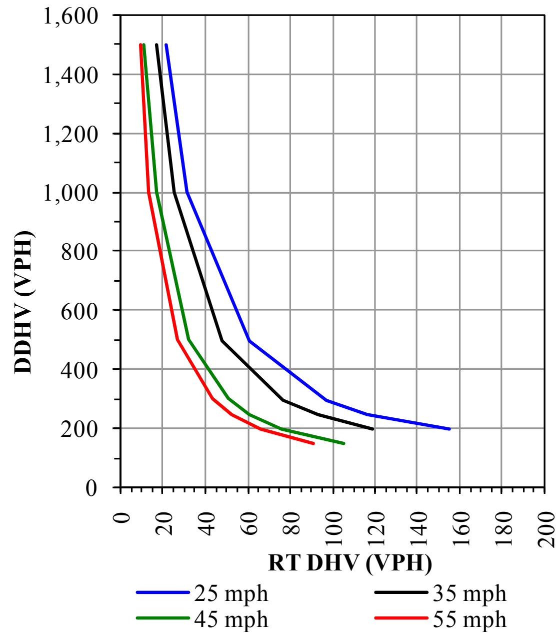


Figure H.3. (Continued)

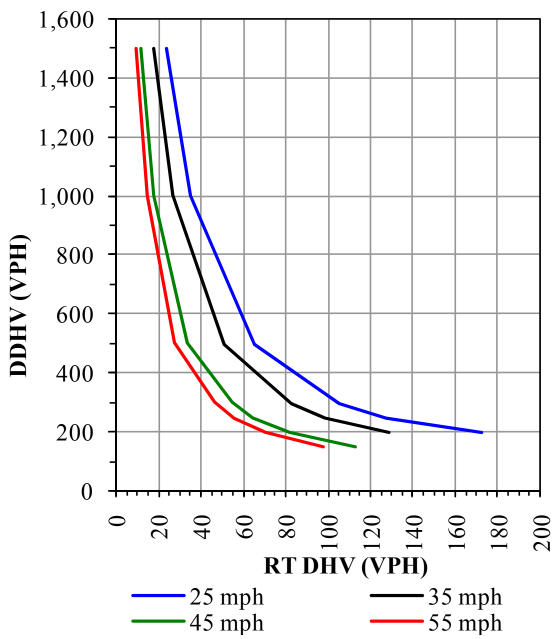
m) Right-turn lane costruction cost = $75,000



n) Right-turn lane costruction cost = $80,000



o) Right-turn lane costruction cost = $85,000



p) Right-turn lane costruction cost = $90,000

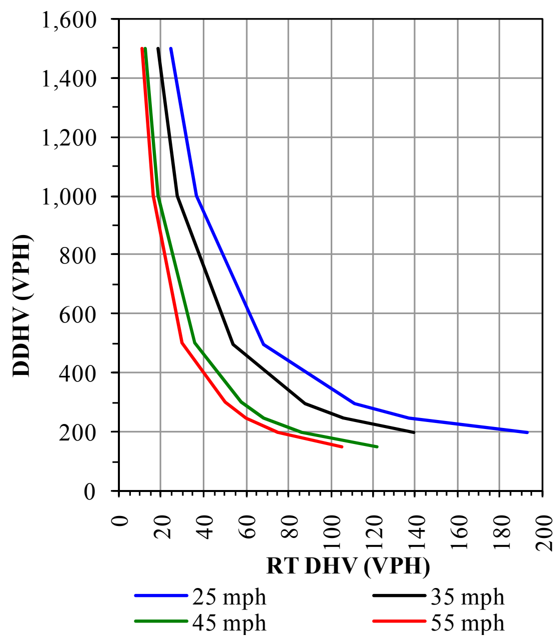


Figure H.3. (Continued)

Table H.3. Volume warrants for right-turn lanes at uncontrolled intersection approaches on two-lane roadways – fuel cost $4/gallon, delay cost $13.42/hour

Minimum Right-turn Design Hour Volume (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	Right-turn Lane Cost = $15,000								Right-turn Lane Cost = $20,000							
	DDHV (vph)								DDHV (vph)							
	100	150	200	250	300	500	1,000	1,500	100	150	200	250	300	500	1,000	1,500
25	33	26	22	19	17	12	7	5	46	36	30	26	22	15	8	6
35	31	23	19	16	14	9	5	4	43	32	25	21	18	12	7	5
45	24	17	14	11	10	6	3	3	32	23	18	15	13	8	4	3
55	22	15	12	10	8	5	3	2	30	21	16	13	11	7	4	3
Speed	Right-turn Lane Cost = $25,000								Right-turn Lane Cost = $30,000							
25	60	46	38	32	28	19	10	7	77	56	46	39	34	23	12	9
35	56	40	32	27	23	15	8	6	71	49	39	32	28	18	10	7
45	41	29	23	19	16	10	5	4	50	35	27	22	19	12	6	5
55	38	26	20	16	14	9	5	3	47	31	24	19	16	10	5	4
Speed	Right-turn Lane Cost = $35,000								Right-turn Lane Cost = $40,000							
25	99	68	54	46	40	26	14	10	NA*	80	63	53	46	30	16	11
35	88	59	46	38	32	21	11	8	NA	68	53	43	37	24	13	9
45	60	41	32	26	22	14	7	5	71	47	37	30	25	16	8	6
55	56	37	28	23	19	12	6	4	66	42	32	26	22	13	7	5
Speed	Right-turn Lane Cost = $45,000								Right-turn Lane Cost = $50,000							
25	NA	93	72	60	52	34	18	13	NA	109	82	67	58	38	20	14
35	NA	79	60	49	42	27	14	10	NA	90	68	55	47	30	16	11
45	83	54	41	34	29	18	9	7	96	61	46	38	32	20	11	7
55	76	48	36	29	25	15	8	6	87	54	40	32	27	17	9	6
Speed	Right-turn Lane Cost = $55,000								Right-turn Lane Cost = $60,000							
25	NA	126	92	75	64	41	22	15	NA	149	102	83	70	45	24	17
35	NA	102	75	61	52	33	17	12	NA	116	83	67	57	36	19	13
45	NA	67	51	41	35	22	12	8	NA	74	56	45	38	24	13	9
55	99	60	45	36	30	18	10	7	NA	66	49	39	33	20	10	7
Speed	Right-turn Lane Cost = $65,000								Right-turn Lane Cost = $70,000							
25	NA	NA	114	91	77	49	26	18	NA	NA	126	99	84	53	28	20
35	NA	131	92	73	62	39	20	14	NA	148	100	80	67	42	22	15
45	NA	82	61	49	42	26	14	9	NA	89	66	53	45	28	15	10
55	NA	72	53	43	36	22	11	8	NA	78	57	46	38	23	12	8
Speed	Right-turn Lane Cost = $75,000								Right-turn Lane Cost = $80,000							
25	NA	NA	140	108	90	57	30	21	NA	NA	155	117	97	61	32	22
35	NA	NA	109	86	72	45	24	16	NA	NA	119	93	77	48	25	17
45	NA	97	71	57	48	30	16	11	NA	105	76	61	51	32	17	11
55	NA	85	62	49	41	25	13	9	NA	91	66	53	44	27	14	10
Speed	Right-turn Lane Cost = $85,000								Right-turn Lane Cost = $90,000							
25	NA	NA	172	127	105	65	35	24	NA	NA	193	137	112	69	37	25
35	NA	NA	129	99	83	51	27	18	NA	NA	139	106	88	54	28	19
45	NA	113	82	65	55	34	18	12	NA	122	87	69	58	36	19	13
55	NA	98	71	56	47	28	15	10	NA	105	75	60	50	30	16	11

* NA – Not applicable.

H.2 Right-turn lanes at driveway approaches

The volume warrants for right-turn lanes at driveway approaches by taking into account their safety as well as operational effectiveness were developed by adopting the same methodology as presented in Chapter 6. The only difference in this case was the incorporation of additional operational savings achievable by providing right-turn lanes. All other relevant inputs for variables required for developing the guidelines were same as discussed elsewhere.

The warrant guidelines for right-turn lanes at driveway approaches are presented graphically in figures as well as are summarized in tables. The guidelines presented in Figure H.4/Table H.4 are based on the fuel cost of $2 per gallon. On the other hand, the warrant guidelines presented in Figure H.5/Table H.5 and Figure H.6/Table H.6 are based on the fuel cost of $3 and $4 per gallon, respectively.

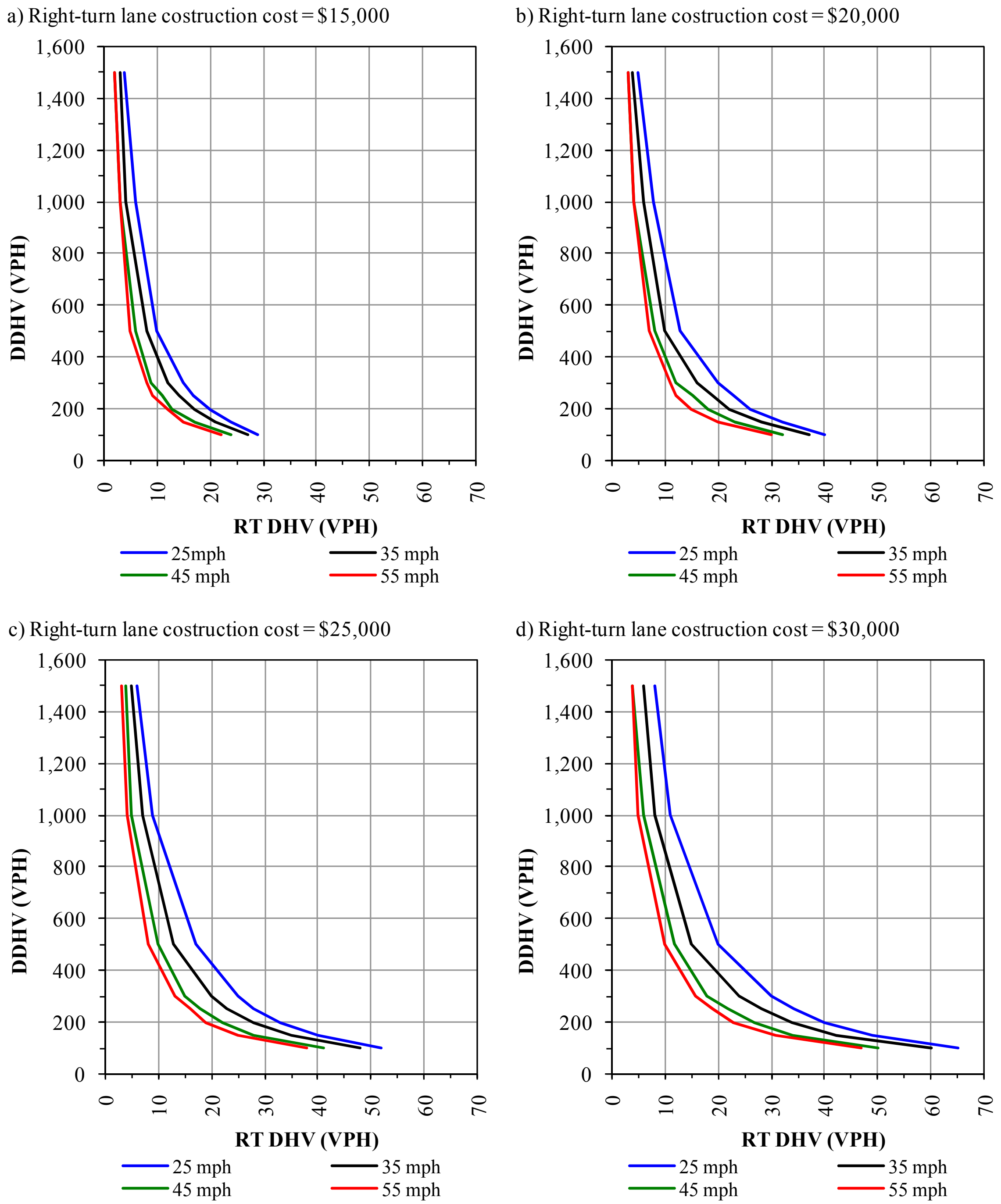
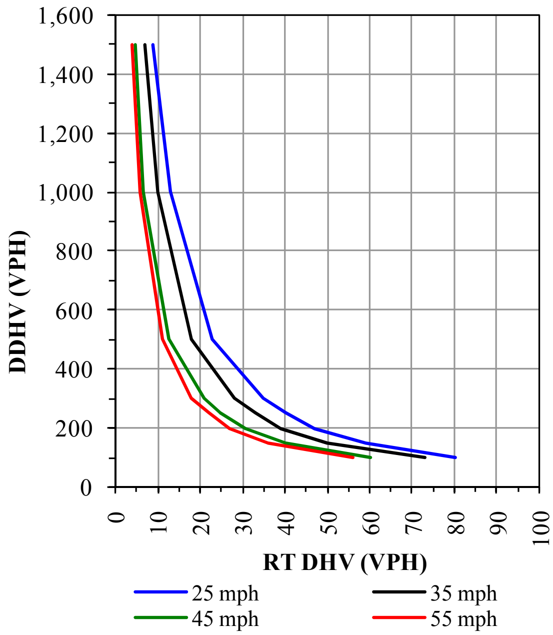
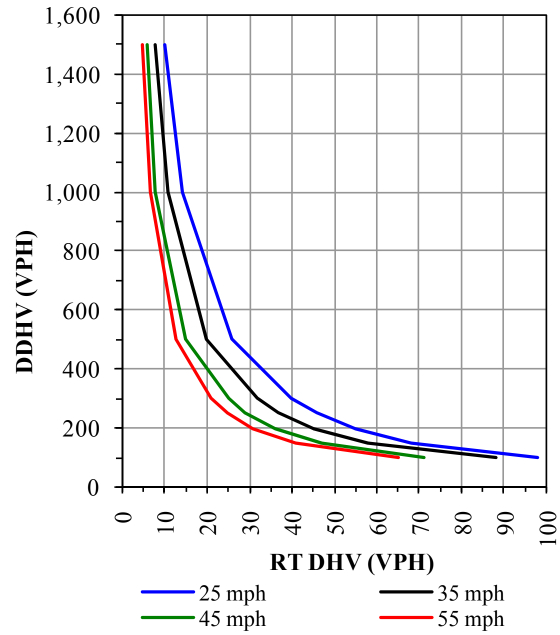


Figure H.4. Volume warrants for right-turn lanes at uncontrolled driveway approaches on two-lane roadways – fuel cost $2/gallon, delay cost $13.42/hour.

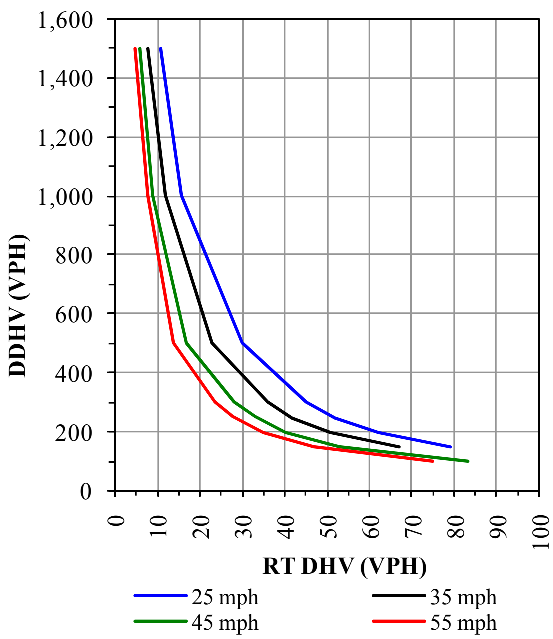
e) Right-turn lane costruction cost = $35,000



f) Right-turn lane costruction cost = $40,000



g) Right-turn lane costruction cost = $45,000



h) Right-turn lane costruction cost = $50,000

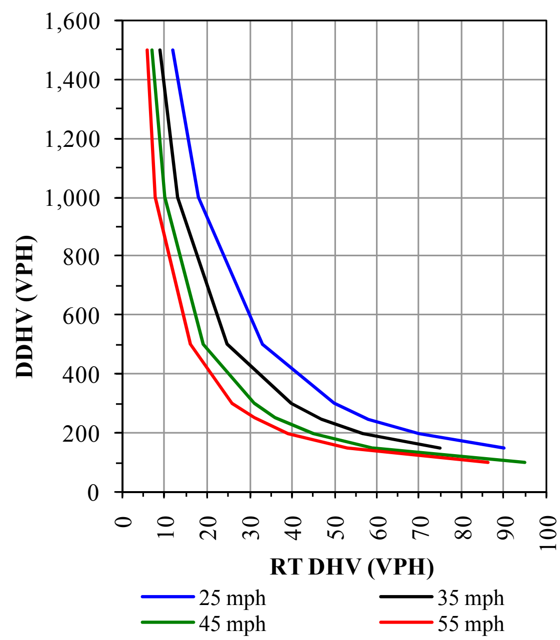


Figure H.4. (Continued)

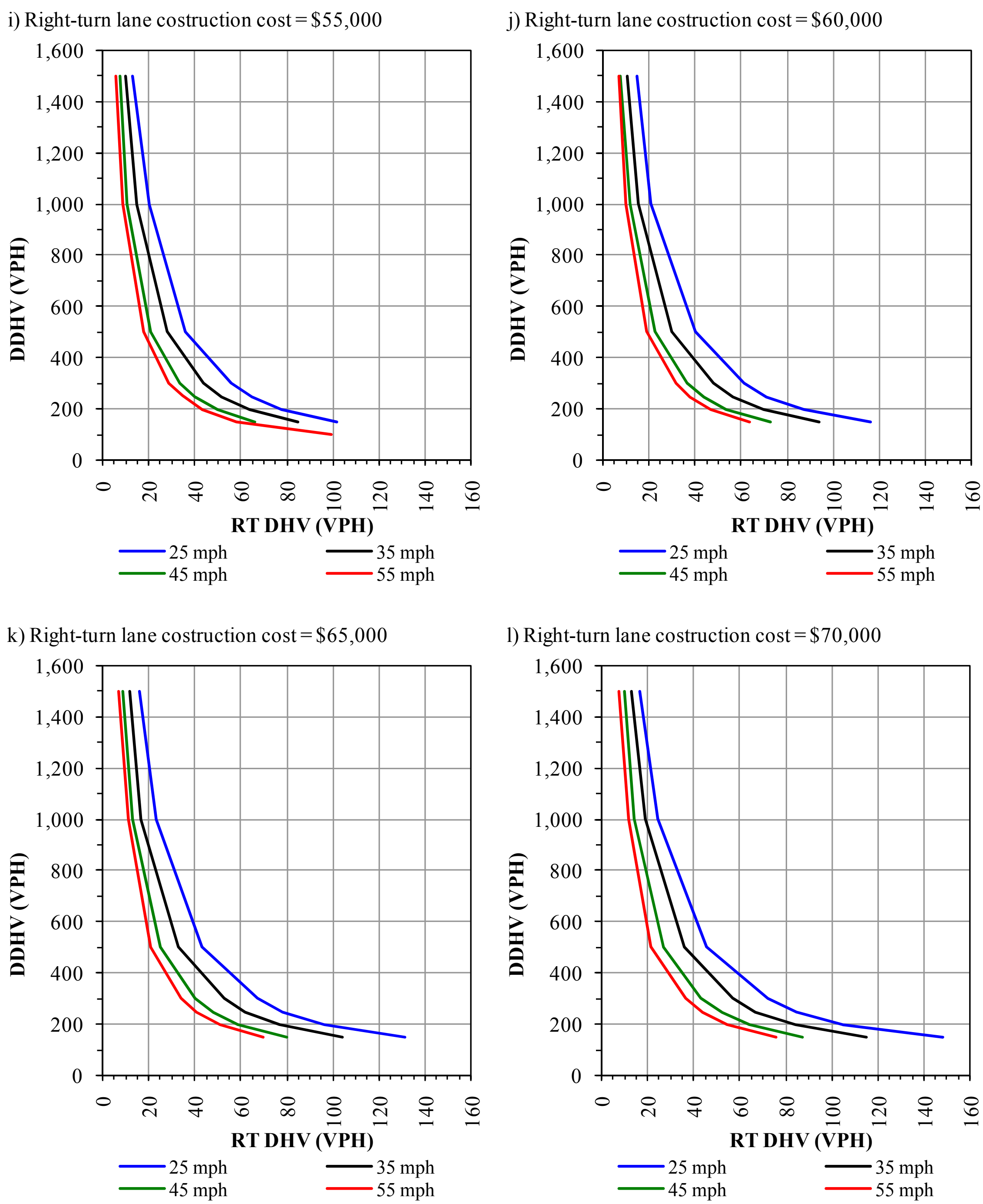
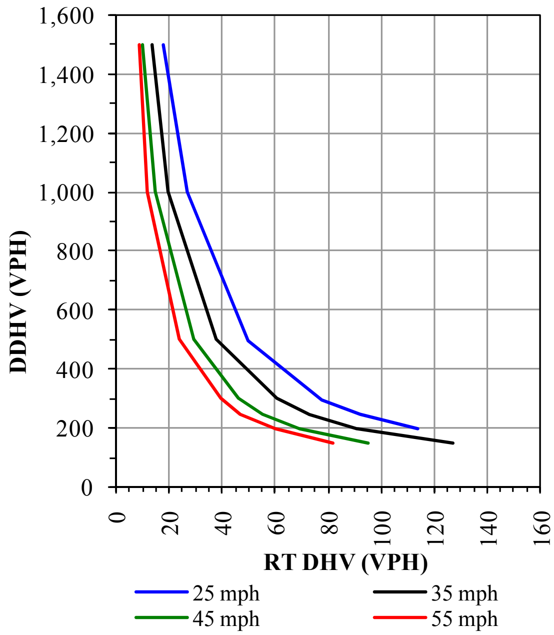
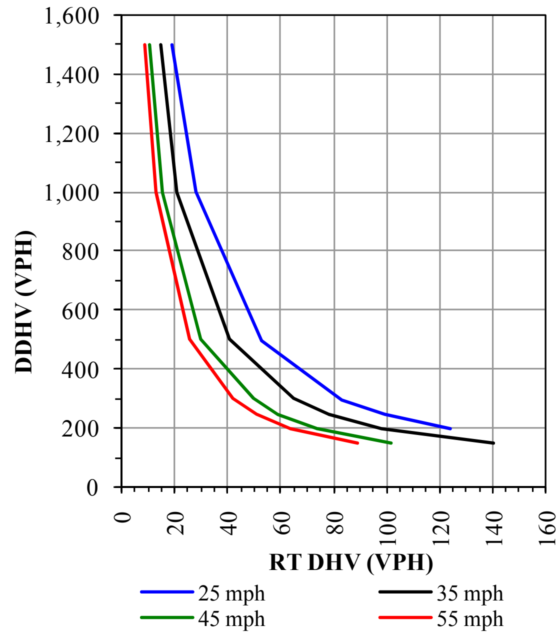


Figure H.4. (Continued)

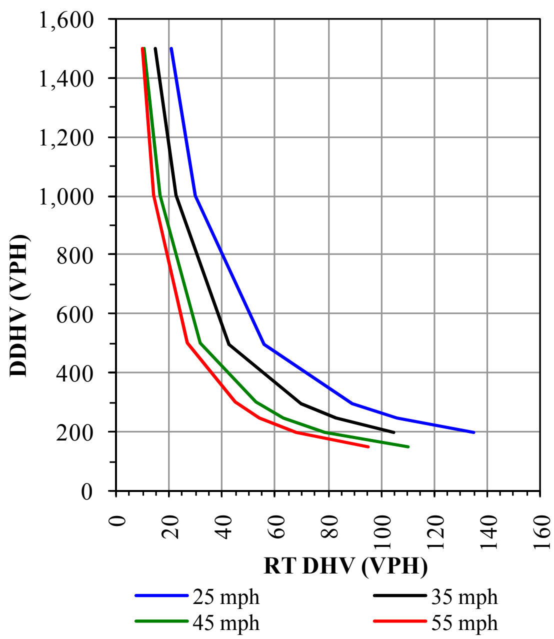
m) Right-turn lane costruction cost = $75,000



n) Right-turn lane costruction cost = $80,000



o) Right-turn lane costruction cost = $85,000



p) Right-turn lane costruction cost = $90,000

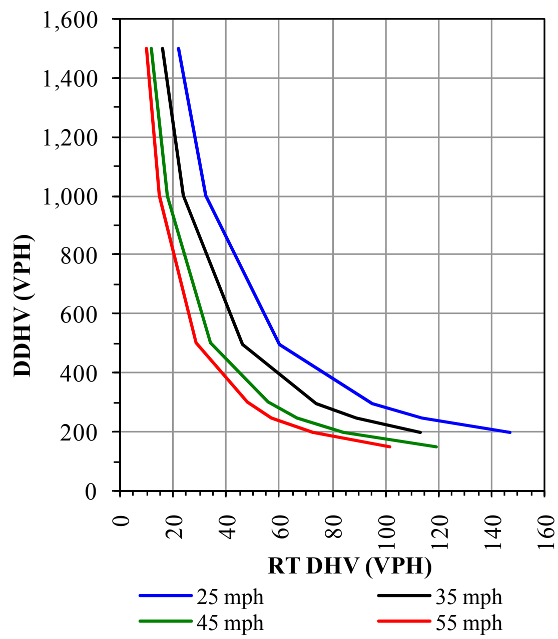


Figure H.4. (Continued)

Table H.4. Volume warrants for right-turn lanes at uncontrolled driveway approaches on two-lane roadways – fuel cost $2/gallon, delay cost $13.42/hour

Minimum Right-turn Design Hour Volume (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	**Right-turn Lane Cost = $15,000**								**Right-turn Lane Cost = $20,000**							
	DDHV (vph)								**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
25	29	24	20	17	15	10	6	4	40	32	26	23	20	13	8	5
35	27	21	17	14	12	8	4	3	37	28	22	19	16	10	6	4
45	24	17	13	11	9	6	3	2	32	23	18	15	12	8	4	3
55	22	15	12	9	8	5	3	2	30	20	15	12	11	7	4	3
Speed	**Right-turn Lane Cost = $25,000**								**Right-turn Lane Cost = $30,000**							
25	52	40	33	28	25	17	9	6	65	49	40	34	30	20	11	8
35	48	35	28	23	20	13	7	5	60	42	34	28	24	15	8	6
45	41	28	22	18	15	10	5	4	50	34	27	22	18	12	6	4
55	38	25	19	16	13	8	4	3	47	31	23	19	16	10	5	4
Speed	**Right-turn Lane Cost = $35,000**								**Right-turn Lane Cost = $40,000**							
25	80	59	47	40	35	23	13	9	98	68	55	46	40	26	14	10
35	73	50	39	33	28	18	10	7	88	58	45	37	32	20	11	8
45	60	40	31	25	21	13	7	5	71	47	36	29	25	15	8	6
55	56	36	27	22	18	11	6	4	65	41	31	25	21	13	7	5
Speed	**Right-turn Lane Cost = $45,000**								**Right-turn Lane Cost = $50,000**							
25	NA*	79	62	52	45	30	16	11	NA	90	70	58	50	33	18	12
35	NA	67	51	42	36	23	12	8	NA	75	57	47	40	25	13	9
45	83	53	40	33	28	17	9	6	95	59	45	36	31	19	10	7
55	75	47	35	28	24	14	8	5	86	53	39	31	26	16	8	6
Speed	**Right-turn Lane Cost = $55,000**								**Right-turn Lane Cost = $60,000**							
25	NA	102	78	65	56	36	20	13	NA	116	87	71	61	40	21	15
35	NA	85	64	52	44	28	15	10	NA	94	70	57	48	30	16	11
45	NA	66	50	40	34	21	11	8	NA	73	54	44	37	23	12	8
55	99	58	43	35	29	18	9	6	NA	64	47	38	32	19	10	7
Speed	**Right-turn Lane Cost = $65,000**								**Right-turn Lane Cost = $70,000**							
25	NA	131	96	78	67	43	23	16	NA	148	105	85	72	46	25	17
35	NA	104	77	62	53	33	17	12	NA	115	84	67	57	36	19	13
45	NA	80	59	48	40	25	13	9	NA	87	64	52	43	27	14	10
55	NA	70	51	41	34	21	11	7	NA	76	55	44	37	22	12	8
Speed	**Right-turn Lane Cost = $75,000**								**Right-turn Lane Cost = $80,000**							
25	NA	NA	114	92	78	50	27	18	NA	NA	124	99	83	53	28	19
35	NA	127	91	73	61	38	20	14	NA	140	98	78	65	41	21	15
45	NA	95	69	55	46	29	15	10	NA	102	74	59	50	30	16	11
55	NA	82	60	47	40	24	12	9	NA	89	64	51	42	26	13	9
Speed	**Right-turn Lane Cost = $85,000**								**Right-turn Lane Cost = $90,000**							
25	NA	NA	135	106	89	56	30	21	NA	NA	147	114	95	60	32	22
35	NA	NA	105	83	70	43	23	15	NA	NA	113	89	74	46	24	16
45	NA	110	79	63	53	32	17	11	NA	119	84	67	56	34	18	12
55	NA	95	68	54	45	27	14	10	NA	102	73	57	48	29	15	10

* NA – Not applicable.

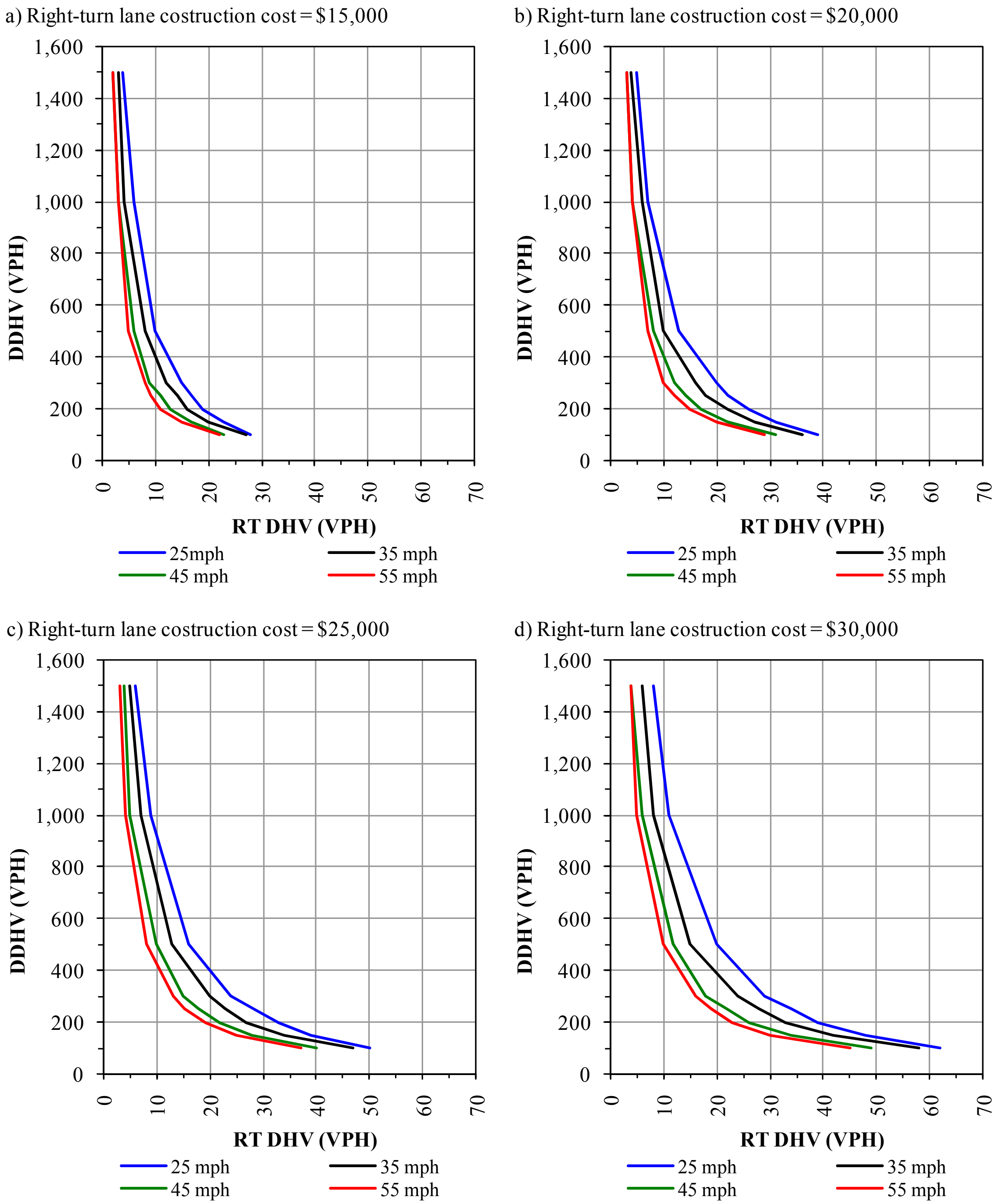


Figure H.5. Volume warrants for right-turn lanes at uncontrolled driveway approaches on two-lane roadways – fuel cost $3/gallon, delay cost $13.42/hour.

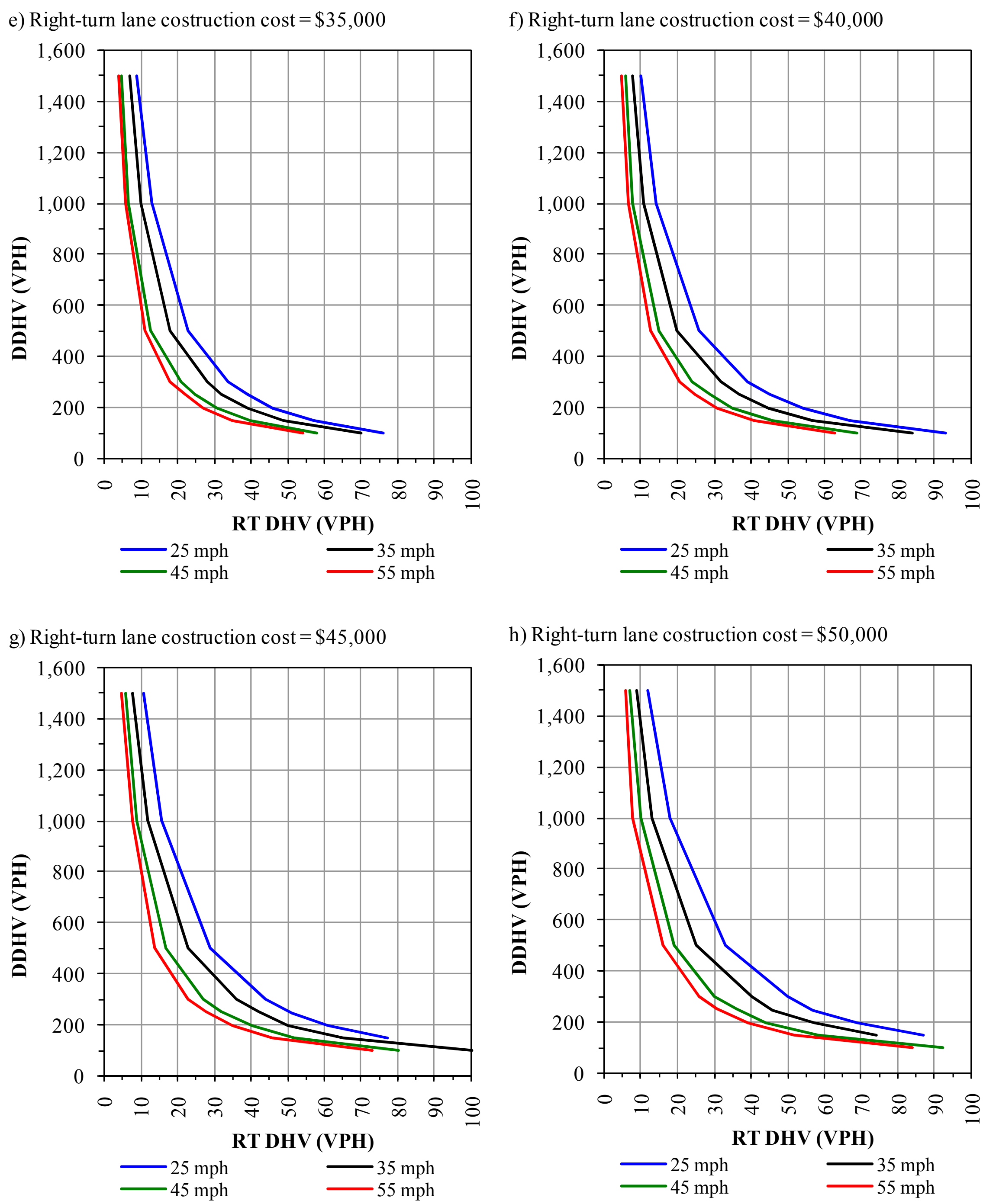


Figure H.5. (Continued)

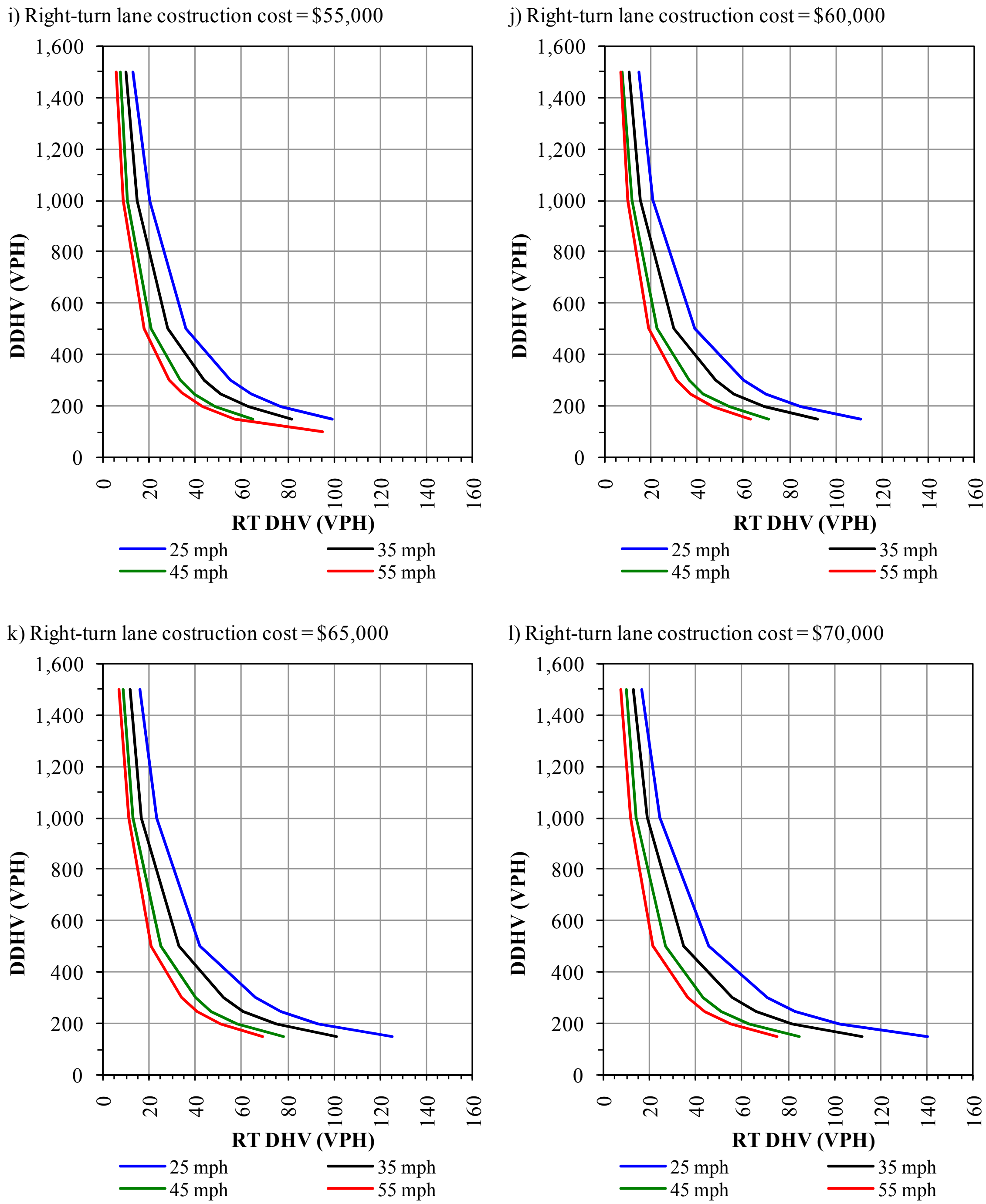
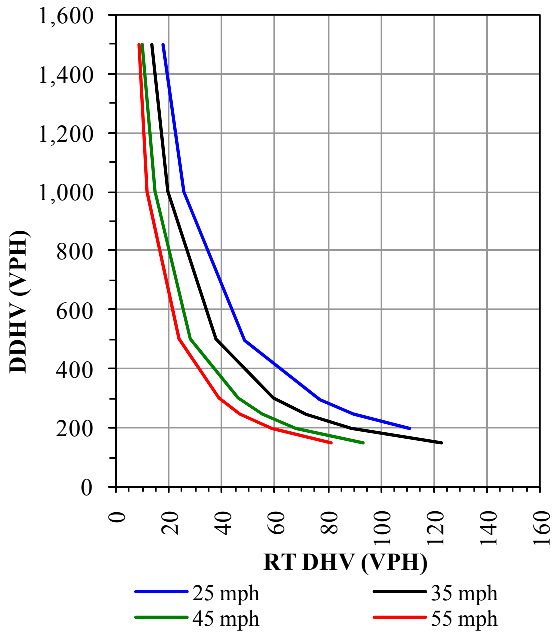
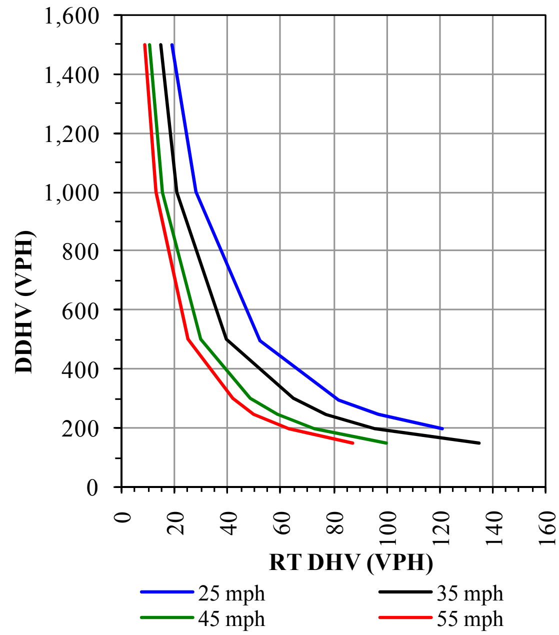


Figure H.5. (Continued)

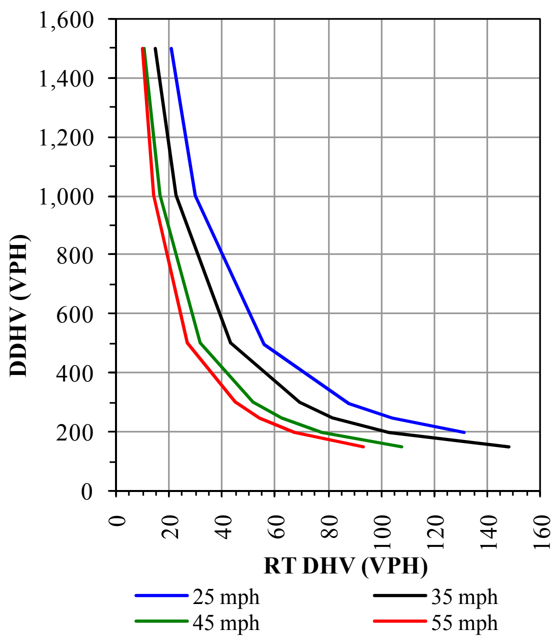
m) Right-turn lane costruction cost = $75,000



n) Right-turn lane costruction cost = $80,000



o) Right-turn lane costruction cost = $85,000



p) Right-turn lane costruction cost = $90,000

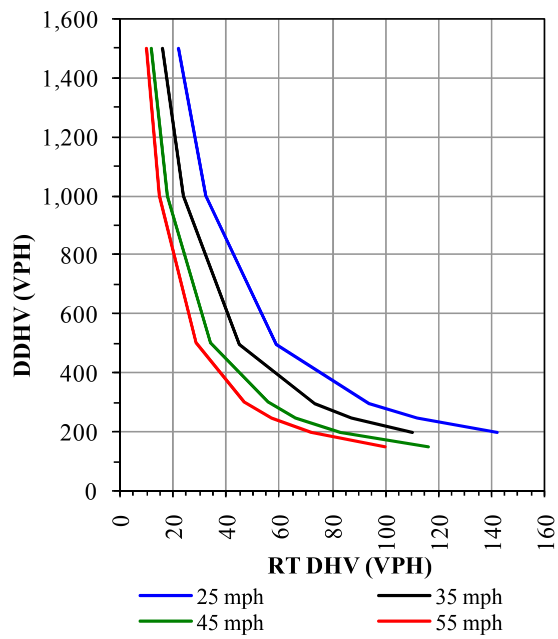


Figure H.5. (Continued)

Table H.5. Volume warrants for right-turn lanes at uncontrolled driveway approaches on two-lane roadways – fuel cost $3/gallon, delay cost $13.42/hour

Minimum Right-turn Design Hour Volume (vph) Required to Warrant a Right-turn Lane																
Speed (mph)	**Right-turn Lane Cost = $15,000**								**Right-turn Lane Cost = $20,000**							
	DDHV (vph)								**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
25	28	23	19	17	15	10	6	4	39	31	26	22	20	13	7	5
35	27	20	16	14	12	8	4	3	36	27	22	18	16	10	6	4
45	23	17	13	11	9	6	3	2	31	22	17	14	12	8	4	3
55	22	15	11	9	8	5	3	2	29	20	15	12	10	7	4	3
Speed	**Right-turn Lane Cost = $25,000**								**Right-turn Lane Cost = $30,000**							
25	50	39	33	28	24	16	9	6	62	48	39	34	29	20	11	8
35	47	34	27	23	20	13	7	5	58	42	33	28	24	15	8	6
45	40	28	22	18	15	10	5	4	49	34	26	22	18	12	6	4
55	37	25	19	15	13	8	4	3	45	30	23	19	16	10	5	4
Speed	**Right-turn Lane Cost = $35,000**								**Right-turn Lane Cost = $40,000**							
25	76	57	46	39	34	23	13	9	93	67	54	45	39	26	14	10
35	70	49	39	32	28	18	10	7	84	57	45	37	32	20	11	8
45	58	40	31	25	21	13	7	5	69	46	35	29	24	15	8	6
55	54	35	27	22	18	11	6	4	63	41	31	25	21	13	7	5
Speed	**Right-turn Lane Cost = $45,000**								**Right-turn Lane Cost = $50,000**							
25	NA*	77	61	51	44	29	16	11	NA	87	69	57	50	33	18	12
35	100	65	50	42	36	23	12	8	NA	74	57	46	40	25	13	9
45	80	52	40	32	27	17	9	6	92	58	44	36	30	19	10	7
55	73	46	35	28	23	14	8	5	84	52	39	31	26	16	8	6
Speed	**Right-turn Lane Cost = $55,000**								**Right-turn Lane Cost = $60,000**							
25	NA	99	77	64	55	36	20	13	NA	111	85	70	60	39	21	15
35	NA	82	63	51	44	28	15	10	NA	92	69	56	48	30	16	11
45	NA	65	49	40	34	21	11	8	NA	71	54	43	37	23	12	8
55	95	57	43	34	29	18	9	6	NA	63	47	37	31	19	10	7
Speed	**Right-turn Lane Cost = $65,000**								**Right-turn Lane Cost = $70,000**							
25	NA	125	93	77	66	42	23	16	NA	140	102	83	71	46	25	17
35	NA	101	75	61	52	33	17	12	NA	112	82	66	56	35	19	13
45	NA	78	58	47	40	25	13	9	NA	85	63	51	43	27	14	10
55	NA	69	51	41	34	21	11	7	NA	75	55	44	37	22	12	8
Speed	**Right-turn Lane Cost = $75,000**								**Right-turn Lane Cost = $80,000**							
25	NA	NA	111	90	77	49	26	18	NA	NA	121	97	82	52	28	19
35	NA	123	89	72	60	38	20	14	NA	135	96	77	65	40	21	15
45	NA	93	68	55	46	28	15	10	NA	100	73	59	49	30	16	11
55	NA	81	59	47	39	24	12	9	NA	87	63	50	42	25	13	9
Speed	**Right-turn Lane Cost = $85,000**								**Right-turn Lane Cost = $90,000**							
25	NA	NA	131	104	88	56	30	21	NA	NA	142	112	94	59	32	22
35	NA	148	103	82	69	43	23	15	NA	NA	110	87	73	45	24	16
45	NA	108	78	63	52	32	17	11	NA	116	83	66	56	34	18	12
55	NA	93	67	54	45	27	14	10	NA	100	72	57	47	29	15	10

* NA – Not applicable.

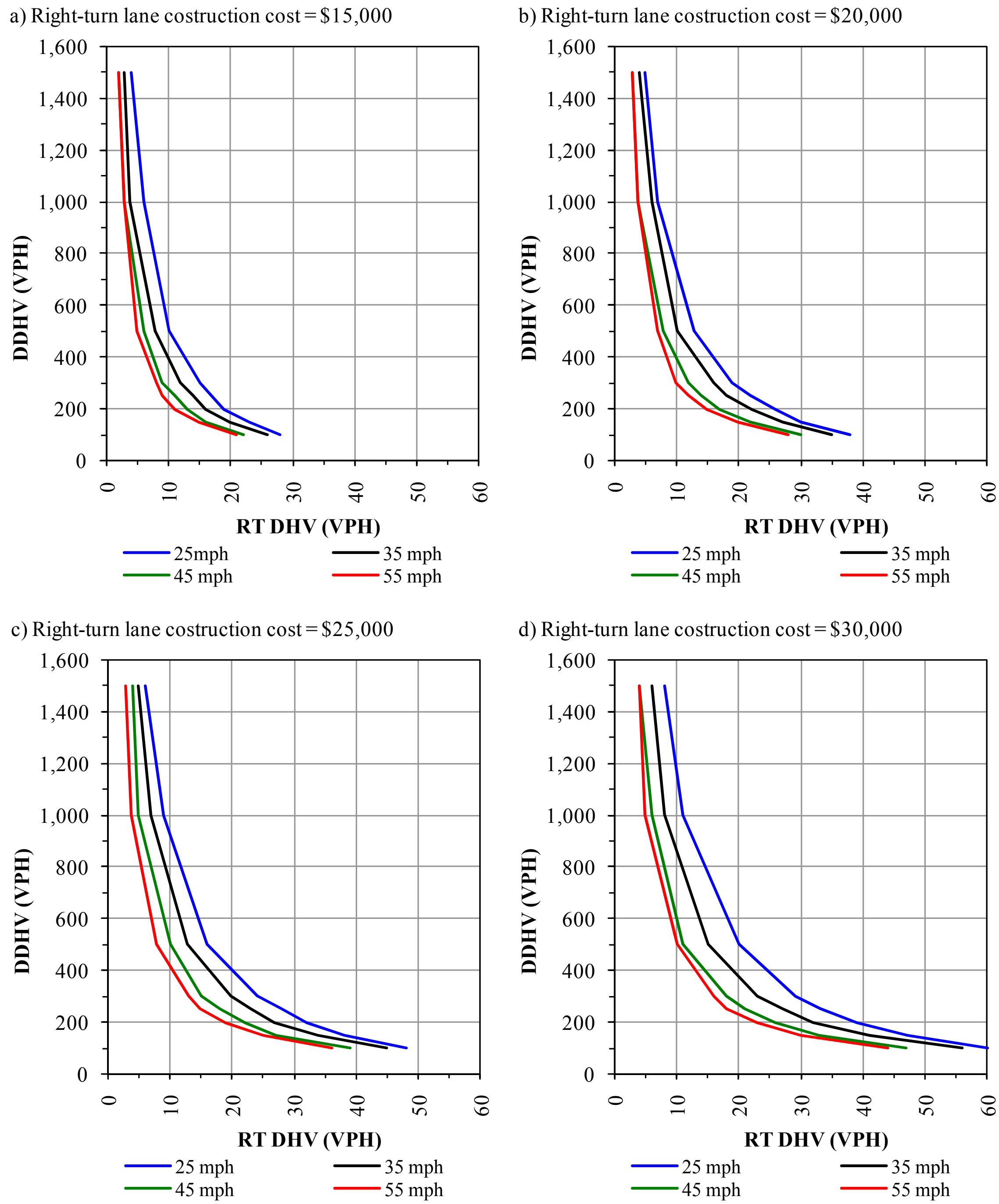


Figure H.6. Volume warrants for right-turn lanes at uncontrolled driveway approaches on two-lane roadways – fuel cost $4/gallon, delay cost $13.42/hour.

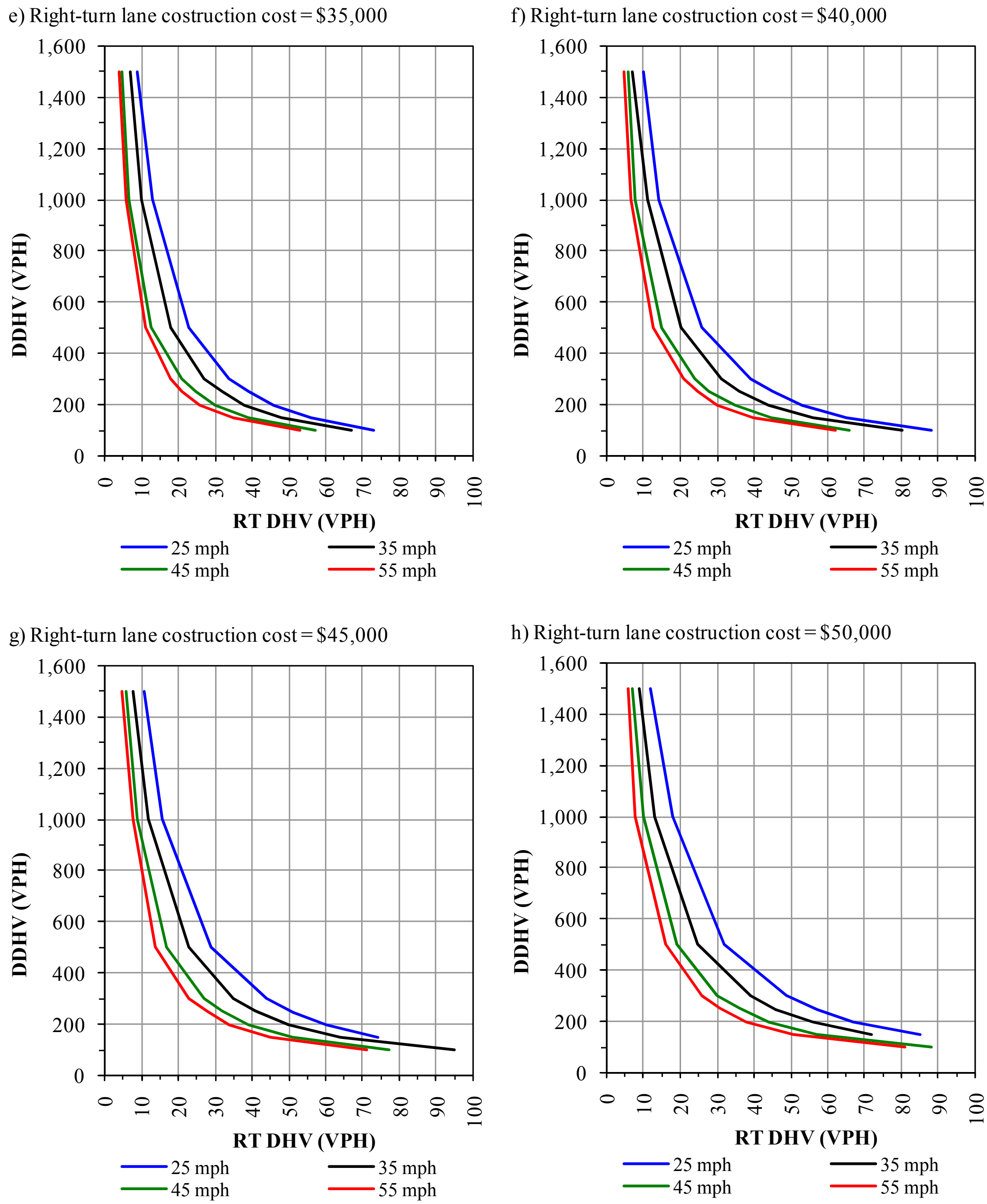


Figure H.6. (Continued)

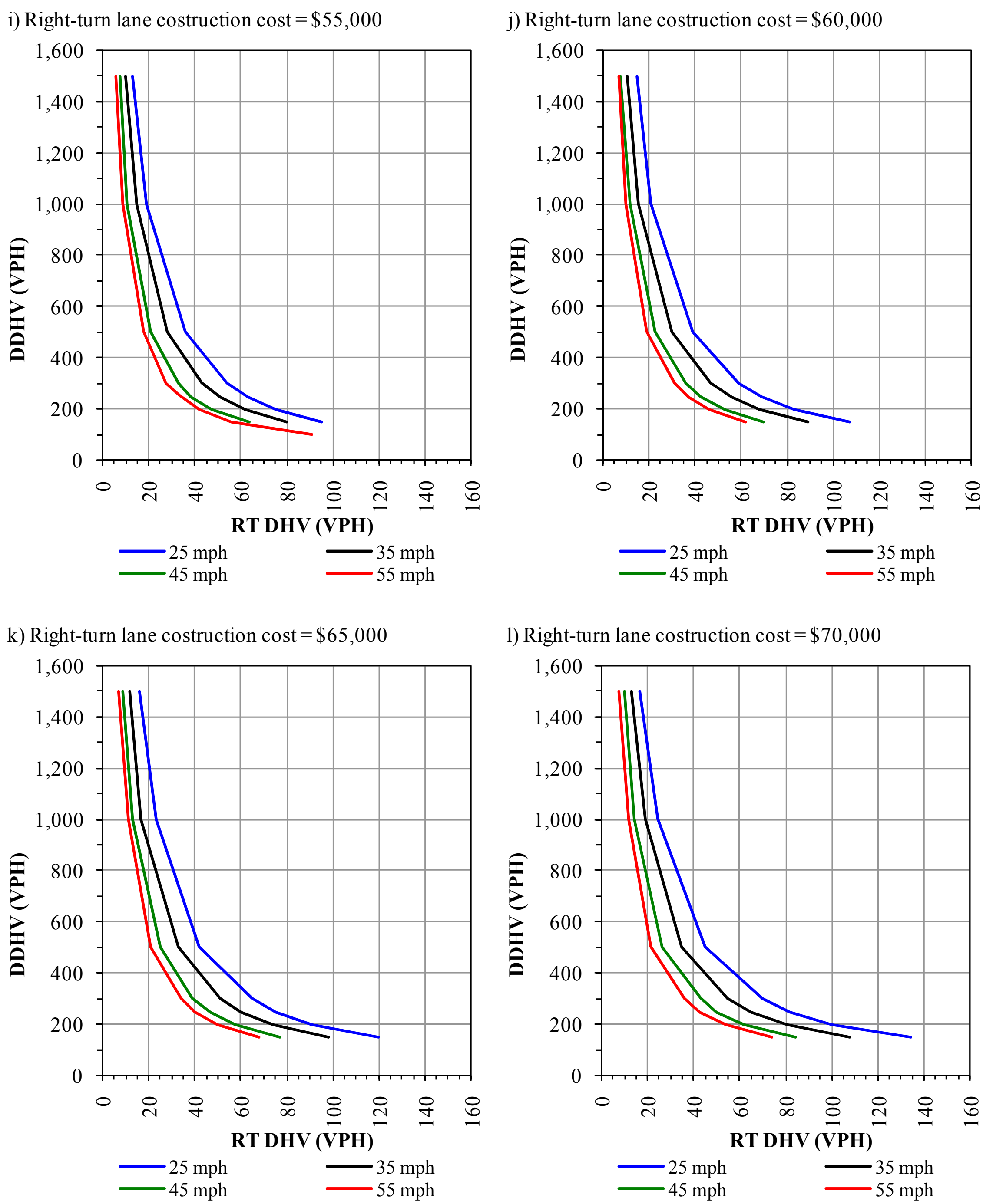
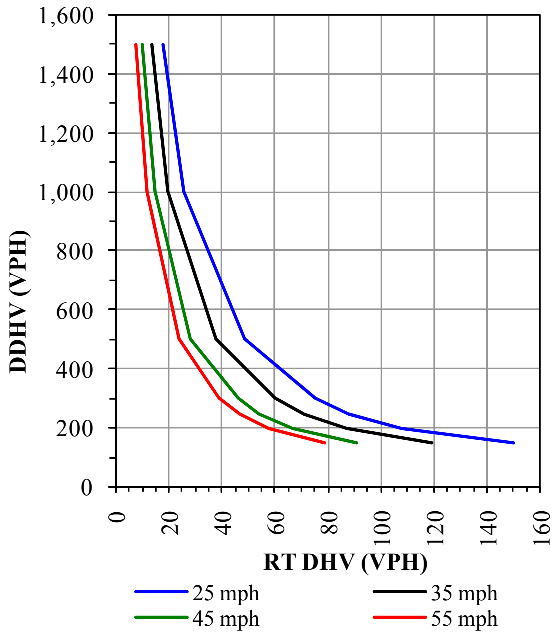
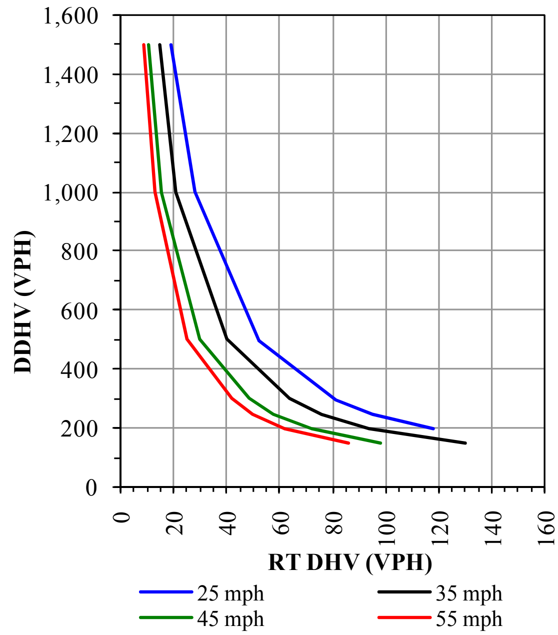


Figure H.6. (Continued)

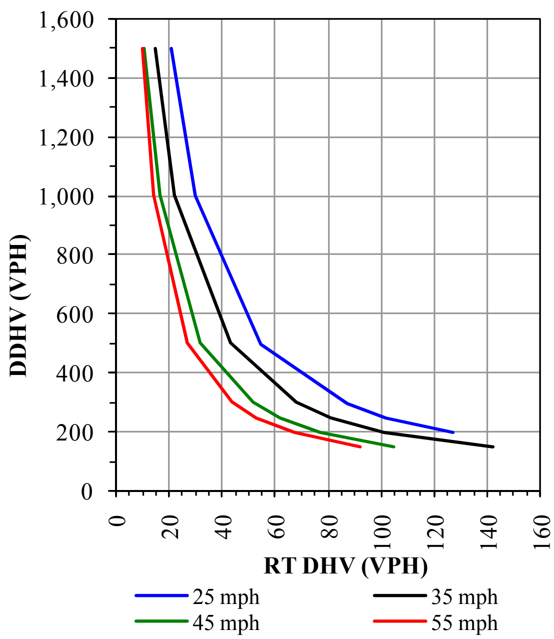
m) Right-turn lane costruction cost = $75,000



n) Right-turn lane costruction cost = $80,000



o) Right-turn lane costruction cost = $85,000



p) Right-turn lane costruction cost = $90,000

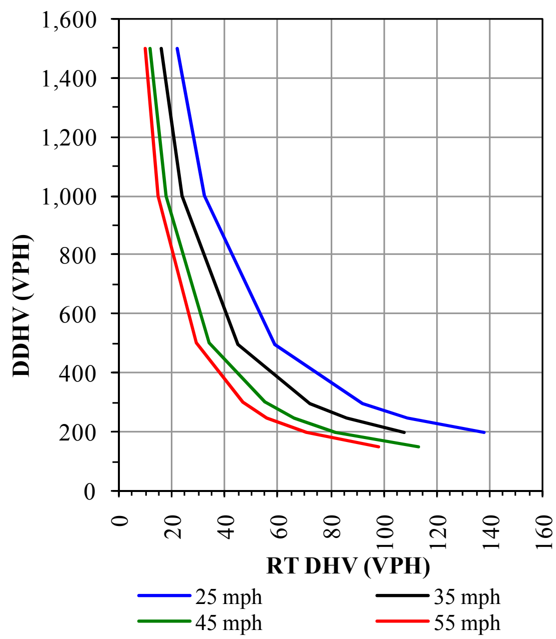


Figure H.6. (Continued)

Table H.6. Volume warrants for right-turn lanes at uncontrolled driveway approaches on two-lane roadways – fuel cost $4/gallon, delay cost $13.42/hour

Minimum Right-turn Design Hour Volume (vph) Required to Warrant a Right-turn Lane																
	Right-turn Lane Cost = $15,000								**Right-turn Lane Cost = $20,000**							
Speed (mph)	**DDHV (vph)**								**DDHV (vph)**							
	100	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**1,500**
25	28	23	19	17	15	10	6	4	38	30	26	22	19	13	7	5
35	26	20	16	14	12	8	4	3	35	27	22	18	16	10	6	4
45	22	16	13	11	9	6	3	2	30	22	17	14	12	8	4	3
55	21	15	11	9	8	5	3	2	28	20	15	12	10	7	4	3
Speed	**Right-turn Lane Cost = $25,000**								**Right-turn Lane Cost = $30,000**							
25	48	38	32	28	24	16	9	6	60	47	39	33	29	20	11	8
35	45	34	27	23	20	13	7	5	56	41	32	27	23	15	8	6
45	39	27	22	18	15	10	5	4	47	33	26	21	18	11	6	4
55	36	25	19	15	13	8	4	3	44	30	23	18	16	10	5	4
Speed	**Right-turn Lane Cost = $35,000**								**Right-turn Lane Cost = $40,000**							
25	73	56	46	39	34	23	13	9	88	65	53	45	39	26	14	10
35	67	48	38	32	27	18	10	7	80	56	44	36	31	20	11	7
45	57	39	30	25	21	13	7	5	66	45	35	28	24	15	8	6
55	53	35	26	21	18	11	6	4	62	40	30	25	21	13	7	5
Speed	**Right-turn Lane Cost = $45,000**								**Right-turn Lane Cost = $50,000**							
25	NA*	74	60	51	44	29	16	11	NA	85	67	57	49	32	18	12
35	95	64	50	41	35	23	12	8	NA	72	56	46	39	25	13	9
45	77	51	39	32	27	17	9	6	88	57	44	36	30	19	10	7
55	71	45	34	28	23	14	8	5	81	51	38	31	26	16	8	6
Speed	**Right-turn Lane Cost = $55,000**								**Right-turn Lane Cost = $60,000**							
25	NA	95	75	63	54	36	19	13	NA	107	83	69	59	39	21	15
35	NA	80	62	51	43	28	15	10	NA	89	68	56	47	30	16	11
45	NA	64	48	39	33	21	11	8	NA	70	53	43	36	23	12	8
55	91	56	42	34	28	18	9	6	NA	62	46	37	31	19	10	7
Speed	**Right-turn Lane Cost = $65,000**								**Right-turn Lane Cost = $70,000**							
25	NA	120	91	75	65	42	23	16	NA	134	100	82	70	45	25	17
35	NA	98	74	60	51	33	17	12	NA	108	81	65	55	35	19	13
45	NA	77	58	47	39	25	13	9	NA	84	62	50	43	26	14	10
55	NA	68	50	40	34	21	11	7	NA	74	54	43	36	22	12	8
Speed	**Right-turn Lane Cost = $75,000**								**Right-turn Lane Cost = $80,000**							
25	NA	150	108	88	75	49	26	18	NA	NA	118	95	81	52	28	19
35	NA	119	87	71	60	38	20	14	NA	130	94	76	64	40	21	15
45	NA	91	67	54	46	28	15	10	NA	98	72	58	49	30	16	11
55	NA	79	58	47	39	24	12	8	NA	86	62	50	42	25	13	9
Speed	**Right-turn Lane Cost = $85,000**								**Right-turn Lane Cost = $90,000**							
25	NA	NA	127	102	87	55	30	21	NA	NA	138	109	92	59	32	22
35	NA	142	101	81	68	43	22	15	NA	NA	108	86	72	45	24	16
45	NA	105	77	62	52	32	17	11	NA	113	82	66	55	34	18	12
55	NA	92	67	53	44	27	14	10	NA	98	71	56	47	29	15	10

* NA – Not applicable.