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Safety Effects of Left-Turn Phasing Schemes at High-Speed Intersections

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This report describes an effort in estimating crash modification factors (CMFs) associated with different left-turn phasing schemes, at intersections where the major approach speed limit exceeds 40 mph. For installation of signals at previously thru/stop-controlled intersections, rear-end crashes increased while right-angle crashes decreased. Installation of the signal had no effect on either major or minor approach left turn crashes as long as the protected-only left turn phasing was used on the major approaches. At one intersection where a signal was originally installed with permitted/protected phasing on the major approaches, we found evidence for an increase in major approach left-turn crashes, which vanished when the major approach left-turn treatment was changed to protected-only. For several other phasing changes it was not possible to construct an after-treatment data set of sufficient size to permit reliable estimation of an effect. This report also describes a simple simulation model for left-turn cross-path crashes, where a probabilistic gap acceptance model for the turning driver is combined with a standard braking model for the opposing driver. The model characterizes left-turn crashes as resulting when the turning driver accepts a minimal gap and takes an atypically long time complete his/her turn, while the opposing driver takes an atypically long time to react before braking. R reconstruction of an actual fatal crash however was more consistent with the opposing driver reacting normally, but with the turning driver selecting an atypically short gap. Characterizing the rate at which such selection errors occur would then be necessary to accurately predict left-turn crash frequencies.

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SAFETY EFFECTS OF LEFT-TURN PHASING SCHEMES AT HIGH-SPEED INTERSECTIONS

Final Report

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Executive Summary

This report describes an effort in estimating crash modification factors (CMFs) associated with different left-turn phasing schemes at intersections where the major approach speed limit exceeds 40 mph. The estimation method employed was an enhancement of the Empirical Bayes approach currently being used in the development of the Highway Safety Manual. In this approach, before-and-after data from a set of intersections where a phasing change has been implemented are supplemented with reference group data from a larger number of intersections where the before condition applied. This reference group is then used to develop a statistical model that predicts crash frequency in the absence of phasing or control changes, and is used to control for selection biases that result when crash experience is used as a factor in determining whether or not a control, or phasing change, should be implemented.

Using data sets constructed from files provided by Mn/DOT and by the Federal Highway Administration's Highway Safety Information System, input data files for all relevant intersections in Mn/DOT's metro district were constructed. Bayes estimates of crash modification factors were then computed using Markov Chain Monte Carlo methods. For installation of signals at previously thru/stop-controlled intersections, we found that, as other studies have reported, rear-end crashes increased while right-angle crashes decreased. Installation of the signal had no effect on either major or minor approach left turn crashes as long as the protected-only left turn phasing was used on the major approaches. At one intersection where a signal was originally installed with permitted/protected phasing on the major approaches, we found evidence for an increase in major approach left-turn crashes, which vanished when the major approach left-turn treatment was changed to protected-only. For several other phasing changes (permitted to permitted/protected on the minor approaches, permitted to protected on the minor approaches, permitted/protected to protected, protected to permitted/protected on the major approaches) it was not possible to construct an after-treatment data set of sufficient size to permit reliable estimation of an effect, but we recommend that these analyses be redone when at least five years worth of after-treatment data are available.

Finally, this report describes a simple simulation model for left-turn cross-path crashes, where a probabilistic gap acceptance model for the turning driver is combined with a standard braking model for the opposing driver. Data for modeling the turning driver's behavior were collected at an intersection near the University of Minnesota campus, while data characterizing the opposing driver's reaction time and braking rate were taken from the literature. After placing plausible lower bounds on acceptable gaps, the model generated collision rates similar to those reported in the literature. The model characterizes left-turn crashes as resulting when the turning driver accepts a minimal gap and takes an atypically long time to complete his/her turn, while the opposing driver takes an atypically long time to react before braking. While this scenario may in fact describe a subset of left-turn cross-path crashes, a reconstruction of an actual fatal crash was more consistent with the opposing driver reacting normally, but with the turning driver selecting an atypically short gap. This suggests that a failure of attention, rather than a failure of gap judgment, may have been responsible. Characterizing the rate at which such attention errors occur would then be necessary to accurately predict left-turn crash frequencies.

Chapter 1: Introduction

In the past few decades, there has been a shift in focus for the transportation engineering community, from new construction to safety and management of infrastructure. Engineers now devote much of their attention to improving the current system from an efficiency and safety standpoint. Also, tightening budgets have created a need for effective programming of safety countermeasures in order to produce the most benefit to society. In the past thirty-five years, a reasonably well-accepted procedure, sometimes called the rational safety planning model (RSPM), has been developed and used to predict the effectiveness of countermeasures, and this involves calculating a crash modification factor (CMF) or accident reduction factor (Davis 2000a). It can be inferred that reliable estimation of the CMF for each type of countermeasure is essential in order to identify the most effective way to improve safety at an intersection. In the past decade a more effective approach, called the Empirical Bayes (EB) method, has been recognized as a way to calculate reliable CMF estimates. The EB method has continually been developed and improved, and it is being promoted to become the standard and staple of professional practice. This research makes use of a related method, called Hierarchical Bayes, to estimate CMFs of signalization and phase-changes at Twin Cities' metro area intersections. These estimates are intended to assist traffic engineers with their decision to install a signal or change the phasing at other intersections.

Traffic signals can provide for orderly movement of traffic, increase the capacity of an intersection if maintained properly, and provide safe intervals to permit vehicles to cross heavy traffic. On the other hand, improper or unjustified traffic signals can create excessive delay, excessive disobedience when drivers become impatient, and increases in the frequency of certain types of crashes (MNDOT 2005). Therefore, the justification of signal installation and proper maintenance is very important.

Currently, the installation of a signal or a left-turn phase change is considered when established guidelines provide rationale for a traffic engineer. The engineer is instructed to use these guidelines along with his or her judgment to make a final decision. Chapter 4C of the 2005 Minnesota Manual on Uniform Traffic Control Devices, developed by the Minnesota Department of Transportation (Mn/DOT), the United States Department of Transportation, and the Federal Highway Administration (FHWA) provides warrants for signal installation, and Chapter 2 of the Signal Design Manual (MNDOT 2006) provides phasing guidance.

The 2005 MN MUTCD contains eight warrants, which, if satisfied, provide rationales to install a signal at an intersection. The first two warrants consider the vehicular volumes and number of lanes on the major and minor approaches, and if they are above a certain threshold a signal is warranted. These first two warrants also consider excessive delays on the minor approach caused by high traffic volume on the major approach, which means that the minor approach vehicles have insufficient gaps for left-turn and through vehicles. The third warrant is intended to be used at an intersection where the traffic entering or exiting the minor-street suffers excessive delay during a minimum of one hour of an average day. The fourth warrant uses pedestrian volume to warrant a signal. The fifth warrant is intended for use at intersections near school crossings. The sixth warrant is intended for use where maintenance of signal coordination is required. The seventh warrant is to be applied where the severity and frequency of crashes creates a reason to consider installing a signal. Finally, the eighth warrant is justified to organize the traffic flow of a roadway network (MNDOT 2005). These warrants should not be taken as rules, but as guidelines because each intersection presents its own unique characteristics.

The safety effectiveness of signal installation was examined by McGee, Taori, and Persaud (McGee et al. 2003) in National Cooperative Highway Research Program (NCHRP) Report 491. They examined intersection-related, rear-end, and right-angle crashes at high-speed intersections (major approach 40 MPH or greater). Their research illustrated a weak reduction effect for intersection-related crashes in general, a definite reduction of right-angle crashes, and a less precise but still definite increase in rear-end crashes. Left-turn crashes were not examined.

Mn/DOT's Signal Design Manual contains selection guidelines for left-turn phasing. It states that permissive or protected-permissive left-turn operation is usually the most efficient, but protected-only is the safest. Although, drivers could lose respect for protected phasing when they think they can make their own safe decision to accept a gap, but proper maintenance and timing can reduce this problem. Currently there exist signal optimization programs that can be used to determine the phasing type and timing, but they do not consider safety. The Signal Design Manual recommends minimum requirements for justification of protected-only phasing, including but not limited to: three or more opposing lanes, limited sight distance, five or more left-turn related crashes per year over a three year period, speeds greater than 45 miles per hour, and dual exclusive left-turn lanes. These requirements all are directly related to the safety of the left-turning movements of vehicles at the intersection.

There has been research done comparing the safety implications of permitted versus permitted/protected left-turn phasing. The majority of research has found that adding any type of phasing to left-turns rather than leaving left-turns as permitted-only usually results in fewer crashes. In fact, Washington et al. (1998) found that when a left-turn phase is provided there are fewer left-turn crashes. Agent (1987) found that the number of left-turn crashes usually decreased when permitted phasing was replaced by permitted/protected phasing. On the other hand, Upchurch (1991) found that with lower left-turn volumes, permitted phasing is safer than permitted/protected phasing. As you can see, there are conflicting findings on the safety implications of these types of phasing.

Other research has been performed that compares the safety of permitted/protected versus protected-only left-turn phasing. In 1982, the Florida Section of ITE (1982) found that with left-turns fully protected the average number of left-turn crashes declined to about 14% of that with protected-permitted phasing, but for other types of crashes the effect was unclear. They also found that when phasing was changed from protected to permitted/protected the average number of left-turn crashes increased seven-fold at the intersections examined, and again the effect on other types of crashes was unclear. Upchurch (1991) found that protected left-turn phasing always produced fewer crashes than permitted/protected at the intersections examined. Hauer (2004) cited an unpublished report by Benioff and Rorabaugh (1980), which found that conversion from protected to permitted/protected resulted in an increase by a factor of 1.4 in total crashes, a fifteen fold increase in left-turn crashes, and a decrease by a factor of 0.4 in rear-end crashes. These results seem to support protected phasing, but a review of research performed on the safety benefits of different types of phasing by Hauer (2004) found that overall when looking at the many different types of research and estimations, there is insufficient and contradictory evidence on whether or not there is a significant effect on crashes.

It must be mentioned that safety should not be the only characteristic examined when considering the phasing because the left-turn phasing can result in increased delay. This effect can especially affect major approach vehicles at high-speed intersections. Wright and Upchurch (1992) found that at one intersection, thru traffic experienced higher delay per vehicle when there existed protected phasing versus permitted/protected on one major approach, while the protected phasing created lower delay on the opposing approach. Their research also found that protected phasing caused more delay per vehicle for left-turning vehicles than permitted/protected left-turn phasing. Research by Asante et al. (1993) and Shebeeb (1995) found similar results. But again, Hauer (2004) found that overall after looking at the many different studies, broad conclusions should not be drawn from this research, and each intersection should be analyzed individually.

From the review of past research, it can be observed that signalization and left-turn phasing must be carefully implemented. The results found in past research vary widely, which could be caused by the different methodologies used. Thus, taking a closer look at the methods used by each investigator could uncover the cause for these differences. Nevertheless, the safety effectiveness of protected left-turn phasing, permitted/protected left-turn phasing, and permitted left-turn phasing is unclear. The purpose of this research is to estimate the CMFs associated with signal installation and left-turn phasing in order to determine the safety effectiveness of each type of countermeasure. The estimations will be performed using state-of-the-art Bayesian methods. Hopefully the research will provide additional guidance in determining the 'best' type of intersection control. It is hoped that the significant CMF estimates will be useful in providing this guidance. This report examines the changes from thru/stop control to signal control, permitted to permitted/protected phasing, permitted to protected phasing, permitted/protected to protected phasing, and protected to permitted/protected phasing. All of the intersections examined are Minnesota State Highways or U.S. Highways, and the majority of these are high-speed intersections (greater than 40 MPH major approach speed limit).

Chapter 2: Estimation of CMF Using a Hybrid Bayesian Approach

2.1 History of CMF Estimation

Chapter 1 introduced the concept of the crash modification factor (CMF), which is an estimate of the reduction in crashes experienced when a countermeasure is implemented. The main goal of the RSPM is to predict the reduction in accidents by multiplying an estimated CMF for a countermeasure by the expected number of accidents without the countermeasure (Y).

$$\text{Expected Reduction} = \text{CMF} * Y \tag{1}$$

A CMF is essentially ". . . a quantitative statement of the result which a countermeasure is expected to cause when implemented…" (Davis 2000a), and when someone uses a CMF they are assuming that current information illustrates a causal connection between a countermeasure and the crash modification. This causal connection is derived from the fact that the crashes experienced when a countermeasure is present are compared to the experience when the countermeasure is absent.

The calculation of CMFs has been done many different ways since the RSPM procedure was first used. One of the early methods was just to perform naïve analyses of observational before/after crash data using the following formula:

$$\text{CMF} = 1 - A/B \tag{2}$$

where B is a measure of crash experience before the implementation of a countermeasure at a pre-identified high-hazard location and A is the measure of crash experience after the countermeasure was implemented (Laughland et al. 1975). The weakness with this method is that the RSPM procedure has often already selected a high hazard location to analyze. Therefore, if an atypically high crash count is used to form the quantity B in equation 2, then A could be expected to be smaller than B even when the countermeasure was ineffective. This is a result of the fact that in any series of values generated by the same underlying random mechanism, more probable lower values follow atypically high values. This is known as regression to the mean and is a possible threat to the validity of observational research (Campbell and Stanley 1963).

In a 1980 paper, Hauer (1980) was the first to recognize regression to the mean effects in the RSPM, and he proposed modifying the estimate of the CMF in order to correct for the bias.

Hauer stated that the estimation of the causal effect should not be a comparison between the 'before' and 'after' counts, but rather between the 'after' count and the count that would have occurred had the treated sites not been treated with a countermeasure. This latter quantity is an example of a counterfactual, that is, an event that would have happened had things been different. Hauer's initial method was to derive an estimate of the counterfactual from a truncated Poisson distribution describing the 'before' counts of the treated sites. These counterfactuals were then used to estimate the CMF.

The next addition to the idea of finding counterfactual outcomes was done by Danielsson (1986). He added an explicit description of the countermeasure's effect as a proportional reduction of the safety variable developed by Hauer. Thus, a good estimate of the reduction led to a good estimate of the CMF. Also, while Danielsson was working on this addition, Hauer (1986) illustrated how empirical Bayesian methods could be used to compute estimates of his safety variable using 'before' counts as well as counts from a reference group of sites similar to the treated sites.

The final addition to the previously described methods, which completed the framework for this report's methods using a Hierarchical Bayes model, was introduced by Abbess et al. (1981). They assumed that the unobserved influences on safety described by Hauer were distributed in the population of sites as independent, identically distributed outcomes of a gamma random variable. Then, given estimates of the gamma distribution parameters, a negative binomial distribution could approximate the conditional distribution of the counterfactual crash count at a given site, and the actual 'after' count could be compared to this to determine the plausibility of a site-specific treatment effect (Davis 2000a).

A complete version of this method was used by Hauer and Persaud (1987), who fitted a Poisson-gamma model to crash counts at rail-highway crossings. Thus, empirical support for the model was provided, and they illustrated how a CMF could be found by acquiring estimates of the gamma distribution parameters from a reference group of treated and untreated sites. Then, they used these parameters to compute Bayes estimates for the predicted crashes at the 'treated sites.'

Since Hauer and Persaud (1987), most of the work in estimating CMFs has built upon their method's framework. Hauer et al. (1988) used the Poisson-gamma model with a generalized linear model to allow the gamma distribution generating a site's safety variable to depend on traffic volumes and other characteristics. Christenson et al. (1992) accounted for systematic variations in the accident rates using generalized linear models, and they implemented a more fully Bayesian approach to estimate the variables of the model.

2.2 Description of Commonly Used Empirical Bayes Approach

At present, the recommended method for estimating CMFs is the empirical Bayesian (EB) approach initiated by Hauer and Persaud (1987), and developed in detail in Hauer (1997). In fact, during the last decade, the ability of highway engineers to explicitly consider safety impacts when making design decisions has been given a significant boost by the development of the Federal Highway Administration's Interactive Highway Safety Design Model (IHSDM) and the Highway Safety Manual (HSM) being compiled by the Transportation Research Board (TRB). Both tools rely heavily on a common method for predicting safety impacts, where a generalized linear model (GLM) is first developed to relate expected crash frequency to exogenous factors such as traffic volume, density of access points, or roadway curvature. This model is then used to predict the crash experience that would be expected in the absence of countermeasures. The crash generating tendency at a site has two components, one being associated with observed covariables, and one due to latent, site-specific features. By combining data from a reference group of untreated sites with pretreatment data from the treated sites, it is possible to develop a generalized linear model to describe how the expected crash frequencies vary as functions of observed covariables, and then to compute estimates of the effects of latent factors specific to each site. These estimates are then used to predict what the crash experience would have been had the treated sites not been treated, and the predicted crash frequencies are combined with the actual after-treatment crash frequencies to estimate the CMF.

Although the EB approach used in the IHSDM and HSM is a clear improvement over naïve before/after analysis (Davis 2000a), several technical considerations can limit its potential usefulness. First, the EB approach requires that the crash data from the reference and treatment groups be overdispersed, since a reliable estimate of the overdispersion parameter is needed to compute the site-specific estimates of crash frequency. When the crash data show little or no overdispersion, application of the EB approach can be problematic. Second, as currently implemented, the EB approach does not account for all sources of uncertainty attached to an estimated CMF. In particular, the values of the parameters for the generalized linear model are usually treated as if they were known with certainty when predicted crash frequencies are computed. Third, to obtain confidence intervals or perform hypothesis tests for an estimated CMF, one must appeal to large-sample asymptotic properties of estimators. These limitations can be especially salient when a local jurisdiction seeks to develop its own estimates of CMFs using local data. In such situations the number of treated locations may be smaller than that available from a statewide or nationwide data base.

Awareness of these issues dates at least to the work of Christianson and Morris (1997), and they presented a hierarchical Bayes approach to modeling Poisson variants that addresses these points. A weakly informative prior distribution was given to the overdispersion parameter, and approximate Bayes estimates of both the generalized linear model's parameters and of the latent effects were computed using some clever approximations. A few years later it was shown that Markov Chain Monte Carlo (MCMC) computation could be used to implement a hierarchical crash model and to identify potentially high risk sites (Davis 2000b). In this report we will use MCMC methods to compute Bayes estimates of CMFs. In essence, the hierarchical Bayes model described by Christianson and Morris (1997) is combined with a model that allows for temporal changes in covariates, described by Hauer, Terry and Griffith (1994). Since, as in Christianson and Morris, the overdispersion parameter is given a weakly informative prior, this report's approach can be used even when the profile likelihood for the overdispersion parameter does not have a bounded maximizing element. No estimated parameters are treated as known with certainty, and the method makes no appeal to large sample asymptotics in order to compute confidence intervals. This Bayesian approach will be used to compute estimates of the CMF associated with a countermeasure associated with signalization or a left-turn phase change at intersections in the Twin Cities metropolitan region of Minnesota. Since a limited number of treatment intersections were available in each countermeasure analysis, the application of large sample statistics was difficult to justify.

2.3 Model Used for the Monte Carlo Hybrid Bayes Approach

As in the more commonly-used EB approach, the generalized linear model relating observed covariates to expected crash frequency for site number k during time interval t takes the form:

$$\bar{\mu}_{kt} = \exp(\beta_0 + \beta_1 X_{kt,1} + \ldots + \beta_m X_{kt,m}) \tag{3}$$

where $\bar{\mu}_{kt}$ = expected crash frequency for 'typical' site with covariate values $X_{kt,1},\ldots,X_{kt,m}$
$X_{kt,j}$ = value of covariable j for site k during time interval t
β_j = GLM coefficients to be estimated

The Bayesian approach then assumes that the expected crash frequency for site k during time t, μ_{kt}, is a gamma random variable with expected value $\bar{\mu}_{kt}$ and dispersion parameter r. Actual crash frequencies Y_{kt} are then modeled as Poisson random outcomes with expected values equal to μ_{kt}. Integrating the joint distribution of Y_{kt} and μ_{kt} with respect to the μ_{kt} then gives the crash frequencies as negative multinomial random variables, with parameters $\beta_0,\ldots,\beta_m$ and r. Estimates of the GLM coefficients and the dispersion parameter are computed, and Bayesian estimates of the μ_{kt} can be computed by approximating their conditional expectations given the crash and covariate data. For time periods of comparable duration, and constant covariate values, these μ_{kt} can then be used to predict crash frequencies, but otherwise some sort of adjustment would need to be applied. Alternatively, one can generate the μ_{kt} as

$$\mu_{kt} = \mu_{k0}\, \bar{\mu}_{kt} \tag{4}$$

where μ_{k0} are gamma random variables with mean equal to 1.0 and dispersion parameter r. This approach is equivalent to the one used above in that it produces the same gamma distributions for the μ_{kt} and the same negative multinomial marginal likelihood for the crash frequencies, but the effects of changes in covariates can be naturally captured by multiplying the updated values for $\bar{\mu}_{kt}$ by the estimates of μ_{k0}.

This multiplicative random effects model can be used to define the likelihood function for crash frequencies. Then, computation of the Bayesian estimates of the GLM model parameters, the dispersion parameter r, and the site specific random effects using the Markov Chain Monte Carlo (MCMC) program Windows Bayesian Inference Using Gibbs Sampling (WinBUGS) 1.4.1 (Spiegelhalter et al. 2003) can be performed. To accommodate the possibility of minimal overdispersion, Christianson and Morris's (1997) shifted Pareto is used as a prior for the overdispersion parameter.

The crash modification effect of a countermeasure is captured by a parameter θ, so that the crash frequency with the countermeasure is modeled as a Poisson random variable with expected value $\theta\mu_{k0}\overline{\mu}_{kt}$. Values of θ less than 1.0 correspond to a decrease in expected crashes due to the countermeasure, while values of θ greater than 1.0 correspond to an increase. If, prior to obtaining data, the uncertainty regarding θ is described using a gamma distribution with parameters a and b, and the values of the GLM parameters β_k and the latent site specific effects μ_{k0} were known then the posterior distribution for θ would be a gamma with parameters $(a+\Sigma\, y_{kt})$ and $(b+\Sigma\, \mu_{kt})$. Bayes estimates of θ can then be computed within WinBUGS 1.4.1 by first sampling from the posteriors for the GLM parameters $\boldsymbol{\beta}$ and the latent effects μ_{k0} and then by taking random draws from the gamma distribution characterizing θ's posterior.

2.4 Estimation Procedure

The estimation of the parameters was performed once the model code and data were entered into WinBUGS 1.4.1. The MCMC sample for μ_0 and the βs was computed by administering the model to the first part of each data file (untreated site-years). The computations were done in two iterative parts. The first part involved 5,000 'burn-in' iterations in order to wash out the effect of the starting point, and the second part involves 10,000 iterations for the actual calculation of the Bayesian estimate. Once the MCMC samples for the μ_0 and βs were calculated, samples from the posterior for θ were estimated. Samples from the posterior for the CMF were computed as

$$\text{CMF} = 1 - \theta \qquad (5)$$

Chapter 3: Change from Unsignalized to Signalized

3.1 Data Preparation

A list containing intersections converted from unsignalized to signalized in the Twin Cities Metro District was obtained from Mn/DOT. The list contained a date corresponding to the installation of a signal at a given intersection. A list of intersections representing signal installation from 1987 to 2000 was compiled, and the crash, roadway, intersection, and traffic data was requested from the Highway Safety Information System (HSIS). The HSIS is a database developed by the Federal Highway Administration (FHWA), which has compiled data collected by nine states. The HSIS currently contains crash, roadway, traffic volume, and intersection data for Minnesota highways from 1987 to 2000. The treatment group was then selected from the returned data file of signalized intersections. The selection resulted in a treatment group containing seventeen intersections, all of which had signals installed from 1991 to 1997. The locations of these seventeen intersections are presented in Table A.1 of Appendix A. The reason that 1990 installations were not used was because the 1988 and 1989 variable representing signalization for each intersection was not updated in the HSIS, and as a result it was not possible to determine the year in which the intersection had the signal installed. The site-years in which the signal was installed were discarded, since these years did not clearly represent either signalized or unsignalized conditions. Also, the seventeen intersections were selected on a basis of being right-angle intersections with four approaches and at least a 40 mph major approach speed limit. All of the intersections were thru-stop controlled before signalization, with protected left-turn protection on the major approaches after signalization.

A request for crash, roadway, intersection, and traffic data for all of the unsignalized intersections in the State of Minnesota was also sent to HSIS in order to construct a reference group of untreated intersections. This request returned an extensive list of all of the intersections in the state that were contained in the HSIS database and included data from 1987 to 2000. Intersections contained in the Twin Cities Metro District were selected from this list and further compilation of only right-angle intersections with four approaches and at least a 40 mph speed limit was prepared. All of the unsignalized intersections were thru-stop controlled. The number of unsignalized intersections in the reference group was 217 intersections. In addition, the treated intersection data before implementation of the countermeasure was included in the reference group data.

The intersections included in the database occur mainly on federal or state trunk highways with only a few along county roads, which were not used for this study because most of their data was incomplete. Not all of the variables in the HSIS database were used in the analysis. The covariates that were used included: access, major approach ADT, minor approach ADT, major approach speed limit, minor approach speed limit, major approach geometry, and minor approach geometry. The access of a roadway was specified as either uncontrolled or controlled in the HSIS database. The geometry characteristics of the approaches that could be determined from the HSIS database included the number of thru lanes and whether turn lanes existed.

The data file used for analysis was constructed in such a way that each year of complete availability of variables for an intersection was given a row in the file. Each entry in the data file is referred to as a site-year. The data file contained 81 treatment site-years and 1,944 reference site-years, which contains the before treatment site-years for the treated intersections.

3.2 Analysis Method

The Bayesian method using MCMC described in Chapter 2 of this report was applied to the data to determine the CMFs, which illustrate how a change thru/stop to signalized affects the number of right angle, rear end, total left-turn, major left-turn, minor left-turn, and intersection related crashes. The program WinBUGS was used to perform the analysis. The method was applied to six different groups of data using the same seven independent variables but a different crash type in each model. The covariates used as the independent variables were altered somewhat within the WinBUGS model. The actual CMF estimation used the natural log difference from mean as the input for major and minor ADT, and a dummy variable value of one was assigned to the major and minor speed limit covariates if the limit was 55 mph or higher using a step function in WinBUGS. The six crash types for which a CMF was estimated included: intersection related, rear end, right angle, total left-turn, major approach left-turn, and minor approach left-turn crashes. The major and minor approach left-turn crash types correspond to the approach from which the left-turn vehicle was turning. For example, if a vehicle was traveling on a major approach to an intersection and wanted to turn left onto a minor approach but was crashed into by an oncoming car, the crash would be labeled a major left-turn crash.

The CMFs were first estimated using all the independent variables in Table 3.1, and then they were estimated using only the variables that were deemed significant in the estimation. This significance was assessed using the step function in WinBUGS, which essentially determined the probability that a variable's regression coefficient was different than zero. A variable was included in this second analysis only if there was at least a 90% probability that it was different than zero.

The results of the two CMF estimations for each type of crash were compared to each other as well as to similar types of crash modification estimates found through literature review. Then, it was determined whether or not the phase change significantly affected the number of crashes.

3.3 Results

The covariates used in the CMF estimations are given in Table 3.1 with a description of them.

TABLE 3.1 Covariate List with a Description of Their Representation

Covariate	Description
X_1	Dummy variable for access. 1=uncontrolled and 0=controlled
X_2	Main AADT (total for both approaches)
X_3	Minor AADT (total for both approaches)
X_4	Major approach speed limit
X_5	Minor approach speed limit
X_6	Dummy variable for major approach left turn lanes. 1=left turn lanes along with 4 or more total thru lanes; 0 otherwise
X_7	Dummy variable for minor approach left turn lanes. 1=left turn lanes along with 4 or more total thru lanes; 0 otherwise

The generalized linear model form produced by the MCMC model is:

$$\bar{\mu} = \exp(\mathbf{X}^{\mathbf{T}} \cdot \boldsymbol{\beta}) \qquad (6)$$

where $\mathbf{X}^{\mathbf{T}}$ is the transpose vector of the covariates described above and $\boldsymbol{\beta}$ is the vector of the coefficients estimated by the MCMC iterates. Posterior means and standard deviations for the β parameters are provided in Table 3.2 along with their significance estimation found using the step function in WinBUGS described in the previous section. The WinBUGS code for the CMF estimation of the major approach left-turn crashes is listed in Appendix B.

TABLE 3.2 β Coefficient Estimates by the MCMC Model Iterations with their Significance for Unsignalized to Signalized with the Major Approach Protected

	Intersection Related			Right Angle			Rear End		
Coefficient	Mean	Std Dev	Prob(β≠0)	Mean	Std Dev	Prob(β≠0)	Mean	Std Dev	Prob(β≠0)
β_0	**0.3925**	**0.1803**	**0.9885**	**-0.6799**	**0.2088**	**1.0000**	**-1.2680**	**0.1850**	**1.0000**
β_1	0.0473	0.1794	0.6029	0.0162	0.0959	0.5327	**0.2578**	**0.1727**	**0.9263**
β_2	**0.3638**	**0.0652**	**1.0000**	**0.2520**	**0.0524**	**0.9966**	**0.9636**	**0.1060**	**1.0000**
β_3	**0.1678**	**0.0298**	**1.0000**	**0.3645**	**0.1401**	**1.0000**	**0.2850**	**0.0521**	**1.0000**
β_4	**-0.1782**	**0.0795**	**0.9891**	0.1119	0.1642	0.7827	-0.0757	0.1334	0.7127
β_5	**-0.1808**	**0.1082**	**0.9522**	-0.0105	0.1399	0.5189	-0.0771	0.1734	0.6772
β_6	0.0876	0.1010	0.8015	**0.2417**	**0.6301**	**0.9566**	**-0.7657**	**0.1534**	**1.0000**
β_7	**-0.7211**	**0.5064**	**0.9167**	-0.6981	0.2324	0.8695	**-0.8559**	**0.5799**	**0.9295**

	Total Left-Turn			Major Left-Turn			Minor Left-Turn		
β_0	**-2.2160**	**0.2785**	**1.0000**	**-3.1390**	**0.4375**	**1.0000**	**-2.7400**	**0.3519**	**1.0000**
β_1	0.1690	0.2789	0.7177	0.4288	0.4130	0.8614	0.0170	0.3301	0.5174
β_2	**0.4432**	**0.1631**	**0.9964**	**0.4345**	**0.2352**	**0.9700**	**0.4507**	**0.1971**	**0.9878**
β_3	**0.5576**	**0.1142**	**1.0000**	**0.5732**	**0.1711**	**0.9992**	**0.5523**	**0.1343**	**1.0000**
β_4	-0.0331	0.2278	0.5502	-0.2631	0.3274	0.7979	0.0502	0.2648	0.5770
β_5	**-0.5886**	**0.2889**	**0.9780**	-0.4793	0.4085	0.8814	**-0.5876**	**0.3545**	**0.9539**
β_6	-0.0349	0.2432	0.5598	-0.2117	0.3610	0.7166	0.0623	0.3010	0.5808
β_7	-0.8999	0.8913	0.8474	0.1682	1.1690	0.5471	**-2.3940**	**1.5020**	**0.9639**

The beta values that are in bold were the ones used in the second CMF estimation since they satisfied the 90% probability test. As you can see, the β_0 and β_2 parameters pass the test for every model. The minor ADT was also found to be important in all of the models, which seems to imply that ADTs are the most important covariates in predicting the number of crashes at the intersections used in these estimations.

The primary objective of this approach was to estimate the CMFs associated with a change from unsignalized to signalized, with emphasis on the major left-turn crash CMF. The resulting CMFs from the MCMC approach are given in Table 3.3. Also listed in Table 3.3 are the CMFs value obtained from National Cooperative Highway Research Program (NCHRP) Report 491 by McGee, Taori, and Persaud (2003). The seventh row of Table 18 on page 23 contained estimates of the crash reduction at intersections where the major approach speed limit was 40 mph or greater, and these were selected as being most comparable to the intersections included in the sample.

TABLE 3.3 Crash Modification Factors Estimated by MCMC Method and NCHRP 491 Results

Crash Type	MCMC Method with all Variables	MCMC Method w/ Sign. Variables	NCHRP Report 491
	CMF Point Estimate (95% Confidence Interval)	CMF Point Estimate (95% Confidence Interval)	CMF Point Estimate (95% Confidence Interval)
Intersection Related	0.0503 (-0.1155, 0.1890)	0.0275 (-0.1319, 0.1649)	0.1500 (0.0320, 0.2680)
Rear End	-1.4300 (-2.1000, -0.8639)	-1.4250 (-2.1080, -0.8585)	-0.9900 (-1.5400, -0.4390)
Right Angle	0.6671 (0.5662, 0.7530)	0.6696 (0.5745, 0.7527)	0.7500 (0.6710, 0.8290)
Total Left-Turn	0.2646 (-0.2067, 0.6071)	0.2509 (-0.2413, 0.5850)	
Major Left-Turn	-0.1918 (-1.4230, 0.5289)	-0.1711 (-1.2360, 0.4895)	
Minor Left-Turn	0.4145 (-0.1333, 0.7566)	0.3967 (-0.1552, 0.7406)	

NCHRP Report 491 found a small reduction for intersection-related crashes in general, a definite reduction of right-angle crashes, and a less precise but still definite increase in rear-end crashes. This report's right angle and rear end results are similar. The rear end CMF indicatess an increase, and the right angle CMF indicatess a definite decrease. But, the CMF estimate for intersection related crashes detects no significant effect. The CMFs relating to left-turn crashes indicates no significant effect because the confidence interval does not allow for a definite statement. The total left-turn result could be resulting from the fact that the decrease that is found in minor left-turn crashes is offset by the increase in major left-turn crashes.

Interestingly, although our sample of treated sites was smaller than that used in NCHRP 491, the precision of the CMF estimates appears to be roughly comparable. But, while computing confidence intervals for NCHRP Report 491 requires appealing to asymptotic normality of the CMF estimators, this report's Bayesian confidence intervals require no such additional assumption. It can be stated with confidence that this study's results provide an independent replication of the results reported in NCHRP Report 491.

Chapter 4: Minor Approach Left-Turn Phasing Changes

4.1 Minor Approach Left-Turn Phase-Change from Permitted to Permitted/Protected

4.1.1 Data Preparation

A list containing intersections whose minor approaches were converted from permitted to permitted/protected left-turn phasing, in the Twin Cities Metro District, was obtained from Mn/DOT. The crash, roadway, intersection, and traffic data for the list were requested from Mn/DOT. The treatment group was then identified from the returned data file of phase-changed intersections, and contained four intersections. The locations of these four intersections are presented in Table A.2 of Appendix A. All of the intersections were four legged right-angle intersections with the major approaches having protected left-turn phasing. There are only four treatment intersections because an investigation of the study area of the Twin Cities Metro District only uncovered four intersections whose minor approaches were converted from permitted to permitted/protected that had sufficient data and met the criteria for selection.

To construct a reference group of untreated intersections, intersection data were acquired from the HSIS. The request returned an extensive list of candidate reference intersections in the metro area. The phasing for these intersections was obtained from Mn/DOT's signal plans, and the reference group was constructed from intersections that have protected left-turn phasing on their major approaches and permitted left-turn phasing on the minor approaches. It was also required that each reference intersection had a total of four approaches, which intersected at a right-angle. There were a total of sixteen reference intersections in this analysis.

The data files were constructed in such a way that each year of complete availability of variables for an intersection was given a row in the file. Each entry in the data files is referred to as a site-year. A data file was created, which contained the information to be used in the analysis. The following independent variables were used: major approach ADT and minor approach ADT. The number of right angle, total left-turn, major left-turn, minor left-turn, rear end, and total intersection-related crashes was also acquired for each site-year. A total of six data files were created, corresponding to six different types of crashes. The resulting file contained 147 reference site-years, which included the before treated site-years for the treated intersections, and 10 treated site-years.

4.1.2 Analysis Method

The Bayesian method using MCMC, described in Chapter 2 of this report, was applied to the data to estimate the CMFs, which reflect how a left-turn phase-change from permitted to permitted/protected affected the number of right angle, rear end, left-turn, and intersection related crashes. Whether the phasing was leading or lagging was not considered in this analysis. The program WinBUGS 1.4.1 was used to perform the analysis. The estimations were run using the two ADT variables described in the previous section. The ADT variables were only used because reliable estimates for the beta values were difficult to estimate because of the small sample size, and the approach of using only ADT variables was replicated from NCHRP Report 491. The covariates used as the independent variables were altered somewhat within the WinBUGS model. The actual CMF estimation used the natural log difference from mean as the input for major and minor ADT. The six crash types for which a CMF was estimated included: intersection related, rear end, right angle, total left-turn, major approach left-turn, and minor approach left-turn crashes. The major and minor approach left-turn crash types correspond to the approach from which the left-turn vehicle was turning. For example, if a vehicle was traveling on a major approach to an intersection and wanted to turn left onto the minor approach, but was struck by an oncoming vehicle, the crash would be labeled a major left-turn crash.

The results of the CMF estimations for each type of crash were examined and compared to similar types of crash modification estimates found through a literature review. The CMF estimates were further examined to determine the influence of the phase change on the different types of crashes.

4.1.3 Results

The covariates used in the CMF estimations are given in Table 4.1.1 with a description of them.

TABLE 4.1.1 Covariate List with a Description of Their Representation

Covariate	Description
X_1	Main AADT (total for both approaches)
X_2	Minor AADT (total for both approaches)

The generalized linear model form produced by the MCMC model is:

$$\bar{\mu} = \exp(\mathbf{X}^{\mathbf{T}} \cdot \boldsymbol{\beta}) \quad (6)$$

where $\mathbf{X}^T$ is the transpose vector of the covariates described above and $\boldsymbol{\beta}$ is the vector of the coefficients estimated by the MCMC iterates. Posterior means and standard deviations for the β parameters are presented in Table 4.1.2.

TABLE 4.1.2 β Coefficient Estimates by the MCMC Model Iterations for Minor Phase-Change from Permitted to Permitted/Protected

	Intersection Related		Right Angle		Rear End	
Coefficient	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
β_0	1.6970	0.1482	0.0879	0.2052	0.9730	0.1927
β_1	0.4826	0.2457	0.6465	0.3927	0.7593	0.3401
β_2	-0.0510	0.0805	0.0132	0.1465	-0.0587	0.1135
	Total Left-Turn		**Major Left-Turn**		**Minor Left-Turn**	
β_0	-0.8433	0.2421	-1.5260	0.3876	-1.5480	0.2353
β_1	-0.6662	0.5001	-0.7687	0.7630	-0.6454	0.4641
β_2	-0.2780	0.2373	-0.5476	0.4007	-0.1042	0.2832

The primary objective of this analysis was to estimate the CMFs associated with a minor approach phase change from permitted left-turn phasing to permitted/protected left-turn phasing. The resulting CMFs from the MCMC approach are given in Table 4.1.3.

TABLE 4.1.3 Crash Modification Factors Estimated by MCMC Method for Minor Approach Phase Change from Permitted to Permitted/Protected

Crash Type	MCMC CMF Estimates
	CMF Point Estimate (95% Confidence Interval)
Intersection Related	0.1472 (-0.1429, 0.3787)
Rear End	0.0381 (-0.3934, 0.3608)
Right Angle	-0.0767 (-1.0820, 0.5374)
Total Left-Turn	0.5379 (-0.2100, 0.9156)
Major Left-Turn	0.6251 (-0.4752, 0.9920)
Minor Left-Turn	0.2661 (-1.2700, 0.9177)

A literature review, described in Chapter 1, was performed in order to compare these results with other research. For example, it has been found that the number of left-turn accidents usually decreased when permitted phasing was replaced by permitted/protected phasing, but it did not have a detrimental effect on overall accidents. Although, Upchurch (1991) found that with lower left-turn volumes, permitted phasing is safer than permitted/protected phasing. A review of reports by Hauer (2004) found that overall when looking at the many different types of research on the effect of phase changes, there is insufficient and contradictory evidence on whether or not there is a significant effect on crashes.

Results for the CMF estimation are given in Table 4.1.3. For intersection-related, right-angle, and rear-end crashes, the relatively small values of the CMF point estimates and the fact that the 95% confidence intervals effectively straddle the value of zero, indicate that the phasing change did not significantly affect these types of crashes. The left-turn point estimates of the CMFs do show marginal evidence of a decrease in crashes, which is similar to some of the reports found in the literature review. But, since the confidence intervals again straddle the value of zero there is little evidence to support the hypothesis that changing the minor approach left-turn phasing from permitted to permitted/protected decreased left-turn crashes. Therefore, it should be stated that the CMF estimations detect no effect on left-turn crashes. The estimates provided in Table 4.1.3 should be used with caution when generalizing to other locations because of the small number of treated locations.

4.2: Minor Approach Left-Turn Phase-Change from Permitted to Protected

4.2.1 Data Preparation

A list containing intersections whose minor approaches were converted from permitted to protected left-turn phasing, in the Twin Cities Metro District, was obtained from Mn/DOT. The crash, roadway, intersection, and traffic data for the list were requested from Mn/DOT. The treatment group was then selected from the returned data file of phase-changed intersections. The selection resulted in a treatment group containing only one intersection, which was a four-legged right-angle intersection, with the major approaches having protected left-turn phasing. The location of this intersection is presented in Table A.3 of Appendix A. There is only one treatment intersection because an investigation of the study area of the Twin Cities Metro District only uncovered one intersection whose minor approaches were converted from permitted to protected that had sufficient data and met the criteria for selection.

To construct a reference group of untreated intersections, intersection data were acquired from the HSIS. This request returned an extensive list of candidate intersections in the metro area. The phasing for these intersections was obtained from Mn/DOT's signal plans, and the reference group was constructed from intersections that had major approach protected left-turn phasing, and permitted left-turn phasing on the minor approaches. It was also required that each reference intersection had a total of four approaches, which intersected at a right angle. There were a total of sixteen reference intersections in this analysis.

The data files used for analysis were constructed in such a way that each year of complete availability of variables for an intersection was given a row in the file. Each entry in the data files is referred to as a site-year. The data acquired allowed the analysis to use the following independent variables: major approach ADT and minor approach ADT. The number of right angle, left-turn, rear end, and total intersection-related crashes was also acquired for each site-year, and a total of six data files were constructed. The file contained 132 reference site-years, including the before treatment site-years for the treated intersection, and one treated site-year.

4.2.2 Analysis Method

The Bayesian method using MCMC described in Chapter 2 of this report was applied to the data to estimate the CMFs, which reflect how a left-turn phase change from permitted to protected affects the number of right angle, rear end, left-turn, and intersection related crashes. Whether the phasing was leading or lagging was not considered in this analysis. The program WinBUGS 1.4.1 was used to perform the analysis. A total of six types of models were run using the two ADT variables described in the previous section but with the six different crash types as dependent variables. The ADT variables were only used because reliable estimates for the beta values were difficult to estimate because of the small sample size, and the approach of using only ADT variables was replicated from NCHRP Report 491. The covariates used as the independent variables were altered somewhat within the WinBUGS model. The actual CMF estimation used the natural log difference from mean as the input for major and minor ADT. Again, the six crash types for which a CMF was estimated included: intersection related, rear end, right angle, total left-turn, major approach left-turn, and minor approach left-turn crashes. The major and minor approach left-turn crash types correspond to the approach from which the left-turn vehicle was turning. For example, if a vehicle was traveling on a major approach to an intersection and wanted to turn left onto the minor approach, but was struck by an oncoming car, the crash would be labeled a major left-turn crash.

The results of the CMF estimates for each type of crash were compared to the results found through a literature review. Finally, CMF estimates were examined to determine the affect of the phase change on the different types of crashes at the intersections studied in this report.

4.2.3 Results

The covariates used in the CMF estimations are given in Table 4.2.1 with a description of them.

TABLE 4.2.1 Covariate List with a Description of Their Representation

Covariate	Description
X_1	Main AADT (total for both approaches)
X_2	Minor AADT (total for both approaches)

The generalized linear model form produced by the MCMC model is:

$$\bar{\mu} = \exp(\mathbf{X}^{\mathbf{T}} \cdot \boldsymbol{\beta}) \tag{6}$$

where $\mathbf{X}^{\mathbf{T}}$ is the transpose vector of the covariates described above and $\boldsymbol{\beta}$ is the vector of the coefficients estimated by the MCMC iterates. Posterior means and standard deviations for the β parameters are provided in Table 4.2.2.

TABLE 4.2.2 β Coefficient Estimates by the MCMC Model Iterations for Phase-Change from Permitted to Protected

	Intersection Related		**Right Angle**		**Rear End**	
Coefficient	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
β_0	1.5760	0.1502	0.1463	0.2221	0.7462	0.1602
β_1	0.4630	0.2240	0.4786	0.3852	0.9398	0.3114
β_2	-0.0653	0.0805	0.0127	0.1446	-0.0972	0.1111
	Total Left-Turn		**Major Left-Turn**		**Minor Left-Turn**	
β_0	-0.9846	0.2728	-1.7570	0.5215	-1.6460	0.2754
β_1	-1.1820	0.4484	-1.5680	0.7903	-1.0740	0.4473
β_2	-0.2501	0.2887	-0.9652	0.4987	0.3531	0.3191

The primary objective of this approach was to estimate the CMFs associated with a minor approach phase change from permitted left-turn phasing to protected left-turn phasing. The resulting CMFs from the MCMC approach are given in Table 4.2.3.

TABLE 4.2.3 Crash Modification Factors Estimated by MCMC Method for Minor Approach Phase Change from Permitted to Protected

Crash Type	MCMC CMF Estimates
	CMF Point Estimate (95% Confidence Interval)
Intersection Related	0.1751 (-0.9858, 0.7874)
Rear End	0.2759 (-1.8800, 0.9838)
Right Angle	-4.4270 (-17.0300, 0.2409)
Total Left-Turn	0.9942 (0.9733, 1.0000)
Major Left-Turn	0.9808 (0.9052, 1.0000)
Minor Left-Turn	0.9903 (0.9565, 1.0000)

The results obtained for the CMF estimates in Table 4.2.3 indicate that there was no significant effect on intersection related crashes, rear end, and right angle crashes, since the confidence intervals illustrate a range that cover both a positive and negative affect. In fact, the right angle CMF is non-informative because of the very large confidence interval. An examination of the confidence intervals for the CMFs relating to the effect of the phase change on total left-turn, major left-turn, and minor left-turn indicates that there was close to a 100% decrease in these types of crashes, and the confidence intervals for these tend to be concentrated on a small range of values near 1.0. This requires some comment. The treated site had five year of before data available, with a total of 8 minor-approach left-turn crashes during this time, and one year of after data available, with zero minor-approach left-turn crashes. Looking only at these data, the maximum likelihood estimates of the mean yearly crash frequency before treatment would simply be the average yearly before count (approximately 1.6 crashes/year) while the maximum likelihood estimate of the CMF would simply be 1.0 minus the ratio of the average after count and the average before count. Since there no after treatment crashes were observed, the maximum likelihood estimate of the CMF would be 1.0. A problem arises however when we attempt to estimate the variance associated with the CMF estimate. The theoretical value would be (1-CMF) divided by the mean before-treatment frequency, but if we substitute our estimated CMF into this expression we get a value of 0 for the estimated variance. That is, the naïve conclusion would be a 100% reduction in crashes, with a 100% confidence placed on this estimate. What has actually happened is that, when we have 0 after-treatment crashes, maximum likelihood methods cannot estimate the variance associated with the estimated CMF. Our Bayesian estimates, because they assume that prior to obtaining data we do not know what value the CMF takes, show a similar, but less extreme tendency. The practical implication is that, when one has zero after-treatment crashes, the best point estimate of the CMF will be a (nearly) 100% reduction, but that this estimate is subject to an uncertainty which the data are not able to estimate. In this case, since the probability of obtaining one year with zero crashes, assuming that the phasing change had no effect, is about exp(-1.6)=0.20, it is not reasonable to attribute the observed reduction to the effect of the phasing change.

4.3: Minor Approach Left-Turn Phase-Change from Permitted/Protected to Protected

4.3.1 Data Preparation

A list containing intersections whose minor approaches were converted from permitted/protected to protected left-turn phasing, in the Twin Cities Metro District, was obtained from Mn/DOT. The crash, roadway, intersection, and traffic data for the list were requested from Mn/DOT. The treatment group was then identified from the returned data file of phase-changed intersections. The treatment group contained two intersections, which were four-legged right-angle intersections with the major approaches having protected left-turn phasing. The locations of these two intersections are presented in Table A.4 of Appendix A. There are only two treatment intersections because an investigation of the study area of the Twin Cities Metro District only uncovered two intersections whose minor approaches were converted from permitted/protected to protected that had sufficient data and met the criteria for selection.

To construct a reference group of untreated intersections, intersection data were acquired from the HSIS. This request returned an extensive list of intersections in the metro area. The phasing for these intersections was acquired from Mn/DOT's signal plans, and the reference group was constructed from intersections that had protected left-turn phasing on their major approaches, and permitted/protected left-turn phasing on their minor approaches. It was also required that each reference intersection had a total of four approaches, which intersected at a right-angle. These requirements were necessary to make the reference group as similar to the treatment group as possible. There were a total of seventeen reference intersections in this analysis.

The data files used for analysis was constructed in such a way that each year of complete availability of variables for an intersection was given a row in the file. Each entry in a data file is referred to as a site-year. The data acquired allowed the analysis to use the following independent variables: major approach ADT and minor approach ADT. The number of right angle, total left-turn, major left-turn, minor left-turn, rear end, and total intersection-related crashes was also acquired for each site-year. Therefore, six different data files were constructed corresponding to each type of crash. The file contained 146 reference site-years, which included the before treatment site-years for the treated intersections, and two treated site-years.

4.3.2 Analysis Method

The Bayesian method using MCMC described in Chapter 2 of this report was applied to the data to determine the CMFs, which reflect how a minor left-turn phase change from permitted/protected to protected affected the number of right angle, rear end, left-turn, and intersection related crashes. Whether the phasing was leading or lagging was not considered in this analysis. The program WinBUGS 1.4.1 was used to perform the analysis. The estimations were run using the same two ADT variables described in the previous section but with different crash types as dependent variables in each case. The ADT variables were only used because reliable estimates for the beta values were difficult to estimate as a result of the small sample size, and the approach of using only ADT variables was replicated from NCHRP Report 491. The covariates used as the independent variables were altered somewhat within the WinBUGS model. The actual CMF estimation used the natural log difference from mean as the input for major and minor ADT. The six crash types for which a CMF was estimated include: intersection related, rear end, right angle, total left-turn, major approach left-turn, and minor approach left-turn crashes. The major and minor approach left-turn crash types correspond to the approach from which the left-turn vehicle was turning. For example, if a vehicle was traveling on a major approach to an intersection and wanted to turn left onto the minor approach, but was struck by an oncoming car, the crash would be labeled a major left-turn crash.

The results of the CMF estimations for each type of crash were compared to results found through a literature review. Finally, the CMF estimates were examined to determine the affect of the phase change on the number of crashes at the treatment intersections.

4.3.3 Results

The covariates used in the CMF estimations are given in Table 4.3.1 with a description of them.

TABLE 4.3.1 Covariate List with a Description of Their Representation

Covariate	Description
X_1	Main AADT (total for both approaches)
X_2	Minor AADT (total for both approaches)

The generalized linear model form produced by the MCMC model is:

$$\overline{\mu} = \exp(\mathbf{X}^{\mathbf{T}} \cdot \boldsymbol{\beta}) \tag{6}$$

where $\mathbf{X}^{\mathbf{T}}$ is the transpose vector of the covariates described above and $\boldsymbol{\beta}$ is the vector of the coefficients estimated by the MCMC iterates. Posterior means and standard deviations for the β parameters are provided in Table 4.3.2.

TABLE 4.3.2 β Coefficient Estimates by the MCMC Model Iterations for Minor Phase-change from Permitted/Protected to Protected

	Intersection Related		**Right Angle**		**Rear End**	
Coefficient	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
β_0	1.7080	0.1915	0.2443	0.2353	0.9450	0.1912
β_1	0.3946	0.2540	0.0101	0.4145	0.7658	0.2949
β_2	-0.0346	0.0724	-0.0217	0.1476	-0.0206	0.1007
	Total Left-Turn		**Major Left-Turn**		**Minor Left-Turn**	
β_0	-0.6476	0.2615	-1.2420	0.3131	-1.4170	0.2500
β_1	-0.0439	0.5002	-0.3263	0.5899	0.6401	0.4756
β_2	0.3634	0.2133	0.2964	0.2734	0.4312	0.2590

The primary objective of this approach was to estimate the CMFs associated with a minor approach phase change from permitted/protected left-turn phasing to protected left-turn phasing. The resulting CMFs from the MCMC approach are given in Table 4.3.3.

TABLE 4.3.3 Crash Modification Factors Estimated by MCMC Method for Minor Approach Phase Change from Permitted/protected to Protected

Crash Type	MCMC CMF Estimates
	CMF Point Estimate (95% Confidence Interval)
Intersection Related	0.0099 (-0.7789, 0.5777)
Rear End	-0.3077 (-1.5800, 0.4999)
Right Angle	0.3308 (-1.6990, 0.9835)
Total Left-Turn	0.9916 (0.9605, 1.0000)
Major Left-Turn	0.9835 (0.9302, 1.0000)
Minor Left-Turn	0.9650 (0.8267, 1.0000)

A literature review was performed in order to compare these results with other research as mentioned in Chapter 1. In 1982, the Florida Section of ITE (1982) found that with left turns fully protected the average number of left-turn accidents declined to about 14% of that with protected/permitted phasing, but for other types of accidents the effect is unclear. Also, Upchurch (1991) found that protected left-turn phasing always produced fewer accidents than permitted/protected at the intersections examined. A review of reports by Hauer (2004) found that overall when looking at the many different types of research on the effect of phase changes, there is insufficient and contradictory evidence on whether or not there is a significant effect on crashes.

The results obtained for the CMF estimations in Table 4.3.3 illustrate that there is no significant effect on intersection related crashes, rear end, and right angle crashes as illustrated by the confidence intervals. An examination of the confidence intervals for the CMF estimations relating to the effect of the phase change on total left-turn, major left-turn, and minor left-turn illustrates that there is a decrease in these types of crashes. Again, however, the small sample of treated site-years makes it difficult to estimate the uncertainty associated with the estimated left-turn CMFs, and one should be cautious when generalizing this result to other locations.

Chapter 5: Major Approach Left-Turn Phase-Changes

5.1: Major Approach Left-Turn Phasing from Protected to Permitted/Protected

5.1.1 Data Preparation

A list containing intersections whose major approaches were converted from protected to permitted/protected left-turn phasing, in the Twin Cities Metro District, was obtained from Mn/DOT. The crash, roadway, intersection, and traffic data for the list were requested from Mn/DOT. The treatment group was then identified from the returned data file of phase-changed intersections, and contained two intersections, which were four-legged, right-angle intersections, with the minor approaches having permitted left-turn phasing. The locations of these two intersections are presented in Table A.5 of Appendix A. There are only two treatment intersections because an investigation of the study area of the Twin Cities Metro District only uncovered two intersections whose major approaches were converted from protected to permitted/protected that had sufficient data and met the criteria for selection.

To construct a reference group of untreated intersections, intersection data were acquired from the HSIS. This request returned an extensive list of intersections in the metro area. The phasing for these intersections was obtained from Mn/DOT's signal plans, and the reference group was constructed from intersections that had permitted left-turn phasing on their minor approaches, and protected left-turn phasing on the major approaches. It was also required that each reference intersection have a total of four approaches, which intersected at a right-angle. There were a total of twenty reference intersections in this analysis.

The data files used for analysis were constructed in such a way that each year of complete availability of variables for an intersection was given a row in the file. Each entry in the data files was referred to as a site-year. The data acquired allowed the analysis to use the following independent variables: major approach ADT and minor approach ADT. The number of right angle, total left-turn, major left-turn, minor left-turn, rear end, and total intersection-related crashes was also acquired for each site-year. The file contained 171 reference site-years, which included the before treatment site-years for the treated intersections, and 6 treated site-years.

5.1.2 Analysis Method

The Bayesian method using MCMC described in Chapter 2 of this report was applied to the data to determine the CMFs, which detect how a left-turn phase change from protected to permitted/protected affects the number of right angle, rear end, left-turn, and intersection related crashes. Whether the phasing was leading or lagging was not considered in this analysis. The program WinBUGS 1.4.1 was used to perform the analysis. The estimations were run using the two ADT independent variables described in the previous section but with counts of the six different crash types as dependent variables. The ADT variables were only used because reliable estimates for the beta values were difficult to estimate as a result of the small sample size, and the approach of using only ADT variables was replicated from NCHRP Report 491. The covariates used as the independent variables were altered somewhat within the WinBUGS model. The actual CMF estimation used the natural log difference from mean as the input for major and minor ADT. The six crash types for which a CMF was estimated included: intersection related, rear end, right angle, total left-turn, major approach left-turn, and minor approach left-turn crashes. The major and minor approach left-turn crash types correspond to the approach from which the left-turn vehicle was turning. For example, if a vehicle was traveling on a major approach to an intersection and wanted to turn left onto the minor approach, but was struck by an oncoming car, the crash would be labeled a major left-turn crash.

The results of the CMF estimations for each type of crash were compared to the results of the literature review. Finally, the CMF estimates were examined to determine the affect of the phase-change on the number of crashes at the treated intersections.

5.1.3 Results

The covariates used in the CMF estimations are given in Table 5.1.1 with a description of them.

TABLE 5.1.1 Covariate List with a Description of Their Representation

Covariate	Description
X_1	Main AADT (total for both approaches)
X_2	Minor AADT (total for both approaches)

The generalized linear model form produced by the MCMC model is:

$$\bar{\mu} = \exp(\mathbf{X}^{\mathbf{T}} \cdot \boldsymbol{\beta}) \quad (6)$$

where $\mathbf{X}^T$ is the transpose vector of the covariates described above and $\boldsymbol{\beta}$ is the vector of the coefficients estimated by the MCMC iterates. Posterior means and standard deviations for the β parameters are provided in Table 5.1.2.

TABLE 5.1.2 β Coefficient Estimates by the MCMC Model Iterations for a Major Approach Phase-Change from Protected to Permitted/Protected

	Intersection Related		Right Angle		Rear End	
Coefficient	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
β_0	1.4730	0.1106	0.5785	0.1361	0.1773	0.1739
β_1	0.6276	0.1838	1.3020	0.2558	0.2041	0.2921
β_2	-0.0376	0.0757	-0.0948	0.1041	0.1046	0.1365
	Total Left-Turn		**Major Left-Turn**		**Minor Left-Turn**	
β_0	-1.1160	0.2337	-1.9030	0.4056	-1.7530	0.2209
β_1	-0.1030	0.4060	0.1400	0.6622	-0.4360	0.4087
β_2	-0.1539	0.2420	-0.5496	0.4307	0.2204	0.2634

The primary objective of this approach was to estimate the CMFs associated with a major approach phase change from protected left-turn phasing to permitted/protected left-turn phasing. The resulting CMFs from the MCMC approach are given in Table 5.1.3.

TABLE 5.1.3 Crash Modification Factors Estimated by MCMC Method for Major Approach Phase-Change from Protected to Permitted/Protected

Crash Type	MCMC CMF Estimates CMF Point Estimate (95% Confidence Interval)
Intersection Related	0.0286 (-0.9706, 0.6264)
Rear End	-0.7914 (-3.9540, 0.5762)
Right Angle	0.9949 (0.9823, 1.0000)
Total Left-Turn	0.0785 (-2.6220, 0.9278)
Major Left-Turn	-12.2500 (-102.8000, 0.7697)
Minor Left-Turn	0.9921 (0.9692, 1.0000)

A literature review was performed in order to compare these results with other research as mentioned in Chapter 1. In 1982, the Florida Section of ITE (1982) found that when phasing was changed from protected to permitted/protected the average number of left-turn crashes increases seven-fold at the intersections examined, but for other types of crashes the effect is unclear. Also, Upchurch (1991) found that protected left-turn phasing always produced fewer accidents than permitted/protected at the intersections examined. A review of reports by Hauer (2004) found that overall when looking at the many different types of research on the effect of phase changes, there is insufficient and contradictory evidence on whether or not there is a significant effect on crashes.

The results obtained for the CMF estimations in Table 5.1.3 illustrate that there is no significant effect on intersection related, rear end, total left-turn, or major left-turn crashes as illustrated by the confidence intervals. In fact, the confidence interval of the major left-turn is so wide that it is non-informative. Therefore, the result of an increase in major left-turn crashes as found in the literature review is not supported by this report's estimations. An examination of the confidence intervals for the CMFs relating to the effect of the phase-change on right angle and minor left-turn crashes illustrates that there is a decrease in these types of crashes. The result of a decrease in minor left-turn crashes is an interesting finding since the minor approach remained permitted left-turn phasing. But, the results presented here should be used with caution when generalizing to other locations because of the small sample size that was available.

5.2: Major Approach Left-Turn Phasing from Unsignalized to Permitted/Protected to Protected

5.2.1 Data Preparation

An intersection for which the phasing changed twice in ten years was discovered while searching for treatment intersections for Chapter 3. This intersection was first changed from thru/stop controlled to signalized with permitted/protected phasing on the major approach. This characteristic is different than the treatment intersections in Chapter 3, which were changed from thru/stop to signalized with protected phasing on the major approach. Then, six years later, the phasing of this intersection was changed from permitted/protected to protected. The location of this intersection is presented in Table A.6 of Appendix A. There was only one treatment intersection because after this intersection was discovered, an investigation of the study area of the Twin Cities Metro District did not uncover any other intersections whose major approach was converted from thru/stop to permitted/protected to protected.

The data for the treated intersection was obtained from HSIS in the manner explained in Chapter 3. The reference data used for the change from unsignalized to signalized with permitted/protected phasing on the major approach was the same reference data used for the CMF estimations in Chapter 3 since the characteristics are identical. Specifically, the treatment intersection had four approaches intersecting at right angles. The reference data used for the change from permitted/protected to protected was obtained by multiplying the reference intersections priors from the first change by the θ from the first CMF estimation, which is the crash modification effect of the intersection control change from thru/stop to permitted/protected for this intersection.

The number of reference intersections was 233 with 1,944 site-years, which included the before treatment site-years of the treated intersection. While, the number of treatment site-years was ten. The data files were set up in the same format as explained in Chapter 3.

5.2.2 Analysis Method

A variant of the Bayesian method using MCMC described in Chapter 2 of this report was applied to the data to determine the CMFs, which are used to determine how the major approach left-turn phasing change from unsignalized to permitted/protected to protected affected the number of right angle, rear end, left-turn, and intersection related crashes. The program WinBUGS was used to perform the analysis. The six estimations were run using the same seven independent variables but with one of the six different crash types as the independent variable. The covariates used as the independent variables were altered somewhat within the WinBUGS model. The actual CMF estimation used the natural log difference from mean as the input for major and minor ADT, and a dummy variable of one was assigned to the major and minor speed limit covariates if the limit was 55 mph or higher using a step function in WinBUGS. The six crash types for which a CMF was estimated included: intersection related, rear end, right angle, total left-turn, major approach left-turn, and minor approach left-turn crashes. The major and minor approach left-turn crash types correspond to the approach from which the left-turn vehicle was turning. For example, if a vehicle was traveling on a major approach to an intersection and wanted to turn left onto the minor approach, but was crashed into by an oncoming car, the crash would be labeled a major left-turn crash.

The resulting estimates of the CMF were examined and the affect of the major approach phasing change from thru/stop to permitted/protected and then from permitted/protected to protected was reported.

5.2.3 Results

The covariates used in the CMF estimations are given in Table 5.2.1 with a description of them.

TABLE 5.2.1 Covariate List with a Description of Their Representation

Covariate	Description
X_1	Dummy variable for access. 1=uncontrolled and 0=controlled
X_2	Main AADT (total for both approaches)
X_3	Minor AADT (total for both approaches)
X_4	Major approach speed limit
X_5	Minor approach speed limit
X_6	Dummy variable for major approach left turn lanes. 1=left turn lanes along with 4 or more total thru lanes; 0 otherwise
X_7	Dummy variable for minor approach left turn lanes. 1=left turn lanes along with 4 or more total thru lanes; 0 otherwise

The generalized linear model form produced by the MCMC model is:

$$\bar{\mu} = \exp(\mathbf{X}^{\mathbf{T}} \cdot \boldsymbol{\beta}) \tag{6}$$

where $\mathbf{X}^{\mathbf{T}}$ is the transpose vector of the covariates described above and $\boldsymbol{\beta}$ is the vector of the coefficients estimated by the MCMC iterates. Posterior means and standard deviations for the β parameters are provided in Table 5.2.2.

TABLE 5.2.2 β Coefficient Estimates by the MCMC Model Iterations for Unsignalized to Permitted/Protected to Protected Phase-Changes on the Major Approach

	Intersection Related		Right Angle		Rear End	
Coefficient	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
β_0	0.4211	0.1481	-0.6713	0.2031	-1.3000	0.2023
β_1	0.0261	0.1530	0.0015	0.1944	0.2757	0.1884
β_2	0.3616	0.0694	0.2508	0.0954	0.9752	0.1089
β_3	0.1699	0.0306	0.3656	0.0507	0.2890	0.0539
β_4	-0.1801	0.0781	0.1303	0.1357	-0.0622	0.1380
β_5	-0.1847	0.1040	-0.0156	0.1755	-0.0737	0.1735
β_6	0.0803	0.0976	0.2246	0.1463	-0.7666	0.1516
β_7	-0.7730	0.4707	-0.6993	0.6282	-0.8471	0.5724
	Total Left-Turn		Major Left-Turn		Minor Left-Turn	
β_0	-2.5310	0.3303	-2.8850	0.2869	-2.9150	0.3064
β_1	0.1436	0.3394	0.1531	0.2817	0.1730	0.2902
β_2	0.5115	0.1763	0.4447	0.1616	0.4530	0.1646
β_3	0.5454	0.1151	0.5541	0.1135	0.5553	0.1107
β_4	0.1311	0.2338	-0.0562	0.2246	-0.0419	0.2246
β_5	-0.6549	0.3043	-0.5682	0.2868	-0.5673	0.2916
β_6	0.0653	0.2757	-0.0288	0.2492	-0.0293	0.2474
β_7	-1.1620	1.0610	-0.8959	0.8903	-0.8930	0.8810

The primary objective of this approach was to estimate the CMFs associated with a change from unsignalized to permitted/protected and then to protected on the major approach. The resulting CMFs from the MCMC approach are given in Table 5.2.3.

TABLE 5.2.3 Crash Modification Factors Estimated by MCMC Method for Change from Unsignalized to Permitted/Protected and Permitted/Protected to Protected

Crash Type	unsig-perm.prot	perm.prot-prot
	CMF Point Estimate (95% Confidence Interval)	CMF Point Estimate (95% Confidence Interval)
Intersection Related	-0.9886 (-2.5840, 0.0025)	0.4192 (-0.0319, 0.7153)
Rear End	0.4539 (-0.8816, 0.9478)	-4.317 (-21.7700, 0.2961)
Right Angle	-0.7644 (-3.5980, 0.4555)	0.2914 (-0.7516, 0.8039)
Total Left-Turn	-12.7400 (-73.3300, -0.2624)	0.9991 (0.9957, 1.0000)
Major Left-Turn	-11.0200 (-53.8800, -0.3956)	0.9989 (0.9958, 1.0000)
Minor Left-Turn	-1.5970 (-12.1900, 0.8743)	0.9916 (0.9664, 1.0000)

The CMF estimates for the first change (thru/stop to permitted/protected) illustrate that the rear end, right angle, and minor left-turn crashes were not significantly affected. While, there is marginal evidence for an increase in total intersection related crashes as illustrated by the confidence interval. The total left-turn and major left-turn CMF estimates provide evidence that these crashes increased after the intersection control change from unsignalized to signalized with permitted/protected left-turns. This result is interesting since it is thought that more intersection control should hypothetically lower left-turn crashes.

The CMF estimates for right-angle and rear-end crashes resulting from the second change (permitted/protected to protected) indicate no significant effect on crashes. The CMF estimates for each type of left-turn crash provide support for the hypothesis that changing the phasing form from permitted/protected to protected was followed by a nearly 100% decrease in left-turn crashes. As with some of the analyses described earlier, the observation of zero after-treatment crashes makes it difficult to estimate the variance associated with the CMF. However, for this site the average number of major approach left-turn crashes when permitted/protected phasing was in operation was (9/5)=1.8, and after converting to protected-only left-turn phasing no major-approach left-turn crashes were reported for five years. If the conversion to protected-only phasing had had no effect, the probability of going five years without a major approach left turn crash would be about $\exp(-1.8)^5 = .00012$. So in this case it is reasonable to conclude that a definite reduction in left-turn crashes has occurred.

A review of accident reports filed when the protected/permitted phasing was in operation revealed that several drivers complained of being unable to see oncoming traffic. One possible explanation for this pattern is that a sight-distance problem similar to that identified by McCoy and his associates (2001), where the ability of a left-turning driver to see oncoming vehicles is restricted when another vehicle occupies the opposing left-turn lane. By concentrating left-turn movements during the permitted phase the original phasing plan exacerbated this problem, which was eliminated when protected-only phasing was implemented.

Chapter 6: Using Simulation Modeling to Assess Safety Effects of Left-Turn Phasing

6.1 Introduction

In the main report for this project we described our efforts at estimating the magnitude of changes in expected crash experience caused by changes in left-turn protection. The methodological approach used was consistent with that underlying the methods being developed for the Highway Safety Manual (HSM). The approach placed a strong reliance on developing generalized linear models for predicting the expected crash frequency at an intersection as a function of major and minor traffic volumes, and a function of possibly other observable features such as approach speed limits, presence or absence of access controls, and presence or absence of left-turn lanes. These models are empirical and make only minimal commitments to any theories of how crashes occur, but they are useful for summarizing associations between crash frequency and other measurable features and for predicting what crash experience would have been if business as usual at an intersection had continued. Predicting the effect of a possible countermeasure requires that the analyst have on hand an estimate of that countermeasure's crash modification factor. As we documented in the main report, computing these estimates for left-turn phasing changes requires adequately-sized data sets from locations where such changes have been implemented.

Bonneson and Lord (2006) have pointed out an interesting similarity between the statistical modeling currently being used to develop the HSM and that used in the early attempts to predict delay at signalized intersections. These initially used linear regression models and naive choice of predictors such as traffic volume, cycle length, length of green phase, and saturation flow, but were were later replaced by regression models that used theoretically sensible combinations of variables, such as degree of saturation and green ratio. Thesein turn were superseded when Webster developed a structural model which described how traffic flow, capacity, and signal timing combine to cause delay. Arguably, the models used in the Highway Safety Manual and described in our main report, although useful for limited purposes, embody a limited understanding of how crashes occur, and we should expect that they will be replaced by better models as this understanding improves. In this chapter we will describe an initial effort at developing a more theoretical model of left-turn cross-path crashes, of the sort that occur during permitted left-turn phases on major intersection approaches.

6.2 Literature on Left-Turn Gap Acceptance

In order to successfully complete a permitted left-turn (LT), a driver must first correctly assess the adequacy of a gap in the opposing traffic stream. A tendency to reject physically adequate gaps can lead to needless delays for the left-turning traffic, while accepting an inadequate gap can lead to conflict or collision with an opposing vehicle. Traditionally, field studies of gap acceptance behavior observed a sequence of time gaps in a traffic stream, along with whether or not each gap was accepted by a waiting driver. Statistical methods were then be used to identify a minimal acceptable gap, known as the critical gap, with the frequency of gaps greater than this critical gap being related to the capacity provided by opposing traffic conditions (e.g. Garber and Hoel 1999). Although relatively easy to carry out, critical gap methods do not readily support the investigation of how other factors might also affect gap acceptance, but starting in the early 1980's researchers have shown how gap acceptance can be treated as a discrete choice problem (Daganzo 1980; Mahmassani and Sheffi 1981; Madanat et al. 1994; Gattis and Low 1999). This allows modeling of how variables other than gap duration might affect a driver's decision to attempt using a gap, and also allows the statistical methods developed for fitting and testing discrete choice models to be used in gap acceptance research. For example Kita (1993) found, not surprisingly, that drivers merging onto an expressway were more likely to accept shorter gaps as they approached the end of the merging lane.

A common assumption in much applied gap acceptance work has been that drivers base their decisions on an assessment of time-to-arrival, which is the time available before an oncoming vehicle arrives at a potential conflict point. This straightforward assumption in turn led to a relatively straightforward procedure for estimating capacity and delay (TRB 2000), but this assumption has been called into question by recent human factors research. In a laboratory study, Caird and Hancock (1994) found that subjects' perceived time-to-arrival was affected by the perceived size of the oncoming vehicle, with a tendency to perceive trucks as arriving sooner than motorcycles, even when the actual arrival times were the same. This suggests that visual cues other than actual time-to-arrival play roles in gap perception. Staplin (1995) conducted controlled field trials where a subject driver was asked to judge the distance at which an oncoming vehicle was too close for a successful left-turn. Staplin reported that drivers aged 56 and older on average tended to identify the same distance as acceptable, irrespective of whether the oncoming vehicle was traveling at 48 km/h (30 mph) or 96 km/h (60 mph). If the selected distance remains the same, doubling the speed of the oncoming vehicle halves the actual time-to-arrival, so that Staplin's findings suggest a tendency among older drivers to accept shorter time gaps as the speed of the oncoming vehicle increases. Even for subjects aged 18-55, who were on average sensitive to the approaching vehicle's speed, Staplin's results can be interpreted as being consistent with a tendency to accept shorter gaps as the speed of the oncoming vehicle increases. Davis and Swenson (2004), using field data, found that distance of the opposing vehicle, and to a lesser extent, the opposing vehicle's speed, allowed one to predict LT gap acceptance at least as well as did the time gap.

6.3 A Structural Model of Left-Turn Cross-Path Crashes

Left-turn cross-path crashes occur when a driver attempts to turn left in front of a vehicle approaching from the opposite direction and is unable to complete the turn before colliding with the oncoming vehicle. Our initial simulation model consists of two components, a gap acceptance model for the left-turn driver, and a simple kinematic braking model for the oncoming vehicle. To develop the gap acceptance model, data on gap acceptance at the intersection of Washington Ave and Harvard St., near the University of Minnesota campus, were used (Davis and Swenson 2004). These data were collected by placing a digital camera on the roof of Moos Tower, facing so that vehicles turning left from the eastbound approach and westbound oncoming vehicles were in the camera=s view. Figure 6.1 shows a view of this intersection from the camera's position. The eastbound and westbound approaches of this intersection both consist of two through lanes, with no exclusive left or right turn lanes, and the signal employs a brief protected phase for eastbound left turns, followed by a longer permitted phase. During several hours of recording it was possible to record the actions of 67 drivers making left-turns during the permitted phase, who made a total of 212 gap acceptance or rejection decisions. For each gap decision, the speed and location of the nearest oncoming vehicle were measured from the video, as was the time needed for each left-turn to be successfully completed. Some descriptive statistics computed from these data are presented in Table 6.1. Time gaps, in seconds, were computed by dividing the distance of the oncoming vehicle from the intersection by its speed. This gives the gaps as they appear at the moment of decision rather than how they might be measured following possible acceleration or deceleration actions by the opposing driver.

Figure 6.1: Camera View from Left-Turn Field Study

Table 6.1: Statistical Summary of Gap Acceptance Data

Variable	Average	Std. Dev.	Minimum	Maximum	25%-ile	75%-ile
Speed (ft/sec)	31.7	9.4	7.4	55.6	24.9	38.6
Distance (ft)	135.7	147.1	0	669.7	41.2	199.6
Gap (sec)	4.2	5.6	0	60.8	1.5	5.5
Speed/Accepted	37.1	8.5	7.4	55.7	32.8	42.9
Speed/Rejected	29.3	8.9	7.5	54.8	23.1	34.9
Distance/Accepted	315.5	148.9	95.8	669.7	210.5	385.1
Distance/Rejected	54.5	38.6	0	248.4	27.3	72.4
Gap/Accepted	9.4	7.7	3.8	60.8	5.5	10.2
Gap/Rejected	1.9	1.3	0	7.3	1.1	2.5
Clearance Time (sec)	3.5	0.6	2.4	4.8	3.0	3.8

The logit model relates gap duration to the probability of acceptance via the equation

Probability [accept | x] = exp(b0+b1x)/(1+exp(b0+b1x))

where x is the independent variable and b0 and b1 parameters to be estimated from data. Because we planned to generalize this model to other, hypothetical, locations, and because this is an initial plausibility assessment rather than a final modeling effort, we decided to use a simple single-variable model with gap as the independent variable. Using the statistical software Minitab, we found that a model which used the natural logarithm of the gap as the independent variable provided a better fit to these data than did one using the raw gap. A statistical summary for our parameter estimates is presented in Table 6.2. The entries in Table 6.2 include each parameters maximum likelihood estimate, the associated standard error for that estimate, and a Z-statistic testing the hypothesis that that parameter equals 0.0 (i.e. does not contribute to our ability to predict gap acceptance). To see how the parameter estimates in Table 6.2 are used, our logit model states that the probability a typical driver at our intersection accepts a four-second gap would be

P[accept | gap=4 seconds] = exp(-11.06 + 7.40*log(4))/(1+exp(-11.06 + 7.40*log(4)) = 0.31

Table 6.2: Estimation Summary of Gap Acceptance Model Parameters

Parameter	Estimate	Std. Error	Z-statistic	Significance
b0	-11.06	2.08	-5.3	P < .0001
b1	7.40	1.18	5.7	P < .0001

Figure 6.2 shows a plot of the probability of accepting a gap as a function of gap duration.

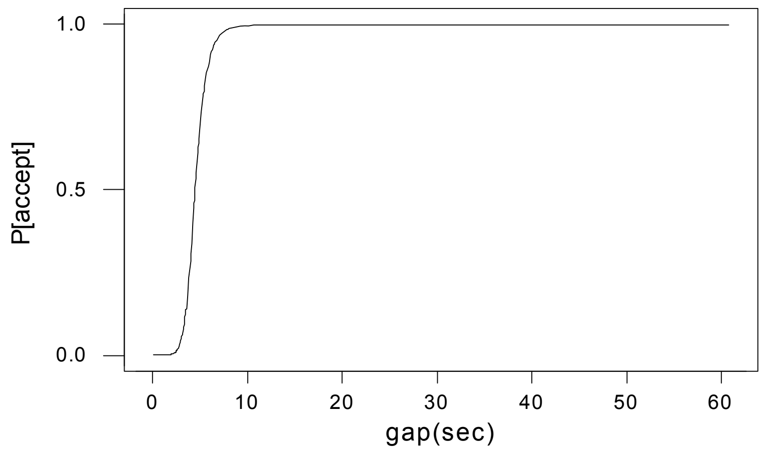

Figure 6.2: Acceptance Probability as a Function of Gap

Our collision model was similar to that described in Davis et al. (2002) for vehicle/pedestrian collisions, where a simple kinematic model is used to compute the stopping distance of the oncoming vehicle as well as its time-of-arrival at the collision point from knowledge of its location and speed and the oncoming driver=s reaction time and braking deceleration. Given the distance and speed of the oncoming vehicle at the time the left-turning driver initiates his turn, we draw random values from probability distributions characterizing the oncoming driver=s reaction time and braking deceleration, and a value for the turning vehicle=s clearance time. We then compute the oncoming vehicle=s stopping distance, and, when this is greater than its initial distance, the time needed for the oncoming vehicle to arrive at the collision point. If the oncoming vehicle stops before reaching the collision point or arrives at this point after the left-turning vehicle clears the intersection, we record a collision as being avoided; otherwise it is recorded as occurring.

A simulation model combining the above components was coded for the WinBUGS simulation software and is presented in Appendix B. Basically, the model takes as input a mean and standard deviation for the distribution of oncoming vehicle speeds, a value for the oncoming traffic flow, and means and standard deviations describing distributions for the reaction times and braking rates for oncoming vehicles. In addition, the logit model parameters for the gap acceptance model, and a mean and standard deviation for the left-turning clearance times are input. The model then proceeds as follows:

1. A random speed for the oncoming vehicle is drawn from a normal distribution having the input values for its mean and standard deviation.
2. A random distance from the intersection for the oncoming vehicle is drawn from and exponential distribution determined by the input mean speed and traffic flow.
3. From these, the corresponding time gap is computed, and the probability of acceptance is computed using the above logit model.
4. A random gap acceptance decision is then drawn from a Bernoulli distribution with the above acceptance probability. If the gap is rejected, we return to Step 1. Otherwise, we move to Step 5.
5. Random values are drawn for the oncoming driver=s reaction time, braking deceleration, and the left-turn clearance time, and whether or not a collision occurs is then determined using these and the braking model.
6. In addition, if the oncoming vehicle would arrive at the collision point within 0.5 seconds of the clearance time without braking, we record a conflict as occurring.

Our first test of the model involved comparing its output to the data collected in the gap acceptance study. Appropriately then, the average and standard deviation for the oncoming vehicle speeds given in Table 6.1 were used, and the oncoming traffic flow was set to q=0.233 vehicles/second, which when combined with the average speed of v.bar=31.7 ft/sec gave an average separation among approaching vehicles of x.bar=31.7/0.233=136 ft. Our Monte Carlo simulation model was run for 100,000 iterations, and Table 6.3 displays summary statistics from this run.

Table 6.3: Results from First Simulation Run: All Gaps Considered

Variable	Mean	Std. Dev.	2.5%-ile	25%-ile	75%-ile	97.5%-ile
Speed (fps)	31.7	9.0	14.0	25.7	37.8	49.4
Distance (ft)	135.3	135.5	3.5	39.0	187.0	503.3
Gap (sec)	4.8	5.9	0.1	1.2	6.3	19.2
Clearance Time (sec)	3.5	0.6	2.5	3.0	3.8	4.8

Comparing Table 6.3 with the corresponding rows of Table 6.1, we see that the simulated speeds and clearance times match the observed data very well, as would be expected since the simulation was constructed so as to replicate these distributions. However, the derived variables, distance and gap, also match reasonably well. In our simulation study 36.7% of the generated gaps were accepted. Since in our data set we observed 67 accepted gaps out of a total of 212, for an acceptance rate of 31.6%, we concluded that the simulation model provides a reasonable representation of gap acceptance behavior.

Our second simulation exercise sought to look at the population of accepted gaps, in part to compare with data presented in Table 6.1, but mainly to see if our model generated reasonable conflict and collision rates. Since the denominator in an estimated conflict or collision rate is usually the number of left-turning vehicles, these rates need to be computed as fractions of accepted, rather than all, gaps. To implement this, we took advantage of WinBUGS ability to simulate conditional as well as unconditional distributions by setting the model's variable 'accept.sim' to the value 1. Because we expected collisions to be relatively rare, this time the Monte Carlo simulator was run for 700,000 iterations. Table 6.4 summarized the results from this run.

Table 6.4: Results of Second Simulation Run: Accepted Gaps Only

Variable	**Mean**	**Std. Dev.**	**2.5%-ile**	**25%-ile**	**75%-ile**	**97.5%-ile**
Speed (fps)	29.1	9.0	11.6	23.0	35.2	46.8
Distance (ft)	261.8	144.4	84.0	162.2	323.4	638.1
Gap (sec)	9.7	7.3	3.6	5.7	11.4	26.6
Clearance Time (sec)	3.5	0.6	2.5	3.1	3.8	4.8
Reaction Time (sec)	0.6	0.3	0.2	0.4	0.7	1.4
Braking (g units)	0.75	0.1	0.57	0.68	0.81	0.96

Compared to the summaries in Table 6.1, our simulated left-turning drivers tended to pick gaps with, on average, lower oncoming vehicle speeds but correspondingly shorter distances than observed at Washington and Harvard. The distribution of simulated accepted gaps however matches very well with the accepted gaps from the field study. In our simulation, about 6% of the accepted gaps resulted in a potential conflict with the oncoming vehicle, while in our field study two of the 57 left-turns for which it was possible to compute clearance times had clearance times that were within 0.5 seconds of the non-braking arrival time of the oncoming vehicle. The estimated conflict rate from the field data would then be 2/57=0.035, with and approximate 95%

confidence interval of (0.00, 0.09), so our simulated conflict rates do not appear to be inconsistent with what we observed in our field study.

Our simulation model also produced a left-turn collisions rate of 80 collisions million left-turning vehicles. Collision rate estimates for this intersection were not available, so we conducted a literature review to see if any other researchers had reported useable estimates of left-turn collisions rates. The idea here was that, although we recognize that there is no reason to think that the collision rate at our study intersection would exactly equal what has been observed at other locations, if our simulation model is reasonable it should produce collision rates with at least same order of magnitude as what other authors have observed. It turns out that left-turn crash experience has been described in a number of ways, including as crash frequencies, but Upchurch (1991) and Maze et al. (1994) presented what we were seeking: crashes per left-turning vehicles. In Upchurch's study, left-turn crash rates ranging between 0.55 and 4.54 crashes per million left-turning vehicles were reported, while Maze et al. reported left-turn crash rates ranging between approximately 0 and 7 crashes per million left-turning vehicles. Clearly then, our simulated crash rate of about 80 crashes per million left-turns is unrealistically high.

One possible reason for the high simulated crash rates is that the crash avoidance actions assumed by the model are unrealistically weak. However, the mean and standard deviation for the reaction time distribution (0.6 seconds and 0.3 seconds) are similar to what Fambro et al. (1996) observed in field studies of alerted braking situations, while the assumed mean and standard deviation for the braking decelerations (0.75 g and 0.1 g) produce braking rates that are substantially higher than those observed by Fambro et al. in their field tests. On the other hand, the minimum clearance time observed in our field study was 2.4 seconds, and our estimated gap acceptance model gives the probability of accepting a 2.4 second gap as

$$P[\text{accept} \mid \text{gap} = 2.4] = \exp(-11.06+7.4*\log(2.4))/(1+\exp(-11.06+7.4*\log(2.4))) = 0.01$$

That is, our gap acceptance model predicts that on average one 2.4second gap would be accepted for every 100 2.4 second gaps that appear. Since the minimum accepted gap in our field study was about 3.8 seconds, it seems clear that our logit model over-predicts the acceptance of short gaps. One way to modify this model would be to specify a minimum acceptable gap such that gaps shorter than this minimum value are always rejected, while gaps above this value are accepted or rejected according to our fitted logit model. Setting the minimum acceptable gap to 2.5 seconds, and leaving all other variables unchanged, produced a predicted crash rate of 2.0 crashes per 100,000 left-turns, while setting the minimum acceptable gap to 3.0 seconds produced a predicted crash rate of 4.4 crashes per 1,000,000 left-turns. This latter value is consistent, at least to an order of magnitude, with left-turn crash rates reported in the literature. We also noted that the 4th edition of the Highway Capacity Manual (TRB 2000) recommends using a minimum acceptable gap of 4.1 seconds for left-turns off of major approaches. For our Washington and Harvard data, the shortest accepted gap we observed was 3.8 seconds, followed by 4.0 seconds, 4.1 seconds, and 4.4 seconds. These considerations suggest that a value of the minimum acceptable gap closer to 4.0 seconds might more reasonably describe our drivers' behavior. When we ran our simulation model with a minimum acceptable gap of 4.0 seconds, but all other model parameters unchanged, we obtained a predicted crash rate of 0, which illustrates that after 900,000 iterations no simulated crash occurred. In conclusion, our combined gap acceptance and collision model appears capable of reproducing observed left-turn collision rates once issues regarding the minimum accepted gap at a particular location have been resolved.

6.4 Illustrative Application of Model

To illustrate how this model might be used, we will consider the problem of assessing predicted collision severity as a function of the speeds of the opposing traffic. More specifically, we will use our model to predict the distributions of impact speeds of opposing vehicles at two hypothetical intersection approaches, one where the mean initial speed of the opposing vehicles is 30 mph and the other where the mean initial opposing speed is 60 mph. The opposing traffic flow is assumed to be 900 vehicles/hour (0.25 vehicles/second) in both cases, and the distributions governing clearance time, reaction time, and braking deceleration are the same as used above. The only other difference between these two cases is that the minimum accepted gap was taken to be 3.5 seconds for the 30 mph approach and 4.0 seconds for the 60 mph approach. This produced roughly comparable left-turn collision rates of 1.25 collisions per million left-turns for the 30 mph approach and about 1.0 collisions per million left-turning vehicles for the 60 mph approach. Using WinBUGS ability to compute conditional distributions via Markov Chain Monte Carlo simulation, we set both the acceptance and collision occurrence variables equal to 1 to obtain distributions of the model variables only for acceptance decisions that resulted in a collision. Impact speeds were computed by first testing if the opposing vehicle would arrive at the collision point during the driver's reaction time, in which the impact speed was set to the opposing vehicles initial speed. If this was not the case, the distance traveled during the reaction time was subtracted from the opposing vehicle's initial distance, and its speed at the collision point was then computed by applying the standard braking deceleration formula to the remaining distance. Table 6.5 summarizes results for the two simulation cases.

Table 6.5: Characteristics of Simulated Collisions

	30 mph Average Opposing Speed Minimum Accepted Gap = 3.5 seconds				**60 mph Average Opposing Speed Minimum Accepted Gap = 4.0 seconds**			
Variable	Mean	25%-ile	75%-ile	97.5%-ile	Mean	25%-ile	75%-ile	97.5%-ile
Impact Speed (mph)	20.3	14.2	26.1	36.7	36.0	27.4	44.1	61.8
Initial Speed (mph)	32.4	28.3	36.5	44.2	62.2	58.05	66.2	74.2
Initial Distance (ft)	178.3	154.6	201.0	248.4	382.4	354.8	408.0	466.2
Reaction Time (sec)	3.2	2.8	3.1	4.4	2.9	2.5	3.3	4.3
Clearance Time (sec)	4.4	4.0	4.6	5.4	5.0	4.6	5.3	6.1
Gap (sec)	3.8	3.6	3.8	4.3	4.2	4.1	4.3	4.7

For the approach with 30 mph average opposing speeds, the mean speed of the opposing vehicle at impact would be about 20 mph, and 50% of the collisions would have opposing vehicle impact speeds between about 14 and 26 mph. For the 60 mph approach, the mean opposing vehicle impact speed would be about 36 mph, 50% of the crashes would involve speeds between 27 and 44 mph, while at least 2.5% would involve speeds greater than 60 mph. Overall then, although the simulated left-turn collision rates for both of these approaches were low enough that neither would probably be regarded as problem approaches, when collisions do occur they would be substantially more severe at the higher speed approach. A justification for using protected left-turn phasing at the high speed approach would then rest not so much on prevention of all left-turn collisions, but protected left-turn phasing would be justified to prevent a small number of more severe collisions.

6.5 Comparison of Simulated Crash Scenario with Actual Crashes

The statistics presented in Table 6.5 also reveal how, at least according to our simulation model, left-turn cross-path crashes occur. First, the accepted gaps for the collisions tend to cluster near the minimum acceptable gaps, 3.5 seconds for the 30 mph approach and 4.0 seconds for the 40 mph approach, with over 97.5% of the gaps accepted in the simulated collisions being within 1.0 seconds of the minimum acceptable gaps. Second, the clearance times in the simulated collisions tend to cluster in the right-hand tail of the original clearance time distribution. That is, the 75th percentile and the maximum value from our original clearance time distribution were 3.8 and 4.8 seconds, respectively, and comparing these values to those reported in Table 6.5 shows that, for the simulated collisions, the turning drivers tended to have atypically long clearance times. Third, a similar, but even more extreme, pattern is shown by the simulated reaction times for the opposing drivers. So, according to our simulation model, a typical left-turning cross-path collision occurs when (a) the left-turning driver accepts a minimally acceptable gap, (b) the left-turning driver then takes an atypically long time to execute the turn, and (c) the opposing driver takes atypically long to react to the possible conflict.

Although plausible, it might be that this is not the complete story, and so it could be informative to compare this scenario to what happened in actual crashes. If one or more crashes had been recorded on our video, we could have used a trajectory extraction method similar to that described in Davis and Swenson (2006) to first make a plot of the turning and opposing vehicles positions as functions of time, and then, from these estimate reaction times, we could estimate clearance times and braking deceleration. These estimates could then be compared to the results of simulation experiments. No such video records of actual crashes were available however, but we did have access to (1) accident reports from eleven left-turn cross-path crashes occurring at the intersection of MNTH 55 and Westview Drive in Hastings, and (2) a detailed investigation, by the Minnesota State Patrol (MSP), of a fatal left-turn cross-path crash occurring at the intersection of Anoka CSAH 23 and the on-ramp leading to ISTH 35.

A study of the descriptive narratives from the MNTH 55 and Westview Drive crashes revealed, on four of the accident reports, the following:

1. Left-turning driver (Veh. #2) " …states she was blinded by headlights of a car in opposite turn lane and did not see #1."
2. "Veh. #1 states he did not see Vehs. 2 and 3"

3. “Veh. 1 did not see Veh. 2 enter intersection”
4. “Driver of vehicle one stated that a vehicle in the eastbound left turn lane of 55 had blocked his view of vehicle 2.”

Although the statements of collision-involved drivers have to be taken with a grain of salt, the above suggest that at least some left-turn cross-path collisions could occur not because the left-turning driver saw, but misjudged, a gap but because the left-turning driver did not notice the opposing vehicle at all.

Turning to the fatal collision on Anoka CSAH 23, the left-turning driver “said he didn’t see vehicle #2 when he began to turn.” The opposing vehicle left a 44-foot skidmark prior to colliding, each vehicle’s final position was documented in the MSP’s scale drawing, and probable estimates of each vehicle’s orientation immediately prior to the collision were also documented. Using the MSP’s estimates of vehicle weights and the vehicles’ approach and departure angles, we embedded the standard momentum conservation method within a Bayesian accident reconstruction model, similar to that described in (Davis 2003). This produced estimates of each vehicle’s speed immediately before the collision, and a standard skidding model then yielded an estimate of the opposing vehicle’s speed at the start of the skidmark. By approximating the path of the turning vehicle with a segment of circular arc joining that vehicle’s position at the moment of collision with the centerline of the lane it departed from, it was possible to estimate that the turning vehicle traveled approximately 53 feet between initiation of the turn and the collision. Dividing this distance by the estimate of the turning vehicle’s pre-collision speed then gave the time elapsing between turn initiation and collision, so then subtracting the time the opposing vehicle spent braking prior to collision from this elapsed time gave an estimate of the opposing driver’s reaction time, which in turn was used to estimate the location of the opposing vehicle when the turning vehicle began to turn. Bayesian estimates of relevant variables were computed using WinBUGS, and summaries of these results are displayed in Table 6.6.

Table 6.6: Summary of Posterior Distributions for Collision Variables

Variable	Posterior Mean	Posterior Standard Deviation	Posterior 2.5%-ile	Posterior 97.5%-ile
Opposing Vehicle's Initial Speed (mph)	51.4	4.5	43.1	60.2
Turning Vehicle's Initial Speed (mph)	14.6	2.1	10.8	19.2
Initial Distance (feet)	172	29.1	138	215
Reaction Time (seconds)	1.4	0.35	0.8	2.2
Gap (seconds)	2.3	0.36	1.7	3.1

The posterior mean for the opposing driver's reaction time was about 1.4 seconds, which is consistent with the average reaction times observed by Fambro et al. in 'surprise' braking situations. The estimated accepted gap is about 2.3 seconds, which is shorter than the shortest accepted gap we observed in our field study (3.8 seconds), shorter than the minimum accepted gaps used by the 2000 HCM (4.1 seconds), and shorter than the minimum gaps we needed to specify in our collision simulation model in order to obtain reasonable collision rates (3.0-4.0 seconds). Overall, the estimates in Table 6.6 are more consistent with the turning driver's statement, that he did not notice the opposing vehicle when he began his turn, rather than with the scenario implied by our simulation model.

6.6 Summary and Conclusion

In summary, our objective was to assess the plausibility of using a simulation model to assess the effect of left-turn phasing changes on crash frequency. If one could predict the probability a left-turn results in a crash as a function of opposing traffic conditions, one could combine this with an estimate of the number of left-turns made during permitted phasing to produce an estimate of the frequency of left-turn crashes for different phasing conditions. Accordingly, we showed how a statistical model could be developed that provided a reasonable description of drivers' acceptance and rejection of gaps, and when coupled with a kinematic collision model and an estimate of the minimum acceptable gap, gave reasonable estimates of left-turn collision rates. In this model, left-turn crashes occur when rare combinations of minimally acceptable gaps, long reaction times by opposing drivers, and long clearance times by the turning drivers combine to produce the crash. However, when we looked at a limited number of actual crashes, these suggested another possible mechanism in which the left-turning driver does not notice, or cannot see, the opposing vehicle.

In principle, if limited site distance is responsible, a geometric model similar to that described by McCoy et al. (2001) could be included to characterize a blind spot in the left-turning driver's field of view. The left-turning driver's gap acceptance decision could be simulated using the first visible vehicle, and simulating the possibility of an additional vehicle in the blind spot would be relatively straightforward. A modified collision rate could then be computed as well. On the other hand, if driver inattention is responsible, we are faced with the problem of characterizing how such lapses occur, which appears to an interesting, but unresolved, issue in human factors research.

In conclusion, we have identified three possible mechanisms by which left-turn cross-path crashes might occur. Simulating two of these, crashes due to atypically long clearance and reaction times and crashes due to blind spots, could be accomplished within the constraints of available knowledge. If we could also determine (if not the actual process) by which attention lapses occur, then simulation modeling of left-turn crashes could be a feasible alternative to statistical modeling.

Chapter 7: Summary and Conclusion

TABLE 7.1 Summary of Effects of Changes in the Intersection Control on Crashes

Countermeasure	Intersection-Related	Rear End	Right Angle	Total Left-Turn	Major Approach Left-Turn	Minor Approach Left-Turn
Signal Installation with Prot Major Approach	No Effect Detected	Increase	Decrease	No Effect Detected	**No Effect Detected**	No Effect Detected
Signal Installation with Perm/Prot Major Approach	No Effect Detected	No Effect Detected	No Effect Detected	Increase	**Increase**	No Effect Detected
Minor Approach Phase-Change from Perm to Perm/Prot	No Effect Detected	No Effect Detected	No Effect Detected	Inconclusive	Inconclusive	**Inconclusive**
Minor Approach Phase-Change from Perm to Prot	No Effect Detected	No Effect Detected	No Effect Detected	Inconclusive	Inconclusive	**Inconclusive**
Minor Approach Phase-Change from Perm/Prot to Prot	No Effect Detected	No Effect Detected	No Effect Detected	Inconclusive	Inconclusive	**Inconclusive**
Major Approach Phase-Change from Perm/Prot to Prot	No Effect Detected	No Effect Detected	No Effect Detected	Decrease	**Decrease**	Decrease
Major Approach Phase-Change from Prot to Perm/Prot	No Effect Detected	No Effect Detected	Decrease	Inconclusive	**Inconclusive**	Inconclusive

Caution: Read discussion below before generalizing results to other locations.

Table 7.1 summarizes the estimation results presented in Chapter 3-5. The most reliable findings, based on a reasonably large data set, pertain to installing signals at thru/stop-controlled intersections. When right-angle, rear-end, and left-turn crashes are lumped together as 'intersection-related' crashes, signal installation appears to have no effect on expected crash frequency. This result breaks down however when considering what happens to the different types of crashes. Signal installation with protected-only phasing on the major approaches was associated with a definite increase in rear-end crashes, a definite decrease in angle crashes, and no change in left-turn crashes. Because of the size of the data set, and because hierarchical Bayes methods were used rather than simple before-after analysis to estimate these effects it can be concluded that signalization probably caused an increase in rear-end crashes, a decrease in right-angle crashes, and no change in left-turn crashes. The findings with regard to rear-end and right-angle crashes are consistent with what other studies have found.

The next most extensive data set was that for converting minor approach left-turn phasing from permitted-only to permitted/protected. For this conversion, 16 reference group intersections and four treatment intersections were identified, for total of 147 and ten site-years respectively. No changes in the expected frequencies of any of the six crash types were detected, and in particular no change in the frequency of minor approach left-turns was detected. However, the rather wide confidence interval associated with this estimate, indicating that the data are consistent with changes in the range of approximately a 100% increase to approximately a 100% decrease, illustrates that it is probably better to interpret this result as being inconclusive rather than as supporting the hypothesis of no effect. A similar interpretation should be given to the results regarding minor approach phasing changes from permitted or permitted/protected to protected. For these situations, a very small number of available treatment site-years produced no recorded after-treatment minor approach left turn crashes, leading to an estimated reduction of nearly 100%. Unfortunately, with such small after-treatment counts, it is not possible to reliably estimate the uncertainty associated with these estimates, and so these results should also be regarded as inconclusive.

It was possible to identify two intersections where the major approach left-turn protection had been changed from protected to protected/permitted, along with a reference group of 20 intersections with identical major and minor approach left-turn protection, yielding a total of 171 site-years of data for the reference group and six site-years of data after the phase change. The results here were similar to those obtained for changes in minor-approach left-turn protection, where the confidence intervals associated with the estimated CMFs are so wide as to be uninformative, or where zero after-treatment crash-counts make it impossible to estimate the uncertainty associated with an apparent large reduction effect.

Finally, one intersection, MNTH 55 and Westview Drive in Hastings, was originally converted from thru/stop-controlled with permitted/protected left-turn phasing on the major approaches. And, after six years, the major approach left-turn phasing was changed to protected-only. Using the unsignalized intersections as a reference group and this intersection alone as the treatment group, it was possible to estimate that while changes in right-angle, rear-end, and minor approach left-turn crashes were insignificant, major approach crashes increased substantially. After conversion to protected-only major approach left-turn phasing no major approach left-turn crashes were recorded over a period of five years. Since the probability of observing five consecutive years of zero crashes give the hypothesis of no effect is small, it is safe to conclude that the observed reduction reflects a real effect on major approach left-turn crash occurrence.

In summary, Mn/DOT's practice of installing signals with protected left-turn phasing on the major approach led to expected effects on rear-end and right-angle crashes, and had no effect, either positive or negative, on left-turn crashes. At at least one location, installing a signal with permitted/protected left-turn phasing on the major approach was followed by marked increase in major approach left-turn crashes, and these were reduced to essentially zero when protected-only major approach left-turn phasing was implemented. For this location it was possible to compute estimates when only a single intersection comprised the treatment group because first, an extensive reference group of unsignalized intersections existed, and second, because five years of after-treatment data were available from this site for each of the two treatment conditions. For several other left-turn treatments of interest it was not possible to obtain sufficiently large after-treatment data sets to support reliable estimation of treatment effects. Since these sorts of changes tend to be fairly infrequent, and since the initial population of candidate intersections included all signalized intersections in Mn/DOT's metro district it is probably not realistic to assume that a substantial number of additional relevant phasing changes will take place anytime soon. But, the experience with MNTH 55 and Westview Drive indicates that, to some extent, long sequences of after-treatment observations at a small number of sites can substitute for large numbers of treated sites. We recommend then that several years from now the analyses described in Chapters 4 and 5 be redone, when at least five years of after-treatment data are available for the treated sites.

Finally, this report describes two related methodological improvement to the state-of-art in safety analysis. The first is a relatively simple method for accommodating changes in AADT or other predictor variables with the hierarchical model framework, so that longer sequences of observations can be used in estimating CMFs. This method was used successfully in estimating changes at a single intersection where five years of after-treatment data were available. The second, as noted in Chapter 2, derives from the fact that the Bayes approach currently being used to support the HCM and the IHSDM requires that crash data be overdispersed. Overdispersion appears to be frequently, though not universally, found in larger data sets, therefore this requirement has not been a problem for the large, often multi-state, samples used in NCHRP-supported research. A question which remains to be adequately addressed however involves the degree to which observed overdispersion is in fact due to violations of the homogeneity assumptions underlying the analysis methods. In the long run, developing a better understanding of the mechanisms causing crashes will probably involve studying more refined, 'purer' samples of crash types and/or locations, much as understanding the chemical properties of a material requires preparing relatively pure samples of that material. Thus, it may well be seen that past overdispersion was to a large extent simply an artifact of mixing fundamentally heterogeneous entities. In the short run then it seems prudent to not lock ourselves into analytic methods that require observation of overdispersion before we can proceed.

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Appendix A
Lists of Treatment Intersections Used

Table A.1 Treated Intersections Used for the Chapter 3 Analysis

Treated Intersection	Data Years	Major Approach	Minor Approach	City
1	1993-2000	MNTH 36	Hadley Ave	St Paul
2	1994-2000	MNTH 41	Lyman Blvd	Chaska
3	1994-2000	MNTH 149	Northwest Parkway	Eagan
4	1995-2000	MNTH 36	Manning Ave	Stillwater
5	1995-2000	MNTH 55	C.R. 101 W Jnc	Hamel
6	1995-2000	MNTH 149	MNTH 110	Mendota Heights
7	1996-2000	USTH 8	Viking	Chisago City
8	1996-2000	MNTH 149	Yankee Doodle	Eagan
9	1997-2000	USTH 12	Willow Drive	Orono
10	1997-2000	USTH 169	117th Street	Champlin
11	1997-2000	MNTH 101	141st Street	Rogers
12	1997-2000	MNTH 101	53rd Street	Rogers
13	1998-2000	USTH 952A	50th Street	Minneapolis
14	1998-2000	MNTH 5	Rolling Acres Rd	Victoria
15	1998-2000	MNTH 5	Ideal	St Paul
16	1998-2000	MNTH 7	Main Street	St Bonifacius
17	1998-2000	MNTH 13	McColl Drive	Savage

Table A.2 Treated Intersections Used for the Chapter 4.1 Analysis

Treated Intersection	Data Years	Major Approach	Minor Approach	City
1	2003-2004	MNTH 13	McColl Drive	Savage
2	1996-2000	MNTH 51	C.R. C2	Roseville
3	2003-2004	MNTH 65	89th Ave	Blaine
4	2004	USTH 12	Willow Drive	Orono

Table A.3 Treated Intersections Used for the Chapter 4.2 Analysis

Treated Intersection	Data Years	Major Approach	Minor Approach	City
1	2004	MNTH 13	Eagle Creek	Prior Lake

Table A.4 Treated Intersections Used for the Chapter 4.3 Analysis

Treated Intersection	Data Years	Major Approach	Minor Approach	City
1	2004	MNTH 41	Pioneer Trail	Chaska
2	2004	USTH 212	Fountain Place	Eden Prairie

Table A.5 Treated IntersectionsUused for the Chapter 5.1 Analysis

Treated Intersection	Data Years	Major Approach	Minor Approach	City
1	2004	MNTH 5	Victoria Drive	Victoria
2	1998-2002	MNTH 156	Villaume Ave	St Paul

Table A.6 Treated Intersection Used for the Chapter 5.2 Analysis

Treated Intersection	Data Years	Major Approach	Minor Approach	City
First Change	1991-1995	MNTH 55	Westview Drive	Hastings
Second Change	1996-2000	MNTH 55	Westview Drive	Hastings

Appendix B
WinBUGS Code for Selected Models

WinBUGS Code for CMF Estimation of Unsignalized to Signalized Major Left-Turn Crashes

```
model signalized
# individual deviations parameterized as multipliers with gamma(r,r) priors
# major approach LT crashes as DV

{
# compute Bayes estimates of GLM parameters and individual intersection deviations

for (i in 1:Nrow) {
logmajadt[i]<-log(X[i,2])
logminadt[i]<-log(X[i,3])
majadt[i]<-logmajadt[i]-mean(logmajadt[])
minadt[i] <- logminadt[i]-mean(logminadt[])
majlim[i]<-step(X[i,4]-54)
minlim[i]<-step(X[i,5]-54)
muhat[i] <-
exp(beta0+beta[1]*X[i,1]+beta[2]*majadt[i]+beta[3]*minadt[i]+beta[4]*majlim[i]+beta[5]*minlim[i]+beta[6]*X[i,6]+beta[7]*X[i,7])
mu[i] <- mu0[Site[i]]*muhat[i]
Y1[i] ~ dpois(mu[i])
 }

# compute simulated after signalization accident counts, along with before/after estimate of reduction factor
for (i in 1:Nafter) {
alogmajadt[i]<-log(Xa[i,2])
alogminadt[i] <- log(Xa[i,3])
amajlim[i]<-step(Xa[i,4]-54)
aminlim[i]<-step(Xa[i,5]-54)
amajadt[i]<-alogmajadt[i]-mean(logmajadt[])
aminadt[i]<-alogminadt[i]-mean(logminadt[])
muhata[i] <-
exp(beta0+beta[1]*Xa[i,1]+beta[2]*amajadt[i]+beta[3]*aminadt[i]+beta[4]*amajlim[i]+beta[5]*aminlim[i]+beta[6]*Xa[i,6]+beta[7]*Xa[i,7]
)
mua[i] <- mu0[Sitea[i]]*muhata[i] }
apost <- a+sum(Ya1[])
bpost <- b+sum(mua[])
theta ~ dgamma(apost,bpost)
arf <- 1-theta
parf <- step(arf)

pbeta0 <- step(beta0)
for (i in 1:Nbeta) {pbeta[i] <- step(beta[i])}

# compute 'arf' for each signalized intersection

Yasite[1] <- sum(Ya1[1:csum[1]])
 muasite[1] <- sum(muhata[1:csum[1]])
 for (j in 2:Nsitea) {
 Yasite[j] <- sum(Ya1[csum[j-1]+1:csum[j]])
muasite[j] <- sum(muhata[csum[j-1]+1: csum[j]]) }
 for (j in 1:Nsitea) {
apostsite[j] <- a+Yasite[j]
bpostsite[j] <- b+muasite[j]
thetasite[j] ~ dgamma(apostsite[j],bpostsite[j])
arfsite[j] <- 1-thetasite[j] }


# Prior distributions
for (i in 1:Nsite) {mu0[i] ~ dgamma(r,r)}
for (i in 1:Nbeta) { beta[i]~ dnorm(0,1.0E-06) }
beta0~dnorm(0,1.0E-06)
rx ~dpar(1,1)
r <- rx-1       }
```

Data

list(Nsite=234, Nrow=1944, Nbeta=7, Nafter=81, Nsitea=17,
csum=c(8,15,22,28,34,40,45,50,54,58,62,65,69,72,75,78,81),a=.01,b=.01)

Site[]	Y1[]	X[,1]	X[,2]	X[,3]	X[,4]	X[,5]	X[,6]	X[,7]
1	0	1	28000	1000	55	25	0	0
1	0	1	35400	1000	55	25	0	0
1	0	1	35400	1000	55	25	0	0
1	0	1	35400	1000	55	25	0	0
2	0	1	21600	405	55	55	0	0
2	0	1	21600	405	55	55	0	0
2	0	1	23200	405	55	55	0	0
2	0	1	23200	405	55	55	0	0
2	0	1	23200	405	55	55	0	0
2	0	1	23200	405	55	55	0	0
2	0	1	23200	405	55	55	0	0
2	0	1	23200	405	55	55	0	0
2	0	1	26400	549	55	55	0	0
2	0	1	26400	549	55	55	0	0
3	0	1	23200	610	45	30	0	0
3	0	1	23200	610	45	30	0	0
3	0	1	29000	610	45	30	0	0
3	0	1	29000	610	45	30	0	0

…

Inits list(beta0=0, beta= c(0, .6, .6, 0, 0, 0, 0), rx=1.7)

WinBUGS Code for Chapter 6 Simulation Model

```
model
# simulation of conflicts and crashes using random acceptance
# IVs=log gap, corrected ML estimates from Minitab
# Fambro et al stats of braking and reaction times
# speed/flow inputs to distance
# impact speeds
# q=.233,v.bar=31.7,tp.bar=0.6,f.bar=0.75
{


# conflict simulation
v.sim.tau <- 1/(v.sig*v.sig)
tc.tau <- 1/(tc.sig*tc.sig)
lambda.sim <- q/v.bar
# lambda.sim <- 1/x.bar
x.sim ~ dexp(lambda.sim)
v.sim ~ dnorm(v.bar,v.sim.tau)I(1,)
gap.sim <- x.sim/v.sim
tc.sim ~ dlnorm(tc.bar,tc.tau)
linmod.sim <- beta01 + beta02*log(gap.sim)
logit(p.sim) <- linmod.sim
u.sim ~ dunif(0,1)
px.sim <- .99999*p.sim*step(gap.sim-gap.min)
# accept.sim <- step(p.sim-u.sim)*step(gap.sim-gap.min)
accept.sim ~ dbern(px.sim)

arrival.sim <- x.sim/(v.sim)
conflict.sim <- accept.sim*step(tc.sim+con.buffer-arrival.sim)

# collision simulation
          g <- 32.2
          # tp.sim ~dunif(0.5,1.5)
          # f.sim ~ dunif(.5,.9)

  tp.sigma2 <- log((pow(tp.sd,2)/pow(tp.bar,2))+1)
  tp.mu <- log(tp.bar)-0.5*tp.sigma2
```

```
    tp.tau <-1/tp.sigma2
    tp.sim ~dlnorm(tp.mu,tp.tau)

    f.sigma2 <- log((pow(f.sd,2)/pow(f.bar,2))+1)
    f.mu <- log(f.bar)-0.5*f.sigma2
    f.tau <- 1/f.sigma2
    f.sim ~dlnorm(f.mu,f.tau)

              a.sim <- f.sim*g
              v.sim.fps <- v.sim
      xbrake.sim <- pow(v.sim.fps,2)/(2*a.sim)
      xprt.sim <- v.sim.fps*tp.sim
      xstop.sim <- xbrake.sim + xprt.sim
       stop.sim <- step(x.sim-xstop.sim);
       fullhit.sim <- step(xprt.sim-x.sim)
       tc1.sim <- x.sim/v.sim.fps
               vbrake2.sim <- max(v.sim.fps*v.sim.fps-2*a.sim*(x.sim-xprt.sim),0)
       tc2.sim <-tp.sim+(v.sim.fps-sqrt(vbrake2.sim))/a.sim
       tc0.sim <- fullhit.sim*tc1.sim + (1-fullhit.sim)*tc2.sim
       pass.sim <- step(tc0.sim-(tc.sim+crash.buffer))
              phit.sim <- .9999*(accept.sim*(1-stop.sim)*(1-pass.sim))
              # hit.sim ~ dbern(phit.sim)
              hit.sim <- accept.sim*(1-stop.sim)*(1-pass.sim)
              v.impact <- hit.sim*((fullhit.sim*v.sim)+(1-fullhit.sim)*(sqrt(vbrake2.sim)))

}
```

Data

list(beta01=-11.06,beta02=7.404, q=0.233,tc.bar=1.23,tc.sig=.17,v.bar=31.7,v.sig=9, con.buffer=0.5,crash.buffer=0,gap.min=0)
list(hit.sim=1)
list(accept.sim=1)
list(tp.bar=0.6,tp.sd=0.3,f.bar=0.75,f.sd=0.1)

Inits

list(beta01=-1,beta02=0,beta03=0)
list(beta01=.3,beta02=.1,beta03=.022)
list(beta01=-1.6,beta02=.04,beta03=-.33)