Development of Guidelines for Permitted Left-Turn Phasing Using Flashing Yellow Arrows

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Final Report 2015-27

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The objective of this project was to develop guidelines for time-of-day use of permitted left-turn phasing, which can then be implemented using flashing yellow arrows (FYA). This required determining how the risk for left-turn crashes varied as traffic-flow conditions varied during the course of a representative day. This was accomplished by developing statistical models, which expressed the risk of occurrence of a left-turn crash during a given hour as a function of the left-turn demand, the opposing traffic volume, and a classification of the approach with respect to the opposing traffic speed limit, the type of left-turn protection, and whether or not opposing left-turn traffic could obstruct sight distance. The models were embedded in a spreadsheet tool which will allow operations personnel to enter, for a candidate intersection approach, existing turning movement counts, and a classification of the approach with respect to speed limit, turn protection, and sight distance issues and receive a prediction of how the risk of left-turn crash occurrence varies throughout the day, relative to a user-specified reference condition.

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ABSTRACT

The objective of this project was to develop guidelines for time-of-day use of permitted left-turn phasing, which can then be implemented using flashing yellow arrows (FYA). This required determining how the risk for left-turn crashes varied as traffic-flow conditions varied during the course of a representative day. This was accomplished by developing statistical models, which expressed the risk of the occurrence of a left-turn crash during a given hour as a function of the left-turn demand, the opposing traffic volume, and a classification of the approach with respect to the opposing traffic speed limit, the type of left-turn protection, and whether or not opposing left-turn traffic could obstruct sight distance. The models were embedded in a spreadsheet tool which will allow operations personnel to enter, for a candidate intersection approach, existing turning movement counts, and a classification of the approach with respect to speed limit, turn protection, and sight distance issues and receive a prediction of how the risk of left-turn crash occurrence varies throughout the day, relative to a user-specified reference condition.

EXECUTIVE SUMMARY

A well-designed and operated traffic signal can increase the capacity of its intersection, reduce the prevalence of certain types of crashes, especially right-angle and left-turn crashes, and provide crossing opportunities for users facing heavy, opposing traffic streams. One important decision in designing a signal is the appropriate treatment given to left-turns (LT), and traditionally the choice has been between protected left-turns, where the left-turning drivers are given right-of-way and opposing traffic required to stop, and permitted left-turns, where left-turning drivers are required to yield to opposing traffic but may make the turn if an adequate gap appears. Protective turn phases can reduce the occurrence of left-turn crashes and allow the turns to be made when opposing traffic is heavy, but giving protective phasing when left-turn demand is light reduces the overall capacity of the intersection and, when opposing traffic is light, protective-only phasing can increase the delay experienced by left-turning drivers. Protective-permissive left-turn treatments (PPLT), where a protective interval is followed or preceded by a permissive interval, attempts to capture some of the benefits of protective LT phasing while avoiding some of the costs. A perennial difficulty however has been providing drivers with indications that clearly distinguish protected from permitted turns, and in 2003 a report commissioned by the National Cooperative Highway Research Program recommended that the flashing yellow arrow (FYA) indication be used to indicate permitted left-turns One potential advantage of four or five-section signal heads with FYA is that protective, permissive, or PPLT treatments can be varied throughout the day as traffic conditions might warrant. However, while tools exist for predicting the operational effects of within-day variation in traffic conditions, predicting how the risk of LT crashes might vary is more problematic.

A review of existing literature indicated that while models do exist for predicting annual totals of LT crashes, predicting how risk varied within a day is still an open question. For this project, in order to accommodate data availability and data quality issues, it was decided to employ a matched case-control study design rather than the traditional cross-sectional design. The cases consisted of 436 left-turn crash events occurring at signalized intersections operated by MnDOT, identified in part from data provided by the Highway Safety Information System and in part using the MNCMAT crash mapping tool. For each case, five hourly periods for the same intersection approach and on the same day as that of the case were then randomly chosen. For both the case and control hours the left-turn volume, the opposing volume, and the opposing left-turn volume were estimated by developing statistical models for adjusting available turning movement counts to the appropriate days and hours. These hourly volumes were then used as independent variables in logistic regression models which used the traffic volumes to discriminate times when crashes occurred from times when crashes were absent. Because a matched case-control design does not allow one to analyze the effect of features that are common to both the cases and controls, such as speed limits or geometric features, the crash-occurring intersections were classified according to opposing speed limit, the type of LT protection, and whether or not the intersection’s geometrics indicated that a left-turning driver’s sight distance could be obstructed by an opposing left-turning vehicle. Separate statistical models were then estimated for each intersection type.

For three of the intersection types, the available sample sizes were sufficient to reliably identify how left-turn crash risk varies as opposing and left-turn traffic volumes vary. The resulting statistical models were then incorporated in a spreadsheet tool which asks a user to enter available hourly turning movement counts for an intersection approach, along with several measurements describing the intersection's geometry. The tool then determines if a potential for sight distance obstruction exists and estimates the hourly left-turn and opposing traffic volumes for those hours not included in the turning movement counts. Finally, using the statistical model appropriate for the intersection approach's type, the tool computes how the relative risk for a left-turn crash varies as the hourly traffic volumes vary throughout the 24 hours of the day.

CHAPTER 1

1. INTRODUCTION

1.1 Background

A well-designed and operated traffic signal can increase the capacity of its intersection, reduce the prevalence of certain types of crashes, especially right-angle and left-turn crashes, and provide crossing opportunities for users facing heavy, opposing traffic streams. One important decision in designing a signal is the appropriate treatment given to left-turns (LT), and traditionally the choice has been between protected left-turns, where the left-turning drivers are given right-of-way and opposing traffic required to stop, and permitted left-turns, where left-turning drivers are required to yield to opposing traffic but may make the turn if an adequate gap appears. Protective turn phases can reduce the occurrence of left-turn crashes and allow the turns to be made when opposing traffic is heavy, but giving protective phasing when left-turn demand is light reduces the overall capacity of the intersection and, when opposing traffic is light, can increase the delay experienced by left-turning drivers. Protective-permissive left-turn treatments (PPLT), where a protective interval is followed or preceded by a permissive interval, attempts to capture some of the benefits of protective LT phasing while avoiding some of the costs. A perennial difficulty however has been providing drivers with indications that clearly distinguish protected from permitted turns, and in 2003 a report commissioned by the National Cooperative Highway Research Program recommended that the flashing yellow arrow (FYA) indication be used to indicate permitted left-turns (Brehmer et al 2003). The FYA indication was later included in the 2009 edition of the *Manual of Uniform Traffic Control Devices* (FHWA 2009). Signals with FYA indications are now seeing widespread use throughout the United States and have become the standard for new signal installations on Minnesota highways.

One potential advantage of four or five-section signal heads with FYA is that protective, permissive, or PPLT treatments can be varied throughout the day as traffic conditions might warrant. Given a specification of an intersection's physical layout and estimates of its hourly turning movement volumes, tools such as Synchro or the *Highway Capacity Manual* can be used to predict the operational effects of different LT treatments but predicting how the risk of LT crashes might vary as traffic conditions change is more problematic. Since safety is also a very important consideration when operating an intersection, in Fall 2012 this project undertook to develop a model which predicts within-day variation of left-turn crash risk.

1.2 Literature Survey

The literature on the safety effects of different forms of left-turn protections is extensive, and in a review prepared to support the *Highway Safety Manual* (HSM) Hauer (2004) discussed 36 papers and reports. Generally, protective phasing had the lowest crash rate while the relative safety of permissive-only versus protective-permissive was somewhat ambiguous. Hauer pointed out that many of these studies suffered from methodological weaknesses which limited the conclusions that could be drawn from them. He also emphasized the studies using data aggregated over a number of intersections will tend to obscure any important differences among those intersections. The HSM currently contains two crash modification factors (CMF) for changes in left turn protection. The CMF for changing to protective phasing is 0.01, indicating a

99% reduction in left turn crashes, while the CMF for changing from permissive to protective/permissive is 0.84, indicting a 16% reduction.

At about the same time as Hauer's review NCHRP Project 3-24 (Brehmer et al 2003) conducted an extensive investigation of practices regarding protective versus permissive left turn phasing, which included agency surveys, laboratory studies of drivers' comprehension of different signal displays, a cross-sectional statistical study comparing the crash rates associated with different displays, and field observations of traffic conflicts involving left-turns. The cross-sectional study suggested that a flashing circular yellow indication for permitted left-turns had a lower crash rate than circular green indications, while the traffic conflict study reported no detectable change in conflicts after installation of flashing yellow arrow indications. NCHRP then funded a follow up (Noyce et al 2007) which investigated the crash experience at 50 intersections before and after installation of FYA indications. Overall, crashes tended to decrease after FYA replaced circular green indications for the permissive phase in PPLT treatments but, not surprisingly, crashes tended to increase when FYA permissive phasing replaced protective-only phasing. The results were inconclusive regarding replacement of circular green permissive-only phasing by FYA, due mainly to the small number of treatment sites available.

Wang and Abdel-Aty (2008) conducted a cross-sectional study of left-turn crash frequency at signalized intersections in Florida. The authors identified 197 four-legged intersections, classified different left-turning maneuvers into 9 patterns, and fit statistical models which related expected crash frequency to variables such as the left-turn and of opposing average daily traffic (ADT) volumes, speed limits of opposing traffic, widths of medians (if any), the type of left-turn protection, and a geographical effect which allowed for differences among the three study counties. A Generalized Estimating Equations (GEE) approach, which allowed for dependencies among the different left-turn patterns, was compared to a Negative Binomial approach which treated the different patterns as independent. The GEE models generally gave better fits to the crash data. For pattern 5, which was crashes between a left-turning vehicle and an opposing vehicle going straight, crash frequency tended to increase as (1) the number of opposing lanes increased, (2) the opposing and left-turn ADTs increased, and (3) as the speed limit for the opposing traffic increased. Protective left-turn phasing tended to decrease crash frequency while PPLT treatments tended to have higher crash frequencies than purely permissive treatments.

Chen et al (2012) evaluated two changes in left turn protection: (1) changes from permissive to PPLT phasing, and (2) change from permissive to protective left-turn phasing. The study employed a before/after with comparison group design to estimate changes in crash frequency associated with changes in left-turn protections. The comparison group consisted of 991 signalized intersections in New York City with permissive left-turn phasing. Treatment group 1 consisted of 59 intersections which had been changed from permissive to protective-permissive phasing, while treatment group 2 consisted of 9 intersections which had been changed from permissive to protective only phasing. The study period of interest was 2000-2007. Estimated left-turn crashes/intersection declined by about 36% in the comparison group, by 17% in treatment group 1 and 77% in treatment group 2. As expected, replacing permissive left-turn phasing with protective-only phasing reduced left-turn crashes. There appeared to be no safety benefit derived from replacing permissive phasing with PPLT phasing.

A study commissioned by NCHRP (Srinivasan et al 2012) evaluated two changes in left turn protection: (1) changes from permissive to PPLT phasing, and (2) use of FYA indication for permitted left turns. This was an extensive study aimed at developing crash modification factors (CMF) for future use in the *Highway Safety Manual*, using an empirical Bayes before/after methodology. For estimating the CMF associated with changing from permissive to protective-permissive phasing, the treatment group consisted of 59 intersections in Toronto, Canada and 12 intersections in North Carolina. The results indicated a modest safety benefit; the estimated CMF was 0.86, corresponding to a 14% reduction in left-turn crashes. For estimating the CMF associated with using FYA for permitted left turns, the treatment group consisted of five intersections in Kennewick, WA, 30 intersections in Oregon, and 16 intersections in North Carolina. The estimated CMFs associated with replacing protective left-turn phasing with flashing yellow arrows ranged between about 2.0 to 3.7, reflecting *increases* in left-turn crashes ranging between 100% and 270%. When flashing yellow arrows were used in permissive phases of signals already having permitted or protected-permitted left turns, the estimated CMFs ranged between about 0.4 and 0.75, reflecting *decreases* in left-turn crashes ranging between 25% and 60%. These results are roughly consistent with those reported in Noyce et al (2007). Replacing protective phasing with FYA permissive phasing is similar to replacing protective phasing with traditional permissive phasing: left-turn crashes tend to increase. On the other hand, when the FYA indication replaced traditional permissive phasing, left-turn crashes tended to decrease. The authors also noted that explicit consideration should be given to CMF variability across sites when evaluating safety improvements.

Pulugurtha and Khader (2014) also investigated safety effects of FYA installation, at approaches with protective, permissive, PPLT, or stop-sign control prior to installation of flashing-yellow arrow signal heads. Eighteen intersections in Charlotte, NC, where FYA signals had been installed, were selected for a before/after comparison. Prior to installation the selected intersections had protected, permitted, protected-permitted, and stop-sign control for left-turns. At least three years before data and 15 months after data were required. Empirical Bayes estimates of each intersection's CMF ranged from 0.00 to 1.41, with an average of 0.39. A CMF of 0.39 indicates a 61% reduction in left-turn crashes. No standard errors or confidence intervals were reported. The mixing of different before left-turn treatments and the relatively small sample size and short after periods make these results difficult to interpret. Six of the 18 intersections had protective left-turn phases prior to conversion to FYA and these experienced no left-turn crashes in the after period, suggesting that FYA reduced left-turn crashes, but without estimates of standard errors it is difficult to see if this observed reduction is statistically significant. Similarly, three of the five intersections using stop-sign control in the before period has zero left-turn crashes in the after period; but, it is not possible to assess the significance of this apparent reduction. The authors recommended additional study with larger samples to substantiate their findings.

Qi et al. (2012) studied intersection approaches operating initially with either protected left turns, or PPLT left turns indicated by circular green, followed by PPLT treatments indicated by flashing yellow arrow. The authors conducted a literature review and survey of professionals regarding use of flashing yellow arrow, a field study of issues involved in implementing flashing yellow arrow at five intersections, a before-after comparison of conflicts at those five intersections, and a before-after comparison of crash experience at intersections in Tyler, Texas, Federal Way, Washington, and Kennewick, Washington. The safety results are difficult to interpret. The Texas crash study compared left-turn crash rates computed before and after installation of flashing yellow arrow, but the crash rates used total entering ADT as the exposure measure and also used the same ADT estimate for the before and after periods. Thus it was not possible to determine if the crash risk for left-turns changed after installation of flashing yellow arrow. Crash rates for the Washington state crash studies appear to have been computed similarly to those for the Texas study but it was not possible to verify this using the data presented in the report. The report suggested that when a solid yellow-solid red change interval is used to divide the protective and permissive phases drivers who have entered the intersection during the solid yellow interval preparatory to making a left turn can then make a hasty turn when the solid red arrow appears, not realizing that a permissive interval will follow. The report also identified several practical issues regarding installation of flashing yellow arrow signals.

A novel approach to providing guidance on within-day LT treatments was developed by Radwan et al (2013).Their main objective was to develop a statistical model which predicted the number of allowable permissive left-turn movements/hour as a function of a range of intersection, traffic, and control features. 13 intersections in Central Florida were identified as covering a range of traffic, geometric, land use, and control features. Video recordings of durations 10-12 hours were made at each of the 13 intersections, and the video data were reduced to extract a variety of hourly measures such as: left turn and opposing traffic volumes, the time allocated for permitted left-turns, opposing and left turn volumes during permitted phasing, time needed to accomplish left turns, critical gaps, percentage of trucks in the left-turn streams. The video data were supplemented with five-year crash data and aerial-photo and field observations. 10 variables were identified as potential predictors of permitted left-turn volume: time-of-day, hourly left turn volume, hourly opposing volume, opposing speed limit, percent of left turn trucks, permitted green time, five-year left turn crash frequency, land use category, a location category, 3-leg vs 4-leg intersection, and number of crossing lanes. A design of experiments approach was used to identify the levels of these variables to include in the statistical analysis. Stepwise regression methods were then used to identify best subsets of the predictor variables and their interactions, and the corresponding coefficients. These results were then incorporated into a Visual Basic program which allowed users to enter data characterizing an intersection approach during a time-of-day and receive a recommendation regarding permitted left-turn treatment. This is an interesting effort at synthesizing a variety of intersection features in order to assess the need for protective left-turn phasing, but the direct focus was on operational effectiveness, with safety effects captured indirectly via surrogates.

For Appiah and Cottrell (2014) the motivation was about whether or not the protective interval of a protective/permissive phase should be separated from the permissive phase by a red-arrow (stop) indication, when the permissive phase is indicated by a flashing yellow arrow. This red arrow phase is called flashing yellow arrow delay. The authors conducted a literature review and reported on several surveys of practitioners. Generally, a majority appeared to favor using flashing yellow arrow delays ranging from 1-8 seconds, although some indicated that short (~ 1 second) delays can be interpreted by drivers as signal malfunctions. A minority opinion appeared to be that flashing yellow arrow delays were no more necessary than delays when a circular green is used to indicate the permissive left turn phase. Using VISSIM, the authors conducted a set simulations at a hypothetical intersection, varying the approach speeds, traffic volumes, and durations of the flashing yellow arrow delay. For the most part, simulated conflicts decreased as the duration of flashing yellow arrow delay increased, and except for situations with low opposing volumes, flashing yellow arrow delay had little effect on simulated delay or queue lengths. The surveys reported in this paper confirmed that debate about flashing yellow arrow delay is ongoing. The simulation study suggested that flashing yellow arrow delay could have a safety benefit with marginal operational costs, but "a more comprehensive study of the optional FYA delay that incorporates data from intersections located in diverse geographical areas with various configurations, traffic characteristics, and timing plans is recommended."

1.3 Outline of Study

A safety performance function (SPF) is generally a statistical model that relates the expected frequency of crashes at a roadway location to observable features such as traffic volumes, speed limits, features of the traffic control, or geometric properties. SPFs play an important role in the predictive methodology described in the *Highway Safety Manual*. For the purpose of making time-of-day decisions regarding left-turn protection we would need a well-supported SPF that described the expected frequency of left-turn crashes during permissive operation, and incorporated hourly turning movement volumes as predictors. Developing such an SPF was initially considered as a goal for this project but preliminary investigations suggested that this would not be feasible. The review of literature identified three studies reporting SPFs for predicting left-turn crash frequency: Wang and Abdel-Aty (2008), Srinivasan et al (2012), and Pulugurtha and Khader (2014). In Wang and Abel-Aty (2008) the dependent variable was left-turn crash frequency over a six-year period and in the other two studies the dependent variable was left-turn crashes per year; none of the reviewed work attempted to model crash frequency per hour. Simple arithmetic shows why this is the case. A study of say, 100 sites over a six-year period, using crashes/year as its dependent variable, would require a data file of 600 rows, one for each site-year. A study of 100 sites over six years with crashes/hour as a dependent variable would require a file of about 5.3 million rows, one for each site-hour. Even if data management was not an issue populating this data file is, at present, highly problematic. Although the crash records maintained my Minnesota's Dept. of Public Safety do identify the date and approximate time of the crash, obtaining the corresponding hourly turning movement volumes is not straightforward. Minnesota does have a program for estimating average annual daily traffic (AADT), typical of what is done in many states, by conducting short counts, usually for 48 hours repeated every two-four years, and then adjusting these to estimate the annual average. The adjustment factors are in turn determined from a limited number of automatic traffic recorders (ATR) which continuously record hourly traffic volumes. This means that historical hourly traffic volumes are generally available only for a very small number of roadway locations. When we turn to turning movement volumes at intersections the problem is, if anything, even less encouraging. The most common practice is count turning movements manually as needed for traffic control decisions, typically during morning and afternoon peak periods but possibly during selected non-peak times, on a single, representative, day. Finally, during the course of this project it was revealed that in generating computerized codes of crash type from the narratives and diagrams in the crash reports left-turn crashes can be mis-identified (Crash Facts, 2012). This suggested that, without manual review of the original crash reports, obtaining a reliable count of reported left-turn crashes would not be possible.

Taking these factors into account it was decided, for this study, to employ a matched case-control study design rather than the traditional cross-sectional design. In a matched case-control design one begins with a representative sample of cases, in this instance hours during which a left-turn crash occurred, and for each case selects one or more control events, e.g. hours during which a left-turn crash did not occur. For each case and control one then obtains measures of the factors of interest, such as hourly turning movement volumes, and then looks to see if the factors can discriminate the cases from the controls. This approach has two advantages. First, the total sample size will usually be a small multiple of the number of cases. For example, a sample of 500 crashes with 4 controls for each case would require a data file with 2500 rows. Second, as long as the tendency to mis-identify left-turn crashes does not favor particular times of day, a sample of left-turn crashes obtained from computerized records should still be representative of what how crash risk varies as traffic volumes vary. A disadvantage of the case-control design is that the resulting statistical model will not predict how the expected frequency of left-turn crashes varies, but only how the risk of a left-turn crash varies in comparison to a specific base-condition. For example, suppose that on an intersection's approach the probability of left-turn crash occurring between 10 PM and 11 PM was $1\text{x}10^{-6}$ but that the probability of a left-turn crash between 4 PM and 5 PM was $3\text{x}10^{-6}$. A case-control design could estimate that the 4-5 PM risk was triple that of 10-11 PM, but not the underling probabilities generating that relative risk. This limitation was considered acceptable as long as the results of a relative-risk analyses could be presented in a readily-interpreted form.

In what follows, Chapter 2 describes the data collected to support this study while Chapter 3 describes the methods used to characterize sight distance for left-turning vehicles and to estimate turning movement volumes for case and control hours. Chapter 4 then describes the statistical analyses used to relate changes in traffic volumes to changes in left-turn crash risk. Chapter 5 describes a spreadsheet tool which implements the results from Chapter 4 in a more user-friendly form.

CHAPTER 2

2. DATA ACQUISITION

This chapter summarizes all activities done in order to complete tasks 2, 3, and 4 of the project. Developing statistical models for left turn crashes requires compiling a master data file. Such a master file contains possible explanatory variables such as geometric characteristics and relevant traffic counts along with the response for all, or a representative sample of, intersection approaches with permissive left-turn (LT) phasing. This chapter is dedicated to the first part of this process; that is, a long list of intersections with permitted left-turns was identified and then relevant geometric characteristics were collected for a sample of them. Also, the list of LT crashes at these intersections and the available traffic counts for relevant turning movements were compiled.

2.1 Identifying Candidate Intersections

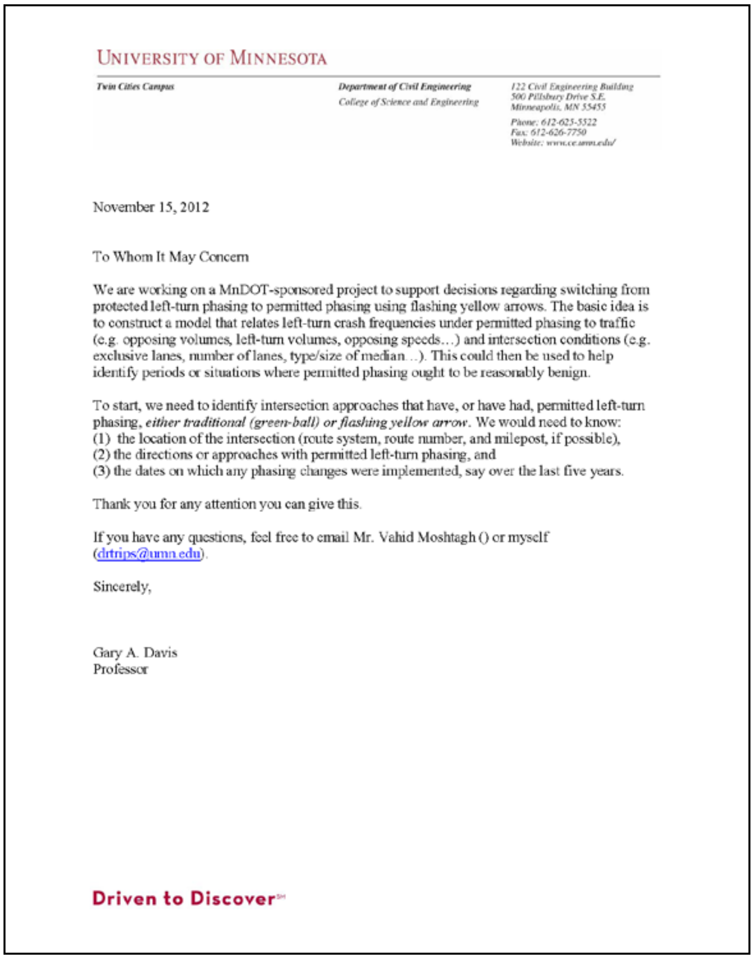
In order to compile a list of intersections having at least one approach with permissive left-turn (PLT) phasing, project staff contacted MnDOT personnel, as well as personnel at seven counties and 61 cities within the Twin Cities metro area, during October and November 2012. Figure 2.1 shows the cover letter used to implement this survey. 30 responses were received, with some reporting no signals with permissive left turn phasing, some referring us to county agencies and/or MnDOT, and 15 providing useable information. This initial information identified about 1250 intersections. Excel files provided by different agencies had different formats and included different information. The following is a summary of the initial information collected from different agencies.

The initial list from MnDOT included 675 intersections. As compared to the files prepared by counties and cities, the MnDOT file contained more details regarding intersection location as well as geometry and control-related information for each approach. Information such as left-turn phasing type (protective, split phase, permissive, protective-permissive, FYA), the number of left turn lanes, and the speed limit for each leg was provided. Thus, completing the required information for these intersections was easier and faster than it is for the county and city intersections.

135 intersections were listed by Hennepin County at which 249 approaches had a permissive phasing. 19 intersections among them had FYA. But no more information was provided. 70 signals with permissive left turn phasing were identified by Ramsey County. Some information about protected or permitted approaches was also given. 151 intersections of which 14 have FYA were reported by Dakota County. Installations and revision dates along with brief phasing information were also included. In addition, details provided for 135 County-owned intersections included:

- phasing
- number of left-turn crashes for some intersections
- speed limits
- limited geometric characteristics

There were 171 signalized intersections within Washington County according to the list given by the County. However, they are not all owned by the County; MnDOT operates 83 intersections, cities owned 29 signals, and the remaining 59 intersections are under jurisdiction of Washington County. Type of left-turn signal for each approach was identified. Also, the date of the last change and the type of previous state of the signal were also reported. 16 intersections with PLT were listed by Scott County personnel along with the left turn phasing type for each direction. They also mentioned the city in which each intersection was located.



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November 15, 2012

To Whom It May Concern

We are working on a MnDOT-sponsored project to support decisions regarding switching from protected left-turn phasing to permitted phasing using flashing yellow arrows. The basic idea is to construct a model that relates left-turn crash frequencies under permitted phasing to traffic (e.g. opposing volumes, left-turn volumes, opposing speeds…) and intersection conditions (e.g. exclusive lanes, number of lanes, type/size of median…). This could then be used to help identify periods or situations where permitted phasing ought to be reasonably benign.

To start, we need to identify intersection approaches that have, or have had, permitted left-turn phasing, *either traditional (green-ball) or flashing yellow arrow*. We would need to know:
(1) the location of the intersection (route system, route number, and milepost, if possible),
(2) the directions or approaches with permitted left-turn phasing, and
(3) the dates on which any phasing changes were implemented, say over the last five years.

Thank you for any attention you can give this.

If you have any questions, feel free to email Mr. Vahid Moshtagh () or myself (drtrips@umn.edu).

Sincerely,

Gary A. Davis
Professor

Driven to Discover℠

Figure 2.1 The cover letter for investigating signal approaches with PLT phases.

We also received information from nine cities which are summarized below:
Apple Valley: 12 locations under the jurisdiction of the City were listed and the type of left turn control (prot., perm., prot/perm) was identified as well.
Eagan: totally 31 intersections were introduced by the City staff. The provided information is described below:

- 9 County-owned places with FYA along with installation date, pre- and post-improvement operations
- 15 County-owned permissive signals
- 3 City-owned permissive signals
- 4 MnDOT-owned permissive signals

Minneapolis: 3 locations with flashing yellow arrow were introduced and no more information was provided.
Golden Valley: 29 places with permissive (any type) left turn phasing were reported. They might also be included in Hennepin County list. Approaches with PLT were also identified. If there had been a change in control type, the date was also mentioned.
Bloomington: Two locations with FYA were identified.
Vadnais Heights: 1 FYA had been implemented for 16 months.
Mendota Heights: There were 11 intersections within this city which have permitted left-turns (circular green); but they all were owned and operated by MnDOT or Dakota County.
Hastings: There was only one traffic signal in Hastings with flashing yellow arrow left turn signal since November 2011.
East Bethel: they reported only 2 signals with PLT which were under jurisdiction of Anoka County and MnDOT.

2.2 Eliminating Redundancies

An initial investigation of the provided lists showed two issues. First, not all of listed intersections had an approach with permitted left turns. That is, all approaches at an intersection were either protected or split phase. Second, intersections were not necessarily unique; they may be been reported by more than one agency. For instance, the City of Eagan reported 31 intersections with PLT while 24 of them were also reported in the Dakota County list and four were MnDOT intersections which were included in MnDOT list. The next step was to eliminate these redundancies and prepare a master list of intersections with PLT within the metro area. This section summarizes the efforts regarding this issue.

MnDOT

The initial list contained 675 intersections, but not all had an approach with permitted left turns. So, intersections lacing approaches with some form of permissive left turn phasing (i.e. permissive, protected-permissive or flashing yellow arrow) were filtered out. Details of this elimination process and the number of intersections excluded due to each reason were:

1- Intersections with no phasing information: 3
2- When the "through" road of a T intersections is one way, so that two approaches have no left turn and one approach has no opposing traffic: 15
3- Four-leg intersections with protected left-turns in all approaches: 86
4- Intersections with combinations of "Protected", "No left-turn, "No opposing traffic", and blank: 101. Different combinations were checked case by case to make sure they were not useful for our purpose.
5- Intersections with "split phase" in two approaches and "protected" or "No left-turn" in other approaches: 42

This reduced the number of MnDOT intersections declined to 428.

Hennepin County

The number on the initial list was 135. In order to check redundancies we needed to first locate these intersections so that they could be compared with MnDOT list. The main problem here was that most of the intersecting roads were often identified in more than one way; that is, roads were called differently by different agencies. For example, County road 130 (CSAH 130) is called

Elm Creek Blvd and also 77th Ave N. When it enters Brooklyn Park it has also the name Brooklyn Blvd. This multiple naming system made locating the intersections difficult and confusing. However there was no overlap between the MnDOT list and Hennepin County's list, so only those intersections whose locations were ambiguous were eliminated. The number of such intersection was 17. Hence, the number of remaining Hennepin County's intersections was 118 including 17 FYAs, with those approaches having permissive left turn phasing being already identified by County personnel.

Dakota County
34 intersections were protected and/or split-phase in all approaches. 19 intersections were protected on the mainline while the side street was one-way or a T junction, which means there was no left turn or there was no opposing traffic. The number of remaining Dakota County intersections was 98 including 14 FYAs. Signal type and phasing information were provided.

Washington County
83 MnDOT-owned intersections were removed. Out of 59 County intersections 14 intersections had no permissive LT signal. They, rather, had protected or split phasing. There existed some approaches in which FYA had been installed but was not yet being used (still run as protected signal), so we considered them as protected indications. Thus, 45 county-owned intersections remained. 4 city-owned intersections had no permissive phase either, so they were removed as well. The number of remaining intersection within Washington County, either county-owned or city-owned, was 45 + 25 = 70. It turned out later (when they were located on a GIS map) that two of county road intersections in this list overlapped with MnDOT intersections.

Scott County
None of 16 intersections identified by Scott County were recognized as redundancies. So, they were all kept in this step.

Ramsey County
Eight intersections had no permissive left-turn signal and therefore were eliminated. 29 intersections are under the MnDOT jurisdiction. Among the 33 remaining intersections, some were ambiguous in terms of type of left-turn signal. Therefore the remaining Ramsey County intersections were also eliminated.

Cities

Apple Valley: Four of the reported intersections were protected on all approaches, leaving eight local intersections at this step.

Eagan: 28 intersections were already included in the MnDOT and Dakota County files. Only 3 intersections were owned by the City. The type of the left-turn control was reported by the city engineers.

Minneapolis: Three locations were identified for FYAs. But no more information was provided.

Golden Valley: 11 intersections out of 29 were owned by Hennepin County or MnDOT. Among the remaining 18 intersections there were still chances for redundancies because of the multiple names for roads. So this case required more attention in the later steps.

Finally, all intersections listed by Mendota Heights and East Bethel were under MnDOT or county jurisdiction. Bloomington, Vadnais Heights and Hastings reported few intersections which recently used FYA and there was no information about the control type before this change. So, they were not usable for our purpose. According to the limited information given by cities and owing the fact that there are plenty of intersection reported by Counties and particularly by MnDOT, only the intersections listed by Apple Valley and Eagan were passed to the next step. Therefore, the number of remaining intersections remaining intersections decreased to 741.

2.3 Geometric Characteristics

The ultimate goal of Task 2 of the project was to gather data on the relevant geometric characteristics of intersections identified in the initial screening. According to the literature review done in the first task and the TAP meeting on December 27, 2012, the following geometric characteristics were needed:

- The number of opposing through lanes (1, 2, 3+)
- The number of exclusive left-turn lanes (0, 1, 2)
- The speed limit of opposing approach
- The width of median
- Left-turn offset

These data were collected by first locating the 741 remaining intersections on a GIS map and then using newly-taken aerial photos to extract geometric characteristics.

ArcMap 10 was employed to locate intersections. Also, 2012 aerial photos of Twin Cities metro (brought up from **http://geoint.lmic.state.mn.us/cgi-bin/wms**? as a WMS Servers) were used as the underlying map. The key point in the locating process was that all available address locators, such as US Streets Geocode Service 10.0 (which we used), required the State and the City of the location the user is trying to locate. The State for all intersections was obviously Minnesota but the City was sometimes an issue. Among our 741 intersections, only Scott County's 16 intersections already had the City information. So, Google map was used to locate the intersections one by one and find out what city they are located in. This information was added to the excel files and subsequently to csv files. These csv files then were imported to ArcMap.

Although two columns of State and City were added to the data, address locators could find only small proportion (less than 10 percent) of the list automatically. The main reason for this was the multiple naming issue mentioned before. Intersections identified by counties were usually referred to using county road numbers or CSAH numbers and GIS address locators waere rarely able to recognize these names. So, Google map was used again to find alternative, more recognizable names, for intersecting roads. Then these alternative names were applied in ArcMap and the locating process carried out. Still there were few intersections not located because of ambiguous addressing or projects constructed during recent past years. Figures 2.2 to 2.4 exhibit the distribution of identified intersections over the Twin Cities Metro area.

2.3.1 *Characteristics of Intersections*

Using the aerial photos we observed and recorded four geometric characteristics (the number of opposing through lanes, the number of exclusive left-turn lanes, the width of median, and the left-turn offset) of each intersection. For those intersections which were not on available aerial photos, Google Map was used. The only required variable (a potential predictor in our model) not observable from aerial photos was speed limit. Fortunately, for the MnDOT list, with more than 400 intersections, this was available in the provided file. The intersections of the other agencies required a different source such as Google Street View.

The geometric data observation process started with MnDOT and Hennepin County intersections. In parallel, inquiries started for the next two tasks regarding crash counts and traffic volumes. During this inquiry, we realized that detailed traffic counts (broken down by turning movements) were not readily available for city roads and county roads. In addition, detailed crash data maintained by Highway Safety Information System (HSIS) had limited coverage of roadways in the state. Among our current list, it turned out that 328 of MnDOT intersections existed in the HSIS database. Hence, the compiling of crash predictors characteristics was focused on MnDOT intersections. This decision was supported by the fact that: (1) the number of remaining intersections (328) was sufficient for statistical modeling purposes and (2) the MnDOT intersections were reasonably representative of Metro area intersections both in spatial distribution and in terms of their characteristics.

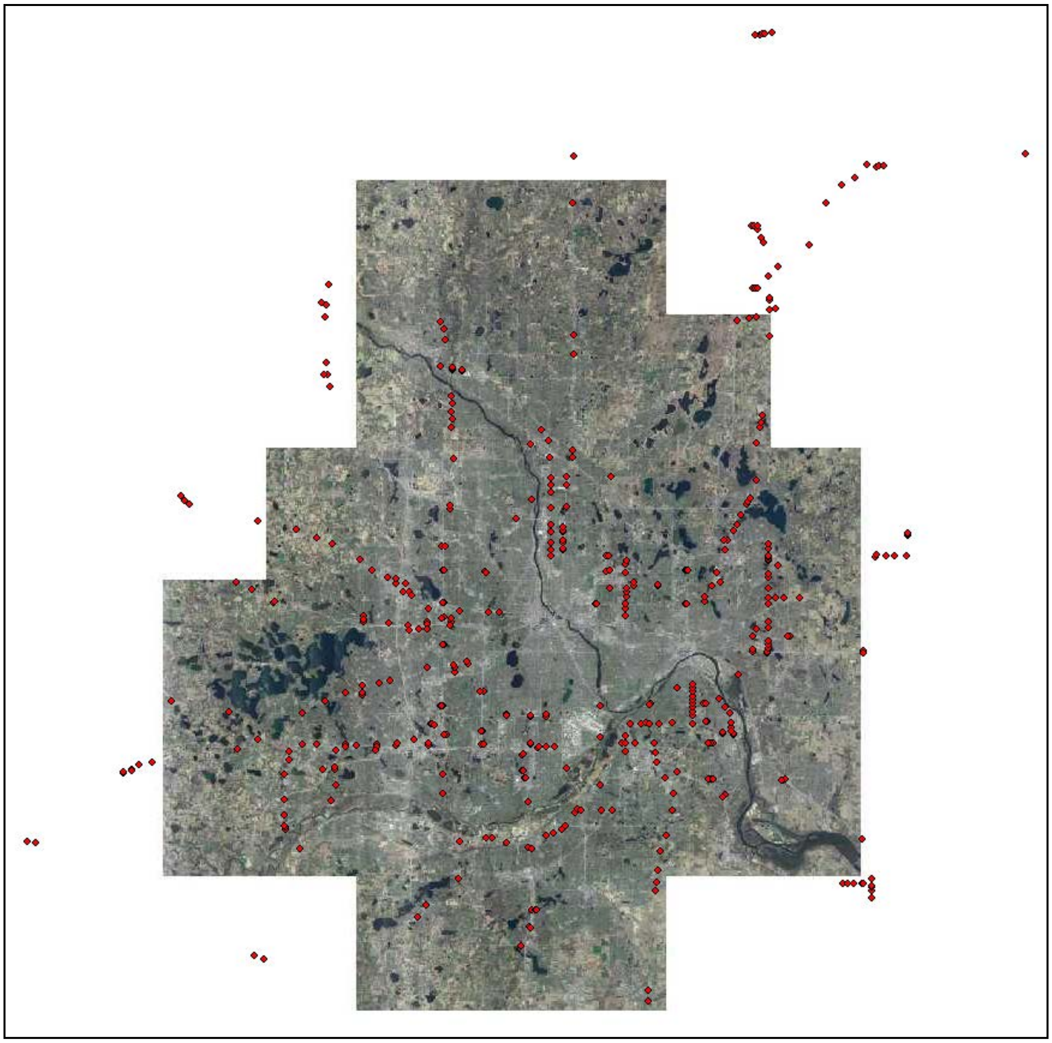


Figure 2.2 Location of MnDOT intersections with permissive left-turn treatments.

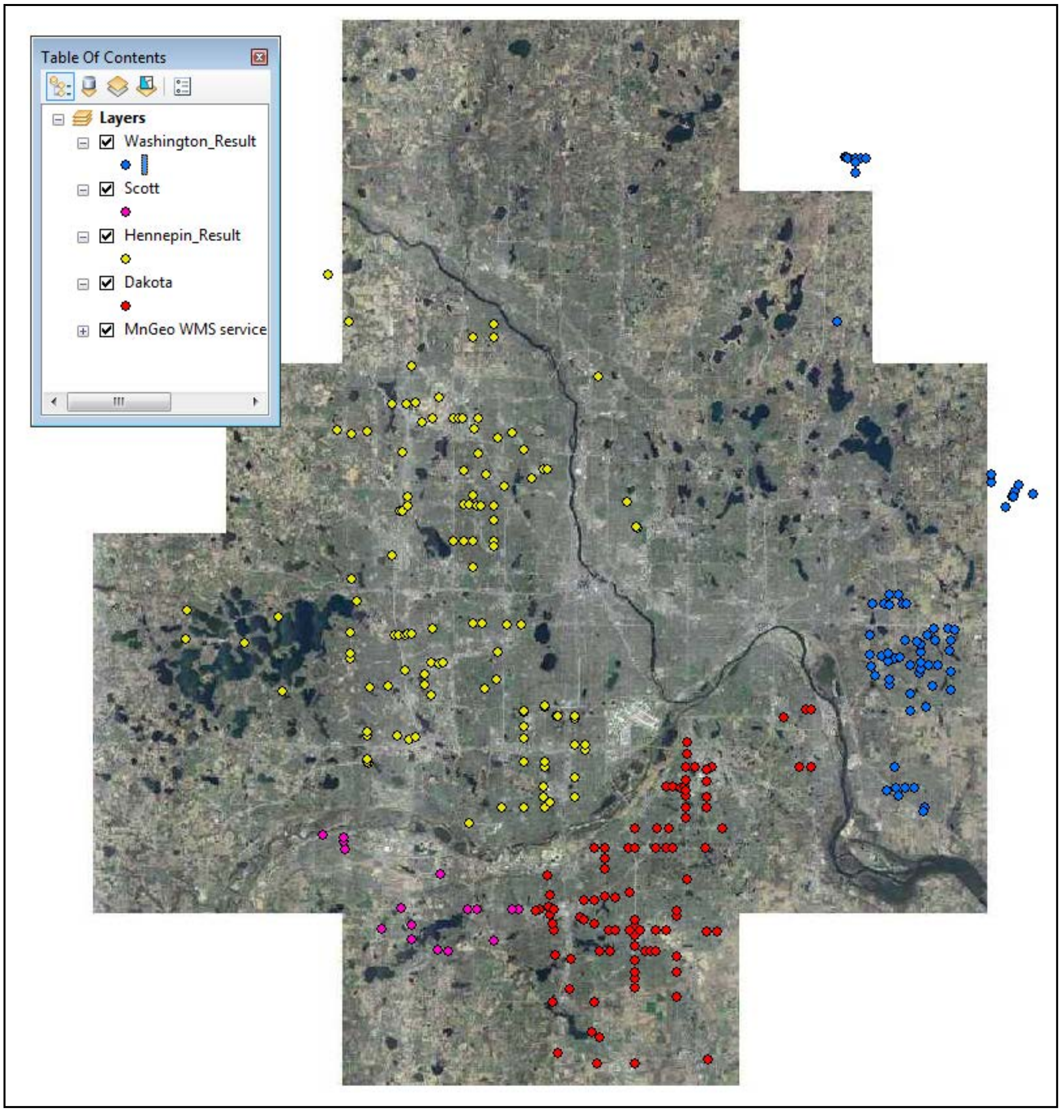


Figure 2.3 Locations of County intersections with permissive left-turn treatments.

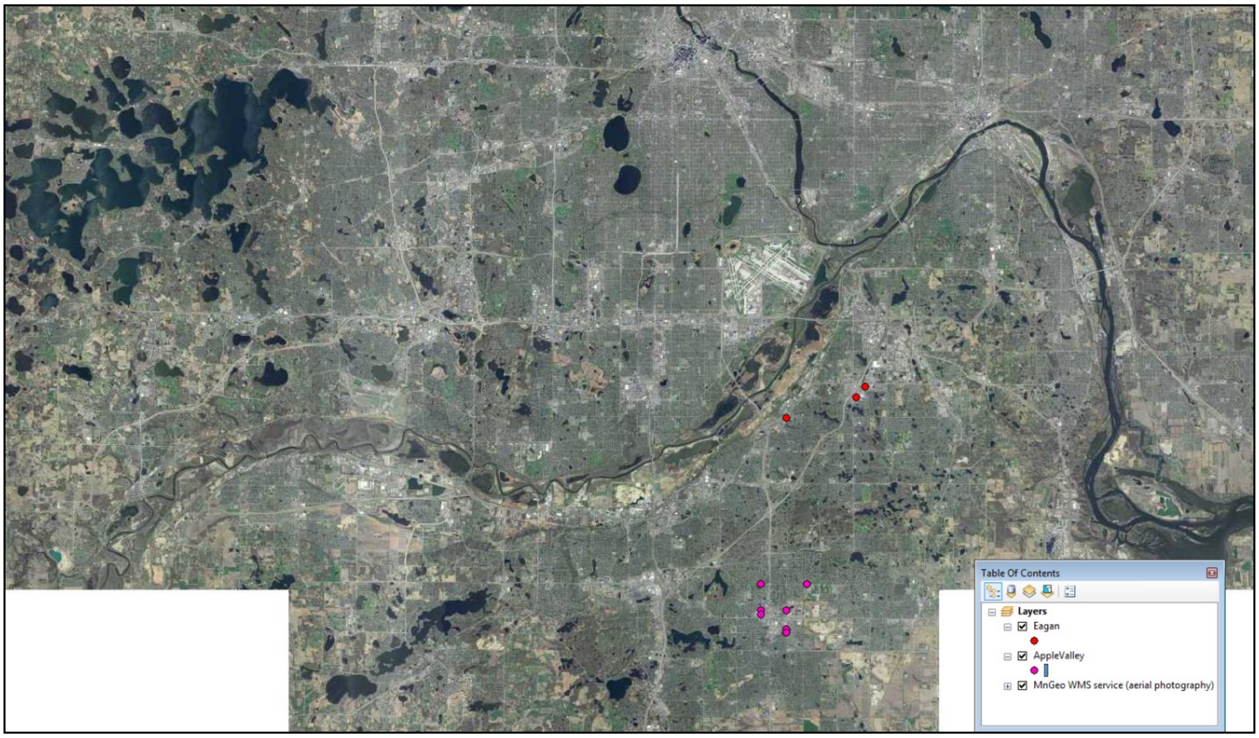


Figure 2.4 Locations of Apple Valley and Eagan intersections with permissive left turn

The posted speed limit and the number of exclusive left turn lanes were already reported in the MnDOT list. Therefore, only the number of opposing through lanes, median size and offset information were needed to be collected for approaches with permitted left turns. These data were stored initially in the GIS files and then exported to Microsoft Excel sheet. It turned out that for several intersections there were inconsistencies between the MnDOT list and what was seen in the aerial photos or Google maps. Those intersections were flagged for removal from our final list leaving 350 intersections for which geometric data were retained. 23 of these were not found in HSIS database. So, the number of intersections from this list which were useful for the next steps was 327. These intersections had 714 approaches with permissive left-turn treatments.

One of the geometric characteristics considered in this study is left-turn offset. Left-turn offset is the lateral distance from the left edge of the left-turn lane to the right edge of the opposing left-turn lane. According to this definition, the offset of zero occurs when the opposing left turn lanes are directly head on. Negative, zero and positive offsets are illustrated in the Figure 2.5.

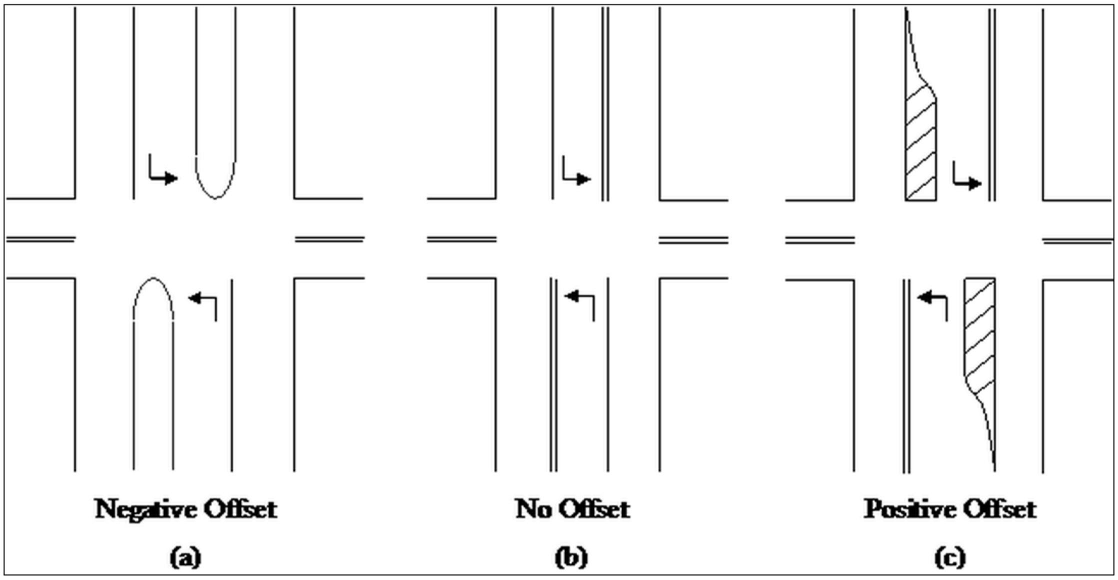


Figure 2.5 Illustration of negative, zero, and positive offset left-turn lanes

In determining offsets, if no opposing left-turn movement was present the offset was coded by 999, and if an approach had only one lane for through and left-turn movement 998 was used for opposing left-turn offset. In the latter case, if a vehicle was waiting for an acceptable gap to make a left-turn, through vehicles cannot proceed into the intersection. Also, if no left-turn vehicle is waiting nothing obstructs the view of opposing left-turn vehicles. Therefore, when there was only one lane for through and LT maneuver, offset for opposing approach was not needed.

From 714 approaches 286 of them (40%) had a negative offset, 163 (23%) had zero offset, 43 (6%) had positive offset and 222 (31%) were coded as 998 or 999. Almost always the size of offset was identical for the two opposing approaches. But, if two legs were not aligned to each other (they form an angle), their offsets can be different. Figures 2.6 and 2.7 illustrate two examples of different offsets for opposing directions.

Figure 2.6 Different offsets for opposing approaches; FID 19: MN 101 & W 78th St

Figure 2.7 Different offsets for opposing approaches; FID 334: US 61 & 147th St

The current list contained a variety of geometric characteristics:

- There were approaches with 1, 2 and 3 opposing through lanes.
- Left-turn control included FYA, permissive and protective-permissive.
- There were approaches with 1 shared, 1 exclusive, 2 exclusive and 1 exclusive + 1 shared left-turn lanes.
- Median width ranged from zero to 30 feet.
- Negative, zero and positive offsets were collected.
- Opposing speed limits for approaches with PLT ranged to 65 mph.

2.4 Compiling Crash Data

In crash record systems, crashes were located by route type (Interstate, US highway, state highway, etc), route number (e.g. USTH 10) and milepost. Route system, number, and milepost information were provided for the MnDOT intersections identified in Task 2, and given the large number of intersections the project team decided to develop the project's database in stages. In stage 1, data for the 428 MnDOT intersections were from HSIS. If sufficient data to support the project's analyses were then available the project would proceed. Otherwise, the data would be supplemented by using MNCMAT, to add intersections not in HSIS.

On May 12, 2013 a request was made to the Highway Safety Information System for crash, roadway, traffic, occupant, and vehicle data for all crashes occurring at the 428 MnDOT intersections identified in Task 2, for the most recent 5 years. It turned out that there were discrepancies in the intersection mileposts as determined in Task 2 and as given in the HSIS database, and after manually resolving these discrepancies, data files were provided by HSIS on May 29. 328 of the 428 requested intersections were included in the HSIS database, and four files were provided for each year form 2007-2011:

- a file containing computerized crash records for that year,
- a file containing intersection feature and ADT data,
- a file containing data on the occupants involved in crashes,
- a file containing data on vehicles involved in crashes.

There were approximately 7900 crash records for the years 2007-2011, of which 575 were classified as left-turn crashes (Accident Diagram Code =3). Summary information on the left-turn crashes follows.

Left-Turn Crash Frequency by Year:

Year	Number of LT Crashes
2007	127
2008	114
2009	89
2010	112
2011	133

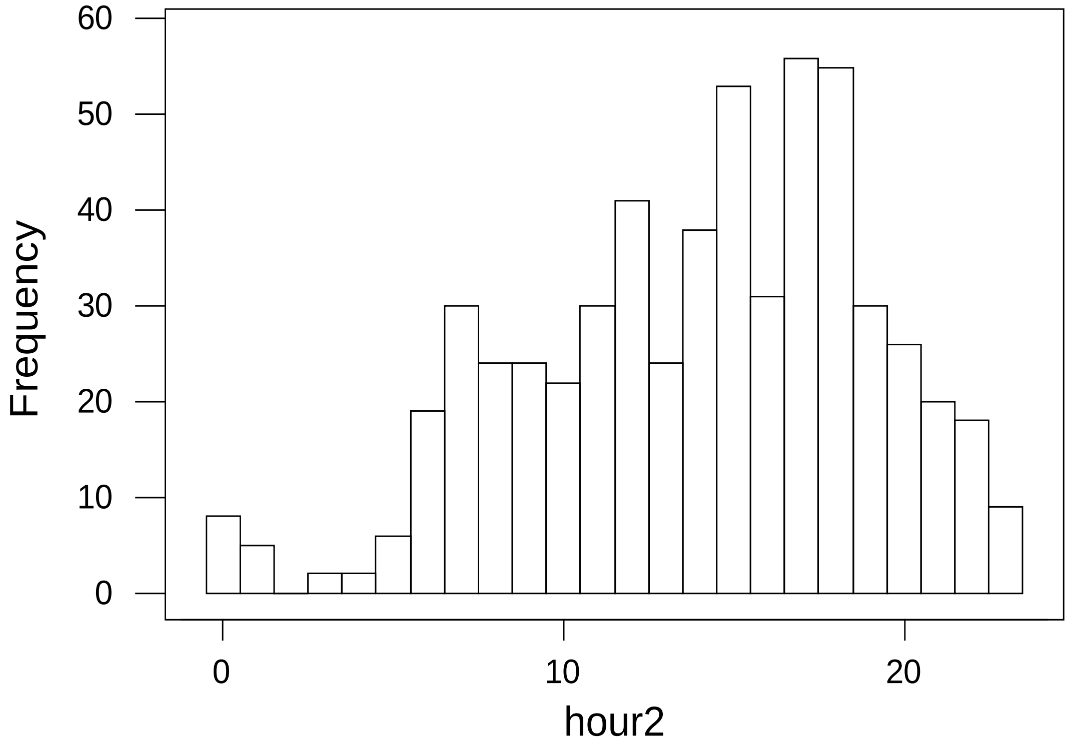


Figure 2.8 Left-turn crash frequency by time-of-day

Table 2.1 Left -turn crash frequency by intersection leg, selected legs

Route	Milepost/Leg	LT crashes
0100000035	085+00.507J52_03	2
0100000035	129+00.388J51_03	2
0100000035	131+00.737951_04	6
0100000035	131+00.737952_04	1
0100000035	135+00.688J52_03	1
0100000094	246+00.659 _03	9
0100000094	246+00.659 _05	2
0100000094	246+00.659351_04	2
0100000094	247+00.612352_04	1
0100000094	253+00.680351_03	2
0100000094	253+00.680352_02	1
0100000094	253+00.680352_03	2
0100000394	000+00.748352_02	1
0100000394	003+00.425452_03	2
0100000494	003+00.848951_04	1
0100000494	064+00.648351_03	1
0100000494	065+00.232951_03	1
0100000694	051+00.351351_04	3
0100000694	051+00.351352_04	1
0100000694	057+00.175351_04	9
0100000694	057+00.175352_03	4
0200000008	008+00.962 _01	1
0200000008	011+00.752 _01	1
0200000010	215+00.062 _01	1
0200000010	215+00.062 _03	2
0200000010	223+00.999 _01	1
0200000010	224+00.807J52_03	3
0200000010	225+00.364351_04	1
0200000012	146+00.062 _03	1
0200000012	147+00.150 _01	1
0200000012	147+00.150 _03	1

For each provided crash, the following variables were investigated through HSIS database and MnDOT list to understand how it happened:

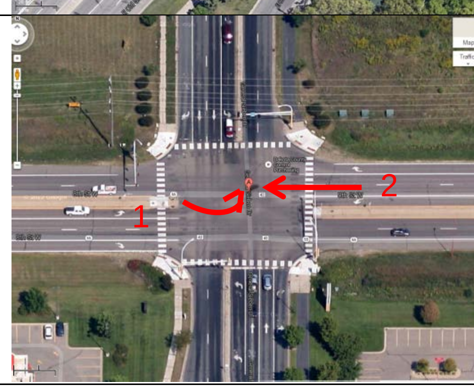
- Accident location
- Intersection leg
- Accident type (acctype)
- Location type (loc_type)
- The control type of involved approaches (trf_cntl in HSIS and APP#_LT_PH in MnDOT data)
- Involved vehicles' travel directions (veh_dir)
- Vehicles' action prior to accident (MISCACT1)
- Contributing factors (contrib1)

In order to interpret codes in HSIS database, the HSIS guidebook in the following link was used: http://www.hsisinfo.org/guidebooks/minnesota.cfm.

By investigating these variables, we can determine if a reported crash is relevant to the project. That is, we expect two vehicles to traveling initially in opposing directions with permitted left-turn phasing; one driver fails to yield right of way (contributing factor 2) to opposing traffic while making a LT. If any part of these conditions change, an ambiguity arises. This might be a trivial ambiguity which can be resolved making a reasonable assumption. But, if it is a non-trivial ambiguity, such as not-specified travel directions, it remains ambiguous unless we access a copy of the crash report with the accident sketch and other required information. There were some cases with solid evidences for an irrelevant crash scenario. Examples include when only one vehicle was involved, when both vehicles were making LTs, or the at-fault driver made a LT on red. Table 3 illustrates examples of clear, trivial ambiguous, non-trivial ambiguous and irrelevant crashes. After investigating 575 crash records, the following results were obtained:

- 21 crashes (3.7%) occurred at 13 intersections having no turning movement counts.
- 129 crashes (22.4%) were irrelevant including:
    - 52 crashes (about 10% of all reported LT crashes) at protected phases
    - 17 collisions with fixed objects, pedestrians, pedalcycles
    - 15 crashes in which both involved vehicles were traveling in the same direction or doing the same action (either going thru or LT)
    - Rollover crashes and other non-permitted LT crashes
- 261 crashes (45.4%) were clear and straightforward
- 85 crashes (14.8%) were slightly ambiguous but resolvable through making reasonable assumptions.
- 79 crashes (13.7%) were too ambiguous to allow making reasonable assumptions.

Table 2.2 Examples of clear, trivial ambiguous, ambiguous and irrelevant crashes

Clear and straightforward 284- 20112570073: MN 5 & MN 101 Veh1: dir 1 (NB); M; LT; fail to yield Veh2: dir 5 (SB); M; Th; no clear factor Veh3: dir 3 (EB); F; stopped in traffic; innocent EW: protected NS: permitted	
Slightly ambiguous 416- 20102560175: MN 51 & Midway pkwy Veh1: dir 1 (NB); F; LT; fail to yield Veh2: dir 99 (?); F; Th; following too closely amb: veh dirs & contrib. factors We assume vehicle 2 was travelling SB	
Too ambiguous 524- 20081450159 MN 77 & Old Shakopee Rd ER Veh1: dir 6 (SW); M; Th; fail to yield & chemical impairment Veh2: dir 4 (SE); F; LT; no clear factor Amb: veh dirs, actions & contrib. factors	
Irrelevant 479- 20113110260 MN 55 & General Sieben Dr Veh1: dir 3 (EB); M; LT; disregard cntl device + inattention or distraction Veh2: dir 7 (WB); M; Th; no clear factor EW: protected NS: prot-perm	

At an August 13, 2013 meeting between project staff and MnDOT staff it was pointed out that, for intersections of interest to MnDOT, staff may revisit the coding of crash types after the crash data were sent to HSIS, sometimes resulting in different frequencies of left–turn crashes. Therefore, during Fall 2013 and Winter 2014 a secondary accident database called Minnesota Crash Mapping Analysis Tool (MnCMAT) was used for two reasons:

1. To make sure all reported permitted left-turn crashes at the 328 intersections within 5 years of interest (2007-2011) were considered.
2. To do more investigation on each crash in order to diminish ambiguities and enhance the reliability of the final case list.

Due to discrepancies between mileposts in MnDOT and corresponding mileposts in HSIS database, a radius of 250 feet around any given milepost was used to extract crashes from HSIS; that is all left-turn crashes within the radius of 250 of the intersection were extracted. Unlike HSIS, MnCMAT gives the location of each crash which is supposedly accurate (There are some inaccuracies[1]; but in most cases it is reliable). MnCMAT indicated that several of the reported crashes in HSIS occurred next to the intersection of interest and so were irrelevant. In addition, 222 new crashes from MnCMAT were identified as relevant crashes and added to the case set.
The investigation using MnCMAT revealed discrepancies between t two databases. The results of this investigation can be summarized as follows:

- 222 new crashes were identified and added to the case set.
- Among 575 priory-reported crashes by HSIS:
    - 60 were not found in MnCMAT of which only 8 were indicated as relevant crashes
    - 439 (76%) were confirmed by MnCMAT
    - 29 turned out to belong to a different location
    - 2 were edited by the new information captured from MnCMAT
    - 45 were excluded from the case set due to new information captured from MnCMAT while they were previously recognized as relevant crashes.
    -

Table 2.3 compares the number of clear and ambiguous crashes before and after MnCMAT investigation. The proportion of ambiguous crashes decreased from 28.5% to 6.4% which results in more reliable data for our modeling purposes and fulfills the second reason for investigating MnCMAT. The resulting list contains 499 relevant crashes.

[1] One of the common cases for crash dislocation is interchanges. The crashes occurred at ramps may be located at either ramp, at crossing point of the highways or even slightly off the interchange.

Table 2.3 The number of clear and ambiguous crashes before/after MnCMAT investigation

Clarity conditions	The number of crashes (percent)	
	Before	After
Clear and straightforward	261(45.4%)	453 (56.8%)
Slightly ambiguous	85 (14.8%)	29 (3.6%)
Too ambiguous	79 (13.7%)	22 (2.8%)
Irrelevant	129 (22.4%)	272 (34%)
No turning movement counts	21(3.7%)	22 (2.8%)
Sum	575	797

2.5 Compiling Traffic Volume Data

As noted in Chapter 1, the likelihood of a left-turn crash occurring during a given hour how depends both on the number of drivers attempting to make left-turns (the exposure) and the number of opportunities to collide with an opposing vehicle. Ideally, continuous hourly counts of the turning movements at intersections would provide the needed information but in practice such extensive traffic counts are not available. For our purposes, the available traffic counts included limited turning movement counts, average daily traffic volumes (ADT), and continuous hourly traffic volumes collected by automatic traffic recorders (ATR). Because the primary motivation of this research is to see how the risk for left-turn crashes changes as traffic volume varies through the day, traffic volumes at hourly level are required and ADT is not helpful.

Again as noted in Chapter 1, his project employed a case-control study design with the 499 left-turn crashes identified above making up the set of possible cases. For each case (i.e. each left-turn crash) we randomly selected 5 additional hourly periods, for the same intersection and on the same day as the case, where a left-turn crash did not occur to form our set of controls. For each case and control hour it is necessary to determine, or at least estimate, the required hourly traffic volumes. This section explains the processes of compiling available volume data.

Turning Movement Counts and Automatic Traffic Records

Our primary data sources are two webpage managed by MnDOT:

1- http://www.dot.state.mn.us/metro/warrant
2- http://www.dot.state.mn.us/traffic/data

Webpage 1 archives hourly turning movement (TM) volumes for all approaches of an intersection. However, these volumes have been counted for signal warrant purposes and therefore were available only for peak hours (variable from 6 to 13 hours) usually for one day and occasionally for a few days within the last 16 years (1997-2013). In other word, hourly turning movement volumes are not continuously available during the 5 years of study period. Figure 2.9 is a snapshot of a pdf file from webpage 1 containing turning movement volumes for 6 hours of day at the intersection of TH61 and 15th St., in Hastings. These counts were collected on February 8, 2006.

	TH-61 Southbound				15TH ST Westbound				TH-61 Northbound				15TH ST Eastbound				
Start Time	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Int. Total
06:00	1	72	4	0	0	6	9	0	34	134	0	0	14	4	8	0	286
06:15	3	82	4	0	1	6	6	0	34	153	2	0	13	7	7	0	318
06:30	3	96	4	0	11	6	6	0	23	186	5	0	20	13	11	0	384
06:45	4	127	8	0	3	8	2	1	27	193	3	0	18	17	22	0	433
Total	11	377	20	0	15	26	23	1	118	666	10	0	65	41	48	0	1421
07:00	1	115	6	0	11	10	5	0	50	193	3	0	25	10	15	0	444
07:15	1	116	5	0	13	12	11	0	37	218	2	0	35	8	23	0	481
07:30	2	134	7	0	4	14	6	1	54	205	2	0	34	25	32	0	520
07:45	1	122	10	0	4	8	4	0	19	186	0	0	21	12	27	0	414
Total	5	487	28	0	32	44	26	1	160	802	7	0	115	55	97	0	1859
08:00	4	108	13	0	5	4	2	0	20	142	3	0	14	3	21	0	339
08:15	2	107	4	0	8	11	9	0	26	148	4	0	24	15	19	0	377
08:30	3	136	15	0	15	11	2	0	32	140	8	0	14	18	18	0	412
08:45	4	126	14	0	9	29	8	0	29	132	7	0	14	12	30	0	414
Total	13	477	46	0	37	55	21	0	107	562	22	0	66	48	88	0	1542
15:00	7	182	12	1	20	34	5	0	36	168	4	0	24	18	25	1	537
15:15	6	192	19	0	20	23	6	0	40	158	1	0	24	14	35	0	538
15:30	12	234	12	1	24	11	6	0	41	175	5	0	33	18	43	0	615
15:45	5	245	21	0	15	13	8	0	24	183	4	0	17	14	30	0	579
Total	30	853	64	2	79	81	25	0	141	684	14	0	98	64	133	1	2269
16:00	9	234	23	0	20	12	9	0	25	205	3	0	30	8	37	0	615
16:15	8	231	12	0	22	15	3	0	38	137	2	0	31	14	36	0	549
16:30	6	259	18	0	18	26	7	0	40	225	8	1	32	7	32	0	679
16:45	6	259	29	0	14	19	2	1	58	198	7	0	32	14	58	0	697
Total	29	983	82	0	74	72	21	1	161	765	20	1	125	43	163	0	2540
17:00	4	238	21	1	27	19	10	1	48	213	5	1	23	14	51	1	677
17:15	2	218	17	0	26	17	3	0	37	176	4	0	36	17	50	0	603
17:30	4	217	19	2	9	14	2	0	36	186	2	1	19	11	48	0	570
17:45	2	193	19	1	25	15	7	2	35	177	7	0	30	10	47	2	572
Total	12	866	76	4	87	65	22	3	156	752	18	2	108	52	196	3	2422

Figure 2.9 A sample of turning movement counts from MnDOT's signal warrant pdf files

To illustrate how traffic volume data were compiled, one of the crashes at this location (see figure 2.10) occurred on January 9, 2010, between a northbound driver turning left from TH 61 to the 15th St. and a southbound driver going through on TH 61. The crash was recorded as occurring at 15:15 (=15.25). The five randomly selected control hours for this case were 8.3, 6.7, 2.7, 20.3, and 1.3. So, the problem was to obtain estimates of the left-turn and opposing traffic volumes for that date and those times. Left turn volumes from northbound column, Thru plus right turn from southbound column and left turn counts from southbound column for all available hours (6 here) were stored in the excel sheet in front of each case and controls.

Figure 2.10 An accident location: intersection of TH 61 and 15th St.

For the case above, between hours 15 and 16, the relevant left turning volume from Figure 2.9 was 141 vehicles while the relevant opposing Th+RT traffic volume was 853+64=917 vehicles, and opposing LT traffic volume was 30 vehicles. However, these counts need to be converted to the crash date. To do so, additional information was needed. Webpage 2 archives continuous 24-hour traffic volumes counted by ATRs throughout the state. So, it can be used to calculate adjustment (or conversion) factors.

For each case/control set a nearby ATR on a road similar to the road on which the crash occurred was selected first. The spatial distribution of ATRs over the Metro area is shown in Figure 2.12. Then, that ATR's hourly volumes for the TM count date and crash date were extracted and recorded in our excel sheet in front of the case-control set of interest. For this example ATR 460 was selected, which is less than a mile west of the accident location. Hourly traffic volumes at ATR 460 on 2/8/2006 and 1/9/2010 are shown in Figure 2.11. A naïve conversion of the Feb. 8, 2006 volumes to Jan. 9, 2010 volumes would proceed as follows. On Feb 8, 2006 (a Wednesday), the hourly volume on ATR460 was 235+260=495 vehicles, while on Jan 9, 2010 (a Saturday), the hourly volume was 185+186=371. The ratio of these two, $^{371}/_{495} = 0.75$. Applying this factor to the Jan 9, 2010 turning movement counts gives:

Left-turning traffic = (141)(0.75) = 106

Opposing thru+RT traffic = (917)(0.75) = 688

Opposing left-turning traffic = (30)(0.75) = 22

Two issues that arose when exploring this approach concerned assessing the accuracy of this adjustment procedure and accommodating those hours of the day for which turning movement counts were not available. These issues will be addressed in Chapter 3.

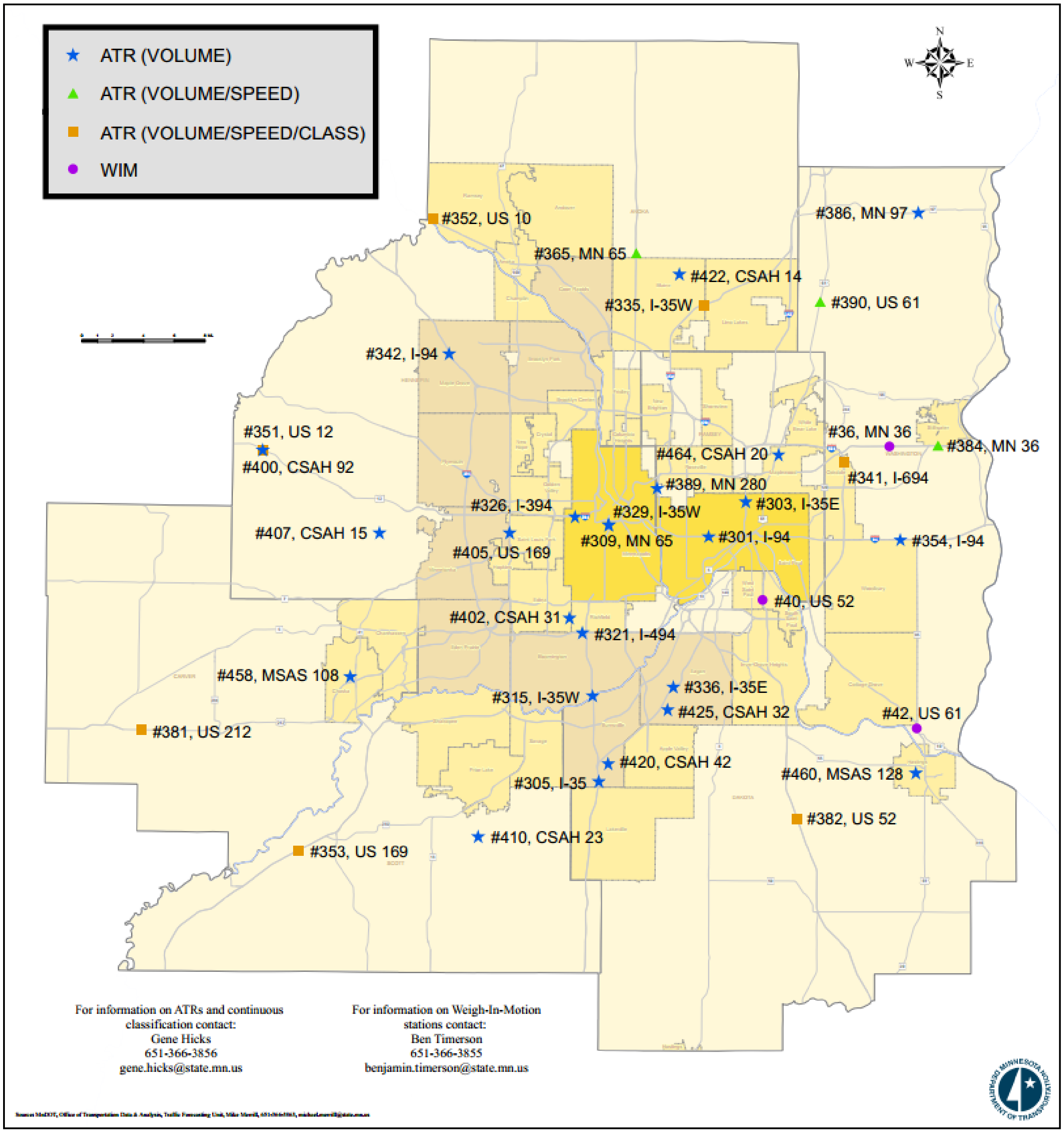


Figure 2.11 Locations of ATRs within metro area in 2011

Because ATR counts were only available from 2002, TM counts from earlier dates could not be converted to the crash date. Therefore, intersections for which no turning movement counts are available for after 2002 were eliminated from the dataset. <u>Among 499 crashes identified in the previous section, turning movement counts were available for 438.</u> So, the size of our final dataset was 438 cases + 5*438 controls = 2628 objects requiring hourly traffic volumes. Figure 2.12 displays a snapshot of the compiled case/control dataset. As shown in this part of the dataset, different locations may have 6 to 13 hourly turning movement counts.

	B	J	L	V	X	Y	AA	AB	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU
1															LT								
2	Case/ Control	date	hour	intersection	LT vehicle dir	ATR1	ATR at crash time	ATR at TM time	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	6-7	7-8
557	Control	5/27/2010	9.05	US 52 & THOMPSO	WB	40	3262	3328	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
558	Control	5/27/2010	0.04	US 52 & THOMPSO	WB	40	535	611	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
559	Control	5/27/2010	15.88	US 52 & THOMPSO	WB	40	5008	3868	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
560	Control	5/27/2010	2.68	US 52 & THOMPSO	WB	40	347	298	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
561	Case	12/15/2011	20.73	US 52 & THOMPSO	WB	40	2234	2164	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
562	Control	12/15/2011	22.28	US 52 & THOMPSO	WB	40	1693	1624	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
563	Control	12/15/2011	18.29	US 52 & THOMPSO	WB	40	4681	4463	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
564	Control	12/15/2011	9.03	US 52 & THOMPSO	WB	40	3411	3328	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
565	Control	12/15/2011	19.86	US 52 & THOMPSO	WB	40	2996	3071	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
566	Control	12/15/2011	15.12	US 52 & THOMPSO	WB	40	3687	3868	46	87	55	39	42	32	35	40	53	48	47	59	58	140	228
567	Case	1/8/2010	3.33	US 61 & 15th St	NB	460	14	19	118	160	107							141	161	156		397	515
568	Control	1/8/2010	10.60	US 61 & 15th St	NB	460	292	308	118	160	107							141	161	156		397	515
569	Control	1/8/2010	18.78	US 61 & 15th St	NB	460	424	478	118	160	107							141	161	156		397	515
570	Control	1/8/2010	20.25	US 61 & 15th St	NB	460	209	255	118	160	107							141	161	156		397	515
571	Control	1/8/2010	19.06	US 61 & 15th St	NB	460	291	328	118	160	107							141	161	156		397	515
572	Control	1/8/2010	1.04	US 61 & 15th St	NB	460	18	17	118	160	107							141	161	156		397	515
573	Case	1/9/2010	15.25	US 61 & 15th St	NB	460	371	495	118	160	107							141	161	156		397	515
574	Control	1/9/2010	8.32	US 61 & 15th St	NB	460	190	299	118	160	107							141	161	156		397	515
575	Control	1/9/2010	6.73	US 61 & 15th St	NB	460	53	156	118	160	107							141	161	156		397	515
576	Control	1/9/2010	2.73	US 61 & 15th St	NB	460	33	11	118	160	107							141	161	156		397	515
577	Control	1/9/2010	20.28	US 61 & 15th St	NB	460	199	255	118	160	107							141	161	156		397	515
578	Control	1/9/2010	1.31	US 61 & 15th St	NB	460	37	17	118	160	107							141	161	156		397	515
579	Case	8/14/2009	13.02	US 61 & 10th St	NB	460	377	358	1	2	5			6	2			6	8	4		659	718
580	Control	8/14/2009	21.14	US 61 & 10th St	NB	460	224	147	1	2	5			6	2			6	8	4		659	718

Figure 2.12 A snapshot from compiled traffic volumes (LT, opposing Th+RT, and opposing LT) for 438 cases and their randomly selected controls

As stated above, ATR counts can be used to compute date adjustment factors. For cases or controls from non-sampled hours (hours for which no turning movement counts are available) another adjustment factor is needed: time-of-day adjustment factor. In the example accident above, for those controls at 2.7, 20.3, and 1.3 we first need to estimate TM volumes at these times from the available TM counts. The developed method will be discussed in the Chapter 3. The critical information for this method is to know how turning movement counts vary during the day. High resolution SMART SIGNAL data can be used to produce such daily TM patterns.

2.6 Smart Signal Data

SMART Signal (Systematic Monitoring of Arterial Road Traffic Signals) collects and archives event-based traffic signal data at multiple intersections in Hennepin County. For this project, 6 intersections on trunk highway 55 in Golden Valley were selected: Boone Ave N, Winnetka Ave (CR 156), Rhode Island Ave, Glenwood Ave, Douglas Dr. (CR 102), and TH 100.

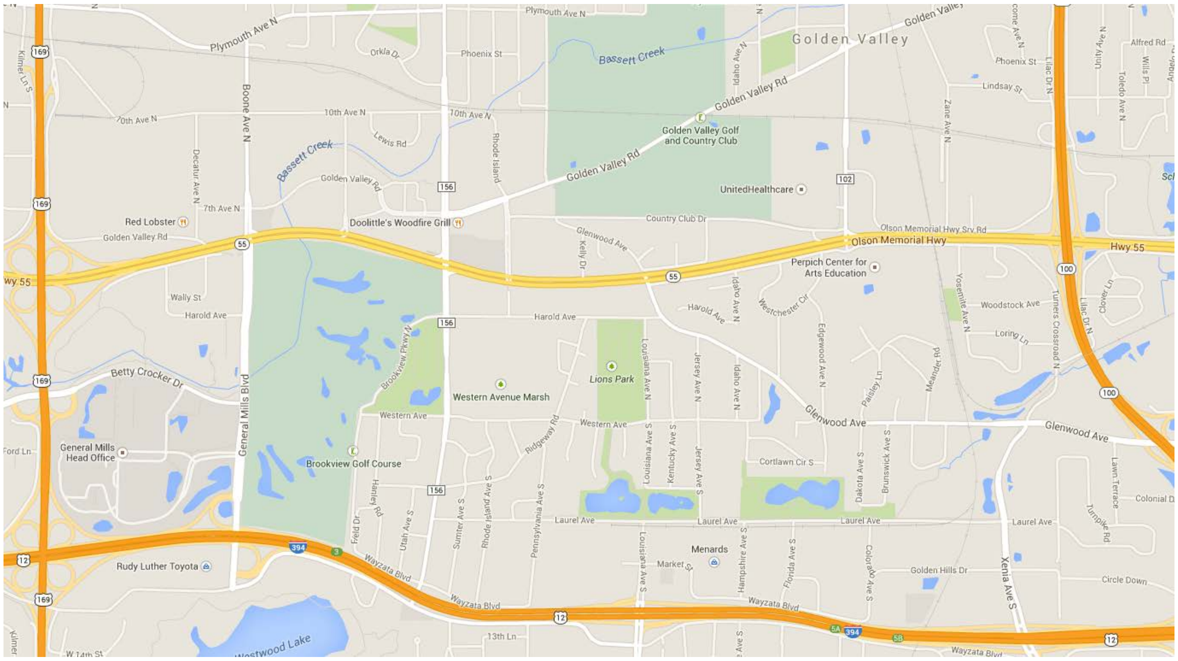


Figure 2.13 SMART Signal locations selected to extract turning movement daily pattern

High resolution information (actuation) for one week (Monday, 6/1/2009 to Sunday, 6/7/2009) at these locations was retrieved. The raw data for each intersection is formatted as bellow. The format of "TimeStamp" is "YYMMDDHHMMSSfff".

TimeStamp	DetectorID	TimeDuration
090601185402859	15	1.469
090601185403390	20	0.344
090601185405015	17	21.625
090601185406187	20	0.312
090601185406203	9	1.218
090601185407375	23	0.828

This raw data need to be aggregated to hourly counts for turning movements of interest. Using loop detector layouts at these intersections, we can understand which DetectorID should be used for each maneuver. Figure 2.14 demonstrates the loop detectors layouts at two locations for example: intersection of TH 55 with Boone Ave and with Rhode Island.

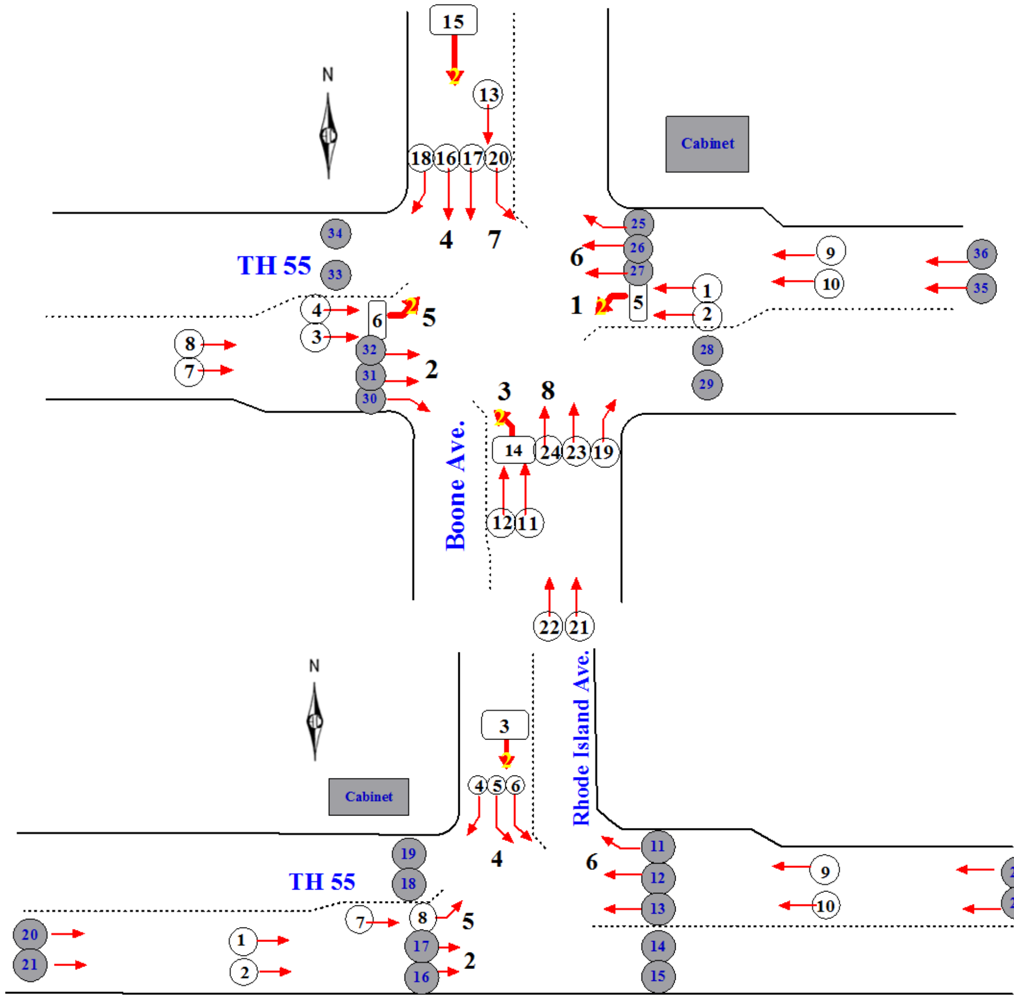


Figure 2.14 Loop detectors layout at two of intersections

Now the aggregation process can be implemented. There are different ways to do this including the following two sets of excel functions although the second method is more efficient and straightforward.

1- MID(), and SUMPRODUCT(); or

2- MID(), CONCATENATE(), and COUNTIF().

For each intersection approach, seven daily patterns for LT and Th+RT can be calculated. Table 2.4 is the final results of the aggregation calculations for one of the 24-hour patterns for LT and Th+RT movements at Boone Avenue intersection eastbound approach and Figure 2.15 illustrates the corresponding patterns. Although Th+RT movement have remarkable am and pm peaks, LT movement outstands at noon. This comparison supports the idea of differentiating patterns for different turning movements even at same location. In other words, the overall pattern of an approach is not necessarily consistent with each TM pattern.

Table 2.4 TH 55 and Boone Ave, EB approach Monday counts

time (date-hour)	LT (3+4)	Th+RT (30+31+32)
09060100	5	56
09060101	1	22
09060102	8	19
09060103	3	23
09060104	4	77
09060105	20	359
09060106	72	1155
09060107	110	2287
09060108	145	2025
09060109	122	1121
09060110	138	806
09060111	166	969
09060112	175	1171
09060113	174	996
09060114	156	1038
09060115	136	1375
09060116	144	1534
09060117	145	1645
09060118	104	952
09060119	82	610
09060120	47	500
09060121	27	365
09060122	15	202
09060123	10	104

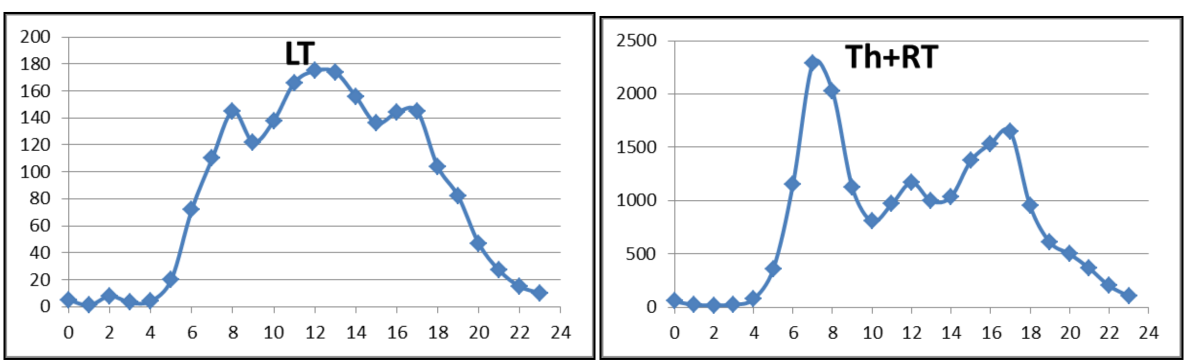


Figure 2.15 LT and Th+RT pattern for a Monday at TH 55 and Boone Ave eastbound

Another informative analysis is to see how a TM pattern at a location can vary through the week. Figure 2.16 enables us to do such analysis. At this location and week three general patterns are identifiable. The first cluster contains Monday and Wednesday with a very high pm peak, medium noon peak and a minor am peak. The second cluster which is consisting of Tuesday, Thursday, and Friday have the same general shape but a less extreme pm peak. At last, the third cluster which represents weekends looks like a wide hump with no considerable am or pm peak.

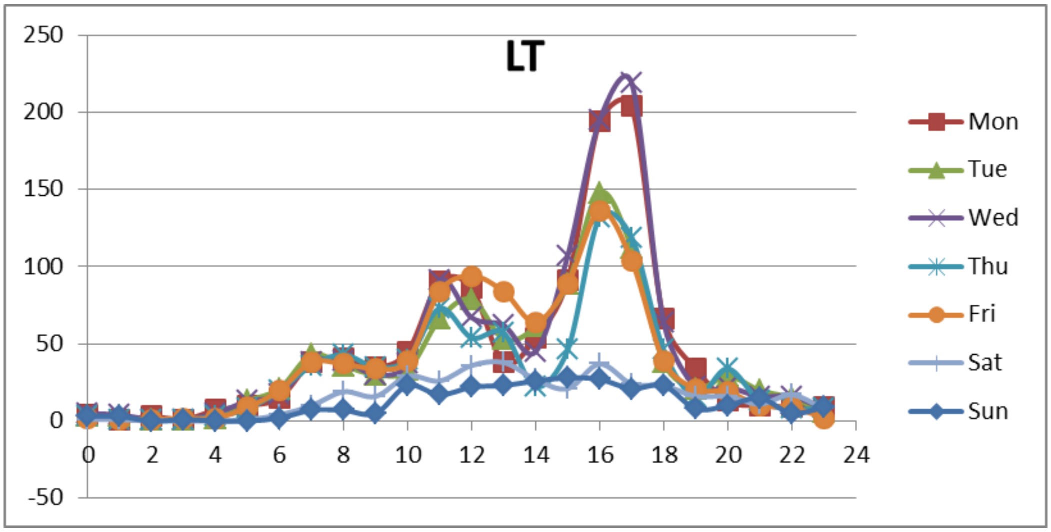


Figure 2.16 LT movement pattern for 7 days of week at TH 55 and Boone Ave northbound

In the end, SMART Signal data resulted in 70 LT patterns and 63 Th+RT patterns.

CHAPTER 3

3. DATA PREPARATION

This chapter describes steps taken with regard to the Task 5 of the project. The objective of this task was preparing data files containing hourly traffic volumes for the case and control hours for each of the 438 case-control sets identified in Chapter 2 which would be the input data for developing a statistical model relating left-turn crash risk to traffic volume.

3.1 Characterizing Sight Distance

One of the prospective predictors identified in the initial steps of this study was left-turn offset. However, this variable is not definable at all locations, as explained in the Chapter 2. Therefore, this variable cannot directly participate in the model. This variable, however, is best seen as a proxy for driver's sight distance which can be readily measured. In addition, what in fact plays a role in left-turn accidents is the sight distance problem, not the left-turn offset itself. Therefore, we decided to include a classification variable called sight distance (SD) issue instead of left-turn offset. SD issue is a function of left-turn offset and some other geometric measures. The process of calculating available SD is a modified version of the method described by McCoy et al. 2001.

3.1.1 Available Sight Distance

Figure 3.1 portrays a typical intersection layout and positions of left-turning vehicles. These features define the sight distance triangle which is the basis for available sight distance (ASD) calculations.

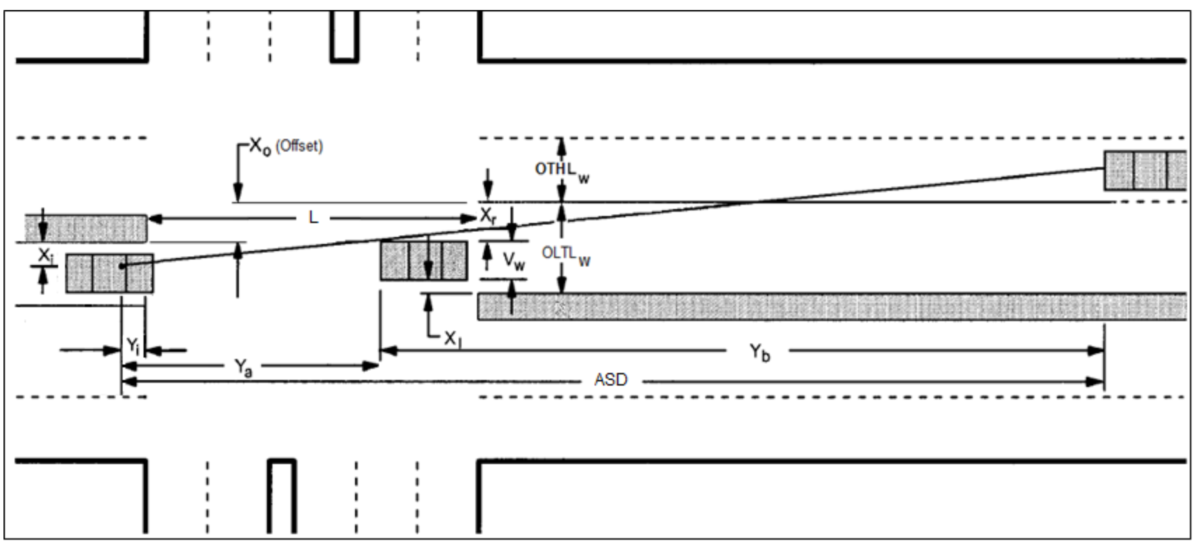


Figure 3.1 Sight distance triangle for LT maneuver at a typical intersection (McCoy et al 2001).

The sight distance available to a left turning driver has two components ASD=Y_a+Y_b with Y_a being the distance to an opposing left-turning vehicle blocking the line of sight and Y_b being the distance beyond the obstructing edge of the opposing left-turning vehicle. Y_a is determined by intersection width, L, and the positions of the left-turning vehicles.

$$Y_a=L-Y_{opp}-Y_i \tag{3.1}$$

where

Y_{opp} = longitudinal distance from the end of the opposing median to the opposing LT vehicle's front bumper,

Y_i = longitudinal distance from the end of the median to the LT driver's eye; positive if inside the intersection and negative if behind the intersection.

Assuming that both vehicles have similar locations and that 8 feet is the distance from driver's eye to front bumper gives, with distances in feet:

$$Y_a = L - 2(Y_i) - 8 \tag{3.2}$$

At most regular intersections Y_i was assumed to be zero, meaning that the driver's eye was in line with the median or stopbar. At larger intersections drivers might advance into the intersection while waiting for an adequate gap, and at these situations a reasonable positive value was used.

From the geometry shown in Figure 3.1, Y_b can be calculated

$$Y_b = \frac{Y_a\left(X_r + {}^{OTHL_W}/_2\right)}{V_o} \tag{3.3}$$

where

X_r = lateral distance of the right edge of the opposing left-turning vehicle from the right edge its lane,

$OTHL_W$ = opposing through lane width,

V_o = the lateral distance between the driver's eye and the right front corner of the opposing left-turning vehicle.

$$X_r = OLTL_W - V_W - X_l \tag{3.4}$$

$OLTL_W$ = opposing left-turn lane width,

V_W = width of design vehicle (assumed to be 7 feet), and

X_l = lateral distance of the left edge of the opposing left-turn vehicle from the left line of its lane.

$$V_o = X_i - X_r - X_o \tag{3.5}$$

X_i = lateral position of driver's eye from the left line of the left-turn lane, and

X_o = left-turn offset as determined in the Chapter 2.

3.1.2 Required Sight Distance

The required sight distance is given by

$$RSD = 1.467(OSL)(G) \tag{3.6}$$

where

OSL = opposing approach's speed limit in mph, and

G = critical gap size for left turn; assumed 5.5 seconds plus .5 seconds for each additional opposing through lane.

3.1.3 Identifying Sight Distance Issues

For each location at which a relevant crash was identified in the data acquisition step (438 crashes), we should decide whether or not there exists a sight distance problem. Locations with left-turn offset code 998 or 999 had no sight distance issue by definition. At other locations, all required geometric measures were collected from Google Map. Below is a snapshot of the data set showing the SD issue analysis at the location of each crash. Equations 3.2-3.6 were used to calculate the required sight distance (column BD), the available sight distance (column BP) and then to determine the SD variable (column BQ).

	A	AZ	BA	BB	BC	BD	BE	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ
1	Relevant crash index (1-499)	# opp Th+RT lanes	median width (ft)	offset	OSL (mph)	RSD (ft)	L (ft)	width of OTHL (ft)	width of OLTL (ft)	Yi (ft)	Ya (ft)	Vw (ft)	X_l (ft)	X_i (ft)	X_r (ft)	Vo (ft)	ASD (ft)	SD Issue
210	235	2	18	-18	45	396.0	100	12	12	0	92	7	1.5	3	3.5	17.5	141.9	1
211	236	2	18	-18	45	396.0	100	12	12	0	92	7	1.5	3	3.5	17.5	141.9	1
212	237	2	18	-18	45	396.0	100	12	12	0	92	7	1.5	3	3.5	17.5	141.9	1
213	238	2	18	-18	45	396.0	100	12	12	0	92	7	1.5	3	3.5	17.5	141.9	1
214	239	2	18	-18	45	396.0	100	12	12	0	92	7	1.5	3	3.5	17.5	141.9	1
215	240	2	18	-18	45	396.0	100	12	12	0	92	7	1.5	3	3.5	17.5	141.9	1
216	241	1	20	-20	40	322.7	120	12	12	0	112	7	1.5	3	3.5	19.5	166.6	1
217	242	1	0	998	30	242.0												0
218	243	1	0	998	30	242.0												0
219	244	1	0	-6	45	363.0	94	13	11	0	86	7	1	3.5	3	6.5	211.7	1
220	245	2	7	-7	45	396.0	144	12	12	0	136	7	1.5	3	3.5	6.5	334.8	1
221	246	2	7	-7	40	352.0	144	12	12	0	136	7	1.5	3	3.5	6.5	334.8	1
222	247	2	7	-7	40	352.0	144	12	12	0	136	7	1.5	3	3.5	6.5	334.8	1
223	248	2	9	-9	40	352.0	122	12	12	0	114	7	1.5	3	3.5	8.5	241.4	1
224	249	2	7	-8	30	264.0	132	12	12	0	124	7	1.5	3	3.5	7.5	281.1	0
225	250	2	7	-8	30	264.0	132	12	12	0	124	7	1.5	3	3.5	7.5	281.1	0
226	251	2	7	-8	30	264.0	132	12	12	0	124	7	1.5	3	3.5	7.5	281.1	0
227	252	2	7	-8	30	264.0	132	12	12	0	124	7	1.5	3	3.5	7.5	281.1	0
228	253	2	13	-11	35	308.0	119	12	12	0	111	7	1.5	3	3.5	10.5	211.4	1
229	254	2	13	-11	35	308.0	119	12	12	0	111	7	1.5	3	3.5	10.5	211.4	1
230	274	2	9	999	45	396.0												0
231	275	2	9	999	45	396.0												0
232	276	2	9	999	45	396.0												0
233	277	2	9	999	45	396.0												0
234	279	1	9	-9	30	242.0	169	12	11.5	0	161	7	1.5	3	3	9	322.0	0
235	280	1	9	-9	30	242.0	169	12	11.5	0	161	7	1.5	3	3	9	322.0	0
236	281	1	10	-9	45	363.0	169	12.5	11.5	0	161	7	1.5	3	3	9	326.5	1
237	282	1	10	-9	45	363.0	169	12.5	11.5	0	161	7	1.5	3	3	9	326.5	1

Figure 3.2 Sight distance analysis at crash approaches

If the opposing approach has a significant horizontal/vertical curve ending at the intersection, the RSD can still be calculated by equation 6; but ASD cannot be calculated by this method. Instead, Google Map's Distance **Measurement** Tool was used to approximate the ASD at these locations.

3.2 Estimating Turning Movement Volumes

As stated earlier, 438 relevant LT crashes were recognized at 328 intersections within the Twin Cities Metro area. Each of these crashes provided a case for our case-control study and to determine the controls we randomly selected five hours from the same day as the crash where a crash did not occur. It was then necessary to produce estimates relevant hourly traffic volumes for both the cases and controls. Following up on a comment offered at the August 13, 2013 meeting of the project's Technical Advisory Panel, a more detailed investigation of methods for estimating the hourly volumes was conducted.

3.2.1 *Adjusting Turning Movement Counts to Different Dates*

To illustrate, one of the crash events in the case-control sample was a left-turn crash occurring on June 16, 2007, between a driver turning left from Dakota County State Aid Highway (CSAH) 50 to an onramp leading to Interstate 35 (I35), and a driver going through on CSAH 50. The crash was recorded as occurring at 8:05 AM, and the problem was to obtain estimates of the left-turn volumes and opposing through plus right-turn volumes, for that date and time. Traffic volume data from two sources were available:

(1) 15-minute turning movement counts, made on a single day during the morning and afternoon peaks (6 AM – 9 AM, 3 PM – 6 PM) and, in some cases, additional non-peak times, and

(2) hourly traffic volumes from MnDOT's automatic traffic recorders (ATR).

Figure 3.3 shows a portion of a turning movement count for this intersection, made on February 15, 2007. Between 8 and 9 AM on February 15 the relevant opposing traffic volume was 246+80 = 326 vehicles, while the relevant left turning volume was 63 vehicles. The question then is how to convert the Feb. 15 volumes to June 16 volumes. Figure 3.4 shows a portion of archived data from MnDOT's ATR 420, located on Dakota county's CSAH 42, about 5 miles north of the crash location. It was also possible to obtain hourly traffic volumes at ATR 420, for the year 2007, as shown in Figure 3.4, and a not unreasonable procedure would be to use the ATR counts to adjust the Feb. 15 volumes to June 16 volumes. On February 15, a Thursday, the total volume between 8 AM and 9 AM at ATR 420 was 1386 vehicles, while on June 16 (a Saturday) the total volume between 8 AM and 9 AM was 1069. The ratio of these is 1069/1386 = 0.771, and applying this to the Feb. 15 turning movement counts gives estimates for June 16 gives a naïve date adjustment:

Opposing traffic = (326)(.771) = 251 vehicles

Left-turning traffic = (63)(.771) = 49 vehicles.

Groups Printed- Cars & Trucks

	RAMP FROM I-35 SB Southbound				CSAH-50 Westbound				RAMP TO I-35 SB Northbound				CSAH-50 Eastbound				
Start Time	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Int. Total
06:00	30	0	7	0	9	28	0	0	0	0	0	0	0	29	20	0	123
06:15	35	0	11	0	4	51	0	0	0	0	0	0	0	39	33	0	173
06:30	51	0	12	0	10	70	0	0	0	0	0	0	0	33	21	0	197
06:45	67	0	20	0	14	59	0	0	0	0	0	0	0	46	23	0	229
Total	183	0	50	0	37	208	0	0	0	0	0	0	0	147	97	0	722
07:00	46	0	12	0	7	71	0	0	0	0	0	0	0	60	42	0	238
07:15	65	0	10	0	12	112	0	0	0	0	0	0	0	69	38	0	306
07:30	55	0	6	0	18	133	0	0	0	0	0	0	0	50	29	0	291
07:45	37	0	12	0	8	71	0	0	0	0	0	0	0	53	21	0	202
Total	203	0	40	0	45	387	0	0	0	0	0	0	0	232	130	0	1037
08:00	53	0	5	0	11	77	0	0	0	0	0	0	0	58	31	0	235
08:15	59	0	15	0	22	81	0	0	0	0	0	0	0	63	21	0	261
08:30	63	0	16	0	13	75	0	0	0	0	0	0	0	65	16	0	248
08:45	54	0	16	0	17	77	0	0	0	0	0	0	0	60	12	0	236
Total	229	0	52	0	63	310	0	0	0	0	0	0	0	246	80	0	980

Figure 3.3 Sight distance analysis at crash approaches

East
Feb 15, 2007 Thursday 127 81 63 36 65 95 255 446 541 550 595 715 950 915 936 1050 1201 1267 1139 812 678 538 337 195 13587
West
Feb 15, 2007 Thursday 92 65 43 32 106 296 720 901 845 796 853 836 945 1010 956 1000 983 990 941 708 567 446 249 143 14523
East
Jun 16, 2007 Saturday 209 133 104 76 64 80 135 279 478 680 873 1076 1244 1182 1247 1218 1178 1171 1001 832 779 671 539 373 15622
West
Jun 16, 2007 Saturday 176 112 89 39 72 116 254 382 591 775 1098 1246 1382 1225 1284 1281 1196 1126 1032 825 702 598 514 317 16432

Figure 3.4 Hourly traffic volumes for ATR 420, February 15 and June 16, 2007.

This adjustment procedure is an example of a common practice, using ATR data to compute an adjustment factor for estimating a desired volume, given a measured volume. Although reasonable, empirical support for this adjustment procedure is limited, especially regarding uncertainty quantification. To begin remedying this situation let

y1 = left turn (or opposing) volume on reference (counted) date
y2 = left turn (or opposing) volume on target date
x1 = ATR count for same day and hour as reference count
x2 = ATR count for same day and hour as target count

The above adjustment procedure can be expressed as

$$y2 = y1(x2/x1) \tag{3.6}$$

Equation (3.6) does not allow for possible uncertainty regarding the target volume y2, but by letting the target volume be a random variable Y2, a generalization of the above adjustment procedure is found by expressing the expected value of Y2 as

$$E[Y2] = \exp\left(\beta_1 + \beta_2 \ln(y1) + \beta_3 \ln(x1) + \beta_4 \ln(x2)\right) \tag{3.7}$$

Since traffic counts are non-negative integers a reasonable starting point is to assume that Y2 is a Poisson random variable with expected value given in equation (3.7). Note that equation (3.6) can be interpreted as a special case of equation (3.7), where the relationship between y2 and the predictors y1,x1, and x2 is deterministic, and where $\beta_1=0$, $\beta_2=\beta_4=1.0$, and $\beta_3=-1.0$.

For 36 intersections of interest it was possible to find two sets of turning movement counts, from different days, and one left turn (or opposing) volume was selected as the "target" while the other was treated as the "reference". Maximum likelihood estimates for the parameters β_1, β_2, β_3 and β_4 were computed using Mathcad (Maxfield 2009) and Pearson residuals for the 36 target counts were then computed via

$$r_i = \frac{y2_i - \hat{y2}_i}{\sqrt{\hat{y2}_i}} \tag{3.8}$$

where $\hat{y2}_i$ is the predicted value for the target count $y2_i$, obtained by substituting the maximum likelihood estimates for β_1, β_2, β_3 and β_4 into equation (3.7). If the Poisson distribution is a reasonable model for the turning movement counts the Pearson residuals should have a sample average approximately equal to 0 and a sample variance approximately equal to 1.0. For the left-turn counts, the sample average for the Pearson residuals was -0.044, but the sample variance was 7.32, indicating that the left-turn counts were over-dispersed; that is, the left-turn counts were more variable than allowed for by the Poisson model. Additionally, approximate 50%, 80%, 90% and 95% prediction intervals were computed for each of the target counts. If the Poisson model is reasonable then these intervals should catch approximately 50%, 80%, 90% and 95% of the observed target counts. Table 3.1 compares the nominal and observed coverage for each of these intervals, along with a z-statistic test of the hypothesis that the observed coverage equals the nominal coverage.

Table 3.1 Nominal and observed coverage for Poisson model. * denotes significance at the 0.05 level.

	Left Turn Volume	
Nominal coverage	Observed coverage	Z statistic
50	33.3	-2.0*
80	50.0	-4.5*
90	58.3	-6.3*
95	68.9	-8.6*

Clearly, the prediction intervals from the Poisson model are too small, causing them to miss a substantial number of target left-turn counts.

One way to allow for overdispersion is to include a random effect *W* in equation (3.7). That is, *Y2* is still considered to be Poisson, but its expected value is now

$$E[Y2] = \exp\left(\beta_1 + \beta_2 \ln(y1) + \beta_3 \ln(x1) + \beta_4 \ln(x2)\right)W \tag{3.9}$$

When *W* is a gamma random variable the marginal distribution for *Y2* is negative binomial, while if *W* is lognormal then the marginal distribution of *Y2* is a Poisson-lognormal mixture (Johnson et al 1992). Alternatively, the log-linear model (3.9) could be replaced by a linear regression model

$$\ln(Y2) = \beta_1 + \beta_2 \ln(y1) + \beta_3 \ln(x1) + \beta_4 \ln(x2) + W \tag{3.10}$$

where the random effect *W* is now taken to be a normal random variable with mean 0 and unknown variance σ^2. This then makes the target count Y2 a lognormal random variable. Using the software WinBUGS (Lunn et al 2014) the Poisson-gamma and Poisson-lognormal versions of (3.9) were fit, along with the lognormal model (3.10). Coverages similar to those shown in Table 3.1 were computed for each model, and it was found that all three models gave essentially similar results. Table 3.2 shows the parameter estimates for model (3.10) for both left-turn and opposing traffic volumes, while Table 3.3 shows the results of coverage tests for model (3.10).

For example, when using model (3.10) to predict hourly left turn volumes, the computed 90% confidence intervals caught 91.7% of the target volumes, and this difference was not statistically significant at the 0.05 level. Overall, the predicted intervals tended to be slightly conservative (i.e. they tended to catch more target volumes than expected.)

Finally, applying the estimates given in Table 3.2, the left turn volume from CSAH 50 to I35, between 8 and 9 AM on June 16 2007, would be a lognormal random variable with expected value

$$E[Y2] = \exp\left(-.4985 + .983\ln(63) - .755\ln(1386) + .826\ln(1069) + \frac{.279^2}{2}\right)$$

$$\approx 50.7\ veh/hour$$

and standard deviation

$$\sqrt{Var[Y2]} = (50.7)\sqrt{\exp(.279^2) - 1} \approx 14.4\ veh/hour$$

Table 3.2 Estimated prediction model parameters for left turn and opposing volumes, lognormal model (3.10).

	Posterior Summary			
Parameter	**Mean**	**Stand. Dev.**	**2.5% ile**	**97.5 %ile**
	Left Turn Volumes			
β_1	-0.4985	0.596	-1.676	0.673
β_2	0.983	0.073	0.838	1.126
β_3	-0.755	0.318	-1.385	-0.130
β_4	0.828	0.324	0.192	1.47
σ	0.279	0.036	0.220	0.361
	Opposing Through Plus Right Turn Volumes			
β_1	0.555	0.476	-0.384	1.493
β_2	1.026	0.048	0.931	1.121
β_3	-0.356	0.252	-0.854	0.138
β_4	0.268	0.252	-0.227	0.767
σ	0.221	0.029	0.174	0.285

Table 3.3 Comparison of nominal and observed coverages for date adjustments of movement counts using the lognormal model (3.10).

	Left Turn Volume		**Opposing Volume**	
Nominal coverage	**Observed coverage**	**Z statistic**	**Observed coverage**	**Z statistic**
50	66.7	2.0*	77.8	3.33*
80	77.8	-0.33	91.7	1.75
90	91.7	0.33	94.4	0.89
95	97.2	0.61	94.4	-0.15

Estimating Hourly Volumes for Non-Sampled Times on a Sampled Day

The above procedure assumes that a turning movement count is available for the same hour as when a target volume is needed. MnDOT turning movement counts are often done for a morning peak (6-9 AM) for mid-day (11 AM – 1 PM) and for an afternoon peak (3 PM – 6 PM). If a target volume is needed for 7-8 PM no corresponding reference count would be available and an additional estimation procedure is needed.

What follows describes an empirical Bayes method similar to that used in Davis and Yang (2006) to estimate classified mean daily traffic. 24-hour counts at a limited number of intersection approaches are used to construct a set of patterns describing how traffic volumes vary during the day. A sample turning movement count is then used to (a) identify the 24-hour patterns most similar to the sample and (b) use the total sample volume plus the identified patterns to estimate the volume at an unsampled hour. More formally, let y_t denote the traffic count during hour t of the day, t=1,..24, and let $\mathbf{z}$ denote the available turning movement count sample. For example if turning movement counts were available from 6-9 AM and 3-6 PM then **z** $=(z_1,z_2,z_3,z_4,z_5,z_6)= (y_7,y_8,y_9,y_{16},y_{17},y_{18})$. The problem then is to estimate the volume for a non-sampled hour, say y_{20}, given the sample **z**. Let Y_t denote the random variable generating the hourly count y_t, and to start assume Y_t is a Poisson random variable with mean $E[Y_t] = \mu_t$. Now let

$$\tilde{\mu} = \sum\nolimits_{\{s:s\ is\ sampled\}} \mu_s$$

$$\rho_t = \mu_t / \tilde{\mu}$$

$$\tilde{z} = \sum\nolimits_{\{s:s\ is\ sampled\}} y_s$$

The parameter ρ_t expresses the expected volume during hour t as a fraction of the expected total volume for the sample. We call the sequence $\boldsymbol{\rho} =(\rho_1, \rho_2,\ldots,\rho_{24})$ a 24-hour <u>pattern</u>. If we knew the 24-hour pattern for the day, then an estimate of, say, y_{20} would be

$$\hat{y}_{20} = \rho_{20}\tilde{z} \tag{3.11}$$

The question then is how to use the turning movement sample **z** to identify an appropriate pattern. Letting Y_T denote the traffic volume for the target hour, it can be shown that if:

(1) Given a pattern $\boldsymbol{\rho}$ and a mean total sample count, $\tilde{\mu}$, $Y_1,Y_2,\ldots Y_{24}$ are independent Poisson random variables with $E[Y_t] = \rho_t\tilde{\mu}$,

(2) The prior distribution for $\tilde{\mu}$ is gamma with parameters (a,b)

(3) The prior distribution over a finite set of known patterns $\boldsymbol{\rho}^1$, $\boldsymbol{\rho}^2$, …,$\boldsymbol{\rho}^n$ is a discrete uniform distribution,

Then the predictive distribution for the target count Y_T, given the sample count **z**, is a discrete mixture of negative binomial random variables

$$f(y_T \mid z) = \sum_{k=1}^{n}\left(\frac{\prod_{s=1}^{m}(\rho_{s,k})^{z_i}}{\sum_{j=1}^{n}\left(\prod_{s=1}^{m}(\rho_{s,j})^{z_i}\right)}\right)\left(\frac{\Gamma(r+y_T)}{\Gamma(r)y_T!}\right)p_{T,k}{}^{r}(1-p_{T,k})^{y_T}$$

$$r = a + \sum_{i=1}^{m} z_i$$

$$p_{T,k} = \frac{b+1}{b+1+\rho_T^k} \tag{3.12}$$

Although complicated, equation (3.12) has a straightforward interpretation. The component

$$\frac{\prod_{s=1}^{m}(\rho_{s,k})^{z_i}}{\sum_{j=1}^{n}\left(\prod_{s=1}^{m}(\rho_{s,j})^{z_i}\right)} = P(k \mid z) \tag{3.13}$$

gives the posterior probability for the pattern $\boldsymbol{\rho}^k$, given the sample **z.** The component

$$\left(\frac{\Gamma(r+y_T)}{\Gamma(r)y_T!}\right)p_{T,k}{}^{r}(1-p_{T,k})^{Y_T} \tag{3.14}$$

gives the probability mass function for the target volume Y_T given the sample **z** and the pattern $\boldsymbol{\rho}^k$. When the prior for $\tilde{\mu}$ is uninformative, so that a << 1, b << 1, the predictive mean and variance for Y_T can be approximated with

$$E[Y_T \mid z] \approx \sum_{k=1}^{n} P(k \mid z)\left(\sum_s z_s\right)\rho_{T,k}$$

$$Var[Y_t \mid z] \approx \left[\sum_{k=1}^{n} P(k \mid z)\left(\sum_s z_s\right)\left(\rho_{T,k}\right)\left(\rho_{T,k} + 1 + \rho_{T,k}(1 + \sum_s z_s)\right)\right] - E[Y_T \mid z]^2 \tag{3.15}$$

To implement this method archived SMART SIGNAL data, collected on Minnesota Trunk Highway (MNTH) 55, were used to compile 70 sets of 24-hour left turn counts and 63 sets 24-hour opposing volume counts, which were then used to compute corresponding 24-hour patterns. Figure 3.5 shows several illustrative patterns for the left-turn volumes, computed for samples consisting of a three-hour AM peak count (6-9 AM) and a 3-hour PM peak count (3-6 PM).

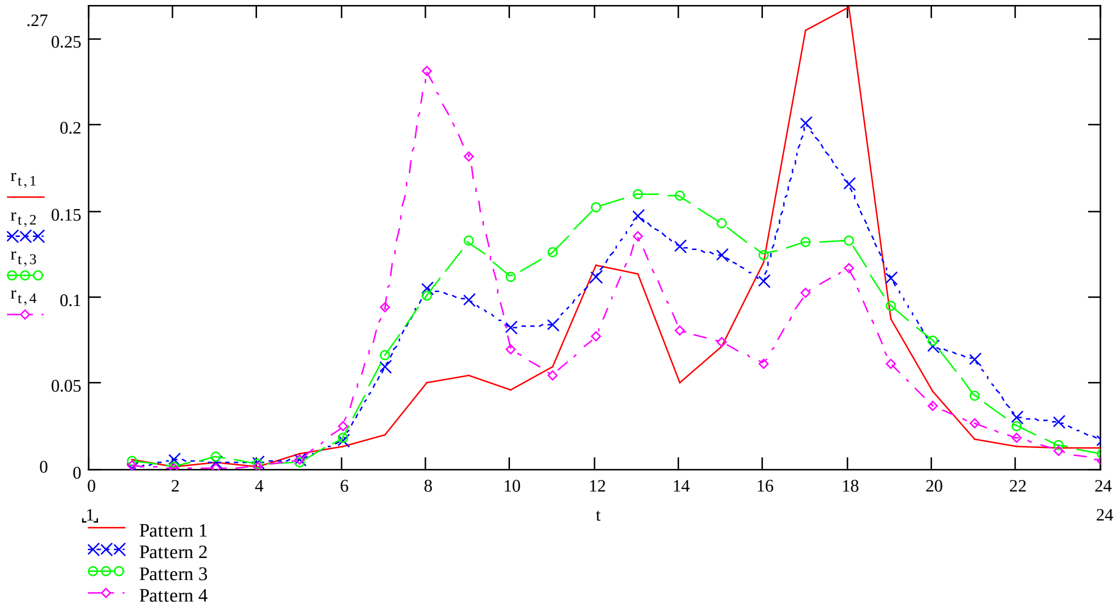


Figure 3.5 Example 24-hour patterns for left-turns along MNTH 55

Pattern 1 shows a major PM peak, a secondary noon peak and a minor AM peak. Pattern 2 also shows three peaks which are less extreme that pattern 1, while pattern 4 shows a marked AM peak. Pattern 3 was typical of weekend traffic.

To illustrate how this estimation procedure works, consider the example introduced at the beginning of section 3.2. The turning movement sample for February 15 2007 consisted of an eight-hour count, from 6-9 AM, 11 AM-1 PM, and 3 PM – 6 PM, giving the sample

z = (37,45,63,91,108,158,221,203)

Using the SMART-SIGNAL data, patterns for the 70 24-hour left turn volume samples were computed and equation (3.13) used to compute the probability of a match between the sample and each pattern. Predicted hourly volumes for the 24 hours of the day, and ±2 standard deviation ranges, computed using equation (3.17) below. (The reason for using equation (3.17) and not equation (3.15) to compute the variances will be explained shortly.) Figure 3.6 shows the actual eight sample volumes along with the predicted hourly left-turn volumes for Feb. 15. For example, the predicted left-turn volume for 1 PM -2 PM is 82.6 vehicles/hour, with a standard deviation of 8.2 vehicles/hour. The predicted value for 11 PM – midnight is 9.4 vehicles/hour, with a standard deviation of 3.3 vehicles/hour.

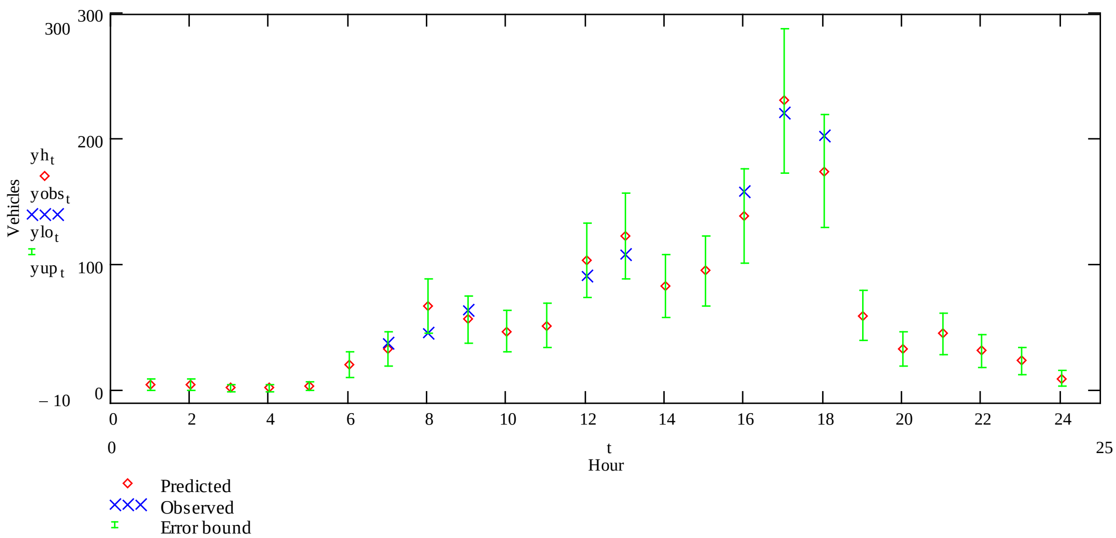


Figure 3.6 Predicted hourly left-turn volumes for Feb. 15, 2007, along with observed counts from the Feb. 15 sample.

3.2.2 *Validation Studies*

A leave-one-out-cross validation was conducted using the 70 24-hour left-turn counts from MNTH 55, by successively removing one 24-hour count from this list, to serve as a test case, and then computing the list of 24-hour patterns from the remaining 69 counts. The most common turning movement sample used by MnDOT consists of an eight-hour count (6-9 AM, 11 AM-1 PM, 3 PM-6 PM), and this was the sampling scheme used in this validation test. Using equation (3.13), the posterior probability for each of the remaining 69 given patterns was computed for the test case and then using equation (3.15) predicted hourly left-turn volumes were computed for 24 test-case hourly volumes. Root-mean-squared (RMS) prediction errors were then computed by averaging the squared difference between the observed and predicted counts for the hours not included in the 8-hour sample. That is

$$RMS = \sqrt{\frac{\sum_{t}(y_t - \hat{y}_t)^2}{(24 - nsamp)}} \tag{3.16}$$

where

y_t = observed count for non-sampled hour t

$\hat{y}_t$ = predicted count for non-sampled hour t

nsamp = number of hours in turning movement count sample.

For the left turns, the average RMS was 8.6 vehicles/hour, the median RMS was 7.7 vehicles/hour and the RMS ranged from 2.1 vehicles/hour to 24.7 vehicles/hour.

Leave-one-out cross validation was then done for the opposing through plus right turn volumes using the 63 24-hour counts available from SMART SIGNAL. Here, the average RMS error was 43.9 vehicles/hour, the median RMS error was 36.3 vehicles/hour with a range of 6.95-228.9 vehicles/hour.

Table 3.4 Root-mean-squared (RMS) estimation errors, and ranges of target volumes.

	RMS Error (Vehicles/Hour)				**Target Range (Vehicles/Hour)**	
Location/Movement	**Mean**	**Median**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Golden Valley/LT	8.6	7.7	2.1	24.7	0	375
Golden Valley/OP	43.9	36.3	6.95	228.9	0	2475
Minneapolis/Olson/LT	13.3	9.3	1.1	128	3	291
Minneapolis/Olson/OP	72.4	66.4	2.1	177	9	1702
Minneapolis/University/LT	10.5	5.5	1.0	53.2	1	293
Minneapolis/University/OP	56.5	48.1	1.9	132.9	3	862

To assess this method's usefulness when predicting volumes at locations not used to construct the pattern sample, a second validation exercise was conducted using turning movement counts collected and archived by the City of Minneapolis. Single-day, 13-hour (6 AM – 7 PM) turning movement counts were obtained for nine intersections on the Olson Highway in Minneapolis, and six intersections on University Avenue North, also in Minneapolis. None of these intersections were used to construct 24-hour patterns. As in the previous exercise, it was assumed that an eight-hour turning movement count was available, and the problem was to estimate left-turn and opposing volumes for the remaining five hours. Results from all the validation tests are summarized in Table 3.4.

3.2.3 *Uncertainty Quantification*

Figure 3.7 displays the observed hourly opposing (through plus right turn) volumes for the intersections along Olson Highway in Minneapolis, along with ± 2 standard deviation error ranges for the estimated volumes, computed using equation (3.15). For those hourly volumes included in the turning movement sample the standard deviation was set to 0, as these volumes were known. The substantial fraction of observed target counts falling outside the error ranges suggests that these opposing volumes are more variable i.e. overdispersed, compared with what the model in equation (3.15) allows for. This suspicion is confirmed when we use equation (3.15) to compute Pearson residuals for the data displayed in Figure 3.7. The average Pearson residual, at 0.71, is reasonably close to 0, but the standard deviation is 3.0. We would expect a standard deviation close to 1.0 if the variance component in equation (3.15) adequately described the variability in the hourly counts.

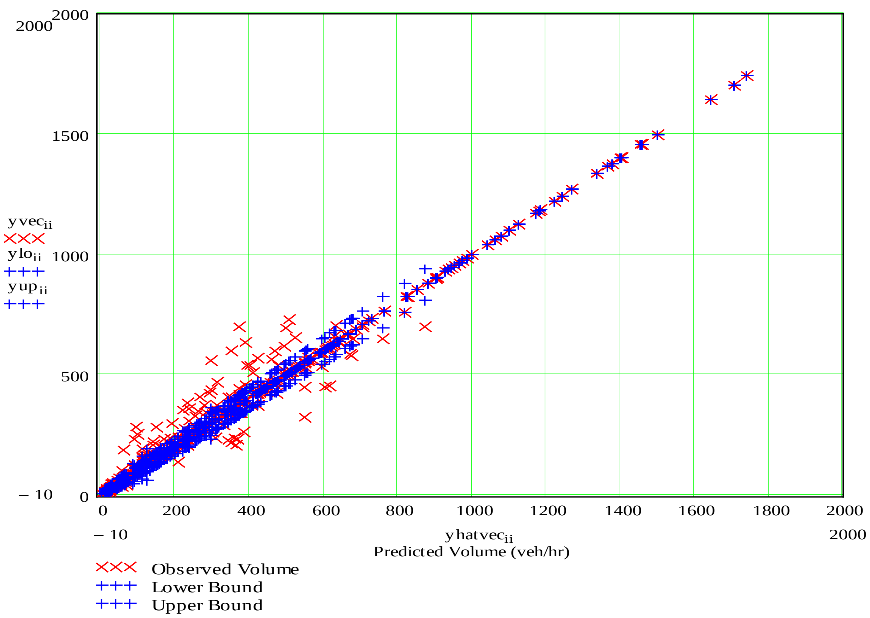


Figure 3.7 Observed and predicted opposing volumes for Minneapolis intersections along Olson Highway.

The derivation leading to equations (3.13-3.15) yielded a predictive distribution for a target volume Y_T, given the turning movement sample and the a pattern coefficient $\rho_{T,k}$, as a negative binomial random variable. One way to include overdispersion in this model is to add a random effect to the pattern coefficient. That is, let $\rho_{T,k}$ denote the pattern coefficient actually generating the target count, and $\hat{\rho}_{T,k}$ denote the observed coefficient from the pattern sample. If

$$\rho_{T,k} = \hat{\rho}_{T,k} W$$

where W is a gamma random variable with mean equal to 1.0 and shape parameter α, then the predictive distribution given in equation (3.14) becomes a negative binomial-gamma mixture. Although the probability mass function of the negative binomial-gamma mixture does not have a closed form, the mean and variance have been given in (Johnson et al 1992). Applying this result leads to a modification to equation (3.17)

$$E[Y_T \mid z] \approx \sum_{k=1}^{n} P(k \mid z)\left(\sum_s z_s\right)\hat{\rho}_{T,k}$$

$$Var[Y_t \mid z] \approx$$

$$\left[\sum_{k=1}^{n} P(k \mid z)\left(\sum_s z_s\right)\left(\hat{\rho}_{T,k}\right)\left(\hat{\rho}_{T,k} + 1 + \hat{\rho}_{T,k}(\sum_s z_s) + \alpha\hat{\rho}_{T,k}\left(1 + \sum_s z_s\right)\right)\right] - E[Y_T \mid z]^2 \qquad (3.17)$$

where $\alpha \geq 0$, governs the overdispersion in the pattern coefficients. For the opposing volumes on the Olson Highway, the value α=0.05 produced standardized residuals with an average of 0.28 and a standard deviation of 1.09.

To illustrate, Figure 3.8 shows observed counts from the Olson Highway approach with largest RMS error, It can be seen that for the five hours not included in the turning movement sample (hours ending at 10 AM, 11 AM, 2 PM, 3 PM and 7 PM) the ± 2 standard deviation ranges computed with α=.05, catch four of the five non-sampled volumes. When equation (3.15) was used only one of the five target counts was caught by the ± 2 standard deviation ranges. Table 3.5 shows estimated values of the overdispersion parameter, and associated statistics of the standardized residuals, for each of the Minneapolis test data sets.

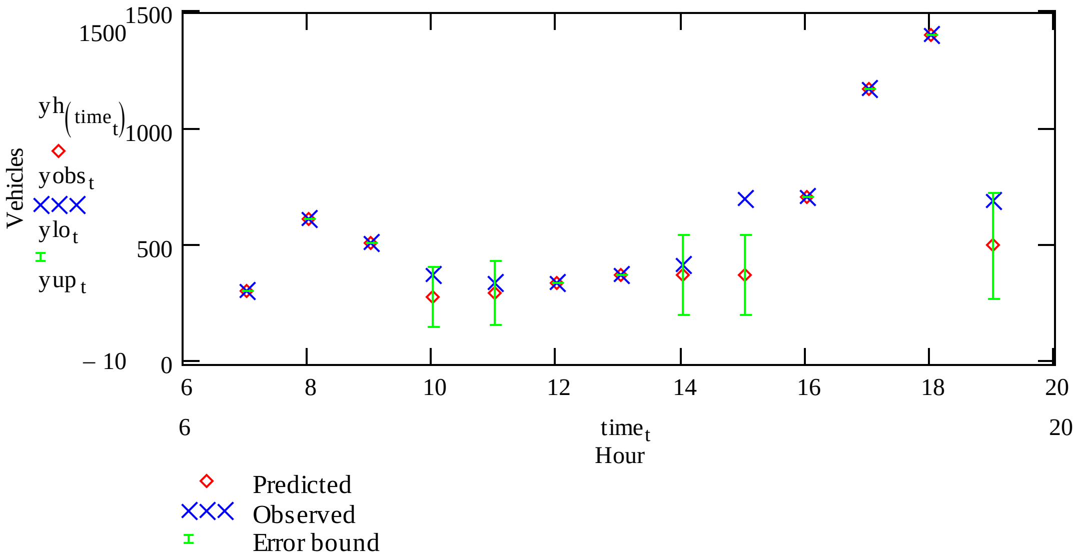


Figure 3.8 Observed and predicted opposing volumes for Olson Highway approach with largest RMS error, computed using equation (3.17), α=0.05.

Table 3.5 Estimated overdispersion parameters, and summary statistics for Pearson residuals, for Minneapolis test data.

		Statistics for Standardized Residuals		
	α	Average	Stand. Dev.	Variance
Olson/LT	0.01	0.18	1.11	1.23
University/LT	0.01	0.26	1.08	1.16
Olson/OP	0.05	0.28	1.04	1.09
University/OP	0.04	0.41	1.09	1.2

3.2.4 *Application*

As stated in the previously, turning movement counts were available only for 438 crashes. The Time-of-day adjustment (when needed) was implemented by a Mathcad code for those cases and their controls. Figure 3.9 is a snapshot of the dataset showing turning movement volumes adjusted to the case/control hours along with their associated standard deviation. Standard deviation for sampled hours is zero because no time-of-day adjustment was needed.

	B	C	D	E	F	G	H	I	J	K	L	M	N
1	case/con	crash index	DOW	Time	LT hour adjust	LT sigma1	LT simga2	TH hour adjust	TH sigma1	TH sigma2	OLT hour adjust	OLT sigma1	OLT sigma2
2414	Case	461	3	15.1	318.0	0.0	0.0	782.0	0.0	0.0	0.0	0.0	0.0
2415	Control	461	3	5.3	67.6	11.3	14.8	140.9	12.0	33.7	0.0	0.0	0.0
2416	Control	461	3	21.1	58.0	7.9	11.4	233.1	15.7	54.4	0.0	0.0	0.0
2417	Control	461	3	19.3	136.2	12.3	22.8	303.3	18.0	70.2	0.0	0.0	0.0
2418	Control	461	3	4.0	29.1	5.6	6.9	2.7	1.7	1.8	0.0	0.0	0.0
2419	Control	461	3	16.8	252.0	0.0	0.0	897.0	0.0	0.0	0.0	0.0	0.0
2420	Case	462	2	16.8	16.0	0.0	0.0	611.0	0.0	0.0	52.0	0.0	0.0
2421	Control	462	2	23.3	1.5	1.5	1.5	20.1	4.5	6.4	3.9	3.2	3.2
2422	Control	462	2	8.7	16.0	0.0	0.0	164.0	0.0	0.0	31.0	0.0	0.0
2423	Control	462	2	9.7	11.7	4.4	4.7	129.0	11.7	31.1	31.4	14.6	15.4
2424	Control	462	2	21.5	4.4	2.7	2.8	46.2	6.9	12.4	12.3	5.4	5.7
2425	Control	462	2	6.2	15.0	0.0	0.0	62.0	0.0	0.0	8.0	0.0	0.0
2426	Case	463	2	15.5	37.0	0.0	0.0	400.0	0.0	0.0	45.0	0.0	0.0
2427	Control	463	2	10.1	16.5	5.4	5.9	127.9	11.6	30.9	30.1	11.1	12.0
2428	Control	463	2	9.2	11.7	4.4	4.7	129.0	11.7	31.1	31.4	14.6	15.4
2429	Control	463	2	7.7	21.0	0.0	0.0	221.0	0.0	0.0	32.0	0.0	0.0
2430	Control	463	2	17.3	16.0	0.0	0.0	647.0	0.0	0.0	32.0	0.0	0.0
2431	Control	463	2	16.9	16.0	0.0	0.0	611.0	0.0	0.0	52.0	0.0	0.0

Figure 3.9 LT, opposing Th+RT, and opposing LT volumes at case/control hours along with their standard deviation

The last step of data preparation is to adjust these counted/estimated turning volumes to the crash date. This can be readily done in Excel, and Figure 3.10 shows his part of the dataset.

	B	E	F	I	L	O	P	Q	R	S
1	case/con	Time	LT hour adjust	TH hour adjust	OLT hour adjust	ATR-Target	ATR-TM	LT date adjust	TH date adjust	OLT date adjust
2414	Case	15.1	318.0	782.0	0.0	5312	5045	354.8	794.7	1.0
2415	Control	5.3	67.6	140.9	0.0	2007	2667	55.9	132.4	1.0
2416	Control	21.1	58.0	233.1	0.0	3341	4791	47.1	206.5	1.0
2417	Control	19.3	136.2	303.3	0.0	3847	5321	113.3	270.6	1.0
2418	Control	4.0	29.1	2.7	0.0	858	865	28.3	2.7	1.0
2419	Control	16.8	252.0	897.0	0.0	5583	4856	302.7	939.8	1.0
2420	Case	16.8	16.0	611.0	52.0	812	1000	13.4	663.6	42.8
2421	Control	23.3	1.5	20.1	3.9	86	96	1.2	25.2	3.1
2422	Control	8.7	16.0	164.0	31.0	400	609	10.9	169.9	20.8
2423	Control	9.7	11.7	129.0	31.4	427	506	9.7	144.4	25.6
2424	Control	21.5	4.4	46.2	12.3	333	339	4.1	54.3	11.2
2425	Control	6.2	15.0	62.0	8.0	402	537	11.3	65.6	6.1
2426	Case	15.5	37.0	400.0	45.0	743	851	32.2	444.3	39.0
2427	Control	10.1	16.5	127.9	30.1	334	338	15.1	154.6	27.2
2428	Control	9.2	11.7	129.0	31.4	433	506	9.9	144.9	25.9
2429	Control	7.7	21.0	221.0	32.0	729	980	16.3	228.7	24.7
2430	Control	17.3	16.0	647.0	32.0	790	957	13.6	709.6	26.9
2431	Control	16.9	16.0	611.0	52.0	820	1000	13.6	665.3	43.2

Figure 3.10 Applying date adjustment equations using ATR counts

Finally, the dataset which will be used for the matched case/control analysis to develop left-turn crash relative risk models looks like Figure 3.11. It contains the case/control indicator, potent geometric characteristics and relevant turning movement volumes.

	B	T	V	W	Y	Z	AA	AB	AC
1	case/con	LT phase	# opp lanes	median width (ft)	OSL (mph)	SD	LT (rounded up to 1)	TH (rounded up to 1)	OLT (rounded up to 1)
2450	Case	Prot.-perm.	2	0	40	0	210.3	524.4	42.6
2451	Control	Prot.-perm.	2	0	40	0	165.4	208.7	26.0
2452	Control	Prot.-perm.	2	0	40	0	164.1	227.9	23.0
2453	Control	Prot.-perm.	2	0	40	0	24.3	72.3	4.2
2454	Control	Prot.-perm.	2	0	40	0	116.1	159.3	18.5
2455	Control	Prot.-perm.	2	0	40	0	191.4	299.8	32.6
2456	Case	Prot.-perm.	2	0	40	0	39.3	228.2	194.0
2457	Control	Prot.-perm.	2	0	40	0	7.2	74.0	40.1
2458	Control	Prot.-perm.	2	0	40	0	30.0	264.0	143.0
2459	Control	Prot.-perm.	2	0	40	0	1.0	8.6	1.8
2460	Control	Prot.-perm.	2	0	40	0	39.3	200.8	161.9
2461	Control	Prot.-perm.	2	0	40	0	3.7	60.4	20.9
2474	Case	FYA	2	10	40	1	13.0	590.4	21.9
2475	Control	FYA	2	10	40	1	1.0	38.8	3.9
2476	Control	FYA	2	10	40	1	11.5	351.5	88.2
2477	Control	FYA	2	10	40	1	9.9	524.7	389.2
2478	Control	FYA	2	10	40	1	11.2	559.7	152.2
2479	Control	FYA	2	10	40	1	2.2	83.9	14.7
2480	Case	Prot.-perm.	1	0	40	0	45.5	372.1	1.0
2481	Control	Prot.-perm.	1	0	40	0	246.2	770.4	1.0
2482	Control	Prot.-perm.	1	0	40	0	1.0	12.6	1.0
2483	Control	Prot.-perm.	1	0	40	0	4.8	41.0	1.0
2484	Control	Prot.-perm.	1	0	40	0	50.2	297.7	1.0
2485	Control	Prot.-perm.	1	0	40	0	194.9	634.4	1.0
2486	Case	Permissive	2	0	35	1	52.6	284.8	46.5
2487	Control	Permissive	2	0	35	1	1.0	7.8	1.0
2488	Control	Permissive	2	0	35	1	46.9	108.9	28.5
2489	Control	Permissive	2	0	35	1	1.0	13.0	1.8
2490	Control	Permissive	2	0	35	1	1.0	6.8	1.0
2491	Control	Permissive	2	0	35	1	1.0	6.6	1.0

Figure 3.11 Final dataset prepared for the matched case/control analysis.

CHAPTER 4

4. Statistical Analyses and Relative Risk Model

This chapter describes the development of a statistical model which relates the risk of occurrence of a left-turn crash in a given hour to the traffic and other conditions prevailing during that hour. As mentioned in Chapter 1, because of the difficulty in obtaining reliable counts of left-turn crashes, the chosen sampling model was a matched case-control design. Before moving to the details of the statistical analyses it might be helpful to see how the matched case-control design relates to the more common method for developing safety performance functions.

4.1 Case-Control Design

To begin, let
Y_{kt} = the (random) number of left turn crashes occurring on approach k during hour t,
$\mu_{kt} = E[Y_{kt}]$, the expected number of left turn crashes on k during t
$x_{kt,1}$ = hourly volume of left-turns from approach k during t
$x_{kt,2}$ = hourly volume of traffic opposing left turns from approach k during t
$x_{kt,3}$ = hourly volume of opposing left turns for approach k during t

A commonly-used form for a safety performance function relating the mean crash frequency μ_{kt} to the traffic volumes is the loglinear model

$$\mu_{kt} = \mu_k x_{kt,1}^{\beta_1} x_{kt,2}^{\beta_2} x_{kt,3}^{\beta_3} \tag{4.1}$$

Here μ_k can be interpreted the expected number of left turn crashes on approach k when all traffic volumes equal 1 vehicle/hour while the parameters β_1, β_2, β_3 reflect the degree to which the expected frequency of left turn crashes changes as the traffic volumes change. The constraint $\beta_1=\beta_2$ leads to the cross-product of left-turn and opposing volumes as a predictor of left-turn crash frequency. An equivalent way of writing (4.1) is the generalized linear model with log link

$$\mu_{kt} = \exp\left(\beta_k + \beta_1 \log(x_{kt,1}) + \beta_2 \log(x_{kt,2}) + \beta_3 \log(x_{kt,3})\right) \tag{4.2}$$

If it were possible to obtain reliable counts of left turn crashes for each hour of, say, three or more years, along with reliable estimates of the corresponding hourly traffic volumes, the approach-specific parameter β_k and the volume effect parameters β_1, β_2, β_3 could be estimated using standard methods for estimating safety performance functions. When these assumptions about data availability are not tenable an alternative sampling model is needed.

To see how the matched case-control design is related the standard approach begin with the common assumption that the random number of left-turn crashes follows the Poisson distribution with mean value given by equation (4.2). Next, since in any given hour the likelihood of two or more left-turn crashes is negligible, that is only 0 or 1 left-turn crash will be observed in a given hour, the Poisson model reduces to

$$
\begin{aligned}
P(Y_{kt}=1) &= \frac{\exp\left(\beta_k + \beta_1 \log(x_{kt,1}) + \beta_2 \log(x_{kt,2}) + \beta_3 \log(x_{kt,3})\right)}{1+\exp\left(\beta_k + \beta_1 \log(x_{kt,1}) + \beta_2 \log(x_{kt,2}) + \beta_3 \log(x_{kt,3})\right)} \\
P(Y_{kt}=0) &= \frac{1}{1+\exp\left(\beta_k + \beta_1 \log(x_{kt,1}) + \beta_2 \log(x_{kt,2}) + \beta_3 \log(x_{kt,3})\right)}
\end{aligned}
\tag{4.3}
$$

which is a logistic regression model. In the matched case-control design used here, the cases are the hours during which relevant left-turn crashes occurred. For each case, five non-crash hours were then randomly selected to serve as the controls. Using the methods described in Chapter 3, the left-turn, opposing, and opposing left-turn volumes for the same approach and on the same day as the crash, were estimated for the case and controls hours. Letting i=1,..,N index the case-control sets, j=1 denote the case and j=2,..,6 denote the controls, the likelihood function generated by the matched case-control sampling is (Hosmer and Lemeshow 2000, p. 226)

$$
L(\beta_1,\beta_2,\beta_3) = \prod_{i=1}^{N}\left(\frac{\exp(\beta_1 \log(x_{i1,1})+\beta_2 \log(x_{i1,2})+\beta_3 \log(x_{11,3})}{\sum_{j=1}^{6}\exp(\beta_1 \log(x_{ij,1})+\beta_2 \log(x_{ij,2})+\beta_3 \log(x_{1j,3})}\right) \tag{4.4}
$$

where

$x_{ij,1}$ = left turn volume for hour j of case-control set i
$x_{ij,2}$ = opposing volume for hour j of case-control set i
$x_{ij,3}$ = opposing left-turn volume for hour j of case-control set i.

Note that parameters for the site-specific effects, β_k in equation (4.3), do not appear in the matched case-control likelihood, since they appear as constants in both the numerators and denominators of their respective likelihood factors. This is a mathematical property of the matched case-control sampling; the practical implication of this property is that the effects of features that are constant to cases and controls, such as an intersection's geometric features, cannot be estimated from matched case-control sampling.

4.2 Site Classification

Chapter 2 described how the data on crashes and intersections were compiled while Chapter 3 described how the traffic volumes for the case and control hours were estimated. Matched case-control designs do not support direct estimation of how risk is affected by those features common to a case and its controls, such as geometric conditions, approach speeds, or signal timing. One way indirectly allow for these effects is to divide the sample of case-control sets into homogeneous groups, and allow the estimates of the parameters β_1, β_2, β_3 to vary across the groups. As a starting point the following features, which Wang and Abel-Aty (2008) found to be associated with aggregate left turn crash frequency, were identified:

Left-turn phasing,
Number of opposing lanes,
Median condition,
Opposing speed limit.

The following describes the classification ultimately used in our study.

4.2.1 Left-turn phasing

Within our sample of 438 crashes there were four different types of left-turn protection: protective-permissive (383 cases), permissive only (39 cases), flashing yellow arrow (FYA) which can be operated as either protective-permissive or permissive (14 cases), and 4-section special operation (2 cases). Figure 4.1 shows the location as well as a street view snapshot of a 4-section special operation on US 61. Since these sites have an unusual geometry and also considering the fact that they contribute only 2 cases out of 438, they were excluded from the study.

Figure 4.1 The site plan and the street view of a LT accident location with a 4-section special operation.

4.2.2 *Number of opposing lanes*

For the purpose of this study, the “opposing lanes” refers to those opposing lanes to which a left-turn vehicle must yield the right of way. Using this definition, through and right-turn lanes can be counted most of the time. The 438 crash sample of this study involves 114 locations with 1 opposing lane, 308 locations with 2 opposing lanes and 16 approaches with 3 opposing lanes.

4.2.3 *Median condition*

Another factor which Wang and Abdel-Aty (2008) found related to aggregate left-turn crash frequency is the presence or absence of a median. Among 438 LT crashes of this study, 187 of them occurred at locations with no median and the remaining locations had a median width ranging from 4 to 28 feet. Below is the histogram for the median widths.

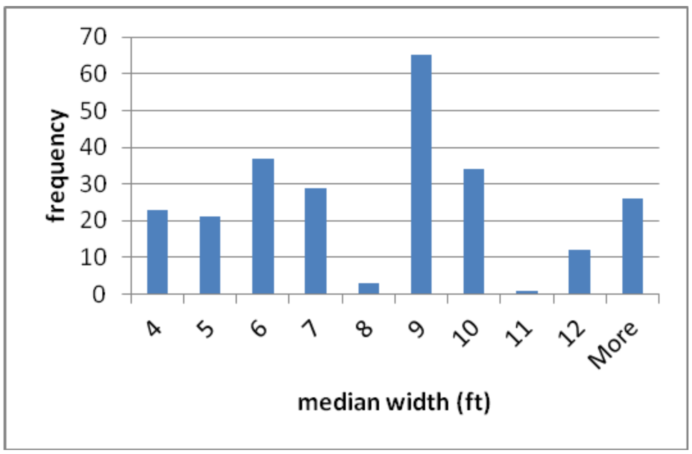


Figure 4.2 Distribution of median widths

Since the minimum width is 4 feet, the sites were divided into two groups: those with no median and those having a median.

4.2.4 *Opposing speed limit*

Wang and Abdel –Aty found that the speed limit for opposing traffic was a reliable predictor of left-turn crash frequency. Accordingly, this information was collected for all the sites and ranged from 20 to 55 mph. The number of locations with the opposing speed limit of 45 mph and above was 96 and the number of locations with the speed limit of less than 45 mph was 342.

4.2.5 *Sight distance condition*

Since an opposing left-turn vehicle can block the view of a LT, knowing whether or not adequate sight distance is provided for a given approach is potentially informative about crash risk. To answer this question, for all the locations a modified version of the formula given by McCoy et al. (2001) was used to determine the available sight distance, where both turning vehicles are assumed to be passenger cars. Comparing the available sight distance at each location to that required to make a left turn allowed us to classify each approach into those with and those without potential sight distance problems. 167 crashes occurred at locations with a potential sight distance problem.

4.2.6 Cross classification of the crash sites

Based on the above five criteria and because each criterion defines two groups, there can be up to $2^5 = 32$ categories of intersections. Table 4.1 shows how the total of 436 case-control sets was distributed over the intersection categories.

Table 4.1 Crash site classification excluding 4-section special signal (436 crashes)

criteria		1 opp lane				2^+ opp lanes			
		prot-perm		perm or FYA		prot-perm		perm or FYA	
		median	no median	median	no median	median	no median	median	no median
<45 mph	SD prob.	3	14	2	6	81	11	8	11
	No SD prob.	8	13	1	12	66	98	4	3
>=45 mph	SD prob.	5	1	0	0	48	0	1	0
	No SD prob.	0	4	0	0	20	11	4	1

As can be seen, only seven of the 32 categories have sample sizes of 20 or more and over half have 10 or fewer, indicating that, for most of these categories, reliable estimation of the coefficients β_1, β_2, β_3 will be problematic. Of the factors affecting left-turn crash frequency listed in Wang and Abdel-Aty's Table 3, median width and number of opposing lanes were somewhat weaker and it was decided to aggregate sites over these two factors to obtain a first, working cross-classification. The working categories, along with the number of case-control sets in each category, are shown in Table 4.2.

Table 4.2 Crash site classification after aggregating over median criterion and number of opposing lanes

		Prot-Perm	Perm or FYA
<45 mph	SD prob.	109	27
	No SD prob.	185	20
>=45 mph	SD prob.	54	1
	No SD prob.	35	5

4.3 Statistical Analyses

Initial statistical analyses were conducted for each of the working categories with 20 or more case control sets in order to (a) determine if left-turn crash risk varied as the hourly left-turn, opposing, and opposing left-turn volumes varied, (b) determine if all three volume variables were needed to predict risk, (c) determine if the sample could identify the separate effects of left-turn and opposing volumes, and (d) assess each statistical model's goodness-of-fit. This procedure will be illustrated in detail for intersection the approaches with opposing speed limits less than 45 mph, with protective-permissive phasing, and with no obvious sight-distance problem. The number of case-control sets for this category was 185.

First, maximum likelihood estimates of β_1, β_2, β_3 were computed by maximizing the likelihood function shown in equation (4.4). For each category the likelihood ratio test was then used to test the hypothesis $\beta_1=\beta_2=\beta_3=0$, i.e. that the hourly volumes provide no information concerning when left-turn crashes are likely to occur. In this case the computed likelihood ratio statistic was 90.35. Comparing this value to a Chi-squared (X^2) random variable with three degrees of freedom gives $p<.001$ for the probability of obtaining a value this large or larger if in fact the variation in hourly volume had no effect on left-turn crash risk. In this case we reject the hypothesis of no effect and conclude that left-turn crash risk is associated with traffic volume. Second, the opposing left-turn volumes were deleted from the model and maximum likelihood estimates for the remaining parameters estimated. The computed likelihood ratio statistic was 2.28 and comparing this to a Chi-squared random variable with one degree of freedom gave a $p>0.1$, indicating that deleting the opposing left-turn volumes did not degrade the model's ability to discriminate cases from controls. Third, the opposing traffic volume was deleted from the model and a maximum likelihood estimate of the β_1 computed. The likelihood ratio statistic comparing the model with only left-turn volume as a predictor to that the left-turn and opposing volume was 3.16 with an associated p value of 0.085. In this case we concluded that a differential effect due to opposing traffic volume was detected with these data.

Finally, a rough goodness-of-fit assessment was done for the model with all three hourly volumes as predictors, using ideas presented in Moolgavkar et al (1984). This required computing, for each case-control set

$$\hat{u}_k^* = \frac{\exp(\hat{\beta}_1 \log(x_{i1,1}) + \hat{\beta}_2 \log(x_{i1,2}) + \hat{\beta}_3 \log(x_{11,3}))}{\sum_{j=1}^{6} \exp(\hat{\beta}_1 \log(x_{ij,1}) + \hat{\beta}_2 \log(x_{ij,2}) + \hat{\beta}_3 \log(x_{1j,3}))} \tag{4.5}$$

which give the predicted probability that the crash occurred during the case hour. The squared Pearson residual for set k is then

$$s_k^* = \frac{1-\hat{u}_{k0}}{\hat{u}_{k0}} \tag{4.6}$$

and Mookgavkar et al (1984) suggest treating s_k^* as the outcome of a Chi-squared random variable with degrees of freedom equal to the number of controls in the case-control set, in this case five. Plotting the s_k^* along with the corresponding expected values and confidence ranges allows us to identify outliers (i.e. atypical case-control sets), and an unlikely number of outliers would indicate a problem with the model's fit. Figure 4.3 shows the squared residuals s_k^* for the 185 case-control sets along with the mean (5.0) and 90% point (9.236) for a Chi-squared distribution with five degrees of freedom. For this group of intersections 13 of the 185 case-control sets showed values of s_k^* exceeding the 90% point while we would expect (185)(.1)=18.5 outliers. An approximate test of the hypothesis that the number of outliers is atypically high is the z-statistic

$$\hat{z} = \frac{13-18.5}{\sqrt{(185)(.1)(.9)}} = -1.35 \tag{4.7}$$

In this case we would reject the hypothesis that there is an atypical number of outliers in this group. Inspection of the 13 outliers indicated that in all instances these resulted when the hourly volumes for the case where notably lower than those for one or more of the control hours; that is, the crash occurred during a low volume hour. Table 4.3 summarizes the results of these analyses for the six working categories having 20 or more case-control sets.

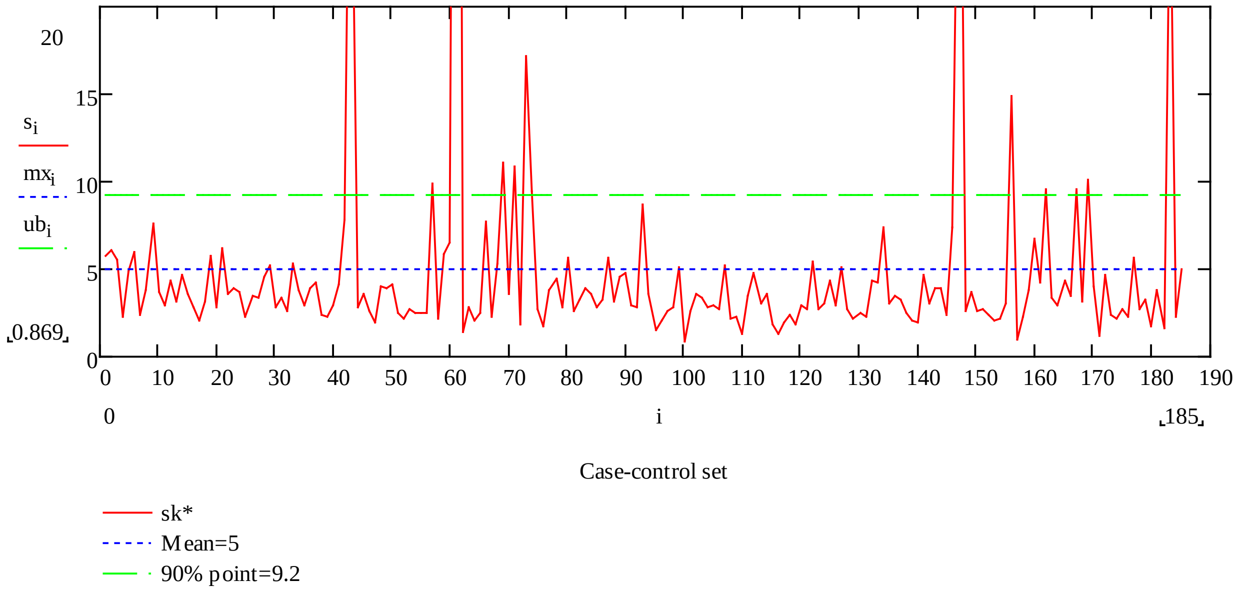


Figure 4.3 Square Pearson residuals for the intersection category 1, along with their expected values and 90% ranges.

Table 4.3 Summary of initial statistical tests and analyses of residuals.

		No volume effect		No opposing LT effect		No opposing volume effect		Outliers		
Category	N	X^2	p	X^2	p	X^2	p	count	Z	P
1	185	90.4	<.001	2.3	>0.1	3.16	< 0.1	13	-1.25	>0.5
2	109	63.2	<.001	0.49	>0.5	8.8	< .001	9	-.61	> 0.5
3	54	34.0	<.001	0.01	>0.5	2.6	> .11	3	-1.09	>0.5
4	35	17.6	<0.01	0.92	>0.5	7.8	< .01	2	-0.85	>0.5
5	27	14.7	< .01	2.13	> .1	0.06	> .5	2	-0.45	>0.5
6	20	17.0	< .01	1.21	> .5	0.4	> .5	1	00.15	>0.5

Definition of Intersection Categories

1: Protective/Permissive LTs, opposing speed limit < 45 mph, No clear sight distance problem
2: Protective/Permissive LTs, opposing speed limit < 45 mph, Possible sight distance problem
3: Protective/Permissive LTs, opposing speed limit ≥ 45 mph, Possible sight distance problem
4: Protective/Permissive LTs, opposing speed limit ≥ 45 mph, No clear sight distance problem
5: Permissive/FYA LTs, opposing speed limit < 45 mph, Possible sight distance problem
6: Permissive/FYA LTs, opposing speed limit < 45 mph, No clear sight distance problem

4.4 Analyses with Measurement Error

As noted in Chapter 3, direct measurements of the movement volumes for the case and control hours were almost always unavailable, so these had to be estimated from existing ATR data and turning movement counts. The estimation method was described in Chapter 3 and included estimation of the standard deviations associated with the volume estimates. However, the preliminary analyses described above did not attempt to account for volume measurement error. Since it is known that measurement error in predictors can bias the estimates of model coefficients (Stefanski et al 1995) it was decided to check the sensitivity of the results to measurement error in the hourly volumes. In this analysis the probability that of a left-turn crash occurring in a given is hour still follows equation (4.3) but now the hourly volumes are treated as not directly observed. Figure 4.4 shows the structure of the measurement error model, with circles denoting unobserved variables and squares denoting variables that were observed. As before the relationship between the actual traffic volumes (x_{real}) and the model coefficients $\boldsymbol{\beta}$ follows the logit model described above and the likelihood for the observed case-control data follows equation (4.4). The main difference is that the actual traffic volumes are now treated as missing data and the available traffic volumes ($x_{observed}$) are treated as uncertain estimates of the actual hourly volumes. Bayes estimates of the coefficients $\boldsymbol{\beta}$ were computed using the Markov chain Monte Carlo (MCMC) software WinBUGS (for each of intersection categories 1-6 for a model having left-turn, opposing, and opposing left-turn volumes as predictors and for a reduced model where opposing left-turn volume is deleted.

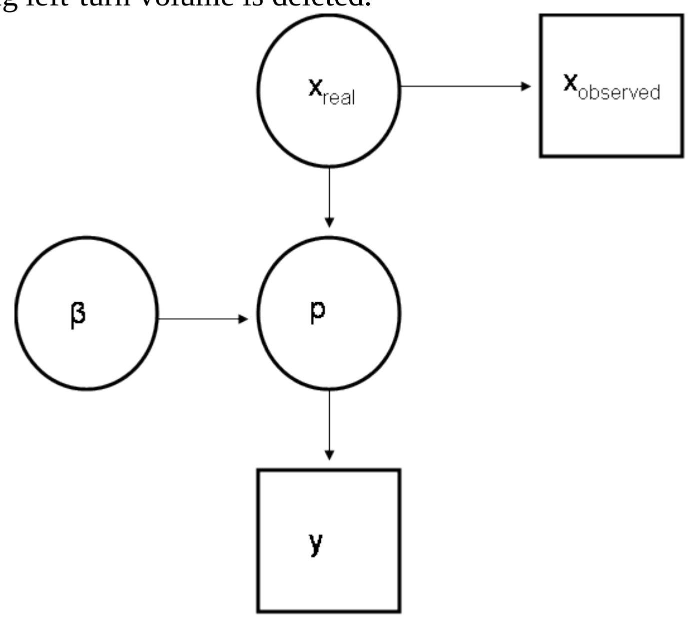


Figure 4.4 Graphical representation of measurement error model.

Tables 4.4 - 4.6 show the maximum likelihood (no measurement error) and Bayes (measurement error) estimates for intersection categories 1-3, for the three categories with largest sample sizes. Also included in the tables are the standard deviations associated with the estimates deviance information criteria (DIC) for the measurement error models. Differences in DIC values can indicate differences in the model fit and it can be seen that for these three data sets the models that remove the opposing left-turn volumes as predictors provide fits essentially equal to models including the opposing left-turn volumes, similar to the results summarized in Table 4.3.

Table 4.4 Category 1 (N=185)

	3-predictor Model				2-predictor Model			
Hourly Volume Predictor	Max Likelihood		Bayes DIC=584.0		Max Likelihood		Bayes DIC=584.2	
	β	s.d.	β	s.d.	β	s.d.	β	s.d.
Left turns	0.39	0.18	0.34	0.15	0.43	0.18	0.38	0.15
Opposing	0.24	0.21	0.30	0.18	0.33	0.2	0.37	0.17
Opposing LT	0.26	0.18	0.23	0.16	--	--	--	--

Table 4.5 Category 2 (N=109)

	3-predictor Model				2-predictor Model			
Hourly Volume Predictor	Max Likelihood		Bayes DIC=337.5		Max Likelihood		Bayes DIC=336.9	
	β	s.d.	β	s.d.	β	s.d.	β	s.d.
Left turns	0.25	0.24	0.30	0.21	0.32	0.22	0.33	0.20
Opposing	0.575	0.29	0.53	0.25	0.69	0.25	0.64	0.22
Opposing LT	0.185	0.27	0.22	0.22	--	--	--	--

Table 4.6 Category 3 (N=54)

	3-predictor				2-predictor			
Hourly Volume Predictor	Max Likelihood		Bayes DIC=168.1		Max Likelihood		Bayes DIC=166.1	
	β	s.d.	β	s.d.	β	s.d.	β	s.d.
Left turns	0.47	0.28	0.44	0.26	0.46	0.28	0.45	0.26
Opposing	0.55	0.46	0.49	0.39	0.52	0.34	0.53	0.31
Opposing LT	-0.04	0.36	0.07	0.31	--	--	--	--

4.5 Using the Results

To summarize, a matched case-control sample of 436 left-turn crashes occurring at MnDOT intersections was compiled by determining the hour during which the crash occurred (the case) and then randomly selecting five non-crash hours for that same day (the controls). Because a matched case-control sample cannot identify the effect of features common to the cases and controls the intersection approaches in the full sample were divided into eight categories according to type of left-turn protection, opposing speed limit, and potential for sight-distance obstructions to the left-turning drivers. Hourly left-turn, opposing, and opposing left-turn volumes were estimated for each case and control hour and generalized linear models which related variation in left-turn crash risk to variation in hourly volumes were fit to the case-control data. For the six approach categories which had sample sizes of 20 or more the opposing left-turn volume had a negligible effect on variation in crash risk. Of these, for categories 5 and 6 it was not possible to reliably separate the effect of opposing volume from that of left-turn volume. For the three categories with the largest sample sizes Bayes estimates of the model parameters, computed assuming that the available hourly volumes were uncertain estimates of the actual volumes, were essentially similar to the estimates computed assuming no measurement error.

Given estimates of the coefficients a comparison of the risk for a left-turning crash during a target hour t to the risk during a reference condition 0 can be computed using the relationship

$$RR = \frac{P(crash \mid x_{1,t}, x_{2,t}, x_{3,t})}{P(crash \mid x_{1,0}, x_{2,0}, x_{3,0})} \approx \exp\left(\beta_1 \ln\left(\frac{x_{1,t}}{x_{1,0}}\right) + \beta_2 \ln\left(\frac{x_{2,t}}{x_{2,0}}\right) + \beta_3 \ln\left(\frac{x_{3,t}}{x_{3,0}}\right) \right) \qquad (4.8)$$

Here $x_{1,t}$,$x_{2,t}$,$x_{3,t}$ denote the hourly volumes of left-turn, opposing, and opposing left-turn traffic during the target hour and $x_{1,0}$,$x_{2,0}$,$x_{3,0}$ denote the corresponding volumes in a reference condition. For example, Table 4.4 gives the estimated coefficients for the two-predictor model for Category 1 intersections, $\hat{\beta}_1$=0.38, $\hat{\beta}_2$=0.37, $\hat{\beta}_3$=0. Substituting these into equation (4.8) with

$x_{1,0}$ = 100 vph
$x_{2,0}$ = 500 vph
$x_{3,0}$ = 0 vph

and letting the left-turn and opposing volumes vary over a plausible range of possibilities produces the contour graph shown in Figure 4.5. (The product of the left-turn and opposing volumes in this reference condition, 50,000, defines a condition where it is recommended that protective left-turn treatments be considered (FHWA 2010), while the left-turn volume of 100 vph has traditionally defined a point where protective phasing could be considered.) In Figure 4.5 the contour 1.5 identifies combination of opposing and left-turn volumes where the risk of a left turn crash is 50% greater than for the reference volumes, the 2.0 contour identifies volume combinations where the risk is double, and so forth.

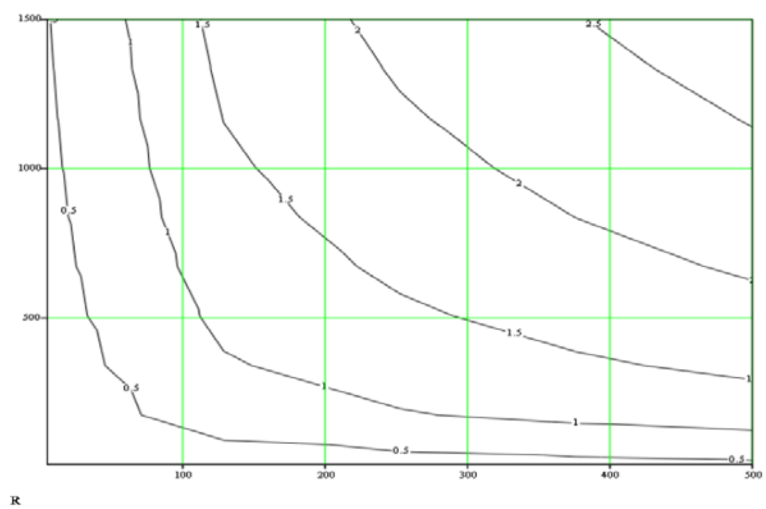


Figure 4.5 Relative risk of left-turn crash as a function of left-turn volume (x-axis) and opposing volume (y-axis).

A potentially more useful application of equation (4.8) would be to predict the variation in left-turn crash risk on a particular intersection approach throughout the 24 hours of a typical day. This can be done by starting with a turning movement sample, using the method described in Chapter 3 to estimate the turning movement volumes for hours not included in the sample, and then using equation (4.8) to predict risk variation for each of the 24 hours. As an example, Table 4.7 shows a turning movement sample for northbound left turs at the intersection of Robert and Mendota, in Inver Grove Heights. Using this sample, left turn and opposing hourly volumes were estimated and these, along with error bars showing the ± 1 standard deviation range are shown in Figure 4.6.

Table 4.7 Turning movement sample for northbound at Robert and Mendota.

	Hour of Count							
	6-7	**7-8**	**8-9**	**11-12**	**12-13**	**15-16**	**16-17**	**17-18**
Left Turn (veh/hour)	43	68	125	91	134	67	88	73
Opposing (veh/hour)	219	363	421	649	822	726	842	836

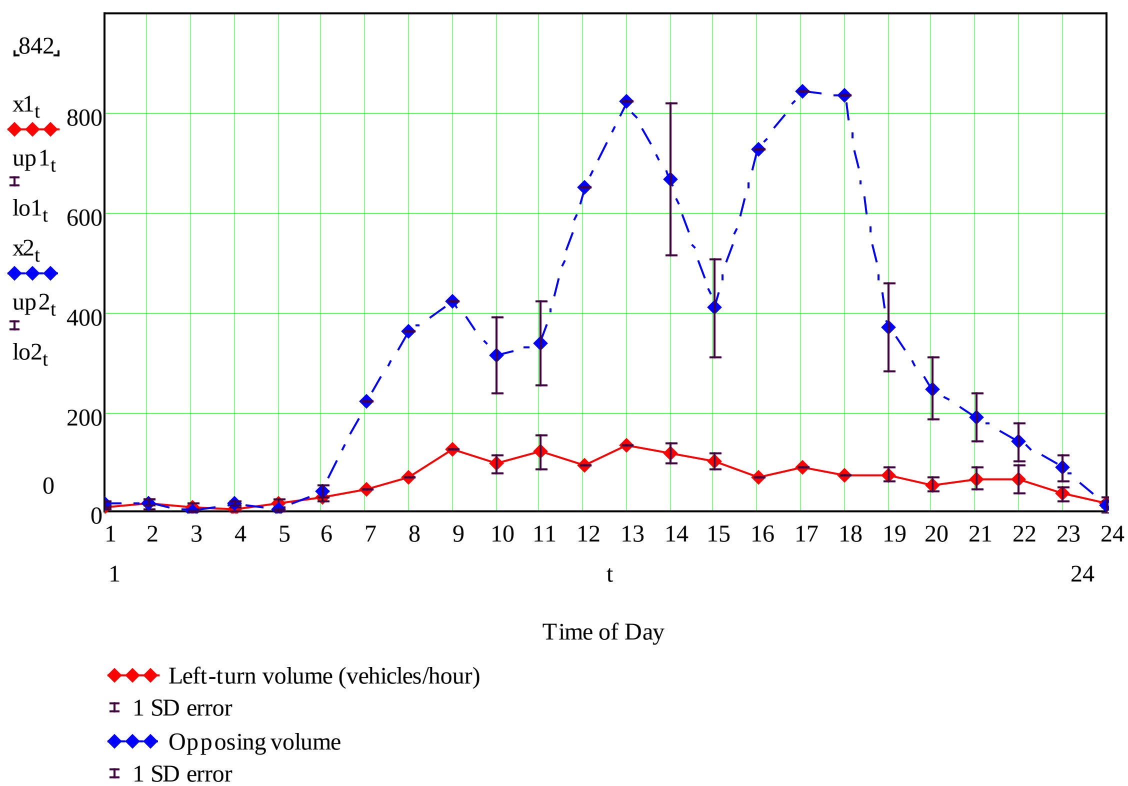


Figure 4.6 Estimated hourly movement volumes, northbound left turns at Robert and Mendota

Taking the volume estimates shown in Figure 4.6 as inputs, equation (4.8) was then used to compute hourly values for relative risk, again with reference values x1,0 = 100 vehicles/hour and x2,0 = 500 vehicles/hour. These are shown in Figure 4.7, again with error bars indicating ± 1 standard deviation ranges.

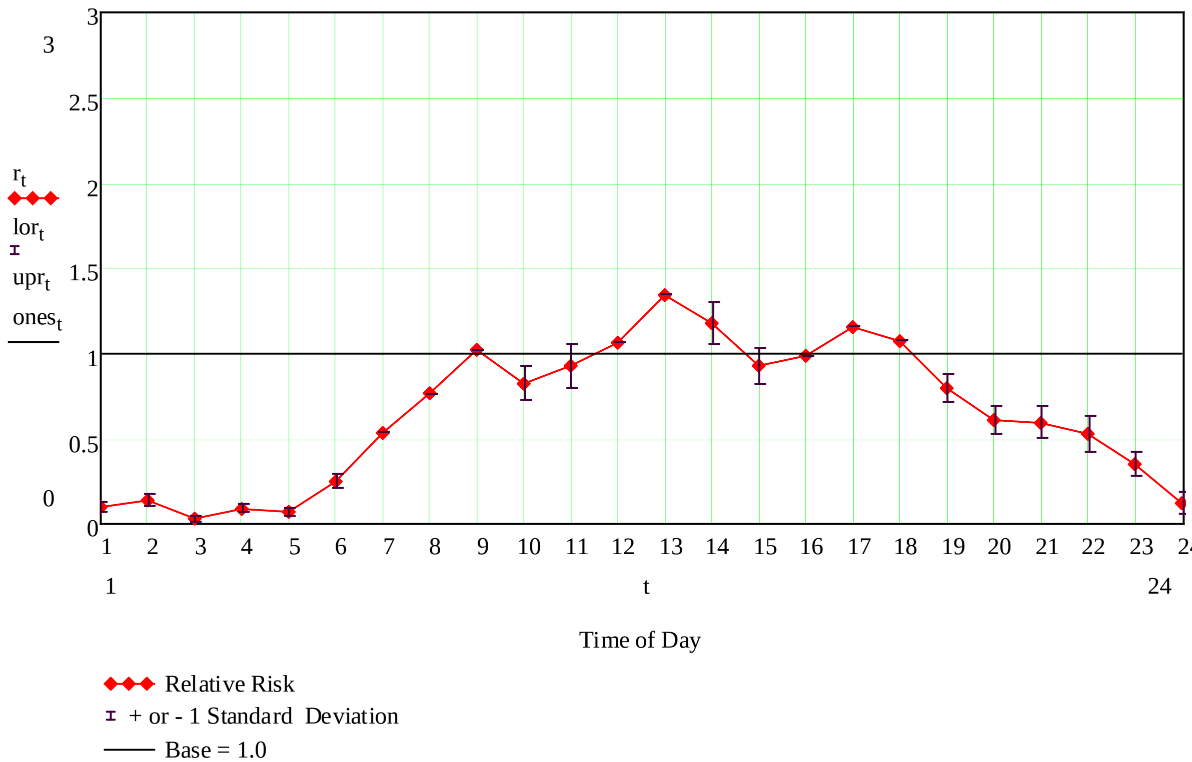


Figure 4.7 Variation of relative risk for left-turn crash during 24 hours of representative day. Northbound left turns at Robert and Mendota.

CHAPTER 5

5. SPREADSHEET TOOL

This chapter belongs to the activities under task 7 of the project. A spreadsheet tool was developed to help signal operation personnel understand how the relative risk (RR) of left turn crashes varies during the day as turning movement counts vary. This spreadsheet tool embeds the statistical models described in Chapter 4 for different types of intersection approaches. It takes the geometric measurements and turning movement counts as input from the user and produces 24-hour RR diagrams.

5.1 Spreadsheet Tool

The spreadsheet tool has 3 main parts:

- SD condition: the first sheet
- RR diagrams: sheets 2, 3
- Supporting data: the last two sheets

All input cells are highlighted green. Users, normally, do not need to change any other cells.

5.1.1 SD Condition

The first step of using the spreadsheet tool is to determine whether or not the intersection approach of interest has a sight distance issue. The answer to this question is one of the factors determining which model coefficients should be used to predict relative risk. Figure 5.1 shows the contents of sheet "SD issue" which is used for this purpose. The procedure starts with a question regarding the existence of opposing LT movements. If the answer to this question is no, the approach does not have a SD problem. No further calculations are needed and user can move forward to the RR sheet. Otherwise, a set of input variables (the green list) is needed in order to calculate required SD (RSD) and available SD (ASD). The first two variables are used to calculate the RSD and the rest are needed for ASD. All these variables are shown in the diagram. However, there are considerations regarding some of these variables.

The number of opposing lanes is the number of lanes that a left-turning vehicle has to cross to complete a left-turn maneuver, including the right-turn lane unless the right turn lane is channelized as a free right turn. In other words, the opposing lanes are those lanes to which the LT vehicle must yield.

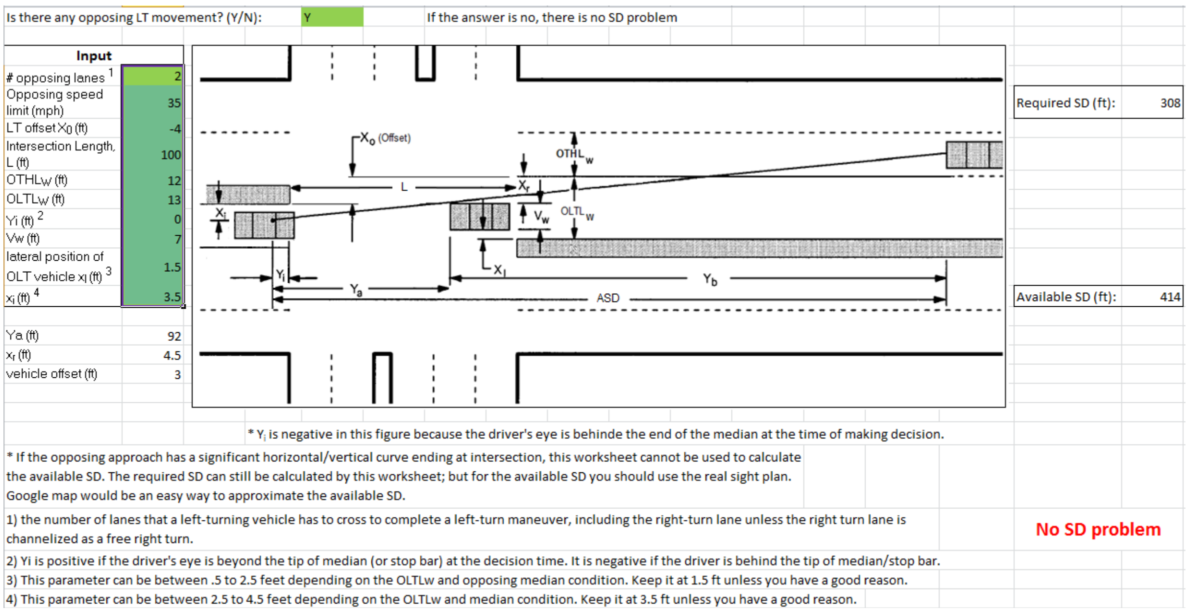


Figure 5.1 Contents of the "SD issue" sheet

Y_i is the longitudinal distance from the tip of the median (or stop bar) to the driver's eye; positive if inside the intersection and negative if behind the intersection. <u>For a majority of intersections Y_i can be considered zero</u>, meaning that the driver's eye is just at the start of the intersection (either end of median or stop bar). At some intersections, though, drivers may advance into the intersection while waiting for an adequate gap. At these situations a reasonable positive value for this variable should be considered. The eastbound and westbound approaches of the intersection shown in Figure 5.2 are examples of such situations ($Y_i \approx 20$ feet would be reasonable for these two approaches).

V_w is the width of the design vehicle and can be taken to be 7 feet, unless the user has a good reason for taking a different value.

X_l is the lateral distance of the left edge of the opposing left-turn vehicle from the left lane strip. This variable is usually between .5 to 2.5 feet depending on the opposing left-turn lane width (OLTLw) and the opposing median condition. User should keep it at 1.5 feet unless s/he has a good reason otherwise.

X_i is the lateral position of driver's eye from the left lane strip. This variable is usually between 2.5 to 4.5 feet depending on the left-turn lane width and median condition. User should keep it at 3.5 feet unless s/he has a good reason otherwise.

Important note: the reference point for measuring $OLTL_w$, X_l, and X_i is the lane strip and not the edge of median.

If RSD > ASD, there is a potential SD problem.

Figure 5.2 Eastbound and westbound approaches: typical locations at which Y_i>0

5.1.2 RR Diagrams

The spreadsheet tool, currently, serves three types of intersection approaches, all with protected/permitted LT signals:

1. Low speed (<45 mph), no sight distance problem
2. Low speed (<45 mph), with sight distance problem
3. High speed (≥45 mph), with sight distance problem

Based on the user input information in the "SD issue" sheet, the tool identifies the intersection type and applies the respective coefficients. If a high speed approach with no sight distance problem is identified, the user will be notified that this tool cannot at present be used. Figure 5.3 shows the contents of the RR sheet. The following sections are recognizable:

1. Model parameters: RR beta coefficients which were estimated in Chapter 4 for each approach type. This should not be edited by the user and they are locked to prevent inadvertent changes.
2. Base condition: The reference turning movement volumes for RR calculations. Higher base volumes result in lower RR and vice versa.
3. Available turning movement counts: Enter the available turning movement counts for the desired approach (in Figure 5.3, for example, these were available for the hours ending at 7, 8, and 9 AM, 12, 1, 4, 5, and 6 PM). If a count is not available for an hour leave that cell blank.

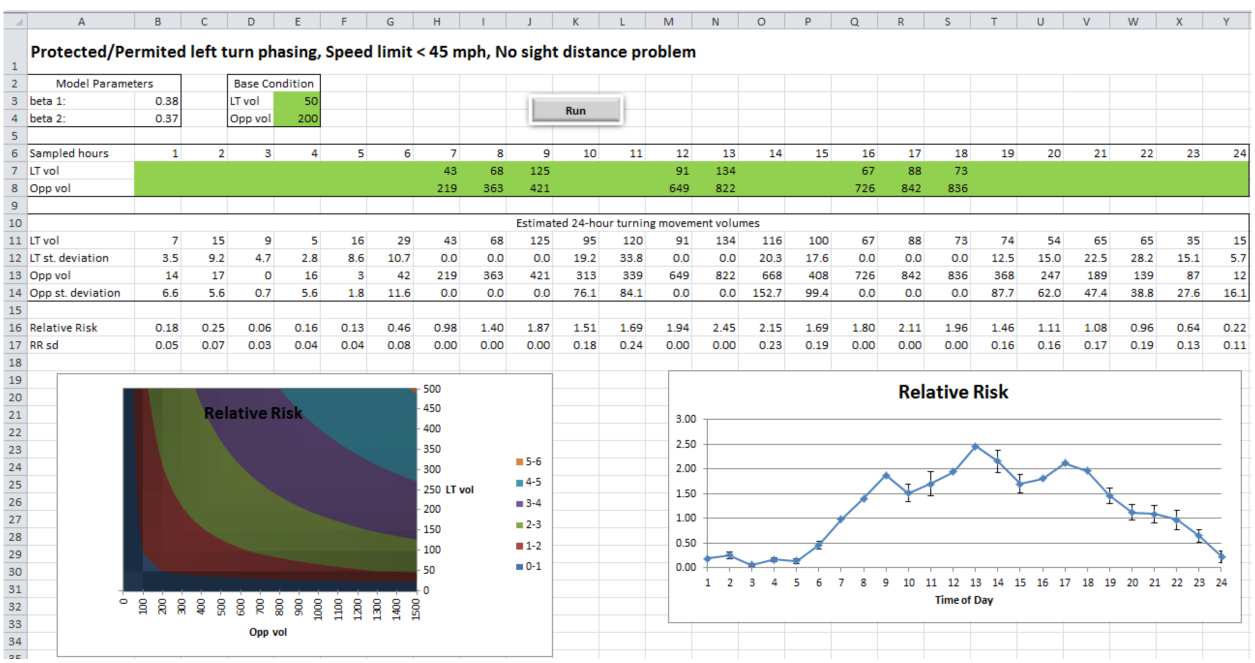
Important note: The opposing volume means the conflicting volumes include those movements to which a left-turn vehicle must yield. So, it usually means through + right turns but occasionally means only through movement. The latter case happens when the right turn is channelized by a traffic island and is no longer a conflicting turning movement.

4. 'Run' button: Press this button to run the VBA macro to first compute estimated hourly volumes for the times when turning movement counts are not available. The macro will also compute the standard deviations associated with these volume estimates.
5. Estimated 24-hour turning movement volumes: the macro will print 24-hour volumes (including counts and estimates) and their standard deviations in this range of the sheet. Although this part is not a user-input part of the sheet, it cannot be locked (protected). Protecting these sheets will cause a run error because it prevents the macro from writing into these cells.
6. 24-hour relative risks: Using model parameters from part 1 and volume estimates from part 5, this part automatically computes the relative risk for a left-turn crash occurring in each of the 24 hours of the sample day. It also computes the standard deviation for each RR.
7. RR Contour map: it displays how relative risk of a left-turn crash at this type of intersection approach varies as a function of LT and opposing hourly volumes.
8. 24-hour RR diagram: This is the final product of the tool. It plots the risk for each hour along with a ±1 standard deviation range for the relative risk estimates.

Caution: User must not insert any row or column into the RR sheet. Doing so will crash the tool because it will cause the macro to read or write using the wrong cells.

5.1.3 Supporting Data

The last two sheets of the tool contain information to support Macro program and contour diagrams. Users normally do not need to edit or even look at the information in these sheets; therefore, they are protected with the password "DavisMoshtagh".



Protected/Permited left turn phasing, Speed limit < 45 mph, No sight distance problem

Model Parameters	
beta 1:	0.38
beta 2:	0.37

Base Condition	
LT vol	50
Opp vol	200

Sampled hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
LT vol							43	68	125			91	134			67	88	73						
Opp vol							219	363	421			649	822			726	842	836						

Estimated 24-hour turning movement volumes

LT vol	7	15	9	5	16	29	43	68	125	95	120	91	134	116	100	67	88	73	74	54	65	65	35	15
LT st. deviation	3.5	9.2	4.7	2.8	8.6	10.7	0.0	0.0	0.0	19.2	33.8	0.0	0.0	20.3	17.6	0.0	0.0	0.0	12.5	15.0	22.5	28.2	15.1	5.7
Opp vol	14	17	0	16	3	42	219	363	421	313	339	649	822	668	408	726	842	836	368	247	189	139	87	12
Opp st. deviation	6.6	5.6	0.7	5.6	1.8	11.6	0.0	0.0	0.0	76.1	84.1	0.0	0.0	152.7	99.4	0.0	0.0	0.0	87.7	62.0	47.4	38.8	27.6	16.1

Relative Risk	0.18	0.25	0.06	0.16	0.13	0.46	0.98	1.40	1.87	1.51	1.69	1.94	2.45	2.15	1.69	1.80	2.11	1.96	1.46	1.11	1.08	0.96	0.64	0.22
RR sd	0.05	0.07	0.03	0.04	0.04	0.08	0.00	0.00	0.00	0.18	0.24	0.00	0.00	0.23	0.19	0.00	0.00	0.00	0.16	0.16	0.17	0.19	0.13	0.11

Figure 5.3 Relative risk sheet of the tool

5.2 A Caveat

The prediction tool relies on statistical models, developed using data from intersections in the Twin Cities metro area. Applying it to other regions should only be done when there is good reason to believe that the statistical models developed in Chapters 3 and 4 are transferable to these regions.

CHAPTER 6

6. CONCLUSION

6.1 Summary

This report described development of a tool to support time-of-day changes between protective and permissive left-turn treatments. A review of existing literature indicated that while models do exist for predicting annual totals of LT crashes, predicting how risk varies throughout the day is still an open question. In order to accommodate data availability and quality issues it was decided to employ a matched case-control study design rather than the traditional cross-sectional design. The cases consisted of 436 left-turn crash events occurring at signalized intersections operated by MnDOT. For each case, five hourly periods for the same intersection approach and on the same day as that of the case were then randomly chosen. For both the case and control hours the left-turn volume, the opposing volume, and the opposing left-turn volume were estimated by developing statistical models for adjusting available turning movement counts to the appropriate days and hours. These hourly volumes were then used as independent variables in logistic regression models which used the traffic volumes to discriminate times when crashes occurred from times when crashes were absent. Because a matched case-control design does not allow one to analyze the effect of features that are common to both the cases and controls, such as speed limits or geometric features, the crash-occurring intersections were classified according to opposing speed limit, the type of LT protection, and whether or not the intersection's geometrics indicated that a left-turning driver's sight distance could be obstructed by an opposing left-turning vehicle. Separate statistical models were estimated for each intersection type. The resulting statistical models were then incorporated into a spreadsheet tool which uses the statistical model appropriate for the intersection approach's type to compute how the relative risk for a left-turn crash varies as the hourly traffic volumes vary throughout the 24 hours of the day.

6.2 Extensions

For those intersection types where data were sufficient to estimate relative risk models, the tool developed in the project should provide a useful complement to operations-based tools such as Synchro and the *Highway Capacity Manual*. However, discussions with potential users have suggested several extensions of this work. First of course, is incorporating additional intersection types. This is mainly an issue of sample size and data collection; once a sufficient sample of case events is available, either by extending the time period over which the cases are collected or extending the sample to include county and/or municipal intersections, model development can proceed as described in Chapters 3 and 4. Second, it has been suggested that a simpler procedure for determining sight distance issues be included. This would require first determining if the new procedure and the original procedure made the same determinations. If so, the new procedure could simply replace the old one; if not, then the relative risk models described in Chapter 4 would have to be re-estimated. Once this had been accomplished, however, modifying the spreadsheet tool would simply involve substituting the new values for the $\boldsymbol{\beta}$ coefficients. Finally, there is the question of transferring the tool to regions not included in our sample. The prediction tool relies on statistical models, and while a well-developed statistical model can provide a reasonable description of the data used to develop it, there is no guarantee that the model can be extrapolated to situations outside the data range. The data used to develop the tool came entirely from the intersections in the Twin Cities metro area. Applying it to other regions should only be done when there is good reason to believe that the statistical models developed in Chapters 3 and 4 are transferable to these regions.

REFERENCES

AASHTO (2010). *Highway Safety Manual*, American Association of State Highway and Transportation Officials, Washington, DC.

Apiah, J., and B. Cottrell (2014). "Safety and Operational Impacts of the Optional Flashing Yellow Arrow Delay", *Transportation Research Record*, **2463**, 26-34.

Bedrick, E., and J. Hill (1996). "Assessing the Fit of Logistic Regression Models to Individual Matched Sets of Case-Control Data", *Biometrics*, **52**, 1-9.

Brehmer, C., K. Kacir, D. Noyce, and M. Manser (2003). *Evaluation of Traffic Signal Displays for Protected/Permitted Left-Turn Control*, NCHRP Report 493, National Cooperative Highway Research Program, Washington DC.

Carroll, R., D. Ruppert, and A. Stefanski (1995). *Measurement Error in Nonlinear Models*, Chapman Hall.

Chen, L., C. Chen, and R. Ewing (2012). "Left Turn Phasing: Permitted, Protected, or Both", *Proceedings of 91st Annual Meeting of the Transportation Research Board*, Paper 12-3252, Jan. 21-26, Washington, DC.

FHWA (2009). *Manual on Uniform Traffic Control Devices*, Federal Highway Administration, Washington DC.

Hauer, E. (2004). *Left-Turn Protection, Safety, Delay, and Guidelines: A Literature Review*, Federal Highway Administration, U.S. Department of Transportation, Washington DC.

Hosmer, D., and S. Lemeshow (2000). *Applied Logistic Regression, 2nd edition*, Wiley, NY.

Johnson, L., S. Kotz, and A. Kemp (1992). *Univariate Discrete Distributions*, 2nd edition, Wiley, NY.

Liu, H., W. Ma., X. Wu, and H. Hu (2009). *Development of a Real-Time Arterial Performance Monitoring System using Traffic Data Available from Existing Signal Systems*, Report 2009-10, Minnesota Dept. of Transportation, St. Paul Minnesota.

Lunn, D., C. Jackson, N. Best, A. Thomas, and D. Spiegelhalter (2014). *The BUGS Book: A Practical Introduction to Bayesian Analysis,* CRC Press, Boca Raton, FL.

Maxfield, B. (2009). *Essential Mathcad, 2nd edition*, Academic Press, Burlington, MA.

Moolgavkar, S., E. Lustbader, and D. Venzon (1985). "Assessing the Adequacy of the Logistic Regression Model for Matched Case-Control Studies", *Statistics in Medicine*, **4**, 1095, 425-435.

Noyce, D., C. Bergh, and J. Chapman (2007). *Evaluation of the Flashing Yellow Arrow Permissive-Only Left Turn Indication Field Implementation*, NCHRP Report W123, National Cooperative Highway Research Program, Washington DC.

Pulugurtha, S. and K. Khader (2014). "Assessing the Effect of Introducing a Permitted Phase Through the Use of Flashing Yellow Arrow Signal for Left-Turning Vehicles", *International journal of Injury Control and Safety Promotion*, **21(4)**, 338-337

Qi,Y., X. Chen, L. Yu, Y. Wang, M. Zhang, P. Yuan and K. Persaud (2012). *Use of Flashing Yellow Arrow Operations to Improve Safety at Signals with Protected-Permissive Left Turn (PPLT) Operations*, Report FHWA/TX-09/0-9568-1, Federal Highway Administration, Washington DC.

Radwan, E., H. Abou-Senna, A. Navarro, and S. Chalise (2013). *Dynamic Flashing Yellow Arrow (FYA): A Study on Variable Left Turn Model Operational and Safety Impacts*, Report to Florida Dept. of Transportation, Tallahassee, FL.

Srinivasan, R., C. Lyon, B. Persaud, J. Baek, F. Gross, S. Smith, and C. Sundstrom (2012). "Crash Modification Factors for Changes to Left-Turn Phasing", *Transportation Research Record*, **2279**, 2012, 108-117.

Wang, X., and M. Abdel-Aty (2008). "Modeling left-turn crash occurrence at signalized intersections by conflicting patterns", *Accident Analysis and Prevention*, **40**, 76-88.

Yang, S. and G. Davis (2002). "Bayesian Estimation of Classified Mean Daily Traffic", *Transportation Research A*, **36**, 365-382.

APPENDIX A

Code for Spreadsheet Tool Macro

Appendix A
Code for Spreadsheet Tool Macro

```
Sub volEst1()
'This subroutine estimates turning movement volumes of non sampled hours

Dim t As Integer, k As Integer, i As Integer, j As Integer
Dim nSamp As Integer, Shift As Integer
Dim nPatLt As Integer, nPatTh As Integer
Dim vLtSum As Single, vOppSum As Single
Dim pnSum As Double
Dim CinvDet As Double
Dim alphLt As Double
Dim alphOpp As Double

Dim vLt() As Double
Dim vOpp() As Double
Dim yy() As Variant
Dim ltPatSum(1 To 70) As Integer
Dim lpn() As Double
Dim pn() As Double
Dim pMatchLt(1 To 70) As Double
Dim pMatchTh(1 To 63) As Double
Dim thPatSum(1 To 63) As Integer
Dim ltEst(1 To 24) As Double
Dim ltSd(1 To 24) As Double
Dim ltSdTemp As Double
Dim oppEst(1 To 24) As Double
Dim oppSd(1 To 24) As Double
Dim oppSdTemp As Double
Dim ltPat(1 To 24, 1 To 70) As Integer
Dim thPat(1 To 24, 1 To 63) As Integer
Dim rhoLt(1 To 24, 1 To 70) As Double
Dim rhoTh(1 To 24, 1 To 63) As Double
Dim SM
Dim rhoPick() As Integer
Dim muLt() As Variant
Dim muTh() As Variant
Dim C() As Variant
Dim Cinv() As Variant

nPatLt = 70
nPatTh = 63
nSamp = WorksheetFunction.CountA(ActiveSheet.Range("B7:Y7"))
'MsgBox "The # of samples is " & nSamp
ReDim rhoPick(1 To nSamp)
ReDim vLt(1 To nSamp)
ReDim vOpp(1 To nSamp)
ReDim muLt(1 To nSamp - 1)
ReDim muTh(1 To nSamp - 1)
ReDim C(1 To nSamp - 1, 1 To nSamp - 1)
ReDim Cinv(1 To nSamp - 1, 1 To nSamp - 1)
ReDim yy(1 To nSamp - 1)
ReDim lpn(1 To 70)
ReDim pn(1 To 70)
```

```
alphLt = 0.01
alphOpp = 0.05
Shift = 0 'The number of rows above the Model Parameters

' Recognizes sampled hours
i = 0
For t = 1 To 24
   If Not ActiveSheet.Cells(Shift + 7, 1 + t) = "" Then
      i = i + 1
      rhoPick(i) = t
   End If
Next t

' Reads sampled turning movement volumes and sums them up
vLtSum = 0
vOppSum = 0
For i = 1 To nSamp
   vLt(i) = ActiveSheet.Cells(Shift + 7, 1 + rhoPick(i)).Value
   vOpp(i) = ActiveSheet.Cells(Shift + 8, 1 + rhoPick(i)).Value
   vLtSum = vLtSum + vLt(i)
   vOppSum = vOppSum + vOpp(i)
Next i


If nSamp < 24 Then
' Reads 24-hour LT patterns
For t = 1 To 24
   For k = 1 To nPatLt
      ltPat(t, k) = Worksheets("LT 24-h paterns").Cells(t, k).Value
   Next k
Next t

' Sums up volumes of LT patterns over sampled hours to be used in rho calculations
For k = 1 To nPatLt
   ltPatSum(k) = 0
   For i = 1 To nSamp
      ltPatSum(k) = ltPatSum(k) + ltPat(rhoPick(i), k)
   Next i
Next k

' Computes rhos
For k = 1 To nPatLt
   For t = 1 To 24
      rhoLt(t, k) = WorksheetFunction.Max(0.0001, ltPat(t, k) / ltPatSum(k))
   Next t
Next k

' Computes pMatches for each LT pattern
pnSum = 0
For k = 1 To nPatLt
   For i = 1 To nSamp - 1
      muLt(i) = vLtSum * rhoLt(rhoPick(i), k)
      For j = 1 To nSamp - 1
         C(i, j) = -1 * rhoLt(rhoPick(i), k) * rhoLt(rhoPick(j), k) * vLtSum
      Next j
```

```
        C(i, i) = muLt(i) + C(i, i)
        yy(i) = vLt(i) - muLt(i)
    Next i
    Cinv = WorksheetFunction.MInverse(C)
    CinvDet = WorksheetFunction.MDETERM(Cinv)
    With WorksheetFunction
        SM = .MMult(yy, .MMult(Cinv, .Transpose(yy)))
    End With
    lpn(k) = 0.5 * Log(CinvDet) - 0.5 * SM(1)
    pn(k) = Exp(lpn(k))
    pnSum = pnSum + pn(k)
Next k
For k = 1 To nPatLt
    pMatchLt(k) = pn(k) / pnSum
Next k

' Estimates and prints LT volumes and associated standard deviations
For t = 1 To 24
    ltEst(t) = 0
    ltSdTemp = 0
    For k = 1 To nPatLt
        ltEst(t) = ltEst(t) + pMatchLt(k) * rhoLt(t, k) * vLtSum
    Next k
    ActiveSheet.Cells(11, 1 + t).Value = ltEst(t)
    For k = 1 To nPatLt
        ltSdTemp = ltSdTemp + pMatchLt(k) * rhoLt(t, k) * vLtSum * (rhoLt(t, k) + 1 + rhoLt(t, k) * vLtSum + alphLt
* rhoLt(t, k) * (1 + vLtSum))
    Next k
    ltSd(t) = Sqr(ltSdTemp - ltEst(t) ^ 2)
    ActiveSheet.Cells(12, 1 + t).Value = ltSd(t)
Next t
For i = 1 To nSamp
    ActiveSheet.Cells(11, 1 + rhoPick(i)).Value = ActiveSheet.Cells(7, 1 + rhoPick(i)).Value
    ActiveSheet.Cells(12, 1 + rhoPick(i)).Value = 0
Next i

' Reads 24-hour Th patterns
For t = 1 To 24
    For k = 1 To 63
        thPat(t, k) = Worksheets("TH 24-h paterns").Cells(t, k).Value
    Next k
Next t

' Sums up volumes of Th patterns over sampled hours to be used in rho calculations
For k = 1 To nPatTh
    thPatSum(k) = 0
    For i = 1 To nSamp
        thPatSum(k) = thPatSum(k) + thPat(rhoPick(i), k)
    Next i
Next k

' Computes rhos
For k = 1 To nPatTh
    For t = 1 To 24
        rhoTh(t, k) = WorksheetFunction.Max(0.0001, thPat(t, k) / thPatSum(k))
    Next t
```

```
Next k

' Computes pMatches for each Th pattern
ReDim C(1 To nSamp - 1, 1 To nSamp - 1)
ReDim Cinv(1 To nSamp - 1, 1 To nSamp - 1)
ReDim yy(1 To nSamp - 1)
ReDim lpn(1 To 63)
ReDim pn(1 To 63)
ReDim SM(1 To 1)
pnSum = 0
For k = 1 To nPatTh
   For i = 1 To nSamp - 1
      muTh(i) = vOppSum * rhoTh(rhoPick(i), k)
      For j = 1 To nSamp - 1
         C(i, j) = -1 * rhoTh(rhoPick(i), k) * rhoTh(rhoPick(j), k) * vOppSum
      Next j
      C(i, i) = muTh(i) + C(i, i)
      yy(i) = vOpp(i) - muTh(i)
   Next i
   Cinv = WorksheetFunction.MInverse(C)
   CinvDet = WorksheetFunction.MDETERM(Cinv)
   With WorksheetFunction
      SM = .MMult(yy, .MMult(Cinv, .Transpose(yy)))
   End With
   lpn(k) = 0.5 * Log(CinvDet) - 0.5 * SM(1)
   pn(k) = Exp(lpn(k))
   pnSum = pnSum + pn(k)
Next k
For k = 1 To nPatTh
   pMatchTh(k) = pn(k) / pnSum
Next k

' Estimates and prints Opp volumes
For t = 1 To 24
   oppEst(t) = 0
   oppSdTemp = 0
   For k = 1 To nPatTh
      oppEst(t) = oppEst(t) + pMatchTh(k) * rhoTh(t, k) * vOppSum
   Next k
   ActiveSheet.Cells(13, 1 + t).Value = oppEst(t)
   For k = 1 To nPatTh
      oppSdTemp = oppSdTemp + pMatchTh(k) * rhoTh(t, k) * vOppSum * (rhoTh(t, k) + 1 + rhoTh(t, k) *
vOppSum + alphOpp * rhoTh(t, k) * (1 + vOppSum))
   Next k
   oppSd(t) = Sqr(oppSdTemp - oppEst(t) ^ 2)
   ActiveSheet.Cells(14, 1 + t).Value = oppSd(t)
Next t
For i = 1 To nSamp
   ActiveSheet.Cells(13, 1 + rhoPick(i)).Value = ActiveSheet.Cells(8, 1 + rhoPick(i)).Value
   ActiveSheet.Cells(14, 1 + rhoPick(i)).Value = 0
Next i

Else
   For i = 1 To 24
      ActiveSheet.Cells(11, 1 + i).Value = ActiveSheet.Cells(7, 1 + i).Value
      ActiveSheet.Cells(12, 1 + i).Value = 0
```

```
        ActiveSheet.Cells(13, 1 + i).Value = ActiveSheet.Cells(8, 1 + i).Value
        ActiveSheet.Cells(14, 1 + i).Value = 0
    Next i
End If

End Sub
```