Development of Guidelines for Flashing Yellow Arrows for Protected/Permissive Use

A Thesis
SUBMITTED TO THE FACULTY OF
THE UNIVERSITY OF MINNESOTA
BY

Vahid Moshtagh

IN PARTIAL FULFILLMENT OF THE REQUIERMENTS
FOR THE DEGREE OF MASTER OF SCIENCE

Advisors:
Professor Gary A. Davis
Dr. John Hourdos

August 2015

Acknowledgement

I would like to express my sincerest gratitude to my co-advisors Professor Gary Davis and Dr. John Hourdos for their strong support and generous guidance throughout my Master studies. Also, I would like to thank Kevin Schwartz and Nicole Flint, of MnDOT, for their assistance throughout the course of the project and their helpful comments on the spreadsheet tool.

Dedication

To my lovely wife and my supportive friend, Shadi Oskooi for everything.

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. In order to relate relative risk values with crash frequency, a method was suggested to combine historic left-turn crashes at the approach of interest with the relative risk contour diagram. This method can be used to identify the threshold relative risk at which a left-turn phasing should change from permitted to protected.

Table of Contents

List of Figures and Tables

1. Introduction

1.1 Background

Accommodating left-turning vehicles at intersections in a safe manner has always been a challenging task for traffic engineers and an area of concern for decision makers of each community. Typically a protected left-turn (LT) phasing eliminates the conflict between left-turners and opposing traffic because it gives the right of way to left-turners and requires opposing traffic to stop. However, it tends to increase the cycle length and consequently the delay particularly when the traffic is light. A permitted left-turn phasing, on the other hand, provides the opportunity for left-turners to use adequate gaps in opposing traffic. So, it can decrease the total delay experienced by them while increases the chance of a LT crash. A protected-permitted left-turn (PPLT) phasing, where a protective interval is followed (lead) or preceded (lag) by a permissive interval, became a standard practice nationwide because it could combine safety benefits of protected mode and operational advantages of permitted mode. However, identifying an appropriate indication for PPLT phasing that can be clearly comprehended by drivers was a field of interest for more than a decade.

In 2003 a report commissioned by the National Cooperative Highway Research Program (NCHRP) recommended that the flashing yellow arrow (FYA) indication be used to indicate permitted left-turns (Brehmer et al 2003). The FYA indication was later adopted by the 2009 edition of the *Manual of Uniform Traffic Control Devices* (FHWA 2009). FYA indications are being installed at more and more intersections throughout the country and have become the standard for new signal installations on Minnesota highways as NCHRP report 493 recommends to MUTCD: “The four-section, all-arrow display face should be the only display allowed.”

In addition to better comprehension of drivers from FYAs, this indication enables signal operation staffs to implement a time-of-day variable LT protection. That is, protective, permissive, or PPLT treatments can be varied throughout the day as traffic conditions might warrant. Signal timing/optimization programs such as Synchro or traffic simulation tools can be used to predict the operational effects of different LT modes; but, predicting how the risk of LT crashes might vary as traffic conditions change is an open question. Since safety is also a very important consideration when operating an intersection, in Fall 2012 this research undertook to develop a model which predicts within-day variation of left-turn crash risk.

1.2 Literature Survey

The literature on the safety aspects of different modes of left-turn control is extensive. Hauer (2004) reviewed 36 papers and reports in an attempt to support the *Highway Safety Manual* (HSM). He summarizes that protective phasing had the lowest crash rate while the safety performance of permissive-only and protective-permissive were quite comparable. Hauer pointed out that many of these studies suffered from methodological weaknesses which limited the conclusions that could be drawn from them. One of those common weaknesses is aggregating data over a number of intersections which can most likely obscure any important differences among those intersections. This problem can also arise when data is aggregating over all approaches of an intersection which may have fundamental differences in potential predictors. The HSM currently contains two crash modification factors (CMF) for changes in left turn protection. The CMF for changing from permissive to protective phasing is 0.01, indicating a 99% reduction in left turn crashes, and 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 3-54 (Brehmer et al 2003) conducted an extensive investigation of practices regarding different PPLT displays which included agency surveys, laboratory studies of drivers' comprehension of different signal displays, a cross-sectional study comparing the crash rates associated with different displays, and field observations of traffic conflicts involving left-turns. For the crash data analysis different rates, crash rate per year, crashes per 100 left-turning, crashes per 100,000 left turning vehicles multiplied by opposing through vehicles, and crash rate per intersection were calculated for various PPLT displays in eight different cities. The study concluded that a flashing circular yellow indication for permitted left-turns usually had a lower crash rate and the circular green indication which was

MUTCD's standard display had the highest rate. 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 (five locations).

Wang and Abdel-Aty (2008) identified 197 four-legged signalized intersections in Florida, classified different left-turning maneuvers into 9 patterns and conducted a cross-sectional study of left-turn crash frequency. They fitted statistical models which related crash frequency to approach features such as the left-turn and opposing average daily traffic (ADT) volumes, opposing speed limit, median condition, the type of left-turn protection (permissive, compound, and protective), the number of opposing lanes, the type of left-turn offset (negative, zero, or positive), and a factor variable representing the two study counties. A Generalized Estimating Equations (GEE) approach was adopted because disaggregating an intersection to its approaches may result in correlated data. This method was compared to a Negative Binomial approach which treated the crashes at different approaches of an intersection as independent. The GEE models generally gave better fits to the crash data. For 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. The geographical indicator turned out to be significant such that the expected crash frequency in one of the two counties was as twice as in the other one.

Lee, Kweon and Dittberner in (2011) focused on three- or four-legged signalized intersections in Northern Virginia. The study intersections included those with one or more lanes of opposing traffic, with left-turn five-section signal heads for protective-permissive left-turn phasing. Five-year crash data from 2003 to 2007 and signal inventory data were used to investigate the frequency of permissive left-turn right-angle crashes during a permissive phasing at an approach-level rather intersection-level. For this purpose, 681 approaches were filtered to be analyzed among which 214 were found only in the signal inventory database and not in the crash database indicating that these locations were not involved in any reported permissive left-turn right-angle crashes for the five years. Also, crash database may have missing years for some intersection approaches. Thus, it was necessary to impute zero crash to these missing locations or years. The panel negative binomial regression model with the compound symmetry correlation structure was employed to develop a safety performance function (SPF) or crash prediction model. The reason for this choice is that the data were collected for multiple years at the same set of intersections; so they are panel data. Besides, the dependent variable (crash frequency per year) is a non-negative integer which typically has skewed distribution; so a negative binomial model is the natural choice. The number of legs turned out to be uninfluential. Speed limit was found to be positively related to crash occurrence but was not statistically significant even at 20% significance level. The final fitted model contained the number of opposing lanes and natural logarithm of AADT. The authors suggested that protective-permissive left-turn phasing is better to be avoided at intersections with three or more opposing lanes under an AADT of about 45,000.

Ozmen, Tian and Gibby (2014) evaluated safety performance of a novel method for operating protected-only left-turn phasing during peak periods at approaches that normally operated with standard MUTCD protected-permitted left turn phasing. Crash data at 10 intersections in Las Vegas were intended to be compared between a 2-year before period and a 2-year after period. The two periods were separated by a one-year period during which the new phasing plan was implemented. At some of these intersections, only the approach with leading LT phase was operated with protected-only phase to eliminate the yellow trap condition. The researchers employed three methods including simple before-after study, before-after study with a comparison group, and LT crash rate calculation. Only left-turn crashes occurring during special time-of-day operation were considered and the crossing approaches were used as comparison group.

Using the first two methods, left-turn crashes showed an increase but the increase was not statistically significant mainly due to the very small sample size. Also, the average crash rate was 0.45 crashes/MEV for both before and after periods. It was concluded that the switch to time-of-day protected left-turn phasing did not cause an obvious safety problem, so it can be considered as a measure to improve operational efficiency. It was also stated that the small sample size and low power of this study warranted caution in generalizing these results.

NCHRP 705 described a set of empirical Bayes before/after studies aimed at estimating CMFs for different safety strategies at signalized intersections two of which were changing permissive LT phasing to PPLT phasing and installation of FYA for permissive left turn as part of an updated HSM methodology. The aggregated estimated LT CMF for changing from protected phasing to permitted phasing using FYA was 2.242, indicating an approximate 120% increase in left-turn crashes. The aggregated CMF for changing from permitted phasing using green-ball to PPLT phasing using FYA was 0.635, indicating an approximate 36% decrease in left-turn crashes while changes from PPLT five-section head to PPLT FYA showed a statistically insignificant decrease in left-turn crashes. It also suggests an approach-level LT CMF of 0.776 and intersection-level CMF of 0.86 for changing left-turn phasing from permitted to protected-Permitted. However, all types of crashes had an insignificant increase at both approach and intersection levels. CMFs for those intersections with more than 1 treated approach were usually smaller than those with only one treated approach.

Srinivasan et al (2012) published more methodological details of the previous study only focusing on the two aforementioned treatments: (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%. The aggregated LT CMF was 2.242 as stated earlier. 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 0.53 and 0.64, reflecting decreases in left-turn crashes ranging between 36% and 47%. These results are roughly consistent with those reported in Noyce et al (2007): When protective phasing are replaced with FYA 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.

Chen et al (2015) evaluated the effectiveness of two changes in left turn protection on different crash type including left-turn crashes: (1) change from permissive to PPLT phasing at 59 intersections, and (2) change from permissive to protective left-turn phasing at 9 intersections. They fitted a negative binomial model with the GEE method to perform a before/after study. In addition to the 68 treatment intersections, the study included a comparison group consisting of 991 intersections in New York with permissive left-turn phasing. A direct result of such design is that changes in crash frequency due to the change in left-turn phasing could be differentiated from the general temporal decrease in crash rates. The study period consisted of five years before and two years after the change and the treatment time spanned from 2000 to 2007. Since traffic volume information was not available to the authors, they used the socio-demographic and land use related variables at census tract level as a measure of effectiveness. 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. This implies an increase in the crash rate when a permissive-only phasing was replaced with a PPLT phasing although the increase was not found to be statistically significant. In consistency with many other studies, replacing permissive left-turn phasing with protective-only phasing reduced left-turn crashes.

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. 11 variables were identified as potential predictors of permitted left-turn volume during the hour: 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. Forward 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.

Rietgraf and Schattler in their 2013 study examined the differences of drivers' behavior at three different permissive left-turn displays: circular green (CG), FYA and flashing red arrow (FRA). The second purpose of this study was to see if implementing multiple left-turn indications has any effect on driver understanding of the CG display. So, a two phase comparative analysis was conducted based on field observations and video taping of driver actions. Six t-intersections for phase one and four four-leg intersections for phase two were investigated in two cities in Illinois. Safety and efficiency of drivers' actions were considered as the measures of effectiveness. That is, any sequence of actions by drivers was classified into the safe or unsafe and the efficient or inefficient action. The drivers' actions observed for this classification included gap size accepted, rejected adequate gap size, slowing down or stopping the vehicle, and presence or absence of oncoming traffic. In order to minimize the impacts of uncontrollable variables, the authors asserts that the study intersections within the three comparison groups were selected to be as similar as possible to each other, with the exception of the indication for the permissive left-turn interval. The comparison between the tree displays indicated that drivers executed safer actions at FRA indications than CG or FYA. However, FRA had the lowest percent of the efficient actions. Significantly higher percent of drivers at FYAs executed a combination of safe and efficient actions than CG display. Comparing drivers' behavior between two cities (one with only CG and the other with multiple indications) in the second phase revealed that the use of multiple types of PPLT control had no negative impact on driver's safety- or efficiency-related behavior. Further studies with larger sample size were suggested before making any policy-related decisions.

Schattler et al (2013) conducted research to evaluate the effectiveness of upgrading the CG indication to the FYA indication on driver comprehension and traffic operations at 16 intersections in Illinois. For the first part an online survey was sent out in two phases with an 11 month gap to detect changes in drivers' comprehension over time. There was no statistically significant difference between the two phases. A total of 363 drivers were asked how they would respond when confronted with seven scenarios. These scenarios were built by a combination of left-turn signal display (CG, FYA, and solid green arrow), adjacent through traffic signal display, and presence or absence of a supplemental traffic sign. The available responses were "Go-You have the right of way", "Yield-Wait for a gap", and "Stop-Wait for signal". The rate of correct, fail-critical, and inefficient responds were calculated based on these three responses. The results of the survey indicated that first; some drivers misunderstand the meaning of a permissive left-turn with CG display and unsafely interpret it as "go". Second, with supplemental sign at the FYA approaches drivers' understanding of the correct "yield" message was significantly improved. Third, drivers have a significantly higher comprehension of the FYA, in terms of taking efficient action, when the adjacent through traffic has a green signal, as compared to a red signal. For the second part of the Study, a before-after comparison was made within 16 study approaches using five variables comprising median gap size accepted, red light running, yellow light running and traffic conflicts. No significant differences were observed in the median gap size accepted and traffic conflicts. The effect on the other variables was minimal and unconvincing. Overall, the FYA did not appear to have any negative impacts on traffic operations.

1.3 Methodology Overview and Outline of Study

The goal of this study initially was to develop a model that can predict the expected frequency of LT crashes at hourly level. So, it can be used by different jurisdictions' engineers to distinguish high-risk times of day from benign hours for a permitted LT phasing. A general term for such models is safety performance function (SPF) which is a statistical model that relates the frequency of crashes to observable/measurable features such as traffic volumes, speed limits, traffic control types, geometric properties, or even socioeconomic variables. The review of literature identified three studies reporting SPFs for predicting left-turn crash frequency: Wang and Abdel-Aty (2008), Lee et al (2011), and Srinivasan et al (2012). 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 works attempted to model crash frequency per hour. Preliminary investigations revealed that developing an *hourly* SPF would not be feasible mainly for two reasons:

1. The accuracy of available crash inventory databases turned out to be questionable as some of left-turned crashes may have been miscoded as right-angle crashes or even other crash types. So, the number of reported LT crashes (dependent variable) from these databases might be inaccurate which will mislead the SPF regression process.
2. The size of required dataset for developing an SPF will exponentially increase when a high-resolution (hourly) SPF is aimed instead of an

aggregated SPF. Simple arithmetic shows why this is the case. A study of say, 300 sites over a five-year period, using crashes/year as its dependent variable, would require a data file of 3000 rows, one for each site-year. A study of the same geographical-temporal size with crashes/hour as its dependent variable would require a file of about 26 million rows, one for each site-hour. Even if data management was not an issue, compiling this data file is not practical mainly due to limited availability of hourly turning movement volumes. Turning movement volumes are typically counted during the peak hours on a single, representative, day for signal warrant/ signal timing purposes. In addition, Automatic traffic recorders (ATR) which continuously record hourly traffic volumes exist at very small number of roadway locations.

For all these reasons, it was decided to employ a matched case-control study design rather than the traditional cross-sectional design. A matched case-control design does not rely on the accuracy of the number of reported crashes because it does not use the crash frequency as its dependent variable. Instead, it begins with a representative sample of cases, in this instance hours during which a left-turn crash occurred, and for each case selects a few control events, e.g. hours during which a left-turn crash did not occur. Then, it tries to see how the potential explanatory variables (independent variables) vary between cases (hours with a crash) and controls (hours with no crash). 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 400 crashes with 5 controls for each case would require a data file with 2400 rows. Second, the results of this method will not be affected by the crash type misidentification problem. On the other hand, a disadvantage of such study design is that the resulting statistical model will not predict the expected frequency of LT crashes, but only how the risk of a LT crash varies in comparison to a 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 $1x10^{-6}$ but that the probability of a left-turn crash between 4 PM and 5 PM was $3x10^{-6}$. A case-control design could only estimate that the 4-5 PM risk was triple that of 10-11 PM. This limitation was considered acceptable as long as the results of a relative-risk analysis could be presented in a readily-interpreted form, a user-friendly spreadsheet tool in this case.

In what follows, Chapter 2 describes the process of data collection while Chapter 3 describes the methods used to characterize sight distance for left-turning vehicles, to estimate turning movement volumes for case and control hours, and to estimate turning movement daily traffic. Chapter 4 then describes the traditional cross-sectional analysis (SPFs) and 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. Finally, conclusions were summarized in chapter 6 and extension studies were recommended.

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 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 permitted 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 first and then relevant geometric characteristics were collected for a sample of them. Also, the list of LT crashes at these intersections, along with available traffic counts for relevant turning movements, were compiled.

2.1 Identify Candidate Intersections

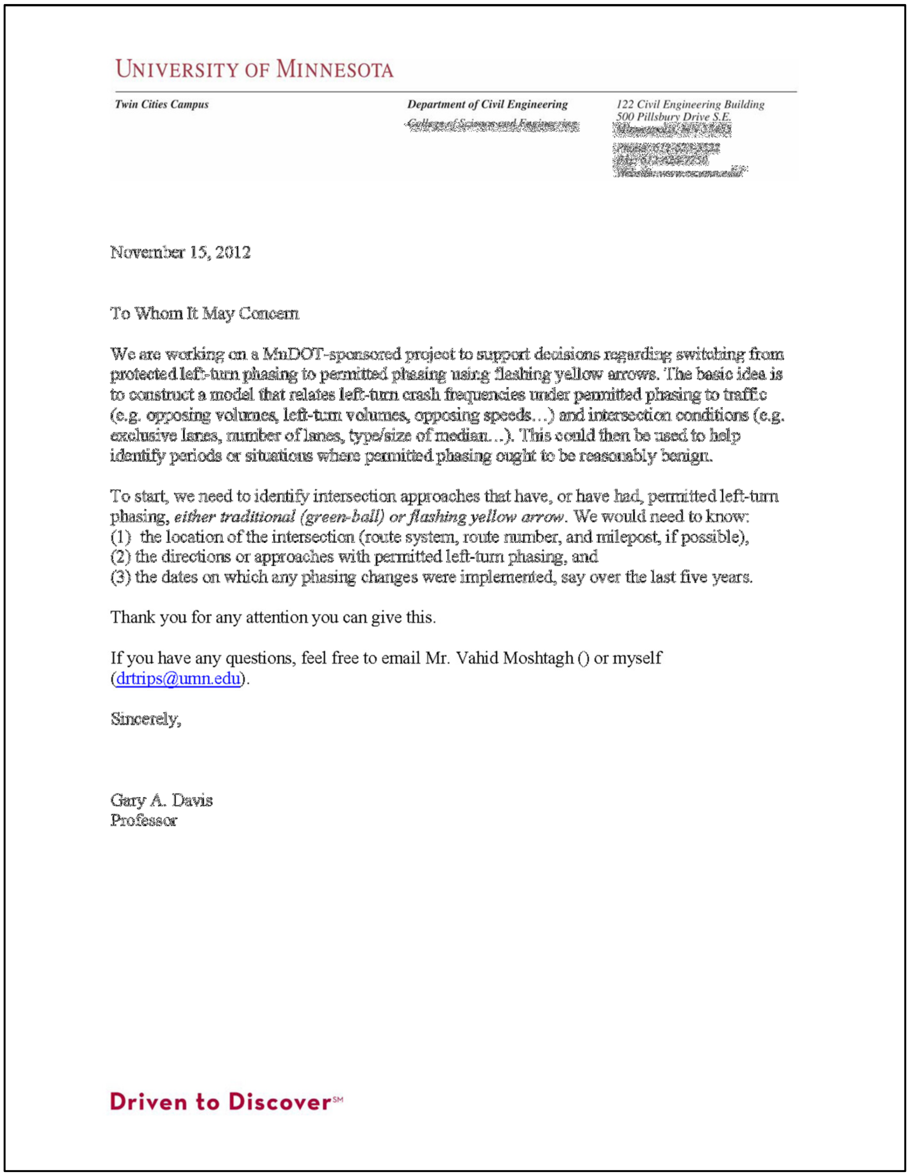
2.1.1 Inquiring Intersections with Permissive Left-Turn Phasing

In order to compile a list of intersections having at list 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 consisted of about 1250 intersections. Excel files provided by different agencies had different formats and included different information. The following is a summary of initial information collected from different agencies.

The initial list from MnDOT included 675 intersections. As compared to the files prepared by counties and cities, 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 (protected, split phase, permissive, protected-permissive, FYA), the number of left-turn lanes, and the speed limit for each leg is already provided. Thus, completing the required information for these intersections was easier and faster than it is for the counties and cities' intersections.

135 intersections were listed by Hennepin County from which 249 approaches had a permissive phasing. 19 intersections among them had FYA. But no more information was provided.



UNIVERSITY OF MINNESOTA

Twin Cities Campus

Department of Civil Engineering

[illegible]

122 Civil Engineering Building
500 Pillsbury Drive S.E.
[illegible]

[illegible]
[illegible]

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.

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. Installing and revising date along with brief phasing information were also included. In addition, Details are provided for 135 County-owned intersections including:

- 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, date of last change and type of previous state of signals were also reported.

16 intersections with PLT were listed by Scout County personnel along with left turn phasing type for each direction. They also mentioned the city in which each intersection is located. This last information will be used later to automatically locate intersections on GIS maps in order to gather geometric characteristics.

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 be also included in Hennepin County list though. Directions with PLT were also identified. If there has been a change in control type, the date was also mentioned.

Bloomington: They only identified two locations which recently owned FYA.

Vadnais Heights: 1 FYA has been implemented for 16 months.

Mendota Heights: There is 11 intersections within this city which have permitted left-turn signal (green ball); but they all are owned and operated by MnDOT or Dakota County.

Hastings: There is 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 are under jurisdiction of Anoka County and MnDOT.

2.1.2 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 metro area. This section summarizes the efforts regarding this issue.

MnDOT

The initial list contained 675 intersections. But, it turned out that not all had an approach with permitted left turns. So, intersections having no approaches with any type 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, 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 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 are ambiguous in terms of type of left-turn signal. Therefore, the existing information about the Ramsey County intersections is not reliable and can be disregarded owing the fact that abundant intersection information has been already acquired.

Cities

Apple Valley: Four of the reported intersections were protected in 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.

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.

2.2 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.

2.2.1 Locating Intersections on GIS Map

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 is 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 first to locate them one by one and find out what city they are located in. this information were 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 locator 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 locator was 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 locating process was carried out. Still few intersections could not be located because of ambiguous addresses or projects constructed recent years.

Figures 2-2 to 2-4 exhibit the distribution of identified intersections over the Twin Cities Metro area. They are well-spread throughout the area.

2.2.2 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 from 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) which 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.

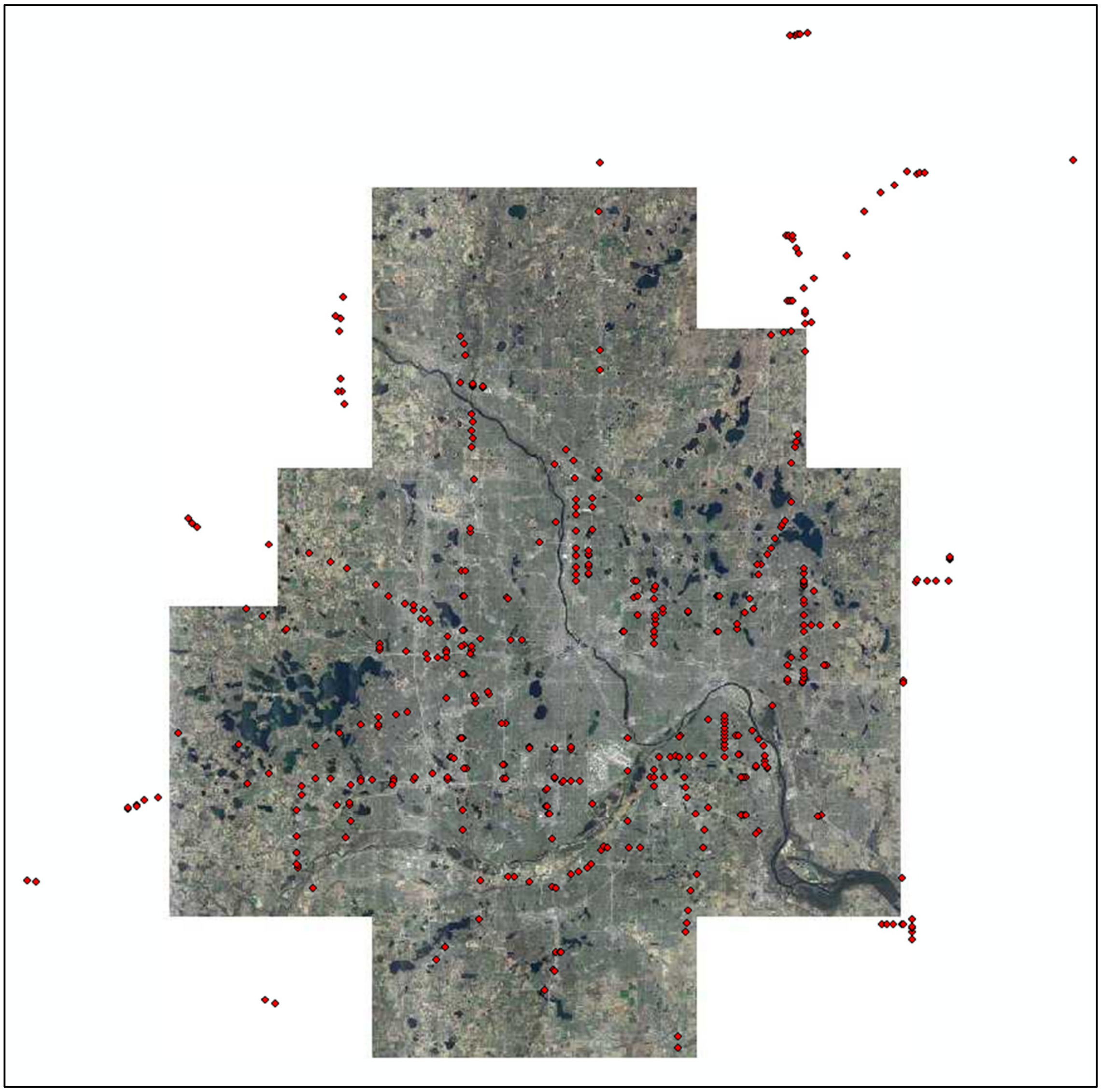


Figure 2-2. Locations of MnDOT intersections with permissive left turn treatments.

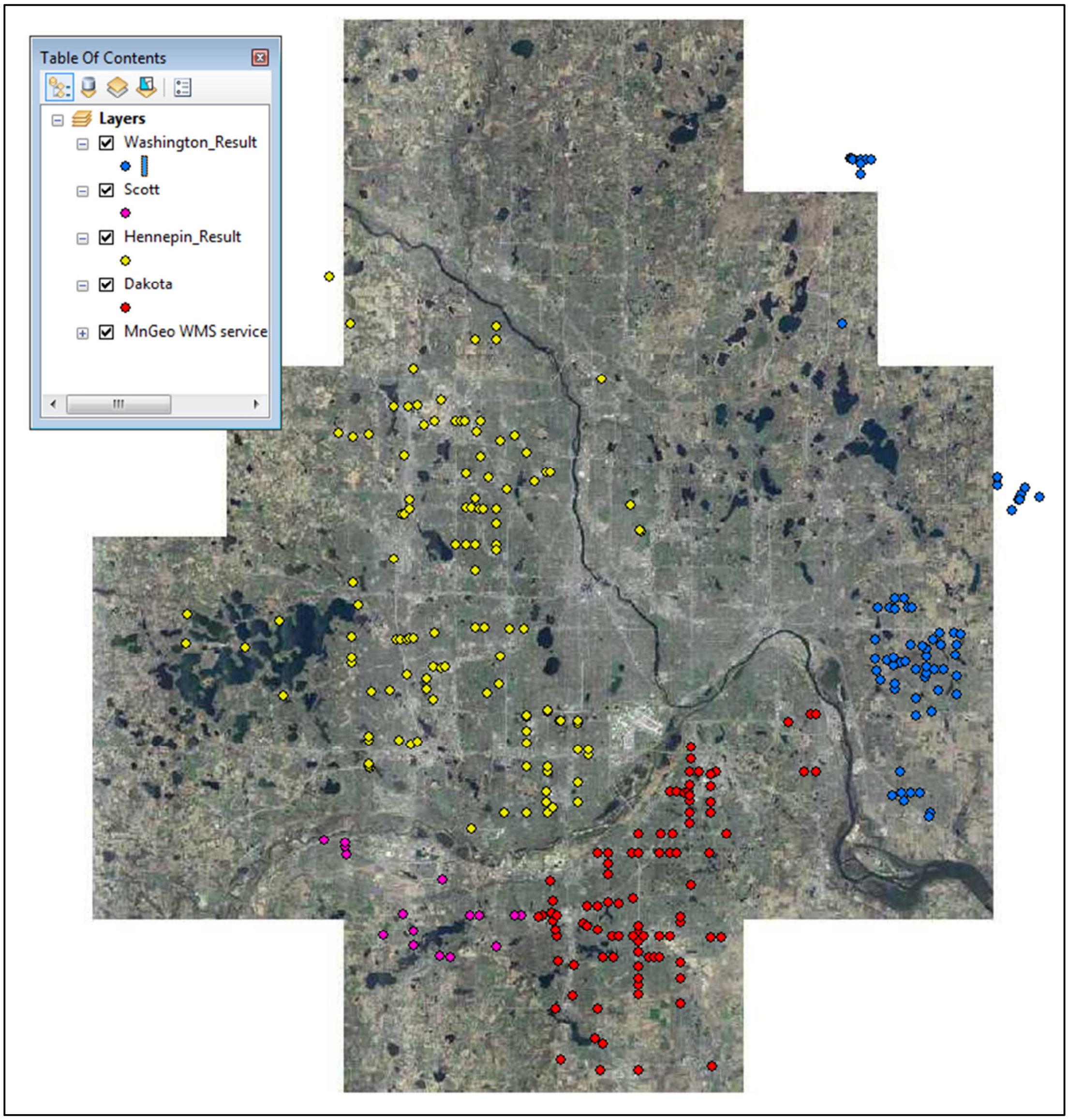


Figure 2-3. Locations of County intersections with permissive left turn treatments.

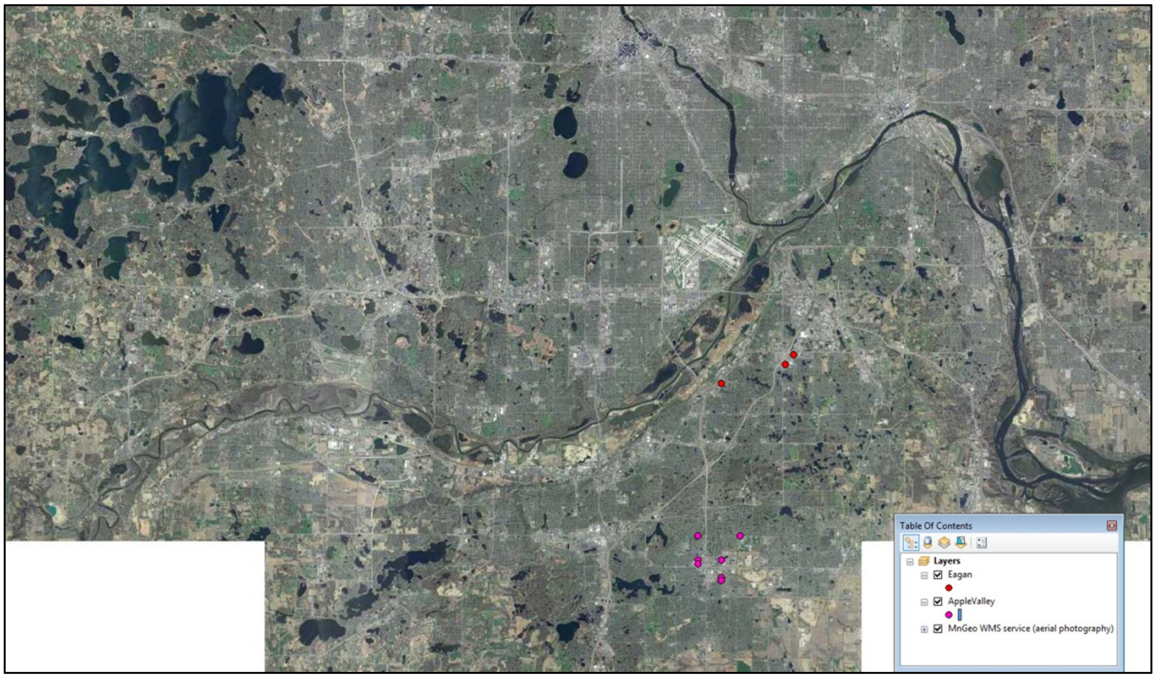


Figure 2-4. Locations of Apple Valley and Eagan intersections with permissive left turn

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+right-turn lanes, median size and offset information were needed to be collected for approaches with permissive left turn. 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 clearly illustrated in the figure 2-5.

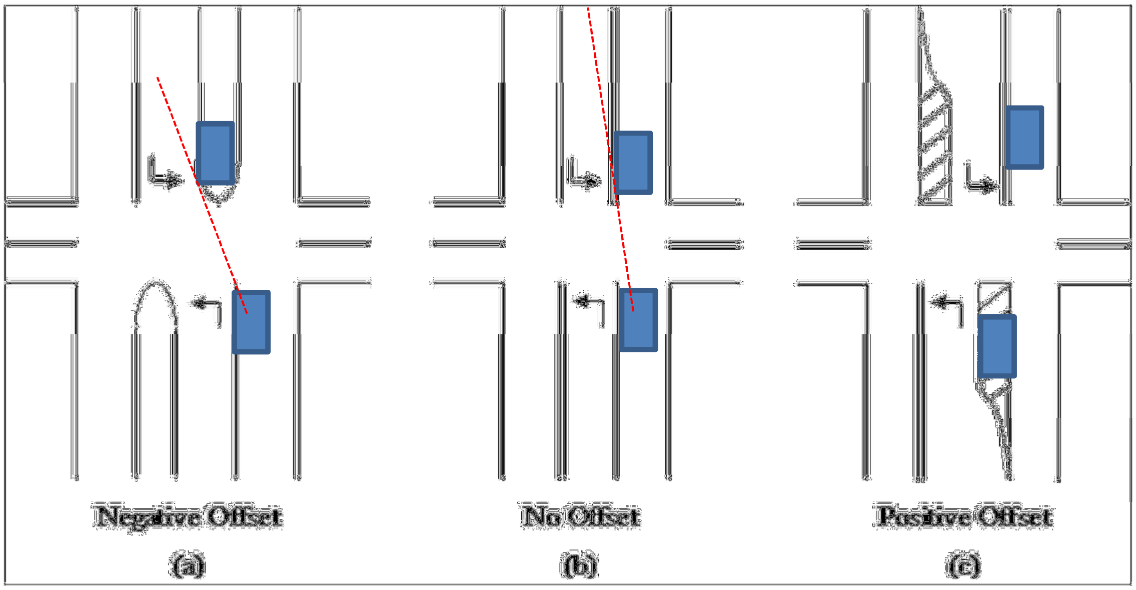


Figure 2-5. Illustration of negative, zero, and positive offset left-turn lanes

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 offset can be different. Figures 2-6 and 2-7 illustrate two examples of different offsets for opposing directions.

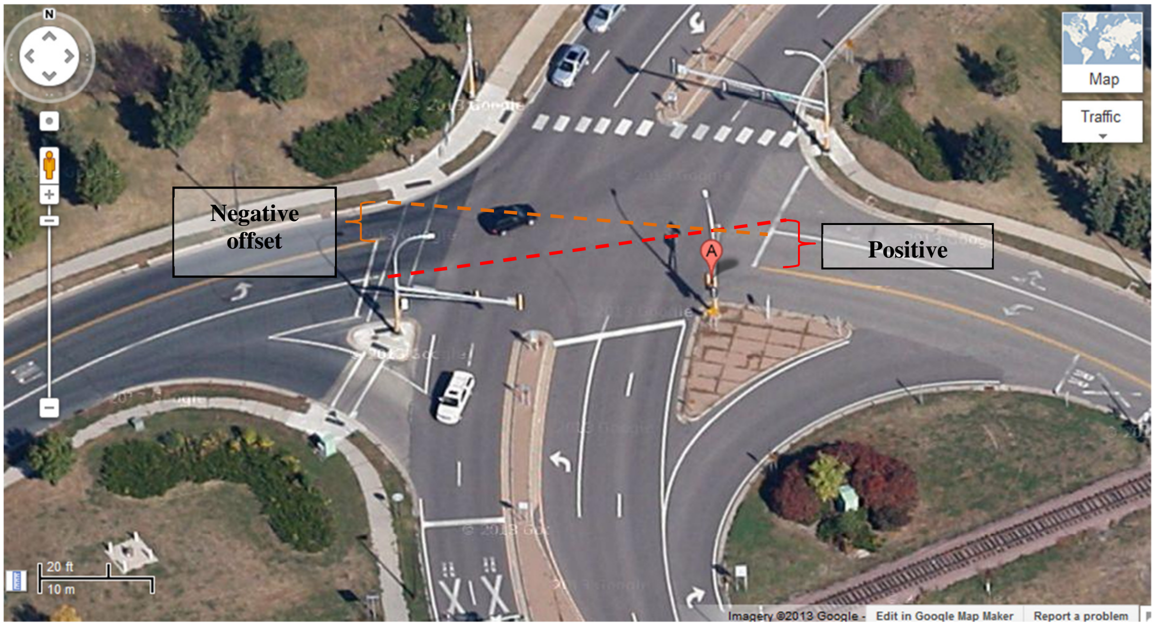


Figure 2-6. Different offsets for opposing approaches; FID 19: MN 101 & W 78th St

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 protected-permissive.
- There were approaches with 1 shared, 1 exclusive, 2exclusive and 1 exclusive + 1 shared left-turn lanes.
- Median width ranges from zero to 30 feet.
- Negative, zero and positive offset were collected.
- Opposing speed limits for approaches with PLT ranged to 65 mph.

Not only each variable have a wide range in our list, but also they have wide combination together; that is, the compiled approaches in the final list fall into many different categories which is an important issue in modeling process. Table 2-1 shows a sample part of the prepared list of intersections. This sample part only contains leg 1 of intersections. The Excel file contains geometric characteristics of all permissive legs of the intersections.

Table 2-1. A sample part of the compiled list of intersections with PLT along with their control types geometric characteristics

ARC_City	Intersection	MILEPOST_N	LEG_1_APP	APP1_LT_PH	Column2	1_Nopln	1_medWi	1_offset	APP1_SP
ANOKA	US 10 & W jct MN 47 (Ferry St) NR	224.80700000000	NB	Prot.-perm.	1 shared	2	0	999	30
ANOKA	US 10 & (7) 7th Ave NR	225.37700000000	NB	FYA	1 exclusive	2	10	999	35
EDINA	MN 100 & W 77th St WR	0.37100000000	EB	Prot.-perm.	1 exclusive	2	0	0	30
EDINA	MN 100 & W 77th St ER	0.37300000000	EB	Prot.-perm.	1 exclusive	2	0	0	30
EDINA	MN 100 & W 70th St ER	1.20000000000	EB	Prot.-perm.	2 exclusive	2	10	999	30
MINNEAPOLIS	MN 100 & 36th Ave N ER w/ Master	11.38000000000	EB	Prot.-perm.	1 exclusive	3	10	999	30
CHANHASSEN	MN 101 & West 78th St	13.53600000000	NB	Prot.-perm.	1 exclusive	2	12	-15	30
OTSEGO	MN 101 & (42) River Rd NE Ramp	44.46500000000	EB	Prot.-perm.	1 exclusive	2	7	999	55
MAPLE PLAIN	US 12 & (83) Halgren Rd	146.06200000000	EB	Prot.-perm.	1 exclusive	1	0	0	50
MAPLE PLAIN	US 12 & (29) Baker Park Rd	147.15000000000	EB	Prot.-perm.	1 exclusive	1	0	999	45
ORONO	US 12 & (6) NR Master	148.56000000000	NB	Prot.-perm.	1 exclusive	1	10	-11	50
WAYZATA	US 12 & 101 W Jct NR	154.98000000000	NB	Prot.-perm.	1 shared	2	0	999	35
MAPLEWOOD	MN 120 & I-94 NR	2.20800000000	NB	FYA	1 exclusive	2	21	999	40
MAPLEWOOD	MN 120 & 3M Innovation Blvd	2.47300000000	NB	FYA	1 exclusive	2	12	-7	40
HOPKINS	I-394 & PLYMOUTH RD (61) N RAMP	0.75400000000	NB	Prot.-perm.	1 shared	2	20	-26	40
GOLDEN VALLEY	I-394 & N Ramp @ General Mills Blvd	3.41400000000	NB	Prot.-perm.	1 exclusive	2	0	999	40
CHASKA	MN 41 & 2ND STREET	1.75200000000	NB	Permissive	1 shared	2	5	-16	30
CHASKA	MN 41 & (10) 4TH ST	1.88300000000	SB	Permissive	1 shared	2	5	-16	30
CHASKA	MN 41 & (18) LYMAN BLVD	6.23000000000	NB	Prot.-perm.	1 exclusive	1	0	3	50
ANOKA	MN 47 & (30) Pleasant St	20.78000000000	NB	Prot.-perm.	1 shared	1	0	-12	30
MINNEAPOLIS	I-494 & 12TH AV. SR	3.34000000000	SB	Prot.-perm.	1 exclusive	1	0	999	30
BLOOMINGTON	I-494 & (35) PORTLAND SR	3.86000000000	SB	Prot.-perm.	1 shared	2	0	999	35
MINNEAPOLIS	I-494 & NICOLLET AV. SR	4.36000000000	SB	Prot.-perm.	1 shared	2	0	999	30

2.3 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,
- and 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

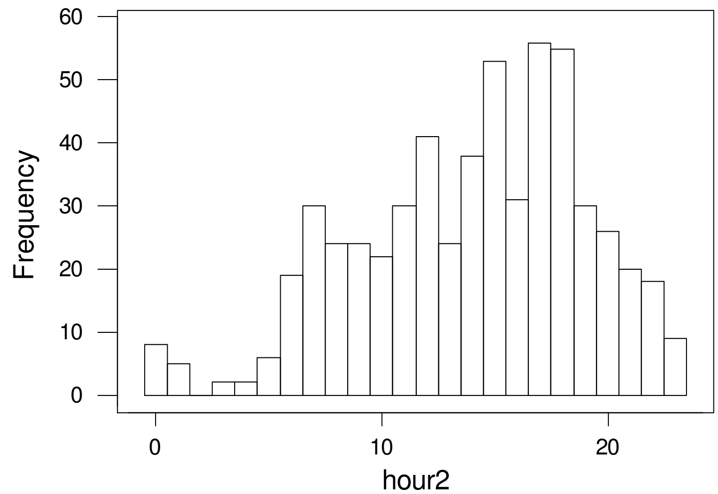


Figure 2-8. Left-Turn Crash Frequency by Time-of-Day

Table 2-2. 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 every single accident, the following variables were investigated through HSIS database and MnDOT list to understand what exactly has 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 2-3 illustrates examples of clear, trivial ambiguous, non-trivial ambiguous and irrelevant crashes.

After investigating 575 accidents, the following results were obtained:

- 21 crashes (3.7%) occurred at 13 intersections have 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 travelling in the same direction or doing the same action (either going thru or LT)
- Rollover crashes and many other non-permitted LT crashes

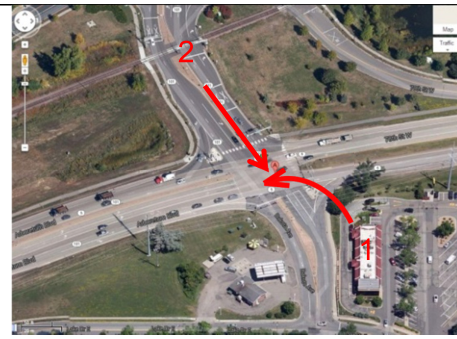
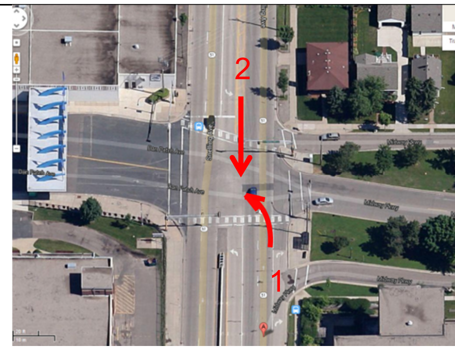
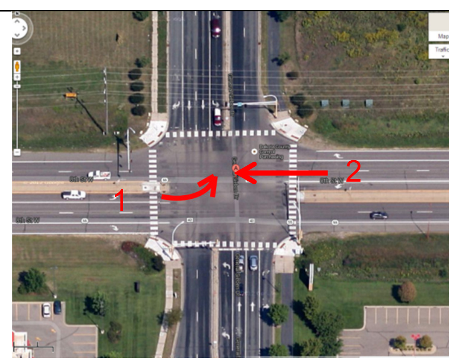
- 261 crashes (45.4%) were clear and straightforward
- 85 crashes (14.8%) were slightly ambiguous but resolvable through making reasonable assumptions.
- 79 crashes (13.7%) were too ambiguous to allow making reasonable assumptions.

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 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.

MnCMAT which is maintained by MnDOT is accessible at http://www.dot.state.mn.us/stateaid/crashmapping.html.

Table 2-3. 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	

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 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. This fulfills the first reason for considering MnCMAT.

The investigation using MnCMAT revealed discrepancies between two databases. The results of this investigation can be summarized as follows:

- 222 new accidents 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 and the rest were presumably irrelevant.
    - 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.

Considering MnCMAT was very essential as many new crashes were added and some crashes were eliminated. So the regression results of the data only based on HSIS could be significantly different from those of HSIS and MnCMAT together. Besides, investigating MnCMAT reduced the number of ambiguous crashes and enhanced the reliability of the case set. Table 2-4 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 final 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 2-4. 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

2.4 Traffic Volume Data

As noted in Chapter 1, the likelihood of a left-turn crash occurring during a given hour 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 count included limited turning movement counts, annual average daily traffic (AADT), 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 is required and AADT will be only used for a complementary regression analysis to develop traditional crash prediction models.

Again as noted in Chapter 1, this 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. Comparing, for example, how hourly traffic volumes differ between the set of cases and the set of controls allows us to determine how the risk of a left-turn crash varies with traffic volume. Therefore, 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. The next chapter explains how traffic volumes are estimated for each case or control using available data.

2.4.1 Turning Movement Counts and Continuous Hourly ATR Counts

Our primary data sources are two webpages 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 are 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. Based on vehicle directions at each crash, corresponding turning movement counts can be retrieved.

For example, one of the crashes at this location (see figure 2-10) occurred on January 9, 2010, between a northbound driver turning left from US highway 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 + 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.

	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

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 of 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 for the crash hour was 235+260=495 vehicles, while on Jan 9, 2010 (a Saturday), the hourly volume was 185+186=371. The ratio of these two, $371/495 = 0.75$, can be used intuitively as the date adjustment factor. 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.

Feb 8, 2006 Wednesday

East: 6 6 3 7 9 32 88 226 144 137 134 158 207 190 233 235 320
319 264 170 102 73 42 25
West: 17 11 8 12 7 17 68 223 155 136 174 162 205 158 253 260 298
266 214 158 153 79 63 24

Jan 9, 2010 Saturday

East: 30 18 12 8 8 18 31 55 96 140 173 216 194 174 185 185 171
221 175 110 93 89 61 48
West: 38 19 21 10 9 11 22 54 94 144 188 213 196 200 170 186 237
181 161 111 106 86 62 50

Figure 2-11. Hourly traffic volumes for ATR 460, for TM count date and crash date from webpage 2

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. Among 499 crashes identified in the previous section, turning movement counts were available for 438. So, the size of our dataset was 438 cases + 5*438 controls = 2628 objects requiring hourly traffic volumes. Figure 2-13 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.

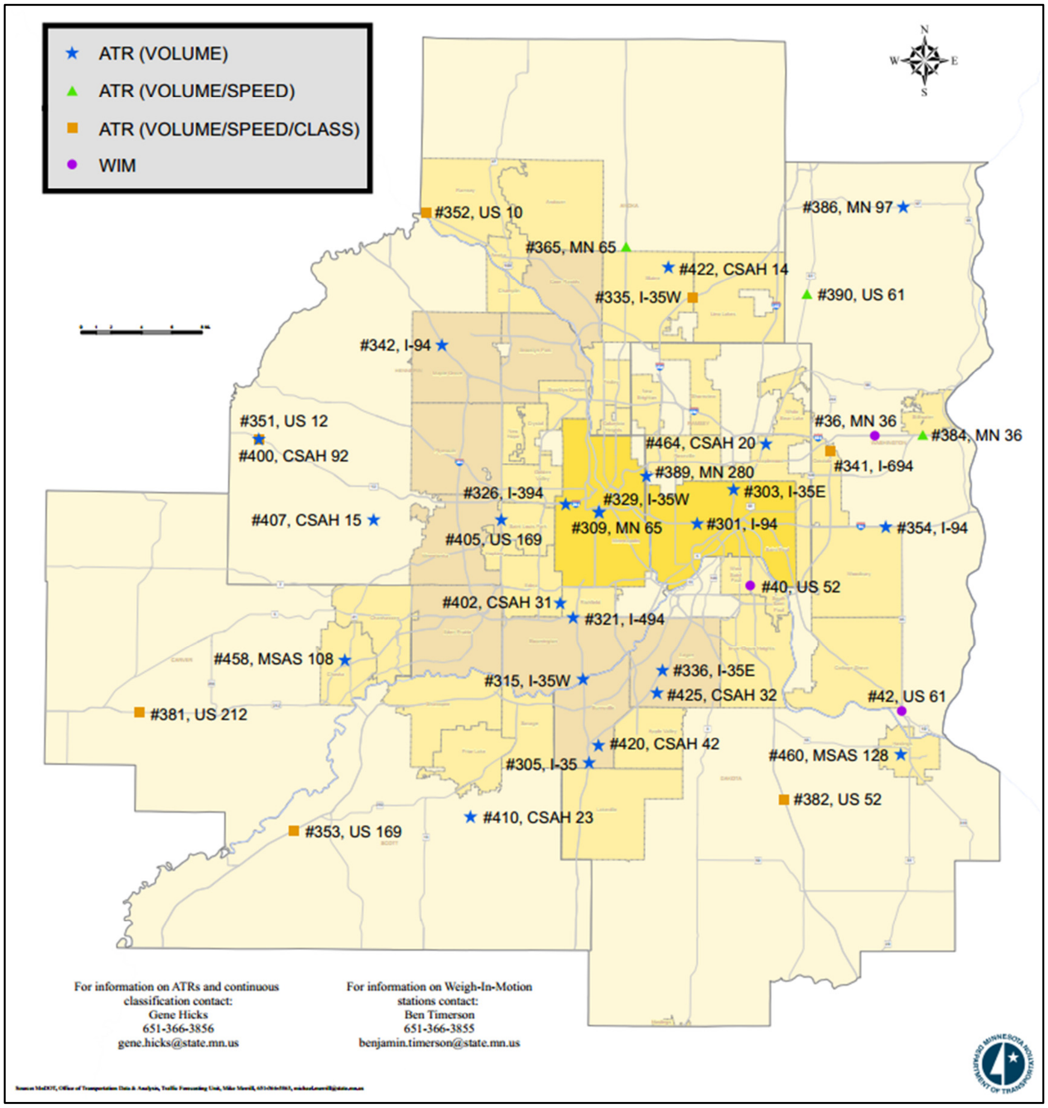


Figure 2-12. Locations of ATRs within Metro area in 2011

	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 2-13. A snapshot from compiled traffic volumes (LT, opposing Th+RT, and opposing LT) for 438 cases and their randomly selected controls

2.4.2 SMART Signal Data

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 next report, Data Preparation. 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.

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.

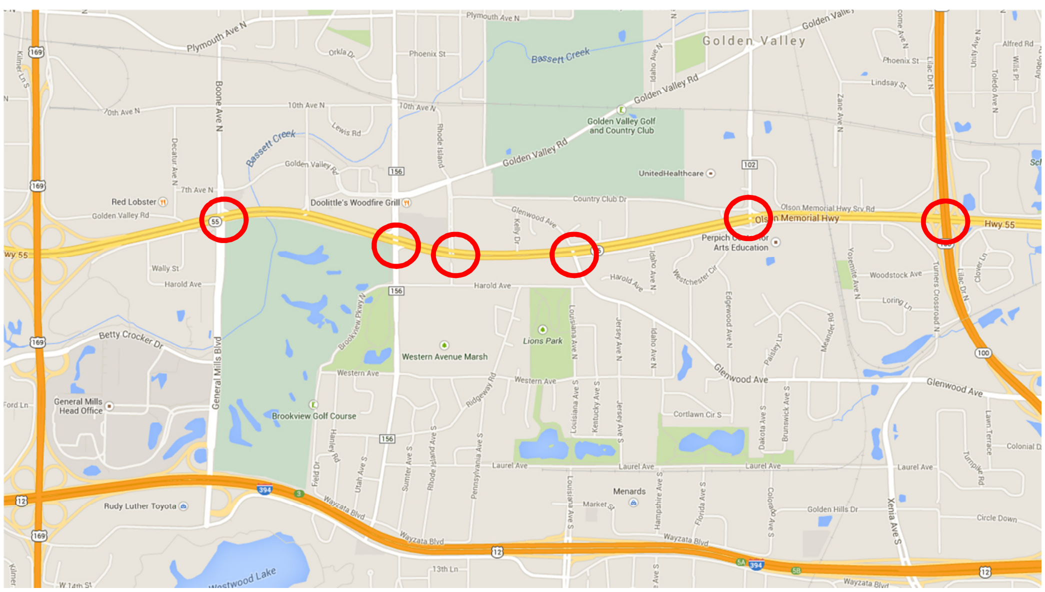


Figure 2-14. SMART Signal locations selected to extract turning movement daily pattern

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 2-15 demonstrates the loop detectors layouts at two locations for example: intersection of TH 55 with Boone Ave and with Rhode Island.

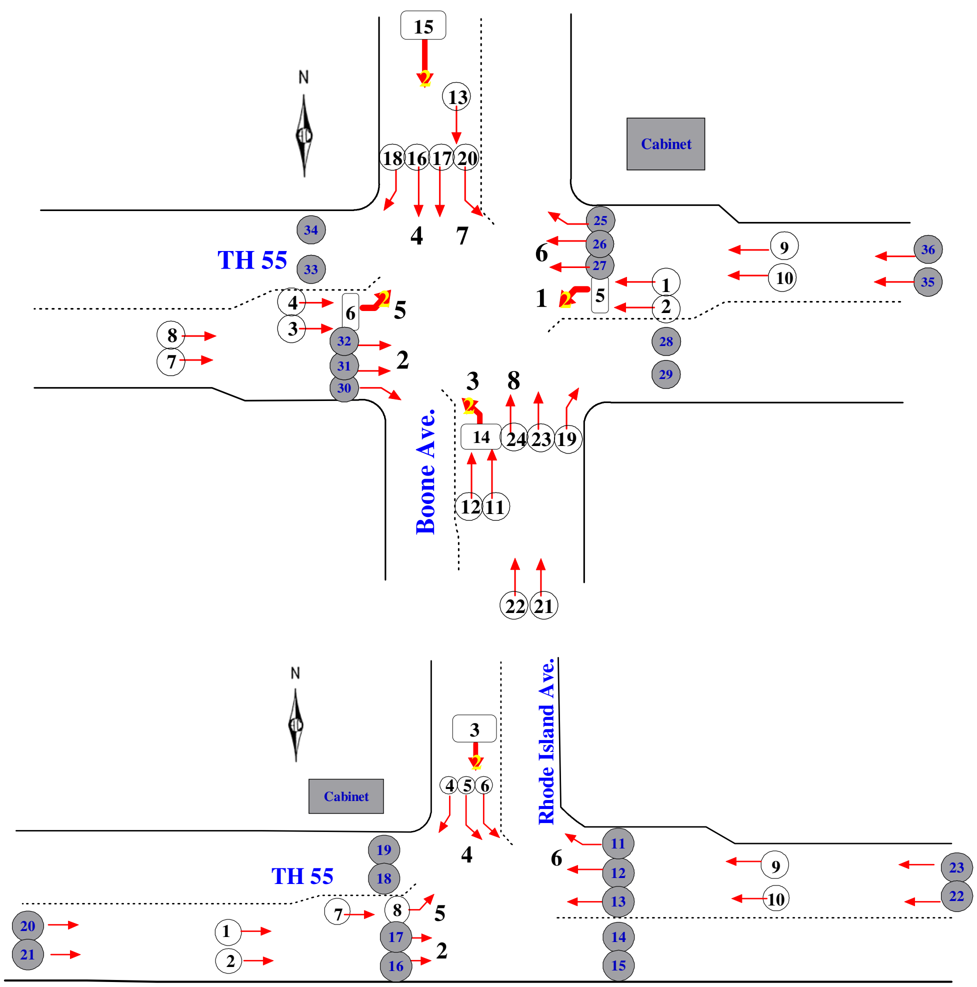


Figure 2-15. Loop detectors layout at two of intersections

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 and drown. Table 2-5 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 2-16 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, overall pattern of an approach is not necessarily consistent with each TM pattern.

Table 2-5. 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

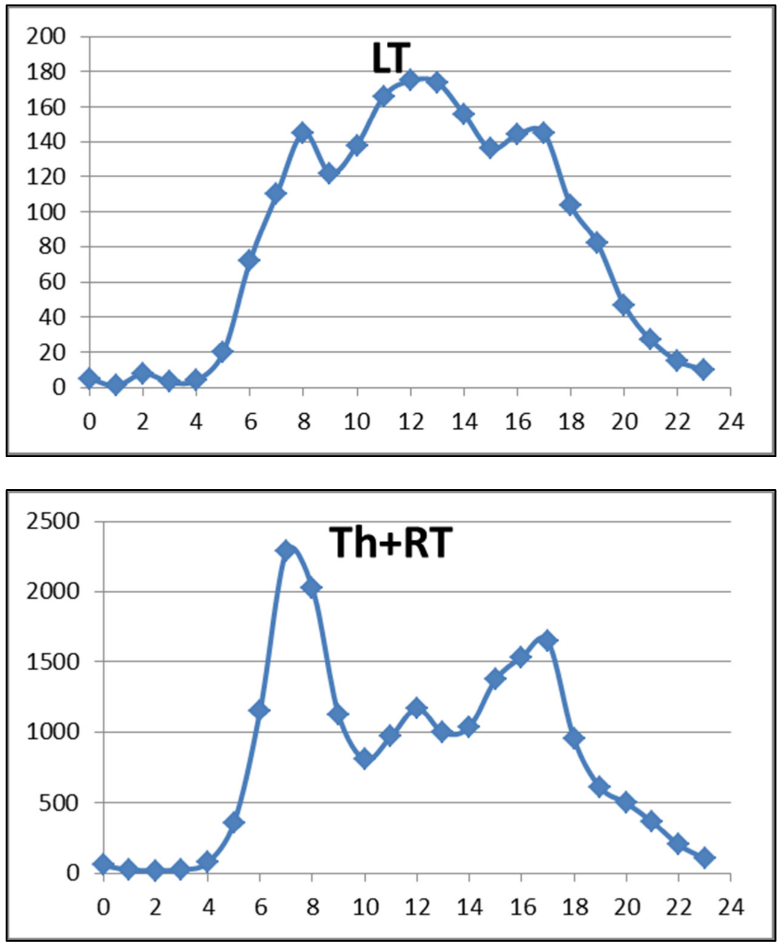


Figure 2-16. LT and Th+RT pattern for a Monday at TH 55 and Boone Ave eastbound

Another informative analysis is that to see how a TM pattern at a location can vary through the week. Figure 2-17 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.

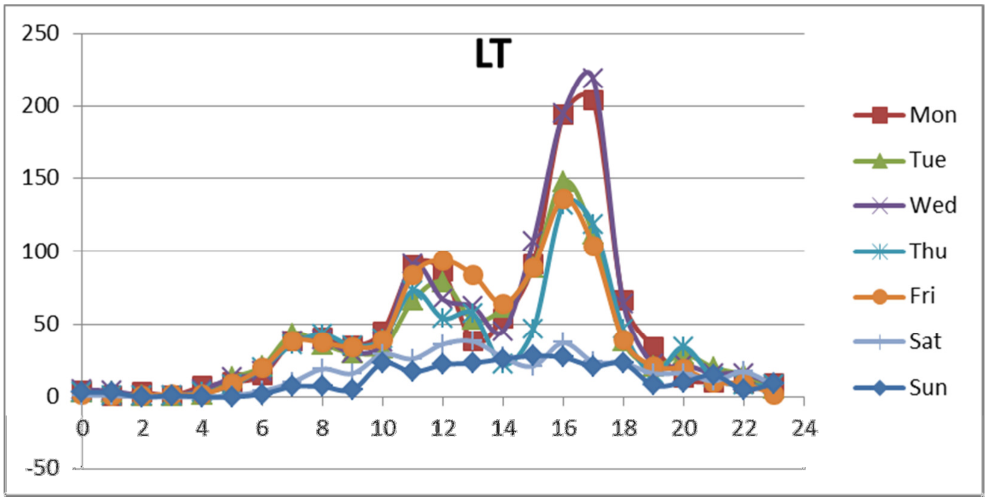


Figure 2-17. LT movement pattern for 7 days of week at TH 55 and Boone Ave northbound

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

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, Sight distance issue, and speed limit.

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. A common situation for this issue is approaches with no opposing left-turn movement (coded as 999). 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 let-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.

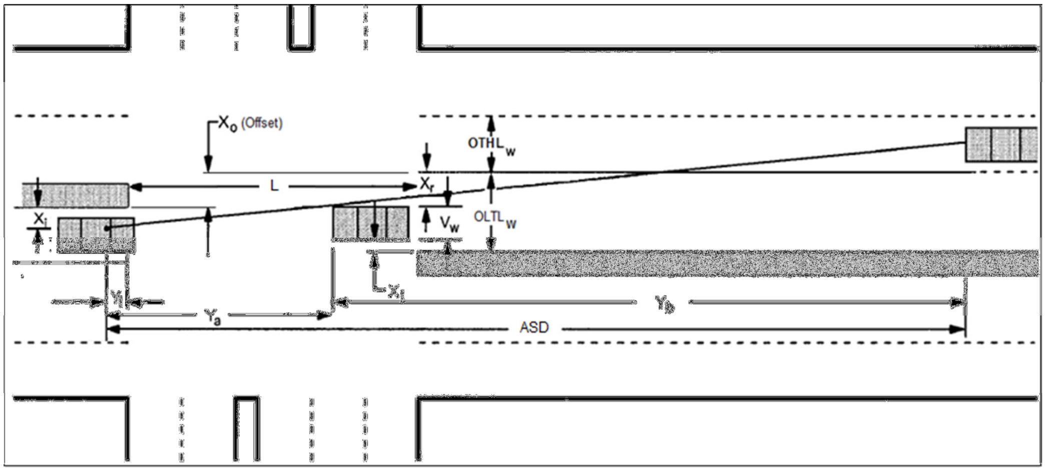


Figure 3-1. Sight distance triangle for LT maneuver at a typical intersection (Source: McCoy et al 2001)

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 longitudinal positioning of the left-turning vehicles.

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

where

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

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

Assuming that both vehicles have similar longitudinal positioning 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:

$$Y_b = \frac{Y_a(X_r + OTHL_W/2)}{V_o} \quad (3.3)$$

where

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

$OTHL_W$ = opposing through lane width,

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

X_r and vehicle offset can be readily calculated from the geometry:

$$X_r = OLTL_W - V_W - X_l \quad (3.4)$$

$OLTL_W$ = 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.

$$V_o = X_i - X_r - X_o \quad (3.5)$$

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

X_o= left-turn offset as defined in the Data Acquisition report.

3.1.2 Required sight distance

The required sight distance is given by

$$RSD = 1.467(OSL)(G) \quad (3.6)$$

where

OSL = opposing approach's speed limit, and

G= critical gap size for left turn; assumed 5.5 seconds plus 0.5 seconds for each additional opposing through lane.

3.1.3 Identifying SD issue

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. SD=0 represents no sight distance issue and SD=1 represents the sight distance issue.

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 3.6; 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, and following up on a comment offered at the August 13, 2013 meeting, a more detailed investigation of methods for estimating the hourly volumes was conducted.

3.2.1 Adjusting Turning Movement Counts to Different Date

In Chapter 2, a date adjustment method based on ATR data was proposed. This method which is an example of common practice, adjusts an existing turning movement count to reflect the day on which a crash occurred and can be formulated as:

$$y2 = y1(x2/x1) \tag{3.7}$$

where

y2 = left turn (or opposing) volume on target date

y1 = left turn (or opposing) volume on reference (counted) date

x2 = ATR count for same day and hour as target count

x1 = ATR count for same day and hour as reference count

Although reasonable, empirical support for this adjustment procedure is limited. Equation (3.7) does not allow for possible uncertainty regarding the target volume y2, but by letting the target volume be a random variable Y2, this situation can be remedied. To this end, a regression model of the form

$$\ln(y2_i) = \beta_1 + \beta_2 \ln(y1_i) + \beta_3 \ln(x1_i) + \beta_4 \ln(x2_i) + e_i \tag{3.8}$$

was used where e_i denotes random error and is a realization of a normal random variable, E, with mean 0 and unknown variance σ^2. Note that equation (3.8) is a special case of equation (3.7), where the relationship between y2 and the predictors y1,x1, and x2 is deterministic, and where β_1=0, β_2=1, β_3=-1.0, and β_4=1.0.

It was possible to identify 36 instances with two sets of turning movement counts from different days. One left turn (or opposing) volume was selected as the "target" while the other was treated as the "reference". Using the software WinBUGS, the lognormal model (3.8) was fit. The code for LT movement can be found in Appendix A and for through movement, appropriate data should be replaced. Table 3-1 shows the parameter estimates for the lognormal model (3.8).

The regression model was then used to simulate the distribution for the target counts. The procedure was evaluated by comparing the nominal coverages for 50%, 80%, 90% and 95% prediction intervals to the actual coverages. That is, 2.5%, 5%, 10%, 25%, 50%, 75%, 90%, 95%, and 97.5% quantiles of estimated TM volumes were computed. These, along with the observed target volumes were output to an Excel file, which then were input into Mathcad program. The observed coverages are shown in Table 3-2.

Table 3-1. Estimated lognormal model parameters for left turn and opposing volumes

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 3-2. Comparison of nominal and observed coverages for date adjustments of movement counts using the lognormal model

	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

For example, when using model (3.8) to predict hourly left turn volumes, the computed 90% confidence intervals caught 91.7% of the target volumes, and this difference is not statistically significant. Overall, the predicted intervals tended to be conservative (i.e. they tended to catch more target volumes than expected.)

Finally, the regression models for date adjustment look like:

$$y2 = EXP\left[-0.4985 + 0.983 \times \ln(y1) - 0.755 \times \ln(x1) + 0.828 \times \ln(x2) + \frac{0.279^2}{2}\right] \quad (3.9)$$

$$y2 = EXP\left[-0.555 + 1.026 \times \ln(\mathrm{y1}) - 0.356 \times \ln(\mathrm{x1}) + 0.268 \times \ln(\mathrm{x2}) + \frac{0.221^2}{2}\right] \quad (3.10)$$

for LT and opposing Th+RT respectively. The standard deviation for turning movement volume estimates can be calculated from $\sqrt{Var[Y2]} = E[Y2]\sqrt{\exp(\sigma^2) - 1}$.

3.2.2 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) mid-day (11 AM – 1 PM) and afternoon peak (3 PM – 6 PM). For a crash (or control) between 7 and 8 AM, corresponding left turn and opposing counts are available and equations 3.9 and 3.10 can be used to adjust the available counts to the target (crash) date. If a target volume is needed for 7-8 PM no corresponding reference count would be available and an additional estimation procedure is needed. This procedure is based on an Empirical Bayes method similar to that used in *(22)* to estimate classified mean daily traffic.

Peak period counts can be adjusted to reflect off-peak traffic volumes if one knows how traffic volumes vary during the day. So, 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 of 24-hour opposing volume counts which were then used to compute corresponding 24-hour patterns. Figure 3-3 shows several illustrative patterns for the left-turn volumes. 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 than pattern 1, while pattern 4 shows a marked AM peak. Pattern 3 was typical of weekend traffic.

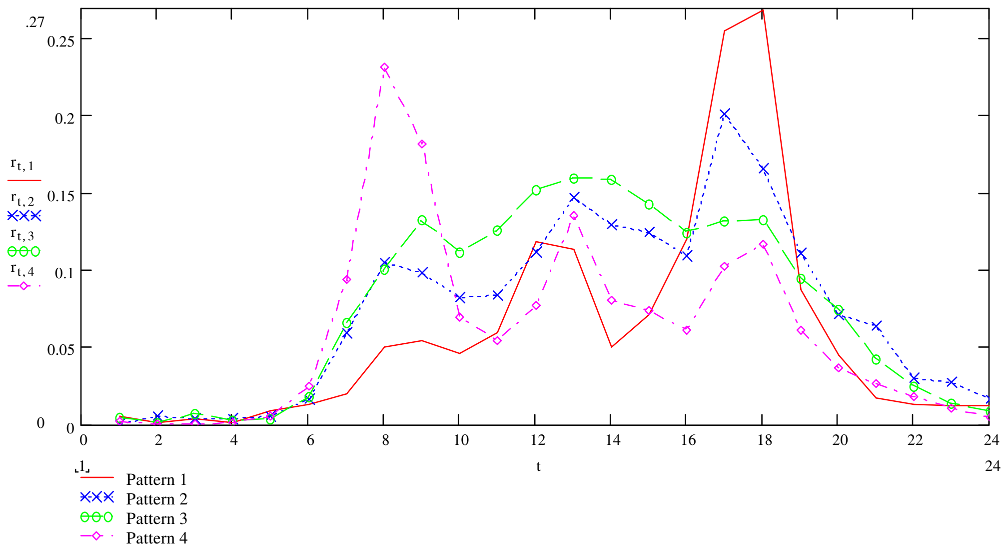


Figure 3-3. Example 24-hour patterns for left-turns along MNTH 55

Next, a method was derived for matching MnDOT 6 to 13-hour turning movement counts to one or more of the patterns. The best-matching patterns, together with the turning movement counts, were then used to estimate hourly volumes outside the range of the turning movement counts.

To illustrate the results of this estimation procedure, consider an approach with eight-hour LT counts consisting of 6-9 AM, 11 AM-1 PM, and 3-6 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. Then the probability of a match between the sample and each pattern was computed. Predicted hourly volumes for the 24 hours of the day, and ±2 standard deviation ranges were computed in the end. Figure 3-4 shows the actual eight sample volumes along with the predicted hourly left-turn volumes for the count date. For example, the predicted left-turn volume for 1-2 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.

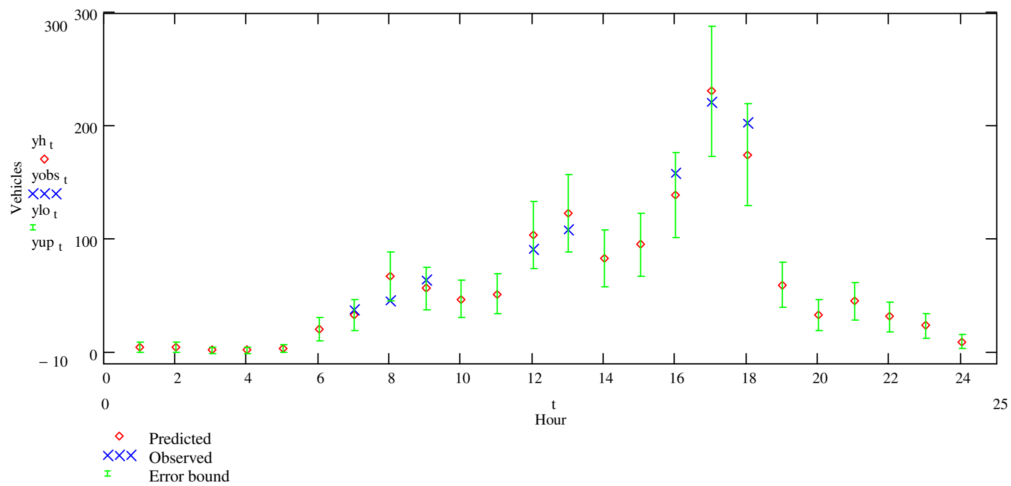


Figure 3-4. Predicted hourly left-turn volumes, 95% error bars, and observed counts

3.2.3 Application

As stated 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 3-5 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 3-5. 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 using the equations 3.9 and 3.10. Figure 3-6 shows this 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 3-6. 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 3-10. 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 3-7. Final dataset prepared for the matched case/control analysis.

3.3 Estimating Average Daily Turning Movement Volumes

Apart from the case/control analysis to develop LT crash relative risk models, a complementary regression analysis was conducted to develop traditional crash prediction models (CPM). Such model requires average daily turning movement volumes (i.e. left-turn AADT and opposing through + right-turn AADT) as the key predictors. Estimating these volumes for the locations can be done using a two-step process:

1. Collecting the "whole" AADTs for the approach of interest and the opposing approach from the GIS file available on MnDOT's Traffic Forecasting and Analysis website.
2. Estimating the turning movement ratios for all approaches and applying them to the whole AADTs from step 1 to convert them to the LT or Th+RT AADTs.

Figure 3-8 shows an example for the step 1 of the process described above. At this location, AADTs for NB and SB directions are the same and available for two years during our study period, 2008 and 2010. The average of the available AADTs was considered for the next calculations.

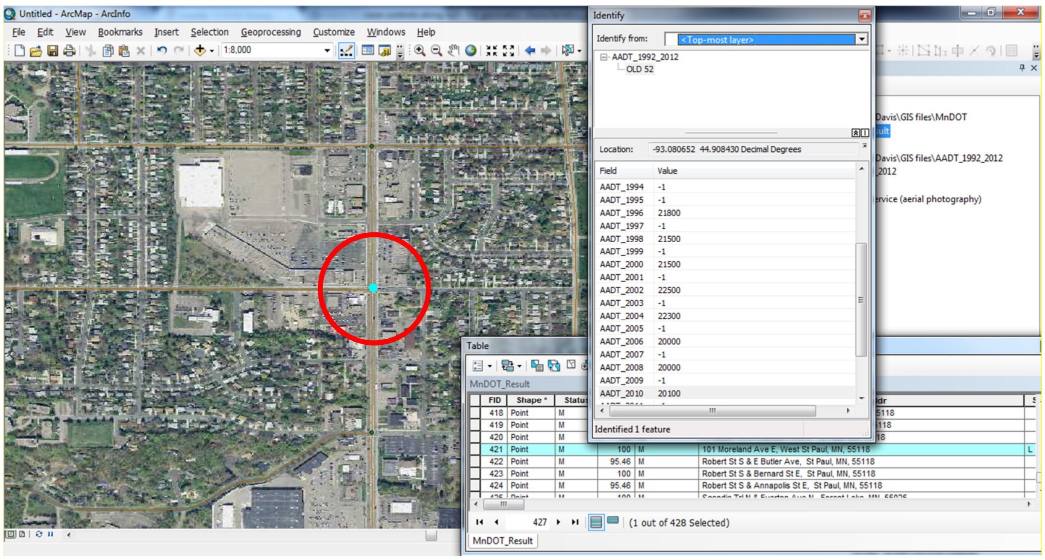


Figure 3-8. Reading approaches' AADTs from the GIS file provided by MnDOT

The following figure which is a snapshot from the dataset shows the availability of the whole AADTs for some of the approaches. There were approaches with one, two and three AADT values during the 5 years of study.

AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN
AADT					opposing AADT						
2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	AADT	opp AADT
	6950		7000			5300		5400		6975	5350
	5300		5400			6950		7000		5350	6975
2500		2175		2150	2250			2225		2275	2238
2250			2225		2500		2175		2150	2238	2275
	5300		5400			7450		7700		5350	7575
	7450		7700			5300		5400		7575	5350
		2600					533			2600	533
		533					2600			533	2600
2350		2450		2500	2125		2225		2125	2433	2158
2125		2225		2125	2350		2450		2500	2158	2433
	6850		7450			7350		6700		7150	7025

Figure 3-9. AADT availability for some of the approaches.

For the second step, converting the whole AADTs to the turning movement AADTs, the turning movement volumes were utilized. Figure 3-10 depicts a sample of this source of information. Using the “grand total” row at the bottom of this figure, the turning movement ratios (LT or Th+RT) can be easily calculated.

	S ROBERT ST Southbound				MORELAND AVE Westbound				S ROBERT ST Northbound				MORELAND AVE Eastbound				
Start Time	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Left	Thru	Right	Peds	Int. Total
14:30	2	177	1	0	5	5	6	2	13	190	5	4	14	4	27	2	457
14:45	4	188	11	3	6	3	3	0	15	224	6	2	8	6	17	0	496
Total	6	365	12	3	11	8	9	2	28	414	11	6	22	10	44	2	953
15:00	4	196	5	5	10	8	4	7	13	190	4	2	11	12	13	2	486
15:15	6	210	10	1	14	8	6	0	8	214	9	2	10	11	14	3	526
15:30	5	238	2	4	5	9	2	4	16	201	9	6	6	8	18	2	535
15:45	6	190	7	3	6	10	3	9	8	215	6	5	9	7	15	3	502
Total	21	834	24	13	35	35	15	20	45	820	28	15	36	38	60	10	2049
16:00	5	231	6	1	8	7	6	3	12	225	2	1	10	7	14	4	542
16:15	6	241	3	12	14	3	6	8	13	225	4	2	9	14	16	1	577
16:30	5	263	5	7	8	6	3	1	21	235	4	4	7	5	25	6	605
16:45	7	278	4	2	15	8	2	0	23	233	6	2	15	9	17	0	621
Total	23	1013	18	22	45	24	17	12	69	918	16	9	41	35	72	11	2345
17:00	7	229	6	2	15	13	6	3	11	242	5	1	6	12	21	3	582
17:15	5	291	11	2	14	6	10	0	15	240	9	2	10	8	17	0	640
17:30	7	254	4	4	13	6	3	3	16	226	14	1	6	7	9	0	573
17:45	1	203	4	6	15	7	5	0	16	210	5	2	15	7	15	5	516
Total	20	977	25	14	57	32	24	6	58	918	33	6	37	34	62	8	2311
Grand Total	70	3189	79	52	148	99	65	40	200	3070	88	36	136	117	238	31	7658
Apprch %	2.1	94.1	2.3	1.5	42	28.1	18.5	11.4	5.9	90.5	2.6	1.1	26.1	22.4	45.6	5.9	
Total %	0.9	41.6	1	0.7	1.9	1.3	0.8	0.5	2.6	40.1	1.1	0.5	1.8	1.5	3.1	0.4	

Figure 3-10. Calculating turning movement ratios for different approaches of an intersection

For instance the eastbound LT ratio at this intersection is $\frac{136}{136+117+238} = 0.277$ or the Th+RT ratio for northbound is $\frac{3070+88}{200+3070+88} = 0.940$.

Multiplying the turning movement ratios to the corresponding whole AADTs results in the LT AADT and the opposing Th+RT AADT. Figure 3-11 is a snapshot from the data structure used to develop crash prediction models which predict crash frequency. The final sample for this complementary regression analysis consisted of 528 (481 excluding FYAs) approaches with 472 (457 excluding FYAs) MnCMAT and 258 (247 excluding FYAs) HSIS accidents.

Intersecti	Dir	MnCMAT	HSIS	LTPH	LT lanes	LTPock	oppLn	medWi	SD	oppSL	LTAADT	oppAADT	AADT
MN 95 & MYRTLE ST (95=MA	SB	0	0	PP	1 exclusive	1	1	0	0	30	25	2991	8050
I-94 & (68) MCKNIGHT SR-B	NB	1	0	PP	1 exclusive	1	2	9	1	40	501	4476	12617
US 61 & 10th St	WB	1	1	Perm	1 shared	0	1	0	0	30	1257	402	4872
MN 65 & 44th Ave NE	NB	3	0	PP	1 exclusive	1	2	7	1	30	698	11395	22525
MN 3 & (42) 150TH STREET	NB	0	0	PP	1 exclusive	1	2	0	0	30	502	5983	11100
US 952A & BERNARD AV (RC	EB	1	1	Perm	1 shared	0	1	0	0	30	144	563	1675
MN 47 & 53rd Ave NE	WB	0	0	Perm	1 shared	0	1	0	0	30	621	817	4475
US 169 & PLY AV E RAMP M	WB	0	0	Perm	1 shared	0	1	10	1	30	59	2003	6200
US 952A & (2/41) ANNAPOL	NB	0	0	PP	1 exclusive	1	2	0	0	35	1005	7152	15200
MN 55 & (63) ARGENTA TR	NB	0	0	PP	1 exclusive	1	2	0	0	50	214	1484	4025
MN 13 & (31) Lynn Ave w/	SB	0	0	FYA	1 exclusive	1	1	0	0	30	177	1460	2740
MN 120 & Century College	NB	1	0	FYA	1 exclusive	1	1	9	1	40	2159	6545	15150
US 212 & (61) SHADY OAK E	EB	0	0	PP	1 exclusive	1	3	0	0	30	1274	7075	14150
MN 21 & 282 2ND ST / 21=B	WB	0	0	Perm	1 exclusive	1	1	0	0	30	507	3515	7150
MN 55 & WESTVIEW DRIVE	SB	0	0	PP	1 exclusive	1	2	0	0	30	375	2035	3313

Figure 3-11. The data structure including number of crashes from MnCMAT and HSIS, control and geometric characteristics, and traffic volumes for developing crash prediction models.

4. Statistical Analyses, SPFs and Relative Risk Models

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. However it can still be beneficial to develop safety performance functions (SPFs) using traditional cross-sectional design for two major reasons: first, to examine different crash databases (HSIS versus MnCMAT) and see how the resulting SPFs compare to the similar SPFs from the literature; and second, to shed light on the potential independent variable (predictors). Despite the fact that the crash frequencies predicted by such models may be unreliable, These SPFs are informative in terms of factors influential on left-turn crashes. Such information can be indirectly used in site classification for the matched case-control design (section 4.3). Therefore, section 4.1 explains the SPF development process.

In addition, before moving to the details of the statistical analyses for relative risk models, it might be helpful to see how the matched case-control design relates to the more common method for developing safety performance functions. Section 4.2 is dedicated to this subject.

4.1 Safety Performance Functions

4.1.1 Motivation and Methodology

As stated in literature review section, the HSM currently suggests a crash modification factors (CMF) of 0.01 for changing to protected phasing. On the other hand NCHRP 705 suggests that CMF for changing from protected phasing to FYA is 2.242 which is equivalent with a CMF of 0.45 for changing from FYA to protected phasing. The aggregated CMF for changing from permitted phasing using green-ball to permitted phasing using FYA was 0.635. Intuitively, it can be concluded that the CMF for changing from permitted phasing using green-ball to protected phasing is $0.45 \times 0.635 = 0.28$ which is considerably different from the aforementioned CMF, 0.01.

In addition, investigating the left turn crashes reported in Highway Safety Information System (HSIS) revealed a large number of crashes occurred at approaches with protected-only phase or at protected time of protected-permitted phases. This, questions the reliability of the CMF for changing to protected phase, 0.01 and most likely the quality of the database used to derive it.

Among the reviewed literature, two studies are close in some aspects to what we would like to do in this section: Wang and Abdel-Aty 2008 as well as Lee, Kweon and Dittberner 2011. However, there are some differences: Wang and Abdel-Aty considered all left-turn crashes including those occurred during the protected phase (either a protected-only phase or protected time of a protected-permitted phase) in which the opposing through vehicle was at fault. These types of crashes cannot be expected to eliminate or diminish as a response to changing a signal to protected phasing.

In Lee, Kweon and Dittberner 2011 only approaches with five-section signal head were considered meaning that traditional three-section signal heads for permitted-only phasing were excluded. Although errors in crash reports are a common problem, no refinement process on the crash data they used has been explained. So they may have missed some relevant crashes because they are mistakenly coded as a different crash type (e.g. head-on or right angle). According to Wang and Abdel-Aty (2008) only 57.6% of their pattern 5 LT crashes were initially reported as LT crash. 31% were coded as angle crash and 4.3% were coded as head-on. Our investigation also showed a very consistent result to Wang and Abdel-Aty's in this regard: only about 55% of the final list of permitted LT crashes was initially reported by HSIS. The rest were discovered in the secondary crash database, MnCMAT managed by MnDOT. Therefore, conducting a kind of refinement on crash databases seems essential in the cross-sectional safety studies which try to fit a SPF based on crash history.

253 intersections having at least one approach with a permitted LT phasing (comprising about 528 approaches) were used for this part of the study. The process of collecting and preparing potential independent variable data was explained in chapter 2 and 3. For dependent variables which is the permitted left-turn crash frequency at each location (approach level data), the data provided by HSIS and MnCMAT was employed. These two databases reported 258 and 472 left-turn crashes at the study intersections respectively.

A generalized linear model (negative binomial regression) was fitted to the two sets of data. Tables 4-1 and 4-2 summarize these models for MnCMAT and HSIS respectively. These functions predict the left-turn crash frequency on a 5-year period. The aggregated data was employed for two reasons:

1. In order to mitigate the common issue of inflated zeroes in accident frequency studies.
2. AADTs are not available for every single year. So, aggregating the data over 5 years significantly increased the probability of having at least one AADT for the approach of interest.

Table 4-1. Primary SPF for left-turn crashes based on MnCMAT

MnCMAT	Estimate	Std. Error	p-value
Intercept	-11.965	1.084	<2e-16
Log(LTAADT)	0.585	0.079	2.49e-13
Log(oppAADT)	0.743	0.093	1.04e-15
Permitted	1.737	0.389	7.99e-06
Prot/Perm	1.540	0.322	1.79e-06
SD=1	0.679	0.144	2.63e-06
Null deviance	651.8 on 527 dof		
Residual deviance	426.4 on 522 dof		
AIC	1177.8		

Table 4-2. Primary SPF for left-turn crashes based on HSIS

HSIS	Estimate	Std. Error	p-value
Intercept	-11.552	1.345	<2e-16
Log(LTAADT)	0.418	0.091	4.07e-06
Log(oppAADT)	0.664	0.111	1.89e-09
Permitted	1.560	0.457	0.000637
Prot/Perm	1.277	0.371	0.000571
SD=1	0.687	0.172	6.46e-05
oppSL	0.027	0.011	0.015974
Null deviance	493.29 on 527 dof		
Residual deviance	368.36 on 521 dof		
AIC	883.33		

The two models were then used to predict the number of accidents under different conditions to see how differently these two respond to similar changes in the explanatory variables. Assume an approach with LT AADT of 1000 and opposing AADT of 5000 and the approach has sight distance problem (SD=1). Now considering different control types can unmask important behaviors of the models.

Table 4-3. The expected number of crashes during 5 years

Explanatory variables	MnCMAT model	HSIS model
LTAADT=1000, oppAADT=5000, SD=1, oppSL=40, FYA	0.39	0.30
LTAADT=1000, oppAADT=5000, SD=1, oppSL=40, PP	1.83	1.06
LTAADT=1000, oppAADT=5000, SD=1, oppSL=40, Perm	2.23	1.40

For MnCMAT model, changing a signal from FYA to protected/permitted increases the crash frequency by %370 (4.7 times) more and changing a protected/permitted phasing to permitted-only increases the LT crash rate by about %20 (1.2 times). For HSIS model these increases are %250 and %32.

It turned out that including FYAs in this analysis is not legitimate for two reasons:

1- They emerge in 2009 while our study period starts from 2007. So, the LT phasing at those locations currently controlled with FYA are unknown before FYA installation. They could have been controlled by any phasing even protected which can explain the very low crash frequencies at those location.

2- Even after FYA installation, we do not know how they have been operated. A FYA signal can operate as protected, permitted/protected or permitted-only.

Therefore, approaches with FYA were excluded from the database resulting the new database contains 481 permitted approaches. All the modelling process was replicated with the new data. It turned out that although there is a %20 difference in LT crash frequency between prot/perm and perm-only phasing, this difference is not significant. For this reason, the LTPH variable was dropped from the final models. The new models for MnCMAT and HSIS are summarized in tables 4-4 and 4-5 respectively:

Table 4-4. Final SPF for left-turn crashes based on MnCMAT

MnCMAT	Estimate	Std. Error	p-value
Intercept	-10.120	0.836	< 2e-16
Log(LTAADT)	0.571	0.080	8.16e-13
Log(oppAADT)	0.718	0.081	<2e-16
SD=1	0.734	0.148	6.58e-07
Null deviance	604.84 on 480 dof		
Residual deviance	396.92 on 477 dof		
AIC	1108.8		
2*log-likelihood	-1098.80		

$$y_{MnCMAT} = EXP(-10.12 + 0.571Ln(LTAADT) + 0.718Ln(oppAADT) + 0.734SD)$$

Table 4-5. Final SPF for left-turn crashes based on HSIS

HSIS	Estimate	Std. Error	p-value
Intercept	-9.530	1.022	<2e-16
Log(LTAADT)	0.408	0.092	8.51e-06
Log(oppAADT)	0.616	0.096	1.68e-10
SD=1	0.768	0.176	1.27e-05
oppSL	0.020	0.011	0.0756
Null deviance	459.41 on 480 dof		
Residual deviance	344.16 on 476 dof		
AIC	827.7		
2*log-likelihood	-815.70		

$$y_{HSIS} = EXP(-9.53 + 0.408Ln(LTAADT) + 0.616Ln(oppAADT) + 0.768SD + .02oppSL)$$

4.1.2 Interpretation and Comparison

The two models were used to predict the number of left-turn accidents under different conditions to test their sensitivity to each independent variable and also to compare them with each other and SPFs from two other studies.

Table 4-6. SPFs sensitivity to turning movement volumes

Volumes	MnCMAT	HSIS
LTAADT=1000, oppAADT=5000	1.95	1.13
LTAADT=2000, oppAADT=5000	2.89	1.50
LTAADT=2000, oppAADT=10000	4.78	2.30

As expected, the HSIS-based model always underestimates the number of accidents by 90 percent in comparison with the MnCMAT-based model. Doubling LT volume will increase the crash frequency by 48 percent and doubling opposing volume will increase it by 65 percent.

Table 4-7. SPFs sensitivity to sight distance issue

Explanatory variables	MnCMAT	HSIS
LTAADT=1000, oppAADT=5000, oppSL=40, SD=0	0.94	0.53
LTAADT=1000, oppAADT=5000, oppSL=40, SD=1	1.95	1.13

The left-turn crash frequency at approaches with SD problem is more than twice as it is for a similar approach with adequate sight distance. A quick conclusion can be that frequency of LT crashes can be reduced by about 50 percent by providing required sight distance.

Table 4-8 and figure 4-1 together can be used to perform a comparison between different SPFs (two from this study and two from the literature review). Two direct conclusions can be drawn from them. The HSIS-based SPF significantly underestimates the crash frequency and The SPF developed based on MnCMAT still predicts considerably less number of LT crashes in comparison with the two other studies. The following reasons can explain this difference:

- Definition of LT crashes: In this study, LT crashes which occurred during protected or red time were excluded from the dependent variable set. It is possible that other studies have not done this refinment.
- Required refinements in crash Datasets: although MnCMAt contains more number of LT crashes compared to the HSIS list, crash type mis-identification is probably a case.
- Geographical differences: Different geographical areas may have different inherent characteristics and models developed for a specific region is not usually transferable to other regions. The presence of the County variable in the Wang and Abdel-Aty model confirms this important effect. As shown in table 4-8, W & A SPF predicts double number of crashes for Hillsborough County compared to Orange County.

Table 4-8. Average number of expected left-turn crashes in 5 years at 281 study locations by different models

	W & A (Hillsborough County)	W & A (Orange County)	Lee et al.	MnCMAT	HSIS
Prot/Perm (325 locations)	3.42	1.71	2.40	1.27	0.66
Perm (156 locations)	0.80	0.40	-	0.33	0.20

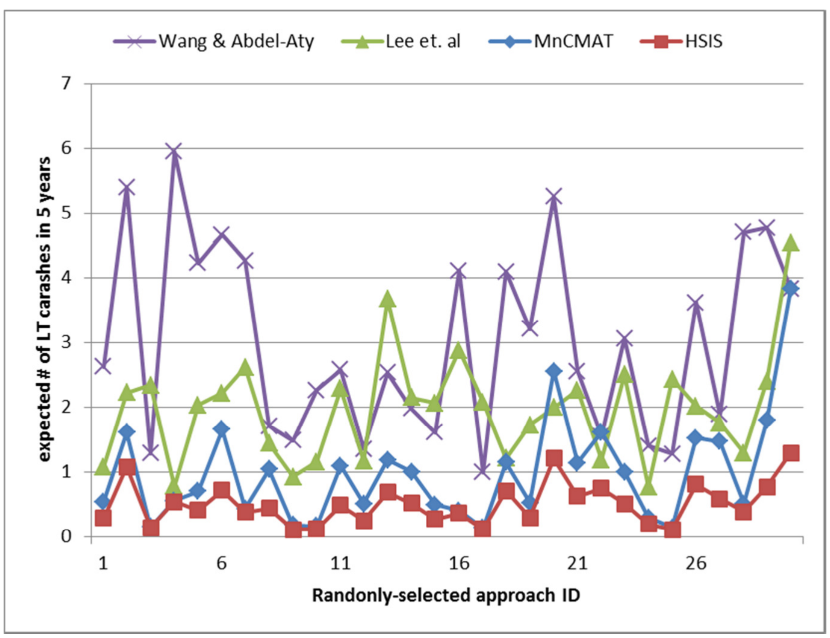


Figure 4-1. Comparing different SPFs at 30 randomly-selected approaches

Other important conclusions that can be made from this part of study and be indirectly used in case-control design study include:

- Despite 20% difference in predicted left-turn crashes between protected-permitted and permitted-only controls, the control type variable was insignificant.
- Consistent with previous studies, AADT is the most influential variable in left-turn accidents.
- The sight distance problem was a significant predictor.
- Median width is not needed in the model in the presence of SD variable.
- Opposing speed limit was marginally significant

4.2 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

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

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)

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

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.

4.3 Intersection 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.

4.3.1 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 4-2 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 4-2. The site plan and the street view of a LT crash location with a 4-section special operation.

4.3.2 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.

4.3.3 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.

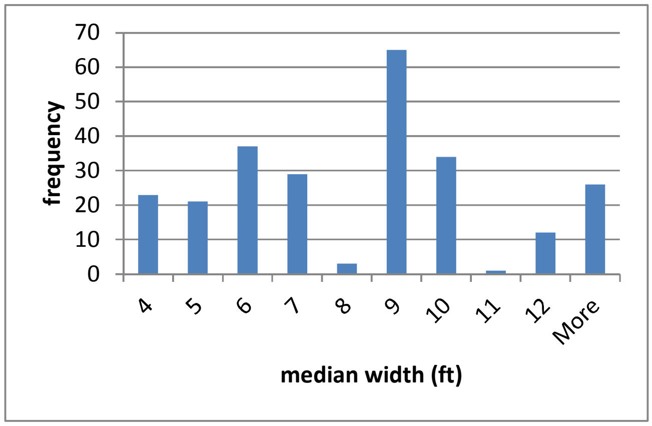


Figure 4-3. Distribution of median widths

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

4.3.4 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.

4.3.5 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.

4.3.6 Cross classification of the crash sites

Based on the 5 criteria and because each criterion defines two groups, there can be up to $2^5 = 32$ groups of intersections. Table 4-9 shows how the total of 436 case-control sets was distributed over the intersection categories.

Table 4-9. 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. There is a strong correlation between median width and the LT offset. It is known that LT offset plays an important role in determining sight distance condition. Geometrically, wider median causes a more negative LT offset and consequently it is more likely that SD problem arises. To show this correlation, the conditional probability of having sight distance problem can be investigated.

Table 4-10. Crash tabulation based on median and sight distance condition

	SD problem (SD)	No SD problem (SD^c)	Marginal values
Median (M)	125	126	251
No median (M^c)	42	145	187
Marginal values	167	271	438

$$P(SD) = \frac{167}{438} = 0.38$$

$$P(SD|M) = \frac{P(SD \cap M)}{P(M)} = \frac{125/_{438}}{251/_{438}} = \frac{125}{251} = 0.50$$

$$P(SD|M) > P(SD)$$

The latter equation states that given the existence of a median for an intersection approach, probability of dealing with the sight distance problem is higher. This correlation implies that the potential effect of median on the left-turn crash risk is partially considered when the SD factor is included in site classification. As stated earlier in this chapter, in the aggregate LT crash frequency models, median width turned out to be insignificant as long as the SD variable was included in the model. Also, that analysis showed that the number of opposing lanes is uninfluential. Therefore, it was decided to aggregate sites over these two factors to obtain a working cross-classification. This drops the number of site categories from 32 to 8. The working categories, along with the number of case-control sets in each category, are shown in Table 4-11.

Table 4-11. Crash site classification after aggregation over median condition and number of opposing lanes

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

4.4 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 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 4-4 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

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

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 4-12 summarizes the results of these analyses for the six working categories having 20 or more case-control sets.

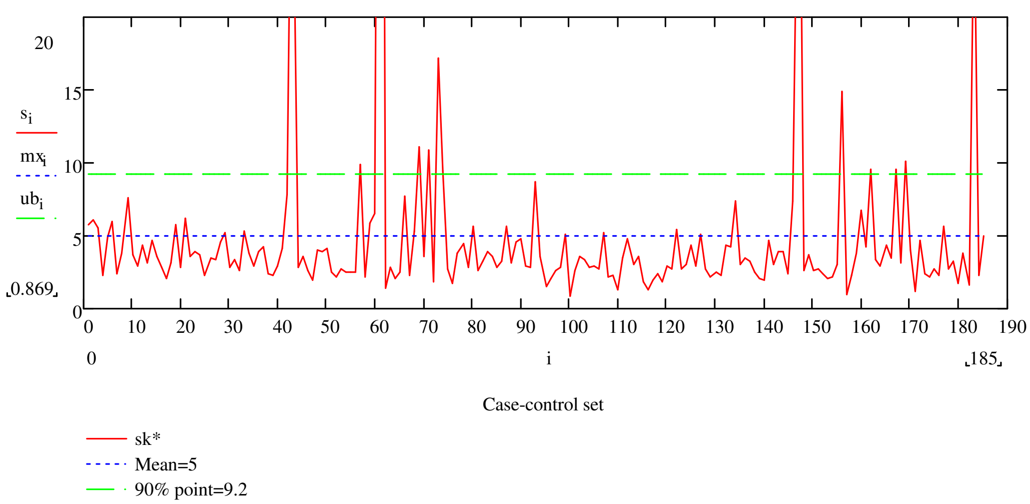


Figure 4-4. Square Pearson residuals for the intersection category 1, along with their expected values and 90% ranges.

Table 4-12. 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

4.5 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 a left-turn crash is occurring in a given hour still follows equation (4.3) but now the hourly volumes are treated as not directly observed. Figure 4-5 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 **β** 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 **β** 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).

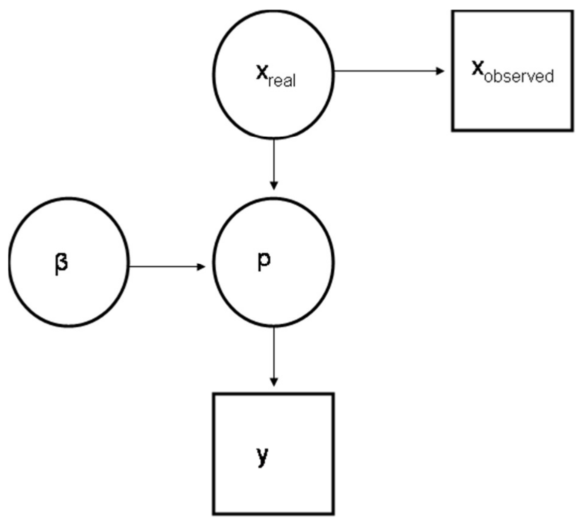


Figure 4-5. Graphical representation of measurement error model.

Tables 4-13 – 4-15 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 4-12.

Table 4-13. 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.	B	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 4-14. 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 4-15. 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	--	--	--	--

4.6 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

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

(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 4-13 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 4-6 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.

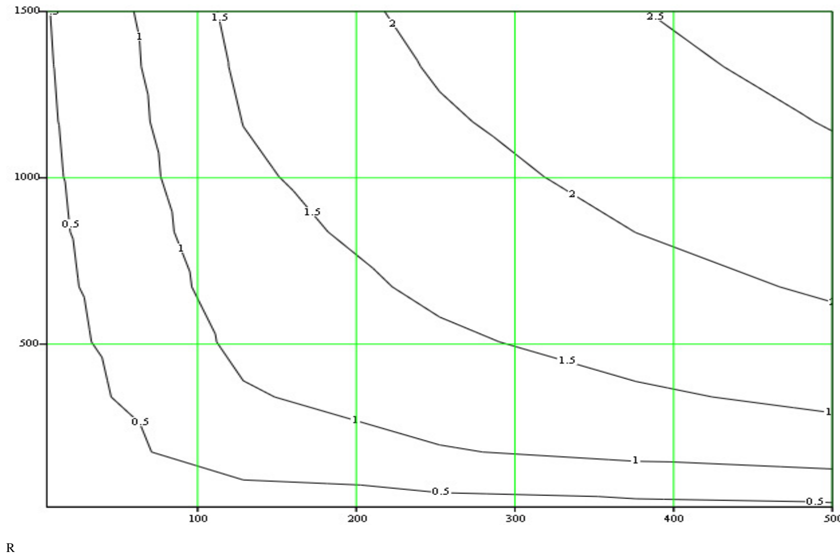


Figure 4-6. Relative risk of left-turn crash as a function of left-turn volume (x-axis) and opposing volume (y-axis).

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 4-16 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 4-7.

Table 4-16. 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

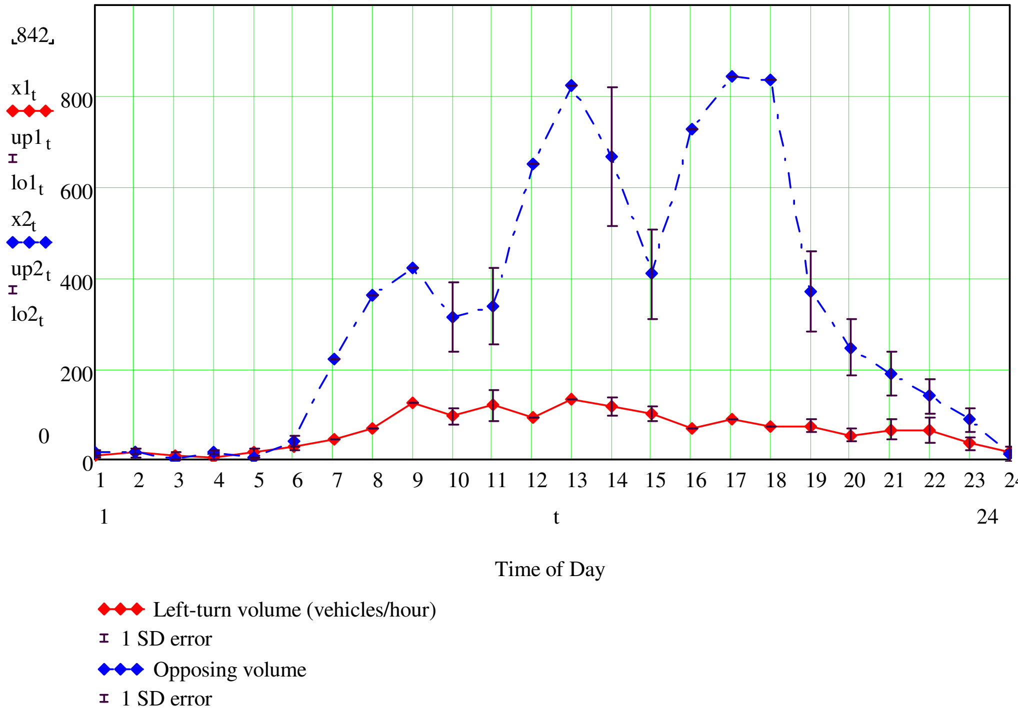


Figure 4-7. Estimated hourly movement volumes, northbound left turns at Robert and Mendota

Taking the volume estimates shown in Figure 4-7 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 4-8, again with error bars indicating ± 1 standard deviation ranges.

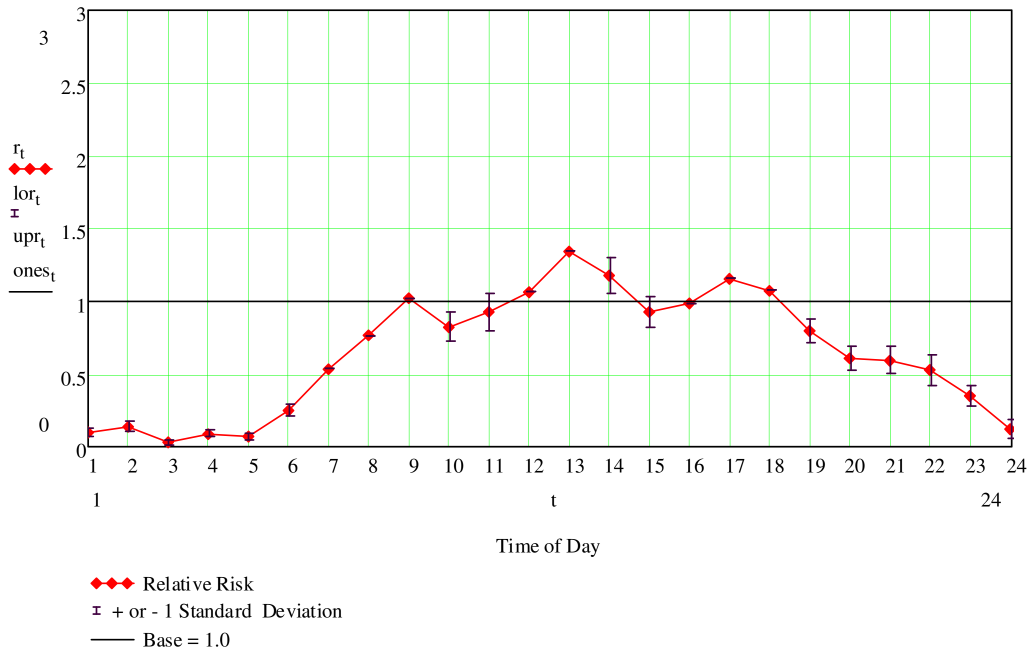


Figure 4-8. Variation of relative risk for left-turn crash during 24 hours of representative day. Northbound left turns at Robert and Mendota.

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 vary during the day as turning movement counts vary. This spreadsheet tool embeds the statistical models developed in task 6 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.

The spreadsheet tool has 3 main parts:

- SD condition: the first sheet
- RR diagrams: The second sheet
- Supporting data: the last three sheets

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

5.1 SD condition

The first step of using the spreadsheet tool is to determine whether or not the intersection approach of interest has sight distance issue. The answer to this question is one of the factors determining which set of beta coefficients should be used by the tool. 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 movement. 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 and available SD. The first two variables are used to calculate the RSD and the rest of them 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 word, those lanes to which the LT vehicle must yield.

Y_i is the longitudinal distance from the start of the median (or stop bar) to the driver's eye; positive if inside the intersection and negative if behind the intersection. For majority of intersections Y_i can be considered zero, meaning that the driver's eye is just at the start of the intersection (either end of median or stop bar). At large 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. 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).

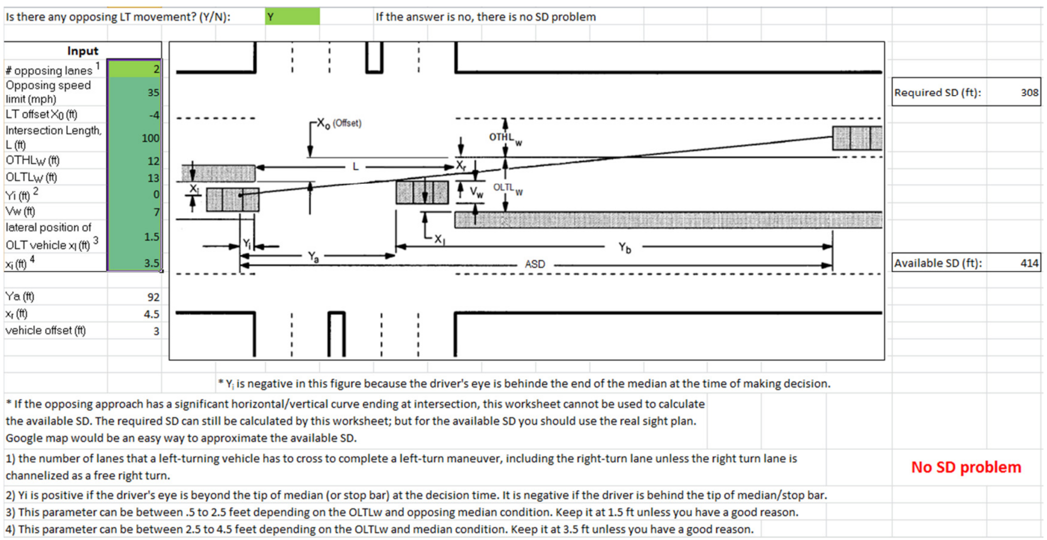


Figure 5-1. Contents of the "SD issue" sheet

V_w is the width of the design vehicle that can always be fixed at 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 opposing median condition. User should keep it at 1.5 feet unless s/he has a good reason. 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. 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 and vice versa.

Figure 5-2. Eastbound and westbound approaches: typical locations at which Yi>0

5.2 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 Task 6 for each approach type. This should not be edited by the user; so 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.

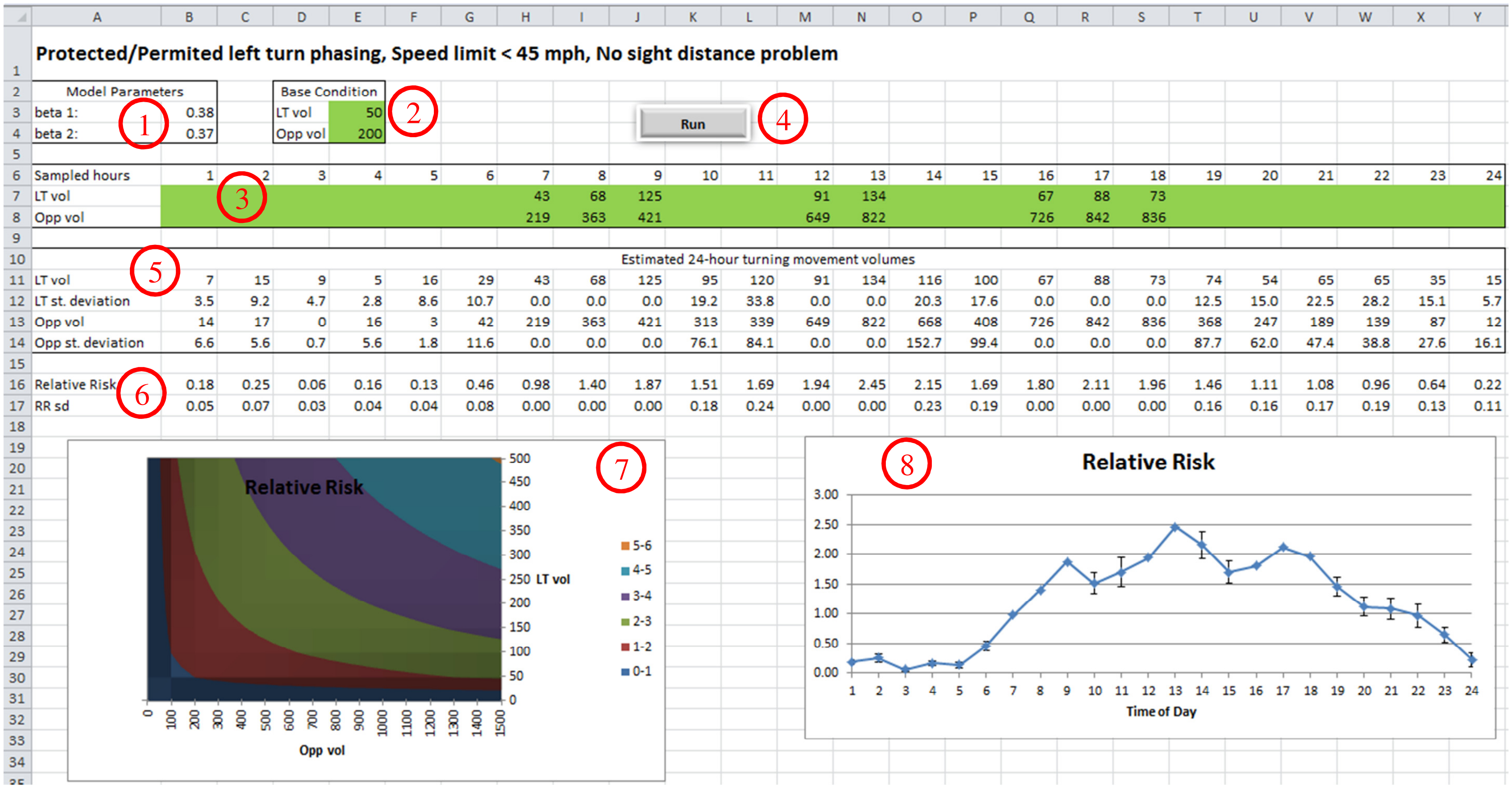
Important note: The opposing volume means the conflicting volumes including those movements to which a left-turn vehicle must yield. So, it usually means through + right turns and occasionally means only through movement. The latter case happens where right turn is channelized by a traffic island and 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 to 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. Besides it computes the standard deviation for each RR. This part should be protected from user changes.
7. RR Contour map: it displays how relative risk of a left-turn crash at this type of intersection approaches 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 sheets. Doing so, will crash the tool because it will make the Macro to read available counts from wrong cells and predict completely wrong volume estimates and finally print them to wrong cells.

5.3 Supporting data

The last three 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

Run

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.

5.4 More Discussions on the Threshold Relative Risk

Consider northbound and southbound direction of CSAH 101 and Seven Hi Drive as an example. Turning movement counts were available for eight hours at this intersection. The 24-hour relative risk diagrams for these approaches were produced by the tool (Figure 5-4). Now the question is what relative risk should be chosen as the protected phase threshold. If we knew what crash frequency is expected at different relative risks, we could choose the threshold more confidently. An intuitive way to relate the crash frequency to the relative risk criterion is to plot the historical LT crashes (during a given period) on the relative risk contours. Figure 5-5 shows this process for crashes occurred between years 2009 and 2014. All crashes at the southbound approach occurred at the relative risk of 1.5 or higher. For the northbound approach though, a lower relative risk might be considered. If the RR of 1.5 and 1.2 are considered for SB and NB respectively, hours 8, 9 and 12-19 may be set for protected phasing.

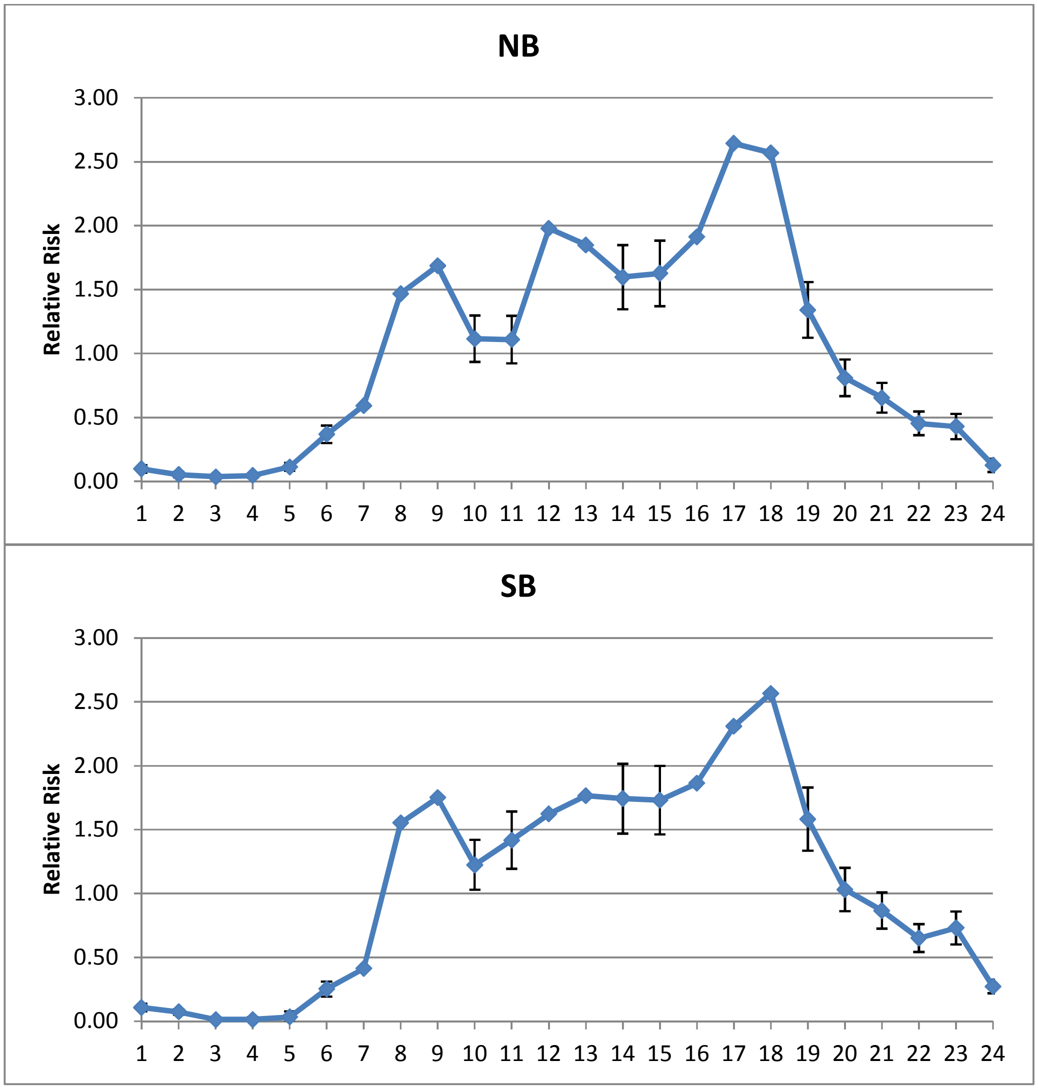


Figure 5-4. Relative Risk diagrams for the base condition: LT vol=50 and Opp vol=200 vph

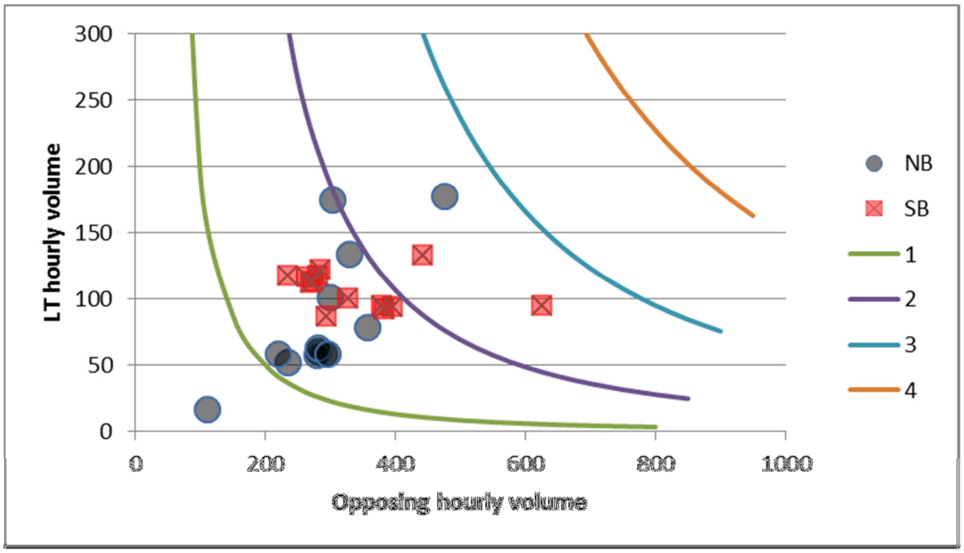


Figure 5-5. 6-year LT crashes at CSAH 101 and Seven Hi Drive northbound and southbound

An important point in plotting crashes is that multiple crashes may happen in one hour. Therefore they will have identical turning movement volume estimates and will be shown as one crash on the diagram. In order to address this issue, a random noise was added to the volume estimates and markers became transparent. So the user can see the density of crashes and choose the threshold relative risk accordingly.

6. Conclusion

6.1 Summary

This research ultimately developed a tool to support time-of-day changes between protected and permitted left-turn treatments. The literature review indicated that almost all existing models predict total number of LT crashes in a year and no work has addressed how the risk of LT crash varies throughout the day. Taking data availability and quality issues into consideration, a matched case-control study design was employed instead of the traditional cross-sectional design. The final list of cases consisted of 436 left-turn crash events occurring at permitted times of signalized intersections operated by MnDOT. For each case, five hourly periods on the same day as that of the case were randomly chosen as controls. Potential geometric features of the approach of interest were then collected. Also, 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. A matched case-control design does not allow one to analyze the effect of features that are common to both the case and its respective controls, such as speed limits or geometric features. Therefore, in order to capture the effect of such variables on risk of LT crash, the crash sites (the approach from which the left-turning vehicle was entering the intersection) were classified according to opposing speed limit, the type of LT protection, and whether or not a left-turning driver's sight distance could be obstructed by an opposing left-turning vehicle. Then, Separate statistical models were estimated for each approach type.

A spreadsheet tool where developed which uses the resulting 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. Since there are not clear guidelines for choosing the base condition (compared to which the relative risk is being calculated) and the threshold relative risk above which the LT crash risk is considered high, an innovative method was introduced. In this method, historical crashes at the approach of interest are plotted on the relative risk contour diagram. Looking at this new combined diagram, the user can readily see what threshold would cut off majority of crashes and based on that s/he can decide during what time of day the signal should be operated with protected phase.

6.2 Extensions

From the eight intersection approach classes identified in table 4-11, data were sufficient to estimate relative risk models for three of them all of which were controlled with PPLT phasing. Two of them have opposing speed limit of less than 45 mph with and without sight distance issue and the third class include the approaches with opposing speed limit of 45 mph or higher and sight distance issue. Note that these three classes encompass majority of intersections and when it comes to LT crashes even a higher majority of crashes belong to them. 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 (beyond 2011) or extending the sample to include county, municipal intersections, and/or even other states, model development can proceed as described in Chapters 3 and 4. The other option can be removing control type from the classification criteria. As founded during the SPFs development, this variable was not influential on crash frequency. Besides, the literature does not provide a solid support for significant difference of protected-permitted and permitted-only phasing. This will decrease the number of site classes to four which results in larger sample sizes and also makes the models applicable to more diverse approach types. Note that at the time of implementation, the signal head will be FYA and neither classic 3-section nor 5-section head signals for which the primary classification was based on will be there.

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; that is, the crash occurring approaches remained in the same site class. 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, modifying the spreadsheet tool would simply involve substituting the new values for the **β** coefficients.

References

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

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 (2015). "Left-Turn Phase: Permitted, Protected, or Both? A Quasi-Experimental Design in New York City", *Accident Analysis and Prevention*, **76**, 102–109.

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.

Lee, J-T, Y-J. Kweon, and R. Dittberner (2011), *Permissive Left-Turn Right-Angle Crashes at Protective-Permissive Five-Section Signal Heads*, Transportation Research Board 90th Annual Meeting, January 23-27, Washington, DC.

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.

Ozmen, O., Z. Tian, and R. Gibby (2014). "Safety of a Special Time-of-Day Protected/Permitted Left-Turn Signal Display", *Accident Analysis and Prevention*, **62**, 95-101.

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.

Rietgraf, A. and K. L. Schattler (2013), "Behavior of Left-Turning Drivers During Permissive Interval of Protected-Permissive Operation Effect of Signal Display", *Transportation Research Record*, **2384**, 35-44.

Schattler, K. L., J. A. Lund, W. B. Lorton, and B. Burdett (2013), *Effects of Flashing Yellow Arrow Signal Displays on Driver Comprehension and Operations*, Transportation Research Board 92nd Annual Meeting, January 13-17, Washington, DC.

Srinivasan, R., J. Baek, S. Smith, C. Sunstrom, D. Carter, C. Lyon, B. Persaud, F. Gross, K. Eccles, A. Hamidi, and N. Lefler (2011). "Evaluation of Safety

Strategies at Signalized Intersections", NCHRP Report 705, National Cooperative Highway Research Program, Washington DC.

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: the Macro code for TM volume estimation

```
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
```