1-1-2003

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By

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Applied Science
Department of Civil Engineering
Ryerson University Toronto

October, 2003

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Abstract

Traffic accidents cause a huge loss to the society. According to statistics, 50% o[f] all accidents occur at urban intersections and 47% of these are due to left-turn collisions. Countermeasure implementation at these locations therefore can play a vital role in the improvement of traffic safety.

This study illustrates a methodology for evaluation of urban 4-legged signalize[d] intersections treated with left-turn priority phasing. The methodology is applied to thre[e] important collisions types; those due to left-turn collisions; those due to left-turn sid[e] impact collisions; and all impact types combined collisions. Data used in this analysi[s] were obtained from the City of Toronto. Safety Performance Functions for left-turn an[d] all impact types combined collisions which were developed by the City of Toronto, wer[e] calibrated and used in an empirical Bayesian methodology that was employed to estimat[e]

the expected frequency of accidents occurring at each intersection in order to evaluate the effectiveness of left-turn priority phasing in reducing this frequency.

The results revealed that left-turn priority phasing can be an effective treatment for addressing and reducing the number of collisions at signalized intersections. Flashing advance green phasing is more effective in improving safety for two of three types; all left-turn and all impact types combined collisions. Left-turn green arrow (protected/permissive) phasing is more effective for left-turn side impact collisions. By implementing this type of treatment, the number of crashes and the associated monetary loss to society could be significantly reduced.

ACKNOWLEDGMENTS

I would like to express my sincere thanks and appreciation to my supervisor, Dr. Bhagwant Persaud, for his total support, excellent research guidance, advic suggestions and patience at each individual step throughout the entire programm Without his help this thesis would not have been possible.

Special thanks to my colleagues and friends in the Department of Civ Engineering Ryerson University for their useful suggestions, ideas, advice ar contributions in accomplishing the objective of this study.

Deepest gratitude to my wife and kids, who had to sacrifice their needs and tin and supported me to finish my studies.

Finally, I would like to express my deep feeling of joy to almighty God for tl spirit and courage to accomplish this research work during one of the crucial phases my career.

DEDICATION

Dedicated to my loving parents.

Table of Contents

List of Tables

List of Figures

GLOSSARY OF NOTATION

AADT	Average Annual Daily Traffic
b	Over dispersion Parameter, relationship between E(k) and Var(k)
C_a	Sum of comparison ratios in the after period
C_b	Sum of comparison ratios in the before period
EB	Empirical Bayesian
F_1	Major Street (high volume road) Average annual daily traffic (AADT)
F_2	Minor Street (lower volume road) AADT
$E(\kappa_{i, y})$	The estimate of the expected number of accidents of entity'i' in year y
K	Count of accidents during the before period on treated entities

MUTCD	Manual of Uniform Traffic Control Devices
π	Number of accidents expected for treated intersection or road segment ha been in the after period had treatment not been applied
λ	Number of accidents observed for intersection or road segment in the aft period
δ	Reduction in expected number of crashes= π - λ
θ	The index of effectiveness
E(θ)	Estimate of the index of effectiveness
α, β1, β2, β3	Model parameters for accident prediction model
PDO	Property damage only
$S^2(\bar{\theta})$	Sample variance of random variable theta
S.D	Standard Error

$Var(k_i)$	Variance of the expected accident frequency at specific site
X_b	Observed number of accidents in the before period
X_a	Observed number of accidents in the after period

Chapter 1 INTRODUCTION

Transportation Engineering plays a very important role in daily life all over the world. Of ıll transportation modes, highway and road transportation are some of the most reliable bases for nass movement in both North America and Europe. This mass movement activity is supported y a worldwide road network. Because of the huge demand for transportation, it has become ıecessary to implement the highest possible range of safe and efficient road networks.

The safety of roads is of growing interest for traffic engineers, politicians, and for the ublic at large. Between the years 1998 to 2001, in the province of Ontario, there was an average f 225,119 accidents, out of which 151,835 accidents per annum occurred on urban roads (MTO Report, 2001). The magnitude of this loss to society is evident when considering the equivalents n dollar amounts. In 1994 in Ontario, the cost of each death was estimated at $831,429, each njury at $20,084, and each property damage only (PDO) accident at $ 6,136.

The authorities responsible for safety on the road system must be able to identify sites that have an unusually high rate of accident occurrence and to apply limited budgets rationally to safety improvements at the sites that are most likely to give the largest safety gain for the dollars spent. Many agencies have developed practices and standards addressing a broad range of road safety considerations involving the vehicle, the driver, and the road. The ultimate goal of these practices and standards is to promote public safety by reducing transportation related deaths, injuries, and property damage.

The most fundamental step in improving safety is determining which sites are truly hazardous. New techniques (e.g., empirical Bayesian (EB) using accident prediction models) incorporate geometric, traffic, and accident history, along with regression models, to analyze the safety of any given site with respect to the number of expected accidents. Empirical Bayesian (EB) estimates may be used to rank potential sites according to the expected number of treatable accidents and to identify the sites that are likely to respond favourably to safety engineering treatments. EB estimates are also useful in before-after studies to evaluate the safety effect of treatments (Hauer, 1997) and it is this application that is the focus of this research.

The objective of this study was to use the EB methodology to evaluate the effectiveness of left-turn priority phasing in the City of Toronto. Three types of accidents were investigated. The first type is those that occur because of all types of left-turn collisions. The second type of accident is left-turn side impact (one vehicle turning left collides with vehicle coming from the opposite direction, going through), and the third is all impact types. For the purposes of this study, fatal injury and severe injury collisions were considered. Property damage only (PDO) accidents were excluded.

This thesis constitutes the following:

- Introduction: Chapter 1 provides a preface and an introduction to the safety related scenario. It deals with the objective of the research study.
- Literature Review: Chapter 2 summarizes the literature review conducted on the evaluation of safety treatment effectiveness by the before-after study using different methods and with emphasis on the EB methodology. A literature review on accident prediction models is also included in this chapter.
- Data: Chapter 3 details the data collected and used in this study. Sources and types of data are explained in detail. Missing data relating to average annual daily traffic (AADT) and data that were not available are estimated. Capacity analysis was carried out and level of service for the intersection under study was obtained using Highway Capacity Software (HCS 2000, Version 4.1 B).
- Methodology: Chapter 4 provides an overview of the methodology used for the before-after study.

- Results and Analysis: Chapter 5 presents and discusses the results obtained using en Bayesian methodology.
- Chapter 6: Conclusions and Recommendations

Chapter 2 LITERATURE REVIEW

The safety of an entity (intersection, road segment, driver, etc.) is the number of crashes, or crash consequences, by kind and severity, expected to occur to the entity during a specified period (Hauer, 1997).

This research mainly examines the safety effect of left-turn priority signal phasing treatments at urban intersections. Hence, to arrive at the primary objective, a thorough literature review has been conducted on previous work relating to safety analysis and implementation of countermeasures by different researchers. This literature review has been structured in the following manner:

- The Before – After Study: Reviews the before-after study, estimation of expected number of accidents, accident prediction models and estimation of the index of effectiveness.
- Left-turn collisions at intersections: Reviews information about collisions at intersections due to left-turn, treatment of collisions during left-turn and left-turn priority signal phasing.

A brief summary is presented at the end of this section showing how this research aims to bridge the gaps identifying in the literature review.

2.1 The Before – After Study

This section provides an overview of the techniques for conducting safety evaluations for roadway countermeasures. The most common method for evaluating the effectiveness of safety treatment is the simple observational before-after study; this consists of comparing the accident count for the before period of an intersection or road segment (entity) to the accident count for the after period. Hauer (1988) pointed out that the before-after study compares two statistical estimates, an estimate of the expected number of accidents after the countermeasure improvement program is implemented and the number of accidents that would have be expected if the treatment had not been implemented. This approach is also supported throu research by Griffin (1989 and 1992).

The before-after study using a comparison group attempts to account for changes, ot than the treatment, that may affect safety between the before and after periods. The changes crashes at comparison group sites are observed over the same period as at the treatment sites provide a better estimate of what would have happened at the treatment sites had the treatm not taken place Hauer (1997). In some cases, the comparison group can be treatment sites, su as when it is assumed that certain accident types will not be affected by the treatment. Kl (1980) and Zador (1982) used daytime accidents as comparison groups for nighttime accider during the evaluation of the effectiveness of raised pavement markers. Griffin (1992) stressed selecting the comparison group to ensure that the group should not be affected by the treatm being evaluated. Hauer (1988) does not consider close physical similarity between the treatm and comparison sites to be critical. Instead, Hauer (1988) maintains that it is more importan have close agreement in the monthly or yearly accident frequencies for both the treatment a comparison groups before implementing improvements for the treatment sites. In other wo Hauer (1997) concluded that it is not vital for the comparison sites to look like the treatm sites, but that it is vital that the comparison sites have accident histories similar to the accid histories for the treatment sites for period before improvement at those sites.

Hauer (1997) suggested that a potential problematic factor in site-specific highway saf studies exists when the comparison group concept does not address regression-to-the-mean b The bias occurs because of the non-random process of treatment site selection. The treatment selection process generally involves selecting sites because of the size of their most rec accident histories (1 to 3 years). Because of this biased selection process, there exists a high probability that a reduction in crashes might be observed even if these sites were left untreated.

The development of the empirical Bayesian methodology (EB) is relatively recent, and applications to date have been limited. This technique is based on the selection of a reference group (a group of intersections consisting of homogeneous sites with the same geometric and traffic flow characteristics) to adjust for the regression-to-the-mean bias. The safety properties are different for each intersection, even if they have similar traffic flows and other similar traits. The safety of entities is usually estimated from the history of their accident counts. However, estimating safety this way becomes difficult when there is an inadequate accident history. The EB method overcomes this limitation by combining accident counts with knowledge about the safety of similar entities which depends on physical characteristics such as road geometry, road environment, and traffic volume. By using these two sources of information, EB estimates improve the accuracy of predictions and compensate for regression-to-the-mean bias (Hauer, 1997).

Estimation of Expected Number of Accidents

An estimate of the mean number of accidents $E(\kappa)$ of an entity is obtained from accident prediction models, also called safety performance functions (Hauer, 1997). The accident prediction models relate the annual accident experience of an entity to its characteristics. Accident prediction models have several uses in safety analysis. They can be used to examine how the actual accident experience of a specific intersection compares to the expected safety performance of similar intersections. These models are also used in the EB method to, in effect, smooth the random fluctuations in accident counts when estimating the number of accidents expected over time at a specific intersection. These expected values are used in before-after studies and can also be used in the screening of potentially hazardous sites for treatment.

Since traffic accidents are random events, statistical principles must be used to build the predictive equations (Lord, 2000). Hauer et al. (1988) developed functions to portray a relationship between traffic flow and collisions of vehicles and to relate accidents for urban signalized intersections. Mountain et al. (1996) used negative binomial regression analysis and developed accident prediction models for roads with minor junctions. Sawalha and Sayed (2001) developed accident prediction models for urban arterial roadways in the City of Vancouver. Bonneson et al. (1993) developed an aggregate model for all accidents at rural road intersections. Al-Turk and Moussavi (1996) and Poch and Mannering (1996) built models by impact types (rear-end, right-angle, etc.). In addition to the total number of accidents, Lau, May, and Smith (1989) proposed a procedure to estimate intersection safety by accident classifications (fatal, injury, and PDO). Hauer et al. (1988) used a model to estimate injury accidents as a fraction of the total accidents. To allow microscopic estimation, Al-Turk and Moussavi (1996) and Hauer et al. (1988) developed models for several time periods (a.m. peak, p.m. peak, etc.). All of these studies used traffic volume as the sole independent variable and provided additional parameters to enable the models to be used in an empirical Bayesian framework. The approach used by Lau et al. (1989) is perhaps more convincing, since it is easy to link intersection safety to economic loss, but this approach does not relate accident frequency to conflicting traffic flow.

Persaud et al. (1998) developed aggregate and disaggregate models to estimate the safety performance of three-legged and four-legged signalized intersections. The disaggregate models predicted accidents for specific conflicting movements, such as collisions between straight and left-turning vehicles as well as right-angle accidents. The aggregate models attempted to relate accidents to causal factors using geometric characteristics as well as traffic volume as independent variables.

The mean number of accidents $E(\kappa)$ of a reference population in fact varies because of factors such as the demographics of drivers, vehicles, road environments, and other factors that could not be included in the accident prediction model. The distribution of this mean within the reference population has been postulated to be adequately represented by the Gamma probability distribution (Hauer, 1988 and 1997). The accident count at a site is described by the Poisson distribution with known mean, and the accident counts within a reference population may be described by negative binomial distribution (Hauer, 1988 and 1997).

To obtain a refined estimate of the mean number of accidents of a specific site, the accident history of the site can be considered as well. In this, the empirical Bayesian procedure, estimates the mean number of accidents (κ) of any intersection of interest based on its accident history and $E(\kappa)$ of the reference population. The EB method aims to smooth out the random fluctuations in accident data by combining $E(\kappa)$ and K. Further discussion on EB estimation is provided in Chapter 4.

The estimates of $E(\kappa)$ of entity come from an accident prediction model (Hauer, 1997). The change of $E(\kappa)$ with time is reflected in a comparison ratio $C_{i,y}$ which is equal to the model estimate for entity i for year y divided by the model estimate for entity i for year 1. Thus,

$$E(\kappa_{i,y}) / E(\kappa_{i,1}) = C_{i,y} \tag{1}$$

The estimation of κ_i of an entity of interest and its variance can be computed using the Equations, 2 and 3 given hereunder:

$$\kappa_i = (b+X_b)/ [b/E(\kappa_{i,1}) + C_b] \tag{2}$$

$$Var(\kappa_i) = \kappa_i / [b/E(\kappa_{i,1}) + C_b] \tag{3}$$

where,

$\kappa_{i,}$= The estimate of the expected number of accidents of entity i.

K = Count of accidents during the before period on treated intersections

b = Over dispersion parameter of the accident prediction model estimated with a neg binomial error distribution.

C_b = Sum of comparison ratios in the before period

Ca = Sum of comparison ratios in the after period

X_b = Number of observed accidents in the before period

The estimate of κ_i is normalized to the base year as follows:

$$\pi_i = (\kappa_i)\, C_a / C_1$$

$$Var(\pi_i) = (\pi^* C_a) / (C_b + b / E(\kappa_{i,1})$$

where,

π_i = The number of accidents expected for a entity i (intersection or road segment). number is estimated on the assumption that there had been no treatı implemented.

λ_i = The number of accidents expected for entity i in the after period where the treatı had been applied.

Estimation of the Index of Effectiveness

There are two methods to estimate safety effect at an entity as shown below.

Method 1: Reduction in Expected Number of Crashes (δ)

This is the difference (δ) between the sums of the π and λ over all sites in a conveı group. Let:

$$\delta = \pi - \lambda$$

The variance of δ is given by:

$$Var(\delta) = Var(\pi) + Var(\lambda)$$

According to Hauer (1997), it can be assumed that π and λ are independent of each other.

Method 2: The Index of Effectiveness (θ)

A biased estimate of θ is given by:

$$\theta = \lambda / \pi \tag{8}$$

The percent change in crashes is in fact, $100(1- \theta)$. From Hauer (1997), an approximate unbiased estimate of θ is given by:

$$\theta = (\lambda / \pi)/ \{1+ [\mathrm{Var}(\pi)/ (\pi)^2]\} \tag{9}$$

where,

θ = The index of effectiveness and the measure of safety improvement.

The variance of θ has been given as:

$$\mathrm{Var}(\theta) = \theta^2 [(\mathrm{Var}(\lambda)/ \lambda^2) + (\mathrm{Var}(\pi)/ \pi^2)]/ [1+ \mathrm{Var}(\pi)/ \pi^2]^2 \tag{10}$$

Once the index of effectiveness (theta) for an individual site is calculated, the composite effect on all treated sites can be calculated by summing up all the values of π, and variance of π, and putting the values in Equation 4 and 5.

2.2 Left-Turn Collisions at Intersections

The increase in traffic volume on urban intersections has led engineers to develop innovative means to control traffic. Traffic signals are considered a way to improve traffic safety and traffic operations at intersections (Pernia et al. 2002). With an increase in traffic volume, a driver has fewer available gaps in the opposing through traffic to execute a left-turn maneuver safely. This section contains information about treatments for reduction of left-turn collisions with more emphasis on left-turn signal phasing.

The treatment of left turn maneuvers at signalized intersections can have a signi

operational and safety impact. While adding left-turn phasing, which provides exclusive tin left turns to maneuver through the intersection, there can also be a major influence on dela all motorists including those turning left. Geometric configuration also plays an important r the operation of left turns at signalized intersections (Sebastian, 1999).

Upchurch (1986) postulated that left-turn lanes may provide a separate area or refug vehicles from through traffic that offset turn lane provides a longer sight distance for left- and that restricted sight distance to opposing traffic creates potential accident situations. Ga al. (2001) concluded that the use of triple left-turn lanes is gaining acceptance as an altern for relieving congestion at intersections with high left-turn volumes. A triple left turn al three lanes of vehicles to turn left simultaneously during a signal phase. It produces a gr discharge of turning vehicles over a shorter amount of times, thus making available addit green time for other traffic movements within the intersection.

Aside from geometric redesign of intersections, the use of left-turn signal phasir perhaps, the primary method of improving safety of left-turns at signalized intersect Upchurch (1986) concluded that phasing operations alone have the greatest effect on left collision rates. The intent of left-turn phasing is to meet three basic criteria:

1) Provide some minimum level of service or maximum delay time for left-turning vehicl
2) Minimize delay on the intersection approach (left, through, and right-turn moven combined) consistent with objective 1, and
3) Minimize left-turn-related accidents to the extent practicable and consistent with obje 1 and 2.

For the practical application of warrants, it is important that the choice of left-turn phasing be a function of easily and quickly measured intersection characteristics or variables. The most promising potential candidate variables are:

- Left-turn volume
- Adjacent through volume
- Opposing volume
- Number of lanes
- Number of left-turn-related accidents

According to the Manual of Uniform Traffic Control Devices (MUTCD, 1998), there are three types of left-turn phasing at signalized intersections: permissive only, protected only, and protected/permissive. The terms permissive only (also called permitted only), protected only and protected/permissive are specifically identified in section B.4.5 of the Manual of Uniform Traffic Control Devices.

Types of left-turn phasing are discussed as follows:

a) ***Permissive Only*** – When left turns may be made on the circular green indication after yielding to oncoming traffic and pedestrians (called permitted mode), the signal display for left turns shall be identical to the display to through traffic. A separate indication or signal face for left turns is not required (MUTCD, 1998). Permissive phasing works well when the left turn volume is low. Average left-turn delay is less in this phasing if the number of lanes is 2 or fewer. Average through delay is less (3 to 6 seconds per vehicle) in this type of phasing (Upchurch 1986).

(b) ***Protected only*** – Left turns may be made only when the left circular green indication is illuminated (MUTCD, 1998). Protected phasing has the highest left-turn delay and the lowest left-turn crash rate. This phasing is considered the safest (Sebastian, 1999). The primary reason for implementing protected-only phasing is to accommodate left t safely when gaps are not available in through traffic or when vision is restri Upchurch(1986) concluded from research that protected phasing is preferred wher designed speed of opposing traffic is more than 45mph, the number of lanes is gr than three, and the sight distance is insufficient (250 ft for speeds of 35 mph or less, 400ft for speeds greater than 35 mph). Protected-only phasing should be impleme as a safety measure because there are fewer numbers of crashes when this typ phasing is implemented (Shebeeb, 1995).

(c) ***Protected/Permissive Phasing*** – This operation involves providing a left-turn arro needed, but left turns may also occur during the circular green indication after yiel to oncoming traffic(MUTCD, 1998). Protected/ permissive phasing significa reduces left-turn delay (compared to permissive phasing) (Sebastian, 19 Protected/permissive phasing has the largest average number of total left-turn cras according to Shebeeb (2003), who suggests that it should not be implemented safety measure, but perhaps this is due to volume?

The protected/permissive phasing may be further categorized as:

- Lead Phase. In this phasing, the green arrow for left-turns starts before the circ green for through traffic.
- Lag Phase. In this phasing, the green arrow for left-turns starts after the circular g for through traffic (Box et al. 2003).

The average number of accidents with protected/permitted lead phasing operation lower compared to protected/permitted lag phasing. However, lag phasing may be considere a method to increase intersection efficiency when there are no indications of possible acci problems (Box et al. 2003).

According to Shebeeb (1995), an increase in the left-turn traffic volume or in the corresponding opposing traffic volume causes a significant increase in the number of left-turn accidents (Shebeeb, 2003). Box et al. (2003) suggested that, at coordinated signalized intersections, leading or lagging designs do not differ in terms of through traffic delays. Instead, their strength and weakness resides mainly in left-turning traffic delay. Lagging designs for the downstream signal generate less delay than leading designs, no matter which design may be used for the upstream signal (Li et al. 2003). Lagging designs at both intersections yield the best results in terms of overall intersection delay (Gan, 2001).

Sebastian (1999) conducted a study and concluded that protected/permissive phasing has a significantly higher left-turn crash rate compared to both protected only and permitted only phasing. Brehmer et al. (2003) evaluated changes in accidents after introduction of protected / permissive left-turn control and concluded that provision of flashing yellow left turn arrow is an effective way to reduce left turn collisions. The flashing yellow arrow indication/display was found to result in a high level of understanding for drivers as compared with the circular green indication. The result of this study also indicates that the flashing yellow arrow display offers more versatile field application features in crash reductions as compared with the circular green indication.

2.3 Summary

Researchers have suggested that improving traffic operation at signalized intersections can be accomplished by employing different traffic operation and efficiency treatments. The safety effect of left turn phasing has been discussed in the literature but only in the context of operational efficiency of intersections. None of these studies really focus on safety evaluation based on left-turn crashes and no evaluation of the left turn priority phasing has used the empirical Bayesian methodology. This methodology is the most advanced one for addressing regression-to-mean bias. Hence, there exists a gap in estimating the safety of left-turn phasing.

This study is focused on evaluating the effectiveness of left-turn priority signal phas for intersections in the City of Toronto. This study simultaneously evaluates the impact on safety effect of treatment of operational measures such as level of service.

Chapter 3 DATA

Data used in this study were obtained from the City of Toronto. The dataset consisted of three parts. Part one was the files containing pertinent physical information of the intersections in the sample; part two were files containing traffic flow data; and part three consisted of files containing extensive records for each accident reported on the city of Toronto roads during the years 1996 to 2000.

3.1 Physical Data

The physical data were obtained from electronic files. A total the 35 intersections selected for study were treated for left-turn priority signal phasing by the City of Toronto. These intersections were treated during the years 1997, 1998, and 1999 by introducing some form of left-turn signal phasing. All of these intersections were four-legged, and located in the urban environment.

The intersection data file contained information about the physical features of the intersections. The following information was collected from this file:

- The vital piece of information in the physical files was PX number (Coded number assigned to intersections). The City uses these coded numbers instead of street names on the intersections. These numbers help to provide access to City data about each intersection.
- Number of legs in an intersection, i.e., three or four
- Number of lanes in each direction (East, West, North, and South)
- Signals-EB/WB.Ramp(signals-NB/SB.Ramps)
- Lane-width at the intersection from all four/three directions
- Street type, i.e., major, minor, arterial , local, or collector

- Treatment types applied, i.e., left-turn priority phasing; flashing advance green (FAG)
left-turn green arrow (LTGA)
- Exclusive/separate left-turn/Right-turn lanes, i.e., yes or no for each intersection

3.2 Traffic Information

The traffic volume for each intersection of interest was of primary importance in research. The original traffic counts database, which consisted of approximately 1,800 signali intersections in Toronto, was obtained from the City. This database consisted of two types digital files. The first type of file pertained to traffic counts that were performed at signali intersections by observers for 8-hour periods, while the second type consisted of traffic cou that were recorded on city streets by automatic counters (over 24-hour periods). Traffic flow c were available for the years 1984 to 1996 for observed counts, and from 1992 to 2001 automatic counts. For each type of information, a different computer file existed for every y of available data. Traffic counts were taken at intersections during the morning, mid-day, a afternoon peaks as well as one off-peak period. For the second type, traffic counts were collec between intersections for a 24-hour period. Peak-hour volumes (a.m./p.m.) were collec directly from electronic files that were available with the City traffic flow database. Two-h counts start at 7:30 a.m., 11:00 a.m., and 4:00 p.m. for the peak periods. For the off-peak peri traffic counts are performed for 1 hour in the morning and afternoon starting at 10:00 a.m. a 2:00 p.m., respectively. Traffic counts are divided into 15-minute periods and include possible movements at an intersection (12 movements for 4-legged intersections, 6 moveme for 3-legged intersections).

Missing traffic flow information was generated by different techniques. This sect provides an explicit methodology used for the generation and preparation of missing data t were required for analysis during this research. Capacity analysis was performed to find HCS (Highway Capacity Software) delay, level of service, and capacity of the intersections in this study in an attempt to relate safety effectiveness to these operational measures.

Procedure to Estimate AADT

To estimate accurately the safety at intersections or any other facility, it is important to have accident and traffic flow data for as many years as possible. Indeed, better and more robust accident predictions and evaluation of countermeasure effectiveness can be developed with a large sample size. In some circumstances, such as when creating accident prediction models that incorporate trends, it is necessary to have complete data for the entire study period (Lord, 2000). Unfortunately, since manual traffic counts are very expensive to perform and the financial resources of transportation agencies are quite limited, it is not possible to record traffic at every intersection for every year. To overcome this drawback, it was necessary to find a method to estimate traffic volume for the missing years.

The following three methods were applied to estimate missing average annual daily traffic (AADT).

- The Method of Least Squares
- Traffic Flow Trend Analysis
- Weighted Average Ratios

The Method of Least Squares

The method of Least Squares was applied to estimate missing traffic flow for signalized intersections in the jurisdiction of the City of Toronto (Lord, 2000). The estimated missing

AADT obtained by this method were used for treated and untreated intersections. The untreat intersections were used as reference group. This procedure is divided in four sequential steps:

- Expand 8-hour counts to the annual average daily traffic (AADT) counts
- Estimate the missing AADTs
- Compute the flows for each leg and movement (i.e., left, right, through)
- Predict hourly flows for different time periods

The database consists of all the signalized intersections that are in the city of Toronto. ' have reliable estimates, a large sample size and detailed information on each intersection in t sample are needed.

Expansion From 8-hour Counts to AADT

Several expansion factors were applied to transform 8-hour observed traffic counts AADT. These factors were created by the City of Toronto from their permanent counti stations. The expansions factors are divided into five categories:

1. Roads that are classified as freeways or expressways
2. Roads located in the downtown core
3. Roads that are classified as suburban arterial roads
4. Industrial and commercial area roads
5. Roads located in residential areas

For each category, a different expansion factor exists for the day of the week and t month of the year. There are a total of 84 expansion factors (7 days *12 months) for ea category. Each leg of an intersection is classified according to one of the five categories. F each leg of an intersection, the appropriate factor was collected from the list of expansion fact and added to a spreadsheet manually. Table 1 shows the expansion factors used for the intersection of Eglinton Avenue (West) and Avenue Road for the year 1997.

Estimating Entering Flows

The AADTs of each movement were initially added together to compute the total entering AADT of the intersection. The task is to estimate the total entering AADT values of the missing years. To fill in the blanks, it was assumed that the traffic from year to year is made of two components.

Table 1 Expansion factors for Eglinton Avenue (W) and Avenue Road

Approach	Road Type	Expansion Factor
North	Residential Street	2.006
South	Downtown Arterial	1.857
East	Sub-Urban Arterial	1.991
West	Sub-Urban Arterial	1.991

The first component represents a Toronto-wide trend change. The second componer specific to each road and is approximately linear.

To estimate the Toronto-wide change, the average entering flow of each intersection ' calculated. Then each entering flow was divided by this average to normalize the entering fl Therefore, the row of numbers should have a mean of 1. The process described above ' performed for each intersection in the study. The mean of the normalized entering flows ' then computed for each year to estimate the Toronto-wide change.

Before moving towards the next step, which involves estimating the trend that is spec to each intersection, the Toronto-wide trends from the normalized entering flows of e intersection under estimation of flow were removed. For example, the normalized entering fl and Toronto-wide normalized entering flow in 2000 for Eglinton Ave. (W) and Avenue R were 1.024 and 0.994 respectively. Here we have to see whether a Toronto-wide trend ' absent. One should expect the normalized entering flow to be 1.024/0.994=1.03. This proc was performed for every year. All entering flows were similarly adjusted (see Figure 1).

Once the normalized entering flows were adjusted, a linear equation was fitted for e intersection. The equation of the fitted line is of the form:

$$Y = \alpha + \beta * X \qquad ($$

where,

Y= Fitted adjusted normalized entering flow

α = Parameters to be estimated in Linear Regression

β = Parameters to be estimated in Linear Regression

X= Number of years since 1984

The Equation (11) was applied to each intersection and parameters α and β were calculated for each intersection separately. This Equation was applied, without validation (Lord, 2000).

Table 2: Total/Normalized/Mean, Entering Flow for Eglinton Ave and Avenue Rd

Year	Total Entering Flow	Normalized Entering Flow	Means of Normalized Flow
1984	52630	0.893	0.837
1985	51710	0.877	0.89
1986	52510	0.891	0.954
1987			0.98
1988			0.957
1989	56740	0.963	1.02
1990	65688	1.114	1.008
1991	73534	1.248	1.02
1992	61114	1.037	1.028
1993			1.046
1994			0.921
1995	56170	0.953	1.07
1996			1.039
1997			1.054
1998			1.065
1999			1.055
2000	60380	1.024	0.994
2001			1.05

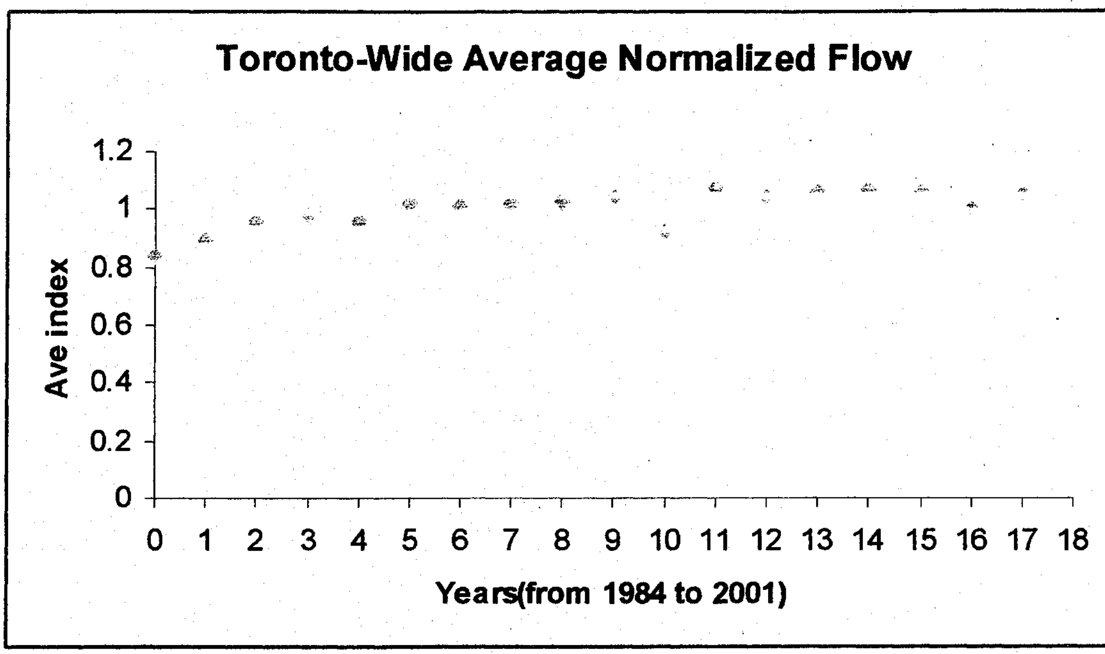

Figure 1: Normalized flow average index from 1984 to 2001

During this process, when only one count was available, α (alpha) was set to be t average of the entering flows and β (beta) was assigned a value of zero. When available cou were more than two, the line was fitted by the least square method. For the intersecti mentioned above, α (alpha) =0.57658 and β (beta) = 422.6. The standard deviation of t estimated AADT (estimated by methods discussed in detail earlier) of each intersection w computed using methodology in Hauer (1993). From this, it is observed that the standa deviation is a function of the standard deviation of each intersection and the Toronto-wide tre simultaneously (Hauer (1993).

Estimating Traffic Flow for Each Approach

Once the entering flow of each intersection was estimated, the total entering flow w reassigned to the respective leg and movement. For each available count described in the fi step, the traffic flow of each movement was divided by the total entering flow for eve intersection. Then, the average proportion of each movement was computed. When more th one year of data were available, there was the possibility of 12 different proportions for a given intersection (4 legged). Once the proportion of every movement was computed, the flows were reassigned to their respective legs and movement. This was performed by multiplying the total estimated entering flow (computed in Step 2) by the proportions calculated in this step. This reassignment process was conducted for every intersection and year.

Traffic Flow Trend Analysis

The 35 treated intersection had some missing years traffic flow data in the before and after periods, respectively. These missing data were estimated separately for each intersection. For the treated intersections, in either before or after periods, with two or more counts available, trend analysis was done to estimate the traffic counts for the missing years. The number of counts available in the before period was more than the number in the after period. Most of the AADT estimates for the treatment groups were obtained by this method. An example of the analysis for Steeles Ave. (West) and Keele St. is shown in Figure 2 for the before period. Statistics of the regression analysis are given in Table 3.

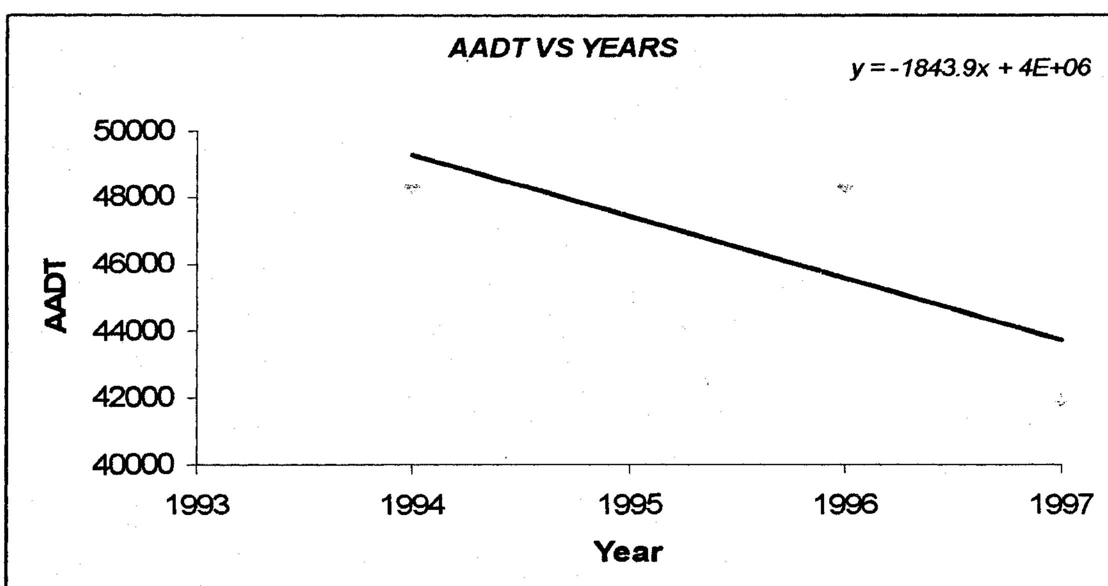

Figure 2: Traffic flow trend with years for Intersection of Eglinton Ave and Avenue Road

Table 3: Statistics of the Regression Analysis

Intersection				PX	Adjusted R-Square
CHURCH	ST	FRONT	ST	15	0.695
EGLINTON	AV	AVENUE	Rd	96	0.685
LAKE SHORE	BL	PARLIAMENT	ST	209	0.943
LAKE SHORE	BL	JARVIS	ST	210	0.205
EGLINTON	AV	MIDLAND	AV	461	0.737
YONGE	ST	AVONDALE	AV	481	0.778
KEELE	ST	SHEPPARD	AV	600	0.608
STEELES	AV	KEELE	ST	602	0.370
FINCH	AV	BAYVIEW	AV	650	0.563
BATHURST	ST	SHEPPARD	AV	672	0.631
ELLESMERE	RD	PHARMACY	AV	693	0.353
EGLINTON	AV	KIPLING	AV	729	0.497
EGLINTON	AV	ROYAL YORK	RD	781	0.637
EGLINTON	AV	SCARLETT	RD	784	0.499
CUMMER	AV	WILLOWDALE	AV	806	0.642
BRIMLEY	RD	PROGRESS	AV	1072	0.828
STEELES	AV	WARDEN	AV	1191	0.498
FINCH	AV	HUMBERLINE	DR	1506	0.905
KENNEDY	RD	MCNICOLL	AV	1586	0.823
KENNEDY	RD	SUFFERANCE	RD	1592	0.592
STEELES	AV	HILDA	AV	1115	1.000
YONGE	ST	BISHOP	AV	1151	0.328

Average Ratio Method

An average ratio method was applied to fill in the blank fields (missing AADT) for some of the intersections in this study. Intersections with maximum number of AADT counts available were used to calculate the averages of AADT for each year. The ratios of these averages relating one year to another were applied to estimated missing AADT based on a year with known AADT. The same process was repeated for before and after periods separately. The average ratio values for the after period years 1997-2000 are shown in Table 4.

Table 4: Average Ratios for 1997-2000

Year	1997	1998	1999	2000	2001
1997	1	0.985	0.978	0.979	0.904
1998	1.015	1	0.992	0.994	0.917
1999	1.023	1.008	1	1.002	0.925
2000	1.021	1.006	0.998	1	0.923
2001	1.106	1.090	1.082	1.084	1

3.3 Accident Data System

Accident data consisted of two electronic files that recorded the accidents from 19 2000. One file contained disaggregated data. This file provided information about each acc that occurred, including day, time, number of vehicles involved, number of persons injur killed, impact, initial direction of each involved vehicle, and maneuver type (left-turn collis rear-end collisions, and angle collisions, etc), and year-wise total of the accidents that occ on each intersection. However, the details of total injury, fatal injury and PDO accidents provided separately. The second file contained aggregated data for each collision type. ' number of collisions for each collision type is given in this file.

3.3.1 Vehicle Movement Information

Vehicle movement information is of primary importance for accident type and coul used to identify the direction of flow for each or both vehicles involved in a collision. research focuses on collisions of vehicles making left-turn movements. Left-turn collisions, turn side-impact collisions (one vehicle turning-left collides with opposing vehicle going str in opposite direction) and all impact types combined collisions were considered for this th Vehicle initial direction was shown in the accident dataset. This detail is shown in Table 5 such information was available in the data provided, but there were some problems in this since some of entries were wrong and/or missing. The second type of information requir identify accidents was impact type, especially where left-turning injury/fatal collisions being investigated. Vehicle impact types are given in Table 6. In the data set, the third ty information of relevance was vehicle maneuvers. This was described by one of the 14 detailed in Table 7. The movement of the vehicle was definable only when the maneuvers specified, for example, 'going ahead', turning-right', or 'turning-left'.

Table 5: Initial Direction Code used in data files

Initial Direction	Direction	Direction code
North	N	1
South	S	2
East	E	3
West	W	4

Table 6: Impact Types with Codes

Impact type code	Maneuver Type	Maneuver Type code
1	Approaching	Approach
2	Angle	Angle
3	Rear End	Rear-End
4	Sideswipe	Sideswipe
5	Turning Movement	Turning
6	SMV Unattended Vehicle	SMV Unatd
7	SMV Hitting Pedestrian	SMV Pedes
99	Other	Other

Table 7: Maneuver Type and codes used in accident data files

Code	Maneuver Type	Maneuver Shown
3	Overtaking	Passing
4	Turning Left	Turn Left
5	Turning Right	Turning Right
7	Changing Lanes	Chg Lane
8	Merging	Merging
9	Reversing	Reverse
0	Unknown	Unknown
6	Making "U" Turn	U-Turn
10	Stopped	Stopped
11	Stopped or Parked	Stop Park
12	Disabled	Disabled
13	Pulling Away shoulder	Pull Away
14	Pulling Onto Shoulder	Pull Onto
99	Other	Other

The fourth type of information provided and required was the accident class. This f consisted of three categories: fatal injury, non-fatal injury, and PDO. It should be noted that other cases, 'non reportable,' and 'other' were also included in this field; some of the accide belonged to these fields. Accident class provides details about fatal injury, severe injury or PD collisions occurred. This research considered only fatal and severe injury collisions.

Table 8: Accident class with codes used in accident data

Accident class code	Type of injury	Code in database
01	Fatal	FA
02	Non-Fatal Injury	PI
03	Property Damage Only	PD
04	Non-Reportable	NR
99	Other	OT

PDO collisions were not considered because of the self-reporting PDO collision data system.

3.3.2 Basic Information

A group of fields representing basic information for each accident was recorded in this segment. The fields that are relevant to this study are listed and described below:

- Accident number. Each accident was referenced by a number. The same accident number was also used in the corresponding police report.
- Accident date. This field recorded the time, day, month, and year when accidents occurred. A separate file for each year and month was created, as needed for before–after study.
- Day of week and time of accident. Information given by both fields can be combined to evaluate the safety of intersections for a.m. and p.m. peak periods. For the purposes of

this study, the a.m. peak period occurs between 8:00 and 9:00 a.m. and the p.m. period occurs between 4:30 and 5:30 p.m. Such periods on Saturday and Sunda excluded from the peak period samples.

- Signal timing, Metro Toronto uses MTSS (Metro Toronto signaling software operating approximately 1800 signalized intersections in its jurisdiction. Signal tir phasing, and relevant information was recorded directly from the database.
- Signals information for the before period was collected from hard copies of available in the Metro Toronto library.
- Turning movement count summary for before and after dates were collected electronic files maintained by the City's transportation department.
- Peak hourly volume for peak 15-minute volume.

3.4 Level of Service and Capacity

Highway capacity software (HCS 2000, Version 4.1 B) was used to estimate capacit level of service during the a.m. and p.m., peak periods of treated intersections.

The following data were required for this process:

- Signal timings (cycle length and phasing) for the intersections under study as extr from Metro Toronto Signalization Software (MTSS).
- Date of modifications made to present signal timing as noted in the files maintaine each intersection of Metro Toronto.
- Flow details extracted from electronic files; 24-hour volume, peak hourly volume to 10:00 a.m. and 4:00 to 7:00 p.m.) and peak 15-minute volume were taken from files. Included was all the traffic moving through, left and right.
- Percentage of heavy vehicles and bikes.

- Pedestrians crossing on all the four sides of intersection.

The data were used to create two data sets. One consisted of geometric and accident data for each intersection during the morning (7:00 to 10:00 a.m.) and afternoon (4:00 to 7:00 p.m.) peak periods. The other consisted of AADTs (estimated in the previous step). Capacity and level of service during peak periods were calculated in accordance with the Highway Capacity Manual (HCM 2000).

3.5 Basic Statistics of the Accident Dataset

Table 9: Basic Statistics of the Reference Population Group Dataset

Year	1997	1998	1999
Number of Sites	568	568	568
All Impact Types(Expected)	3643.6	3759.3	3868.65
All Impact Types(Observed)	2678	2971	3047
Left-turn(Expected)	726.5	749.59	771.06
Left-turn(Observed)	522	574	591
Left-turn Side Impact(Observed)	454	493	573

Table 10: Basic Statistics of the Treated Group Dataset

Dataset	**1997**	**1998**	**1999**
Number of sites	9	5	21
FAG Treated	6	1	8
LTGA Treated	3	4	13
AADT Range	46790-84982	24672-62842	21852-9173
Ave AADT	52535	57590	42194
Observed Accidents After (left-turn)	67	28	57
Accidents Before (left-turn)	45	46	169
Observed Accidents After (Side)	64	24	47
Accidents Before(Side Impact)	33	37	83
Observed Accidents After (All Impact)	139	154	705
Accidents Before (All Impact)	282	103	205

Chapter 4 METHODOLODY

This chapter presents an overview of the methodology adopted for evaluating the safety of left-turn priority phasing at Toronto signalized intersections. The chapter comprises 2 sections. Section 1 explicitly focuses on empirical Bayesian estimates (EB) and elaborates on the steps involved in this method. Section 2 maps out the methodology for safety evaluation of the treatment implemented.

4.1 Empirical Bayesian Estimates

The empirical Bayesian methodology is a technique to avoid regression-to-the-mean bias; it is a method of estimating κ that coherently exploits not only accident counts, but also information contained in the traits of an entity. This technique is based on the selection of a reference group (a group with the same traits as the treatment group) to adjust for the regression-to-the mean bias. In fact, the safety properties of different intersections are different even they have the same traffic flow and other similar traits. Because each intersection is unique, it is not enough to use accident counts alone to estimate its safety. The empirical Bayesian method overcomes this limitation. It combines information about accident counts with knowledge about the safety of similar entities (entities in the reference population). The first source includes the physical characteristics of the intersections, such as geometric design, road environments, traffic volumes, and so forth. The second source is the accident history of intersections. By using these two sources of information, the empirical Bayesian method improves the accuracy of predictions and compensates for regression-to-the-mean (RTM) bias (Hauer, 1997).

4.1.1 Empirical Bayesian Equations

According to the empirical Bayesian methodology, if the estimates of the mean *ı* similar sites and variance Var(κ), and the accident count X_b, for a given period are known, refined estimates of expected (κ) and Var(κ) of specific intersection can be calculatє Equations (2) and (3), described in Section 2.1.

By examining the series of equations presented, a few points become apparent. variance of the estimates, Var (κ), decreases as the number of years of data used in the an increases and as the value of the over dispersion parameter (b) increases. Fundamentall makes sense. As more years of data are used, more information is known about each site, an estimate of each κ will be better. As the differences between sites are better explained i model, then the variance of estimates, Var (κ), should decrease. As the value of b increases Var(κ) estimated from the regression model decreases. Therefore, as b increases, the regre model explains more of the variation in accident experience across sites, and the estimate will also improve.

4.1.2 Regression Models

Regression equations are used to estimate Ê (κ) (the mean number of accident/year Var (κ) (the variance of this estimate) for the reference population of interest. Fundamentall regression estimate of accident occurrence at a site is the average accident frequency reference population with identical characteristics. These estimates are adequate for exam the trends in the data. When a multivariate model is fitted to accident data, it estimates the] as a function of variables (covariate) (Hauer, 1997). However, for evaluation of s improvements, to estimate what would have been expected had no safety improvement implemented, this information is inadequate. The EB approach overcomes this limitatioı using two sources of information, regression estimates and the actual accident history of sites, the estimates of accident occurrence are both site-specific and more accurate.

4.1.3 Accident History

Accident history plays a vital role in obtaining the refined estimates. Accident counts are obtained according to accident types relevant to the study. The main objective of this study is to evaluate the safety of intersections in terms of left-turn collisions, so information about left-turn injury crashes was needed for this study. When the accident history for an entity is available, its safety property can be refined by combining two clues in safety, the accident history of the site and $E(\kappa)$ from the accident prediction model of the reference population, using the empirical Bayesian methodology to get refined estimates. Available accident history for as many years as possible helps to develop more refined estimates.

4.2 Evaluation of Safety Effectiveness

This section describes the methodology adopted to evaluate the safety improvement resulting from left-turn signal phasing on three types of collisions: all impact type, left-turn and left-turn side impact collisions.

4.2.1 Accident Prediction Models

The accident prediction models were developed by the City of Toronto.

The model for all left-turn collisions is:

$$\text{Accidents/year} = 1.059\alpha\,(F_1+F_2)^{\beta 1}\,(LT/\,(F_1+F_2))^{\beta 2} \qquad (12)$$

where,

F_1 = Major Street average annual daily traffic (AADT)

F_2 = Minor Street average annual daily traffic (AADT

LT = Total of all left-turning AADT on an intersection

α = 0.00000000685

β_1 = 1.846 (0.065)

β_2 = 0.46 (0.042)

Over dispersion Parameter (b) = 1.8

The same models was used for left turn side impact collisions except the paramet which was calibrated for this collision type using a procedure described later The calibı value of α for left-turn side impact collisions was 0.00000000534.

The accident prediction model for all impact type collisions is:

$$\text{Accidents/year} = \alpha\, F_1^{\beta 1} * F_2^{\beta 2} * e^{\beta 3\, F2}$$

where,

F_1 = Major Street Average annual daily traffic (AADT)

F_2 = Minor Street Average annual daily traffic (AADT)

α, β_1, β_2, β_3 are model parameters for given accident prediction model.

Intersection groups are defined as:

Group 4 contains intersections of minor arterial and minor arterial.

Group 7 contains intersections of major arterial and minor arterial.

Group 8 contains intersections of major arterial and major arterial.

Over dispersion Parameter (b) values for all groups are given in Table 11.

Table 11: Group and parameter values for all impact type collision models

Group	Alpha	Beta1	Beta2	Beta3	b
Group 4	0.0014575	0.434	0.382	0.00000947	7
Group 7	0.0015492	0.434	0.382	0.00000947	5.3
Group 8	0.0016319	0.434	0.382	0.00000947	5.6

.2.2 Calibration of Models

This section presents a calibration procedure followed in this study. Alpha (α), the model parameter in the accident prediction models (shown by Equations 12 and 13), captures the influence of all factors that change from year to year. These changes are in weather, economic conditions, and other similar factors but not traffic flow. Alpha (α) changes from year to year. The effect of specific change from year to year (i.e., weather) affects all road sections in the same manner (Hauer, 1997).

Accident prediction models applied in this study for safety effectiveness evaluation were calibrated for each year. Accident prediction models (left-turn and all impact types combined) were applied to estimate the expected number of crashes for each year. The observed number of crashes at untreated sites in the reference population each year was divided by the expected number of crashes from the original accident prediction models to obtain calibration ratios. The original model α was multiplied by the calibration ratio of the corresponding year to get an α for that year.

Models used in left-turn side impact collisions were calibrated by using the ratio of left-turn side impact collisions to all left-turn collisions.

Table 12: Calibrated α values for left-turn, left-turn side impact and all impact types collisi models

Year	1996	1997	1998	1999	2000
All Left-turn collisions	4.77E-09	5E-09	5.41E-09	5.75E-09	6.86E-09
Left-turn side impact	5.34E-09	5.96E-09	6.37E-09	6.65E-09	6.65E-09
All impact type combined	0.00112	0.001138	0.001158	0.001281	0.001389

α was multiplied by ratios calculated for each year. The model parameter, β determ the manner in which $\kappa_{i,y}$ depend on $F_{i,y}$. β remains constant as $\kappa_{i,y}$ in the accident predic model is assumed to depend on traffic flow in same manner for all road sections and years.

4.2.3 Procedure for Safety Treatment Evaluation

Steps involved in the safety treatment evaluations procedure are given as:

Step 1

The relevant accident prediction models were used to estimate the expected an number of accident/year, $E(\kappa_{i,})$, for each intersection and year. During the treatment y $E(\kappa_{i,})$ for months before and after treatment was calculated separately.

Step 2

The comparison ratio (ratio of expected number of accidents at a particular entity particular year to the expected number of accidents at a particular entity and base year) calculated, as given by the Equation (1) in Section 2.1. Comparison ratios for each year du the before and after period was calculated, summed up comparison ratios for each before and after period, denoted as C_b and C_a.

where,

C_b = Sum of comparison ratios in the before period.

C_a = Sum of comparison ratios in the after period.

Step 3

The empirical Bayesian method was applied to refine the estimate of accidents/year. The required Equations are discussed in Section 2.1. Calculate the values of κ_i and Var (κ_i) applying Equations (2) and (3).

Step 4

Calculate the index of safety effectiveness, which is the ratio of the observed number of crashes in the after period to the expected number of crashes in the after period had no treatment been applied. The index of effectiveness (θ) and Var (θ) are given by Equations (8) and (10). These Equations are given in Section 2.1.

From the index of effectiveness, the accident reduction factor (ARF) is calculated:

$$ARF = (1 - \theta)$$

Percent reduction in collisions is given as:

$$ARF = 100\,(1 - \theta)$$

ARF values, if positive and statistically significant, indicate that safety treatment is effective; otherwise, negative values indicate that safety treatment is not effective.

Once the index of effectiveness (theta) for an individual site is calculated, the composite effect on all treated sites was calculated by summing up all the values of λ and π, and variance of

π, and putting these values in Equation (4) and (5); these results show the overall safety effec

treatment.

Chapter 5 ANALYSIS, RESULTS AND DISCUSSION

5.1 Background

As mentioned earlier, the objective of the study was to evaluate the change in the numbers of injury (fatal and severe) collisions following the left-turn priority phasing treatment at signalized intersections in the City of Toronto. The treatment consisted of an additional form of left-turn priority phasing at one or more approaches during certain periods of the day. In several cases, priority phasing of some form was already in place and, a few cases, additional other minor modifications had been done to the intersections. Therefore, the evaluation is of the combined effects of adding varied levels and types of left-turn priority phasing and implementing other related modifications.

To properly account for changes in traffic volume and for possible regression-to-the-mean effects, empirical Bayesian analysis, following the state-of-the-art methodology (Hauer, 1997), was performed as discussed in Chapter 4. Regression models developed by the City of Toronto were used. This methodology estimated the number of collisions that would have happened in the after period had there been no change in priority phasing. These estimated collisions were compared to the observed number of accidents in the after period. Changes in approach AADT and other factors were also considered.

5.2 Analysis

A sample of 35 intersections was included in this analysis; all of these intersections were treated during the years 1997 to 1999. Table 13 provides information about treatment type implemented and number of intersections treated during each year.

Table 13: Intersections treated, Year, and Phasing type

Year	Number Treated	LTGA	FAG
1997	9	3	6
1998	5	4	1
1999	21	13	8

Intersections treated during the year 2000 were excluded since there were no accid count data available for the after period (2001 and beyond). Effectiveness of treatment evaluated by the method already discussed in Section 2.1. The index of effectiveness (θ) metl was employed in this study to evaluate the reduction in collisions following implementatior left-turn priority signal phasing. The index of effectiveness (θ) at an individual entity approximately equal to the ratio of the number of crashes occurring after conversion to expected number of accidents had conversion not taken place. The composite effect over all s was also evaluated. The % reduction in crashes (accident reduction factor) is given by:

$$100\,(1 - \theta)$$

The analysis relates to the following three categories:

- Left-turn collisions
- Left-turn side-impact collisions
- All impact types combined collisions

The accident reduction factor, following the index of effectiveness, was evaluated for each treated intersection. The overall effect of each treatment type (FAG and LTGA) was also evaluated.

The accident prediction models comprise eight different groups. Each group was specific for a different classification of road (discussed in detail in section 4.2.1). This study falls under three of those eight groups, each of which has different values for model parameters and over-dispersion values.

5.3 Results

5.3.1 Results for Left-turn Collisions

Table 14 presents the results for the overall estimate of the safety improvement effect for all 35 intersections in the sample, along with estimates for groups categorized by the type of left-turn protection, i.e., flashing green advance (FAG) and left-turn green arrow. Table 15 presents results of safety treatment for individual intersections. Estimates of the safety effect for some individual intersections show unfavourable effects, but these are generally statistically insignificant and are due to chance (as indicated by the asterisk). Changes at individual intersections without the asterisk are statistically significant (at the 5% level). The effect of a treatment may vary from intersection to intersection due to factors such as geometry and traffic volume. These results indicate a 16% slight overall reduction in collisions for all sites combined. The reduction obtained for intersections with flashing advance green treatments was 16% compared to left-turn green arrow phasing which had a 17% reduction in accidents. The results are statistically significant (at the 5% level), but the difference between the two results is not statistically significant. All 35 intersections in this study were protected/permitted; 15 had flashing advance green phases, while the rest of the intersections were treated with LTGA (lef turn green arrow).

Table 14: Safety effect by type of Protection for left-turn collisions

Conversion Group	Number In Group	Collisions in After Period		Index of Effectiveness (Std Error)	Point Estimate of % Reduction in Collisions
		Expected Without LT Treatment(B) (Std Error)	Observed After Treatment(A)		
All	35	179.57(14.37)	152	0.84(0.018)	16
FAG	15	80.84(9.69)	69	0.84(0.040)	16
LTGA	20	98.73(10.61)	83	0.83(0.032)	17

Table 15: Results of Left-turn collisions analysis for individual Intersections

Intersection				Treatment	Collisions		Year	Index of Effectiveness	Volume	
					Observed	Expected without treatment			Before	After
CHURCH	ST	FRONT	ST	LTGA	0	0.93	1998	0.00	15003	14345
LAWRENCE	AV	MARKHAM	RD	LTGA	10	12.19	1998	0.79*	30766	31522
FINCH	AV	BAYVIEW	AV	FAG	6	4.09	1998	1.34*	38033	37460
BATHURST	ST	SHEPPARD	AV	LTGA	5	5.26	1998	0.85*	31566	31421
YONGE	ST	BISHOP	AV	LTGA	7	4.69	1998	1.32*	29753	29456
YONGE	ST	AVONDALE	AV	FAG	2	12.49	1997	0.15	42491	41074
KEELE	ST	SHEPPARD	AV	FAG	6	7.10	1997	0.72*	31866	30114
STEELES	AV	KEELE	ST	FAG	18	22.01	1997	0.74*	38481	40411
ELLESMERE	RD	PHARMACY	AV	FAG	4	2.63	1997	1.12*	23395	23886
EGLINTON	AV	KIPLING	AV	LTGA	5	7.92	1997	0.55*	30609	33741
STEELES	AV	HILDA	AV	FAG	6	2.55	1997	1.73*	26289	27851
STEELES	AV	WARDEN	AV	LTGA	15	26.85	1997	0.52	42476	42710
FINCH	AV	MARKHAM	RD	LTGA	8	13.62	1997	0.52	33938	35288
STEELES	AV	MCCOWAN	RD	FAG	3	4.37	1997	0.54*	23301	22862
EGLINTON	AV	AVENUE	Rd	FAG	1	1.57	1999	0.50*	28527	29616
STEELES	AV	YONGE	ST	LTGA	5	5.46	1999	0.87*	45764	45867
KINGSTON	RD	BRIMLEY	RD	LTGA	0	2.22	1999	0.00	18957	20027
LAKE SHORE	BL	LESLIE	ST	FAG	0	0.57	1999	0.00	21649	21239
LAKE SHORE	BL	PARLIAMENT	ST	LTGA	0	0.61	1999	0.00	17873	19033
LAKE SHORE	BL	JARVIS	ST	FAG	6	4.75	1999	1.21*	29764	28676
EGLINTON	AV	MIDLAND	AV	LTGA	3	3.71	1999	0.75*	33118	35384
WARDEN	AV	ST CLAIR	AV	FAG	4	5.36	1999	0.69*	25298	26536
DUFFERIN	ST	BRIDGELAND	AV	LTGA	4	2.02	1999	1.80*	28215	27397
LESLIE	ST	SHEPPARD	AV	LTGA	4	3.61	1999	1.05*	42183	39090
EGLINTON	AV	ROYALYORK	RD	LTGA	3	1.24	1999	2.01*	27105	27264
EGLINTON	AV	SCARLETT	RD	LTGA	6	1.84	1999	2.89*	29657	28855
CUMMER	AV	WILLOWDAE	AV	FAG	1	0.83	1999	0.95*	14515	15477
MARKHAM	RD	PROGRESS	AV	FAG	9	5.22	1999	1.65*	38679	38468
MARTIN GROVE	RD	RATHBURN	RD	FAG	0	0.52	1999	0.00	10926	11670
MCCOWAN	RD	PITFIELD	RD	LTGA	4	1.98	1999	1.81*	28272	27064
BRIMLEY	RD	PROGRESS	AV	FAG	3	6.77	1999	0.42	25887	28530
FINCH	AV	WESTMORE	DR	LTGA	0	0.75	1999	0.00	13751	12336
FINCH	AV	HUMBERLIE	DR	LTGA	0	1.39	1999	0.00	18829	21404
KENNEDY	RD	MCNICOLL	AV	LTGA	3	0.90	1999	2.84	19943	20867

* (the asterisk) indicate that safety effects on individual intersection are statistically insignificant

5.3.2 Results for Left-turn Side-impact Collisions

Results of separate analysis conducted for left-turn side-impact type of collisions are presented in Tables 16 and 17. Table 16 presents the composite effect results for each treatment type and all treated sites. These results show a 19% reduction overall in left-turn side impact collisions following implementation of left-turn priority signal phasing on the 35 intersections. The intersections with flashing advance green phasing had a reduction in collisions of 12%, while those treated with left-turn green arrow phasing had a 25% reduction for left-turn side-impact collisions. These results are statistically significant (at the 5% level). Table 17 presents the safety effect of each of the 35 intersections. Estimates of the safety effect for some individual intersections show unfavourable effects. Conclusions should not be drawn from these results because there is a likelihood that the change in safety for individual intersections, as indicated by the asterisk, is due to chance. The effects at individual intersections without the asterisk are statistically significant (at the 5% level)

Table 16: Composite safety effect for all intersections by type of protection for left-turn side impact collisions

Conversion Group	Number In Group	Collisions In After Period		Index of Effectiveness(Std Error)	Point Estimate of % Reduction in Collisions
		Expected Without LT Treatment(B) (Std Error)	Observed After Treatment(A)		
All	35	165.23(14.07)	135	0.81(0.02)	19
FAG	15	74.19(9.55)	66	0.88(0.04)	12
LTGA	20	91.08(10.34)	69	0.75(0.02)	25

Table 17: Results of left-turn side-impact collisions analysis for individual intersections

Intersection				Treatment	Collisions		Year	Index of Effectiveness	Volume	
					Observed	Expected without treatment			Before	After
CHURCH	ST	FRONT	ST	LTGA	0	0.89	1998	0.00	15003	14345
LAWRENCE	AV	MARKHAM	RD	LTGA	8	13.20	1998	0.58*	30766	31522
FINCH	AV	BAYVIEW	AV	FAG	6	10.63	1998	0.51	38033	37460
BATHURST	ST	SHEPPARD	AV	LTGA	5	6.82	1998	0.65*	31566	31421
YONGE	ST	BISHOP	AV	LTGA	5	5.16	1998	0.83*	29753	29456
YONGE	ST	AVONDALE	AV	FAG	2	10.23	1997	0.17	42491	41074
KEELE	ST	SHEPPARD	AV	FAG	6	7.58	1997	0.68*	31866	30114
STEELES	AV	KEELE	ST	FAG	18	15.66	1997	1.00*	38481	40411
ELLESMERE	RD	PHARMACY	AV	FAG	4	2.82	1997	1.04*	23395	23886
EGLINTON	AV	KIPLING	AV	LTGA	5	8.89	1997	0.49	30609	33741
STEELES	AV	HILDA	AV	FAG	5	2.89	1997	1.28*	26289	27851
STEELES	AV	WARDEN	AV	LTGA	13	23.05	1997	0.51	42476	42710
FINCH	AV	MARKHAM	RD	LTGA	8	8.57	1997	0.77*	33938	35288
STEELES	AV	MCCOWAN	RD	FAG	3	3.12	1997	0.71*	23301	22862
EGLINTON	AV	AVENUE	Rd	FAG	0	1.25	1999	0.00	28527	29616
STEELES	AV	YONGE	ST	LTGA	3	4.44	1999	0.63	45764	45867
KINGSTON	RD	BRIMLEY	RD	LTGA	0	2.11	1999	0.00	18957	20027
LAKE SHORE	BL	LESLIE	ST	FAG	0	0.62	1999	0.00	21649	21239
LAKE SHORE	BL	PARLIAMENT	ST	LTGA	0	0.62	1999	0.00	17873	19033
LAKE SHORE	BL	JARVIS	ST	FAG	6	4.38	1999	1.30*	29764	28676
EGLINTON	AV	MIDLAND	AV	LTGA	2	4.07	1999	0.46*	33118	35384
WARDEN	AV	ST CLAIR	AV	FAG	3	5.38	1999	0.51*	25298	26536
DUFFERIN	ST	BRIDGELAND	AV	LTGA	4	1.89	1999	1.88*	28215	27397
LESLIE	ST	SHEPPARD	AV	LTGA	3	3.51	1999	0.80*	42183	39090
EGLINTON	AV	ROYAL YORK	RD	LTGA	2	1.06	1999	1.50*	27105	27264
EGLINTON	AV	SCARLETT	RD	LTGA	3	1.86	1999	1.41*	29657	28855
CUMMER	AV	WILLOWDALE	AV	FAG	1	0.83	1999	0.95*	14515	15477
MARKHAM	RD	PROGRESS	AV	FAG	9	4.36	1999	1.94*	38679	38468
MARTINGROVE	RD	RATHBURN	RD	FAG	0	0.50	1999	0.00	10926	11670
MCCOWAN	RD	PITFIELD	RD	LTGA	4	1.23	1999	2.70*	28272	27064
BRIMLEY	RD	PROGRESS	AV	FAG	3	3.90	1999	0.68*	25887	28530
FINCH	AV	WESTMORE	DR	LTGA	0	0.50	1999	0.00	13751	12336
FINCH	AV	HUMBERLINE	DR	LTGA	0	1.26	1999	0.00	18829	21404
KENNEDY	RD	MCNICOLL	AV	LTGA	3	0.83	1999	2.99*	19943	20867

* (the asterisk) indicate that safety effects on individual intersection are statistically insignificant

5.3.3 Results for All Impact Types combined

A separate evaluation was conducted for all impact types combined collisions. Tab presents the composite effect for all the treated intersections and treatment groups. These re indicate an overall reduction in collisions of 12%. Intersections treated with flashing adv green show slightly more favourable results (15%), but the difference is statistically insignif (at the 5% level). The reduction in collisions for intersections treated with left-turn green a was 10%. These results are statistically significant (at the 5% level). Table 19 shows the re at individual intersections. Estimates of the safety effect for some individual intersectioı indicated by the asterisk, show unfavourable effects, but these are generally statisti insignificant and are likely due to chance.

Table 18: Composite safety effect for group of intersections by type of protection for all impact types of collisions

Conversion Group	Numbers in Group	Collisions In After Period		Index of Effectiveness(Std Error)	Point Estimate % Reduction Collisions
		Expected Without LT Treatment(B)(Std Error)	Observed After Treatment(A)		
All	35	672.11(28.62)	590	0.88(0.108)	12
FAG	15	336.67(21.82)	287	0.85(0.141)	15
LTGA	20	335.45(19.81)	303	0.90(0.141)	10

Table 19: Results of All impact collisions analysis for individual intersections

Intersection				Treatment	Collisions		Year	Index of Effectiveness	Volume	
					Observed	Expected without treatment			Before	After
CHURCH	ST	FRONT	ST	LTGA	4	5.64	1998	0.65	15003	14345
LAWRENCE	AV	MARKHAM	RD	LTGA	32	40.60	1998	0.78*	30766	31522
FINCH	AV	BAYVIEW	AV	FAG	29	28.44	1998	0.99*	38033	37460
BATHURST	ST	SHEPPARD	AV	LTGA	21	23.02	1998	0.89*	31566	31421
YONGE	ST	BISHOP	AV	LTGA	17	15.67	1998	1.04*	29753	29456
YONGE	ST	AVONDALE	AV	FAG	15	14.93	1997	0.93*	42491	41074
KEELE	ST	SHEPPARD	AV	FAG	39	38.24	1997	0.98*	31866	30114
STEELES	AV	KEELE	ST	FAG	52	74.73	1997	0.67	38481	40411
ELLESMERE	RD	PHARMACY	AV	FAG	21	31.76	1997	0.64	23395	23886
EGLINTON	AV	KIPLING	AV	LTGA	23	33.19	1997	0.66*	30609	33741
STEELES	AV	HILDA	AV	FAG	18	22.23	1997	0.77*	26289	27851
STEELES	AV	WARDEN	AV	LTGA	51	62.47	1997	0.79	42476	42710
FINCH	AV	MARKHAM	RD	LTGA	40	29.30	1997	1.28	33938	35288
STEELES	AV	MCCOWAN	RD	FAG	23	25.75	1997	0.84*	23301	22862
EGLINTON	AV	AVENUE	Rd	FAG	11	16.94	1999	0.63*	28527	29616
STEELES	AV	YONGE	ST	LTGA	21	17.56	1999	1.18*	45764	45867
KINGSTON	RD	BRIMLEY	RD	LTGA	1	8.87	1999	0.11	18957	20027
LAKE SHORE	BL	LESLIE	ST	FAG	5	4.02	1999	1.18*	21649	21239
LAKE SHORE	BL	PARLIAMENT	ST	LTGA	4	4.03	1999	0.93*	17873	19033
LAKE SHORE	BL	JARVIS	ST	FAG	17	18.06	1999	0.93*	29764	28676
EGLINTON	AV	MIDLAND	AV	LTGA	12	16.70	1999	0.71*	33118	35384
WARDEN	AV	ST CLAIR	AV	FAG	13	19.46	1999	0.65*	25298	26536
DUFFERIN	ST	BRIDGELAND	AV	LTGA	16	12.09	1999	1.30*	28215	27397
LESLIE	ST	SHEPPARD	AV	LTGA	14	16.02	1999	0.86*	42183	39090
EGLINTON	AV	ROYAL YORK	RD	LTGA	5	8.07	1999	0.59*	27105	27264
EGLINTON	AV	SCARLETT	RD	LTGA	12	10.11	1999	1.16*	29657	28855
CUMMER	AV	WILLOWDALE	AV	FAG	4	4.92	1999	0.76*	14515	15477
MARKHAM	RD	PROGRESS	AV	FAG	19	17.99	1999	1.04*	38679	38468
MARTIN GROVE	RD	RATHBURN	RD	FAG	1	2.90	1999	0.31	10926	11670
MCCOWAN	RD	PITFIELD	RD	LTGA	10	6.27	1999	1.54*	28272	27064
BRIMLEY	RD	PROGRESS	AV	FAG	20	16.30	1999	1.19	25887	28530
FINCH	AV	WESTMORE	DR	LTGA	5	5.05	1999	0.95*	13751	12336
FINCH	AV	HUMBERLINE	DR	LTGA	2	7.66	1999	0.25	18829	21404
KENNEDY	RD	MCNICOLL	AV	LTGA	6	5.03	1999	1.15*	19943	20867

* (the asterisk) indicate that safety effects on individual intersection are statistically insignificant

5.4 Disaggregate Analysis: Results and Discussion

This section presents a disaggregate analysis, considering the impact of different fac on safety improvement effects at intersections where left-turn priority treatment implemented.

5.4.1 Safety effect and collisions per year in the before period

Analysis was performed to examine the safety effect of conversion related to expected number of collisions in the before period (all three collision types). Figures 3, 4, an shows scatter plots of the data for three collision types. A fitted regression line confirms w seems evident from these plots -- that there is no apparent relationship between the sa improvement effect of left-turn priority phasing and the expected number of collisions in before period. The standard errors indicate that the slopes of the trend lines are statistic insignificant.

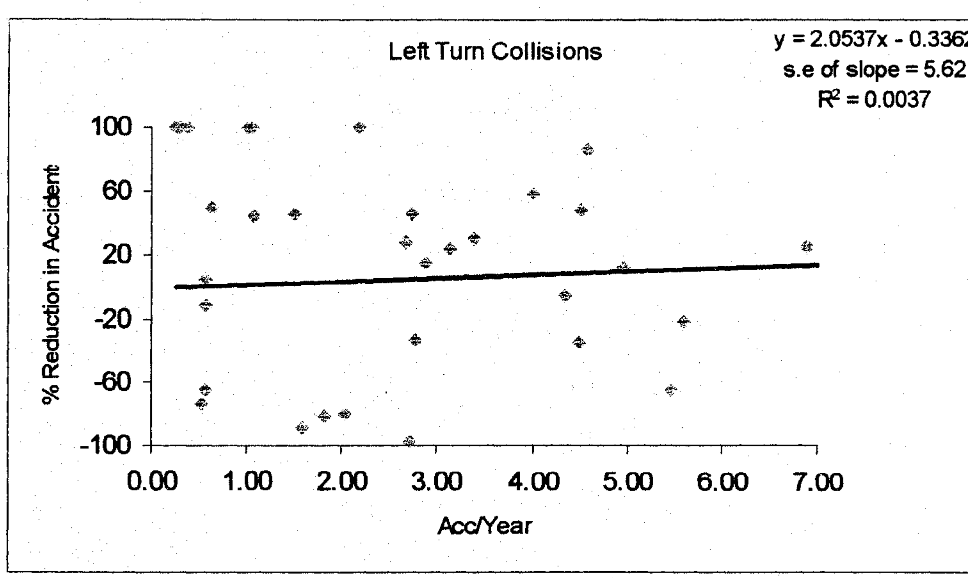

Figure 3: Safety effect vs. expected number of left-turn collisions

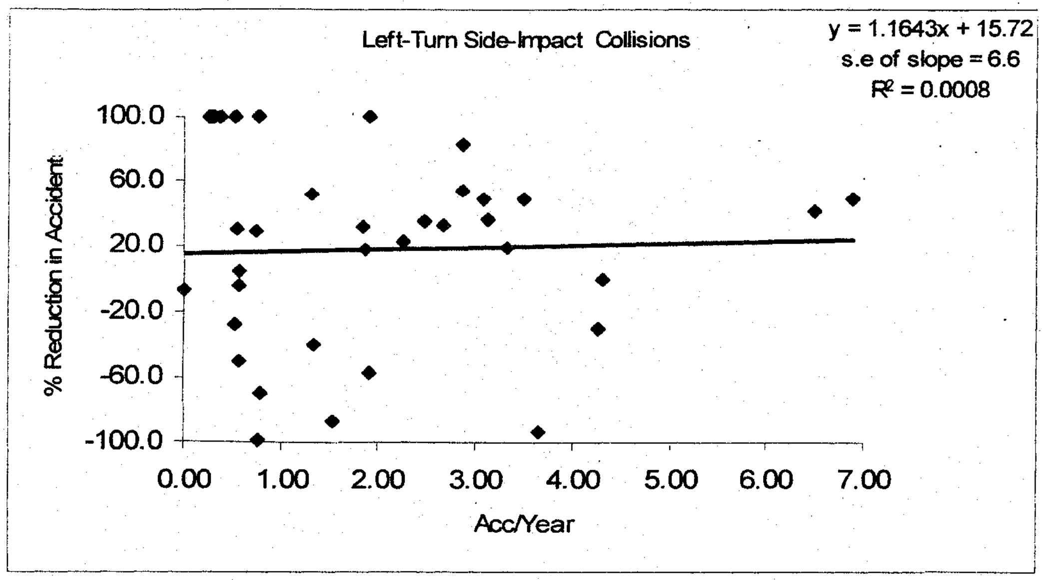

Figure 4: Safety effect vs. expected number of left-turn side-impact collisions

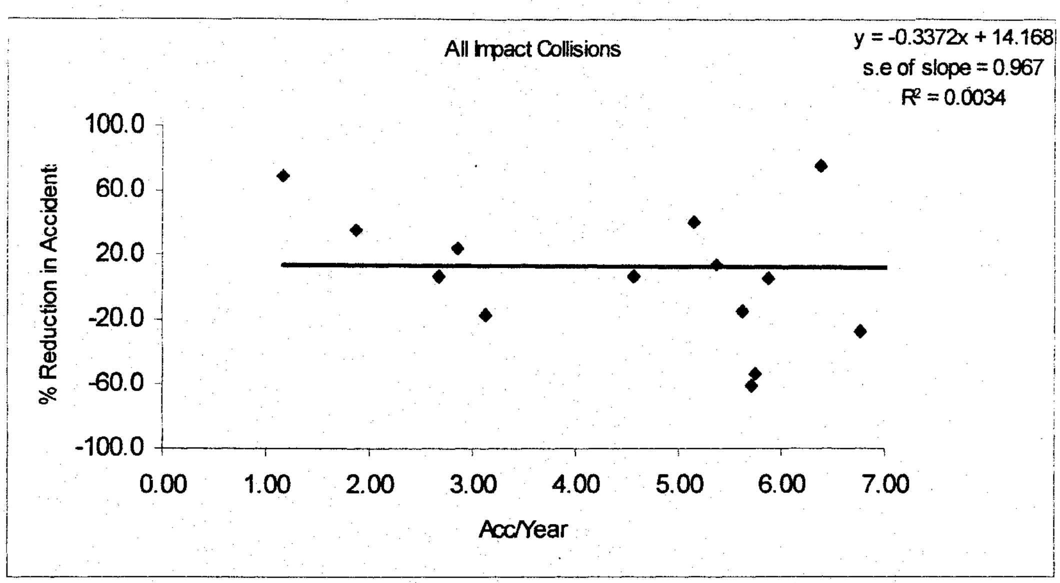

Figure 5: Safety effect vs. expected number of all impact type collisions

5.4.2 Safety improvement effect vs. Entering Volume

The relationship between the effectiveness of treatment and the total entering AAD' the before period was evaluated using the results shown in Figures 6, 7, and 8. The Equatio trend lines and adjusted R^2 values are shown on the relevant Figures, along with the stan errors of the slope. The slopes of regression lines drawn are statistically insignificant at the level for all left-turn and left-turn side impact collisions and statistically significant at the level for all impact type combined. The latter result should not be taken to imply that a l traffic volume in itself is associated with a larger reduction in accidents (safety improve effect) since lower traffic volumes might be correlated with other factors that may also contri to a reduction in collisions.

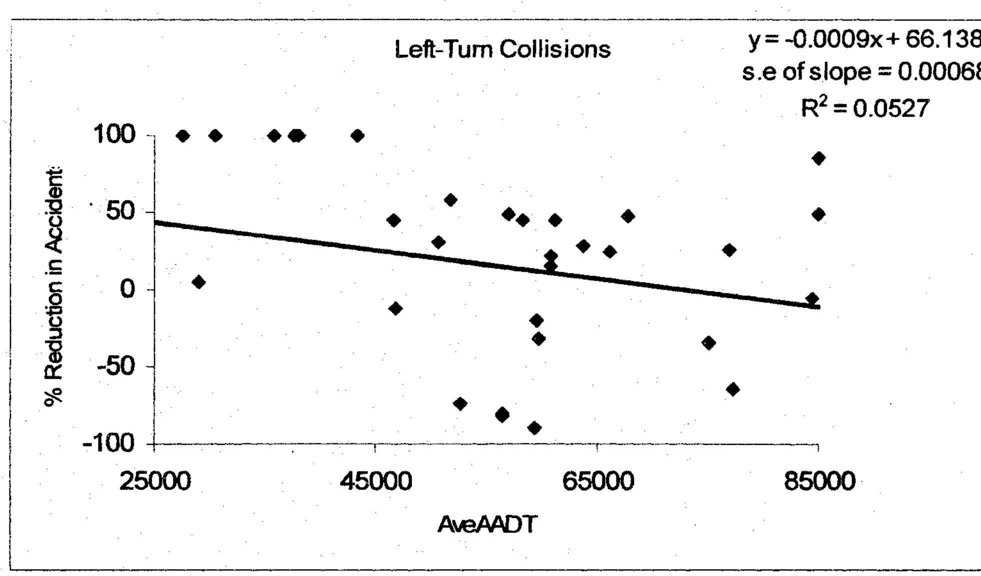

Figure 6: Effectiveness of treatment vs. entering AADT for left-turn collisions

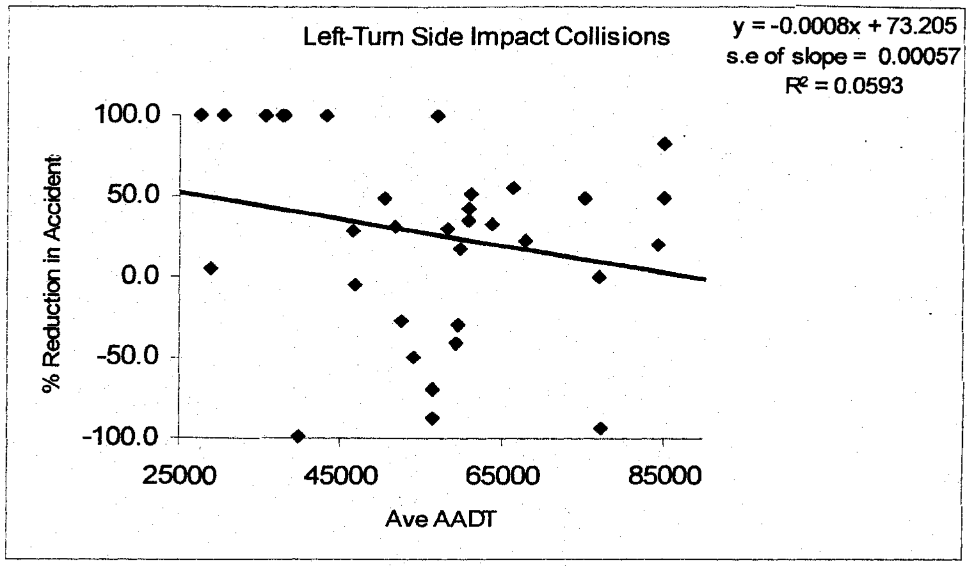

Figure 7: Effectiveness of treatment vs. AADT for left-turn side impact collisions

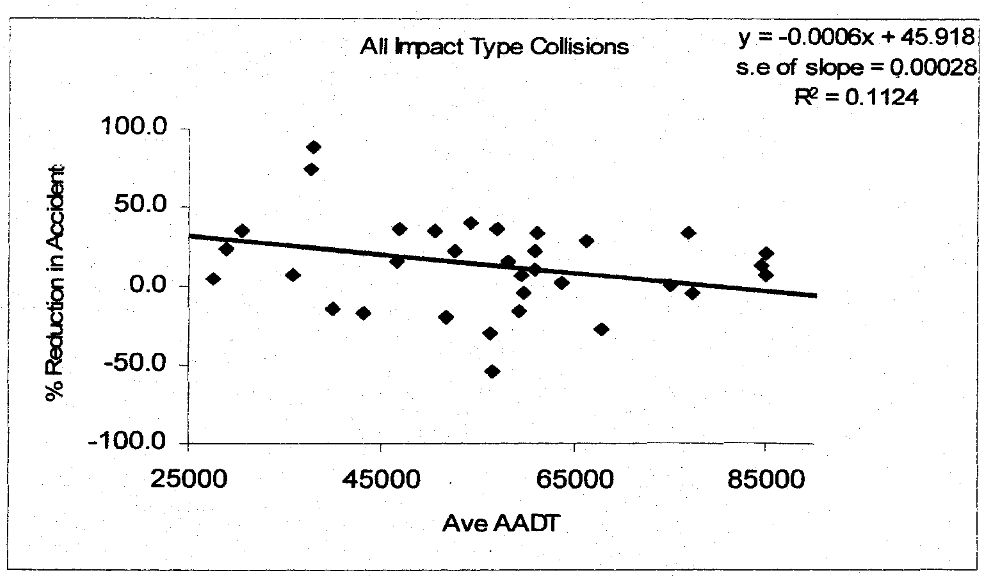

Figure 8: Effectiveness of treatment vs. AADT for all impact type collisions

5.4.3 Safety effect vs. Capacity, and Delay

Traffic volumes, intersection geometrics, signal timing and phasing data for morning afternoon peak periods were collected from the City for the periods before and a implementation of left-turn priority signal phasing. Capacity analysis was performed for e intersection for the two peak periods (morning and afternoon) before and after convers Highway Capacity Software (HCS 2000) was used to calculate capacity, and control delay, latter being the measure of Level of Service (HCM). An analysis was performed to examine impact of these factors on the safety effect of left-turn priority phasing. Table 19 shows results of the capacity analysis for both the morning and afternoon peak periods for both type left-turn signal phasing.

The relationship between the effectiveness of safety treatment and average control de in the peak periods is depicted in Figures 9, 10, and 11. Figures 9, 10, and 11 pertain to morn peak periods for left-turn collisions, left-turn side impact collisions and all impact ty combined, respectively, for each individual intersection. The relationship between sai improvement and average control delay for the afternoon rush period is presented in Figures 13 and 14, respectively, for all three types of collisions. The slopes of fitted regression li drawn for Figures 9, 12 and 13 (delay vs. % reduction in collisions) are statistically signific (at the 5% level) and for Figures 10, 11 and 14 are statistically insignificant (at the 5% level). the whole these results (all with negative slopes) can be taken to indicate a relationship betw safety effect and average control delay. As control delay increases, the less likely it is for sai to be improved by left-turn phasing.

Table 20: Capacity, LOS and Signal Timing Data for Peak Periods before Treatment

Intersection				Morning Rush Periods				Afternoon Rush Periods			
				Delay(LOS)	Capacity	Cycle Length	Phases	Delay(LOS)	Capacity	Cycle Length	Phases
CHURCH	ST	FRONT	ST	126.3(F)	3501	70	3	27(C)	3485	70	3
STEELES	AV	YONGE	ST	30.2(C)	9584	110	3	34.8(C)	9622	110	2
KINGSTON	RD	BRIMLEY	RD	108(F)	7298	100	4	98(E)	7089	100	2
.AKE SHORE	BL	PARLIAMENT	ST	32.5(C)	10488	110	3	49.8(D)	10152	110	3
LAWRENCE	AV	MARKHAM	RD	92.3(F)	11081	100	2	84.7(F)	11509	100	3
EGLINTON	AV	MIDLAND	AV	96.7(F)	13206	120	3	104(F)	12984	120	3
DUFFERIN	ST	BRIDGELAND	AV	63(E)	17986	100	2	62.3(E)	17805	100	2
BATHURST	ST	SHEPPARD	AV	136.6(F)	9871	100	4	13.5(B)	10007	100	4
EGLINTON	AV	KIPLING	AV	40(D)	10688	100	4	30.2©	9915	100	4
LESLIE	ST	SHEPPARD	AV	98.2(F)	10079	130	3	73.2(E)	9312	135	3
EGLINTON	AV	ROYAL YORK	RD	18.5(B)	15406	100	3	18.8(B)	15230	100	3
EGLINTON	AV	SCARLETT	RD	143.7(F)	8249	100	3	77.1(E)	8411	100	3
MCCOWAN	RD	PITFIELD	RD	95.8(F)	12314	120	3	131.5(F)	12691	120	3
YONGE	ST	BISHOP	AV	48(D)	4827	90	2	45.4(D)	4891	90	2
STEELES	AV	WARDEN	AV	70.2(E)	11848	110	4	60.6(E)	11704	100	3
FINCH	AV	MARKHAM	RD	30.3(C)	8746	120	4	28.2(C)	9056	120	4
FINCH	AV	WESTMORE	DR	12.7(B)	7976	65	2	13.7(B)	8069	65	2
FINCH	AV	HUMBERLINE	DR	14.4(B)	12450	90	2	15.7(B)	12621	80	2
KENNEDY	RD	MCNICOLL	AV	89.02(F)	6339	100	3	74.6(E)	5993	110	2
KENNEDY	RD	SUFFERANCE	RD	34.8(C)	10700	105	3	9.4(A)	10600	105	3
EGLINTON	AV	AVENUE	Rd	19(B)	7588	80	2	29.7(C)	7453	80	2
.AKESHORE	BL	LESLIE	ST	58.6(E)	8580	120	3	23.5(C)	7695	100	4
.AKESHORE	BL	JARVIS	ST	86.1(E)	9132	110	3	92.5(F)	8574	110	3
WARDEN	AV	ST CLAIR	AV	29.3(C)	12388	95	3	21.8©	12240	100	3
YONGE	ST	AVONDALE	AV	38.2(D)	9221	100	2	52.1(D)	9189	100	2
KEELE	ST	SHEPPARD	AV	32.9(C)	12149	110	3	52.3(D)	13417	100	3
STEELES	AV	KEELE	ST	46.6(D)	14543	110	2	86.3(F)	13853	120	2
FINCH	AV	BAYVIEW	AV	42(D)	10083	110	3	54.6(D)	10226	110	3
ELLESMERE	RD	PHARMACY	AV	31.9(C)	8139	110	3	61.1(E)	8128	120	3
CUMMER	AV	WILLOWDALE	AV	24.4(C)	6142	90	2	21.3(C)	5776	90	2
MARKHAM	RD	PROGRESS	AV	60(E)	15925	120	3	61.8(E)	14870	120	3
ARTINGROVE	RD	RATHBURN	RD	10(A)	17005	70	2	12.6(B)	16900	70	2
BRIMLEY	RD	PROGRESS	AV	57.1(D)	13728	95	3	55.8(D)	13393	95	3
STEELES	AV	HILDA	AV	95(E)	10313	110	4	92.3(E)	9946	110	4
STEELES	AV	MCCOWAN	RD	24(C)	11596	90	4	19.6(B)	11700	90	4

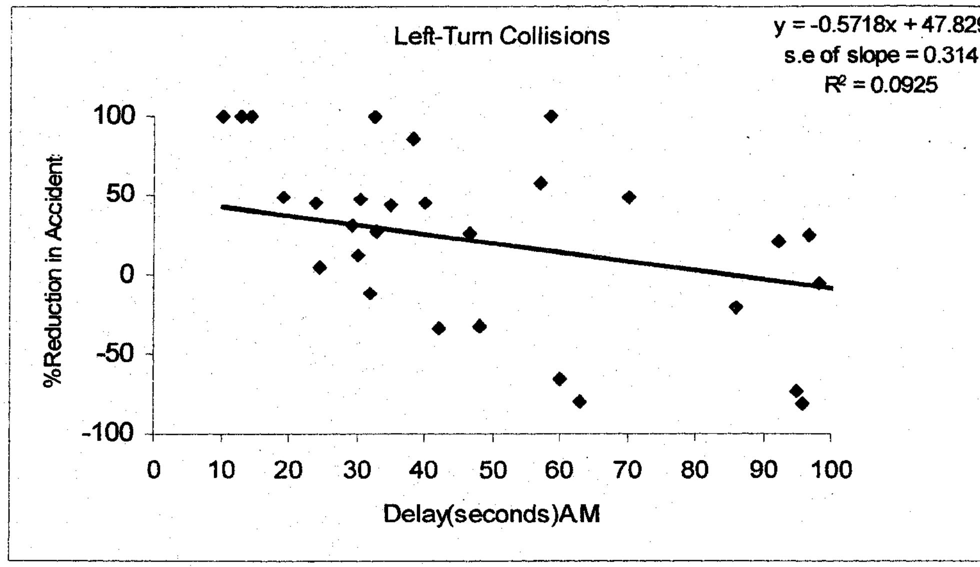

Figure 9: Relationship of safety effect vs. control delay for left-turn collisions/year

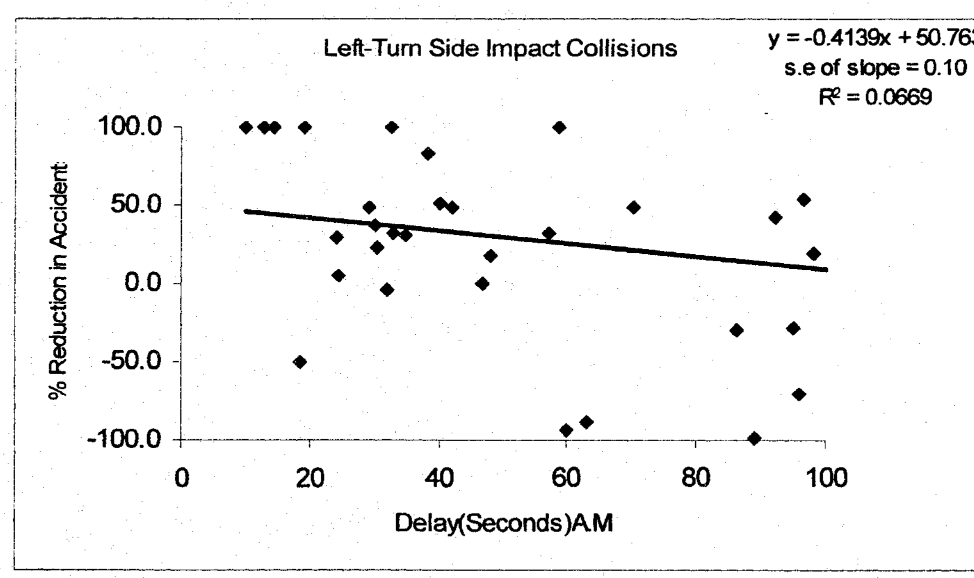

Figure 10: Safety effect vs. control delay for left-turn side impact collisions/year

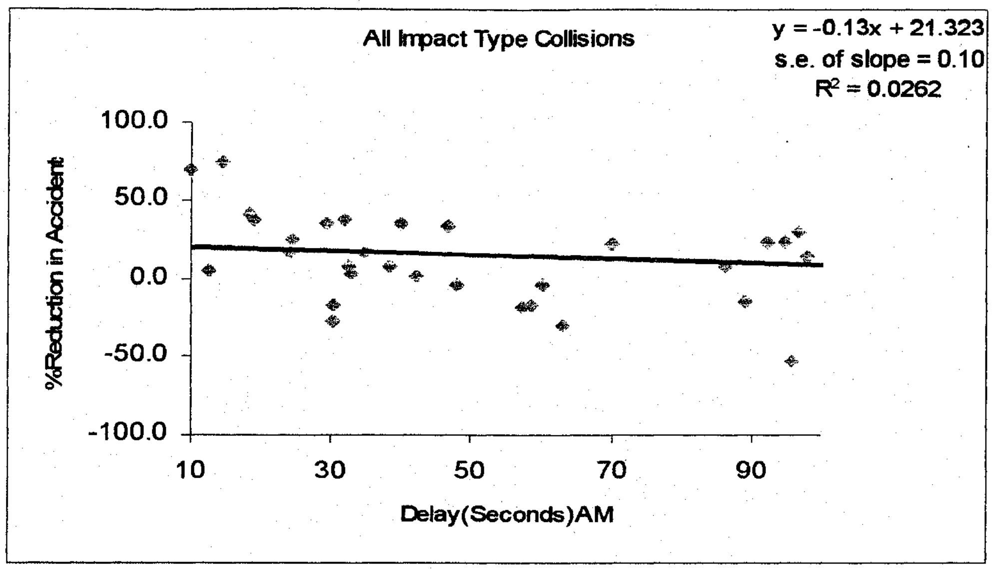

Figure 11: Safety effect vs. control delay for all impact type of collisions/year

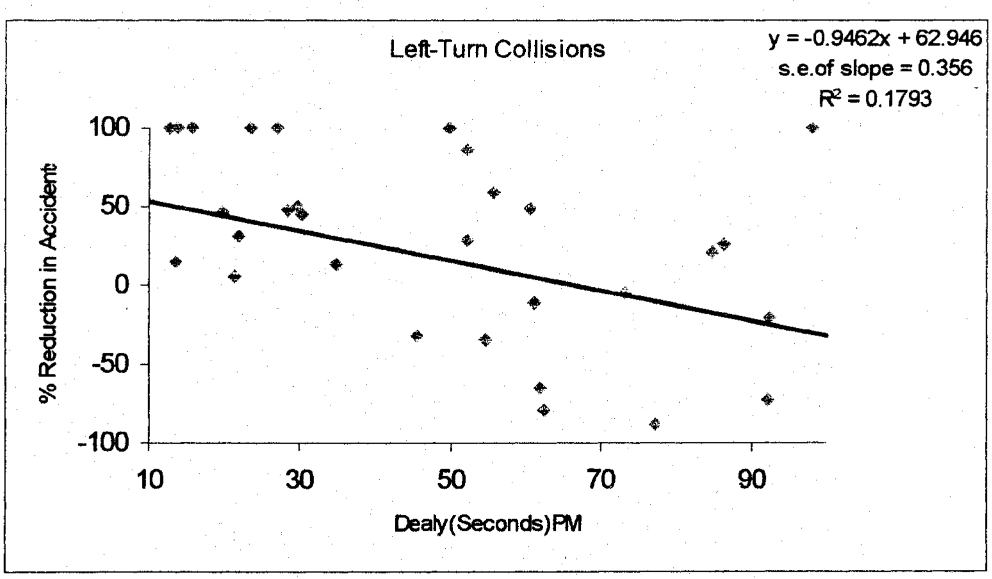

Figure 12: Safety effect vs. control delay for left-turn collisions/year

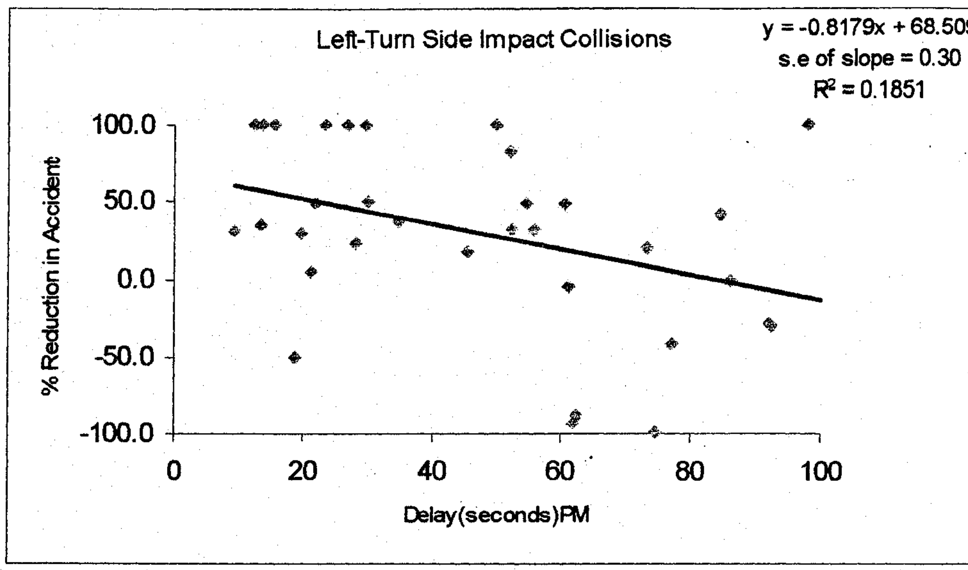

Figure 13: Safety effect vs. control delay for left-turn side impact collisions/year

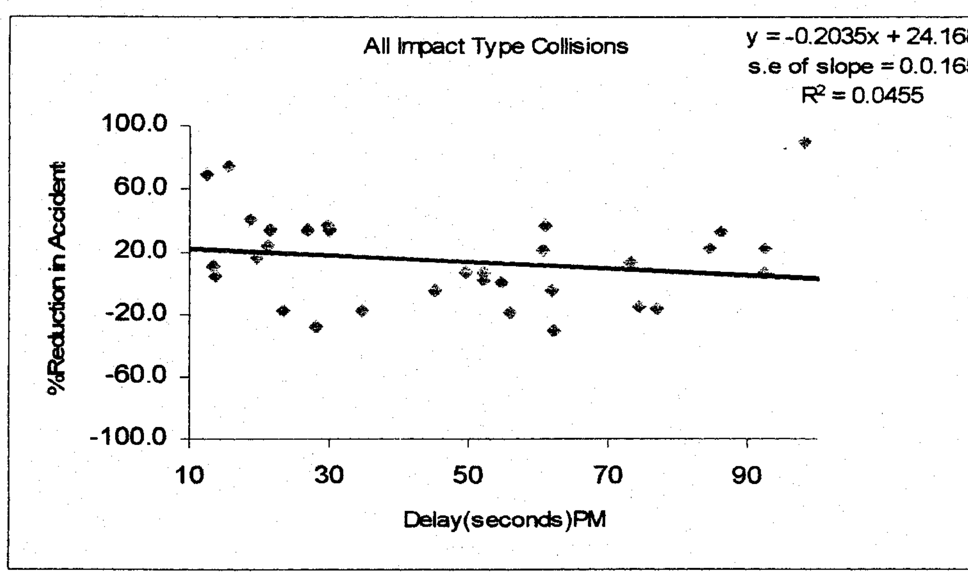

Figure 14: Safety effect vs. control delay for all impact collisions/year

Figures 15 through 20 depict the relationship between the safety effect and capacity and volume/capacity (v/c) ratio. Morning and afternoon peak periods values were averaged. A fitted regression line to the data in Figures 15, 16 and 17 (safety effect vs. capacity) indicates a trend that suggests that, the higher the capacity, the more the decrease in the collisions will be with implementation of a left-turn priority phasing. However, these trends are statistically insignificant (at the 5% level). For the safety effect vs. v/c ratio plots, the slopes of fitted regression lines drawn for Figures 18 and 19 are statistically significant at the 10% level and while the slope for Figure 20 is statistically insignificant at the 5% level.

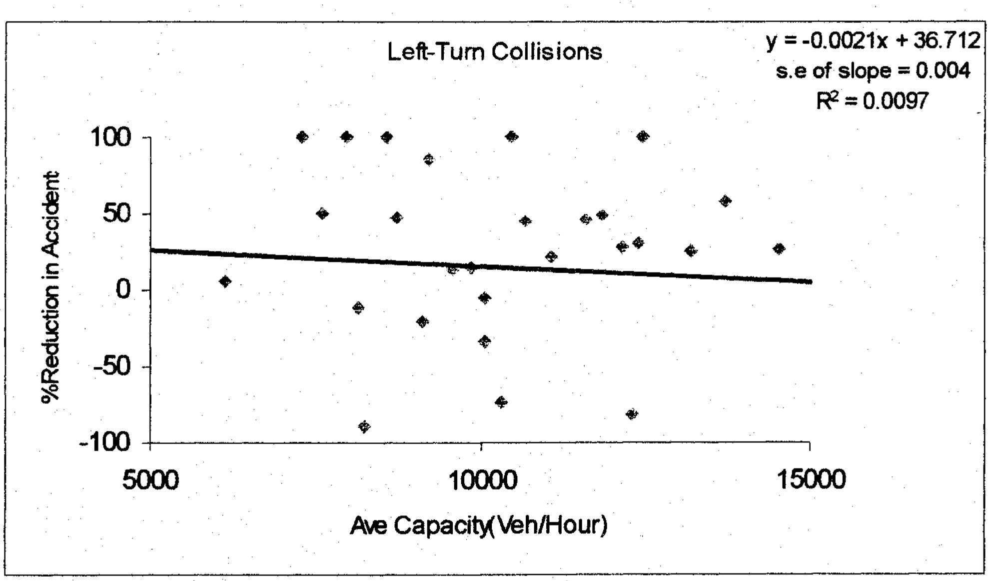

Figure 15: Safety effect vs. rush period capacity for left-turn collisions/year

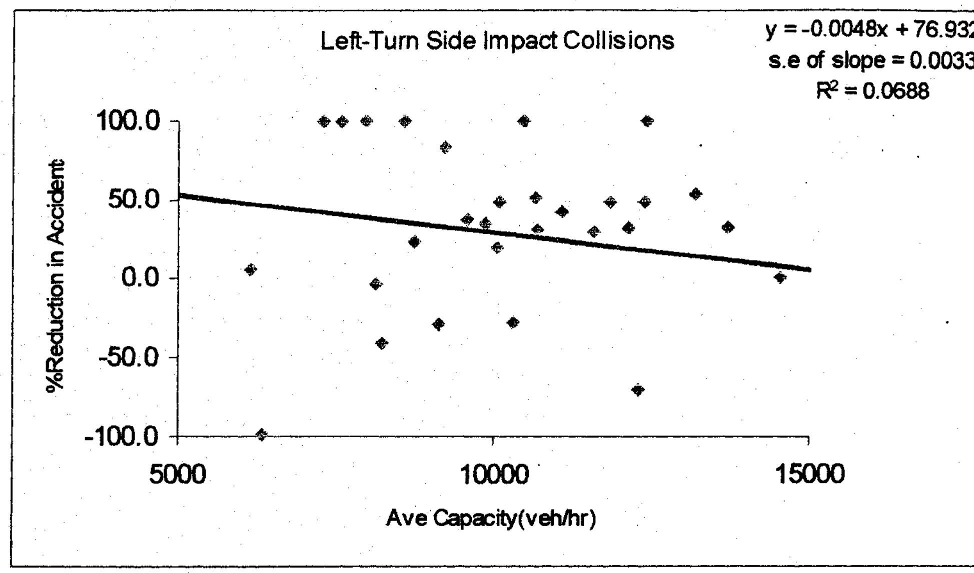

Figure 16: Safety effect vs. rush period capacity for left-turn side impact collisions/y

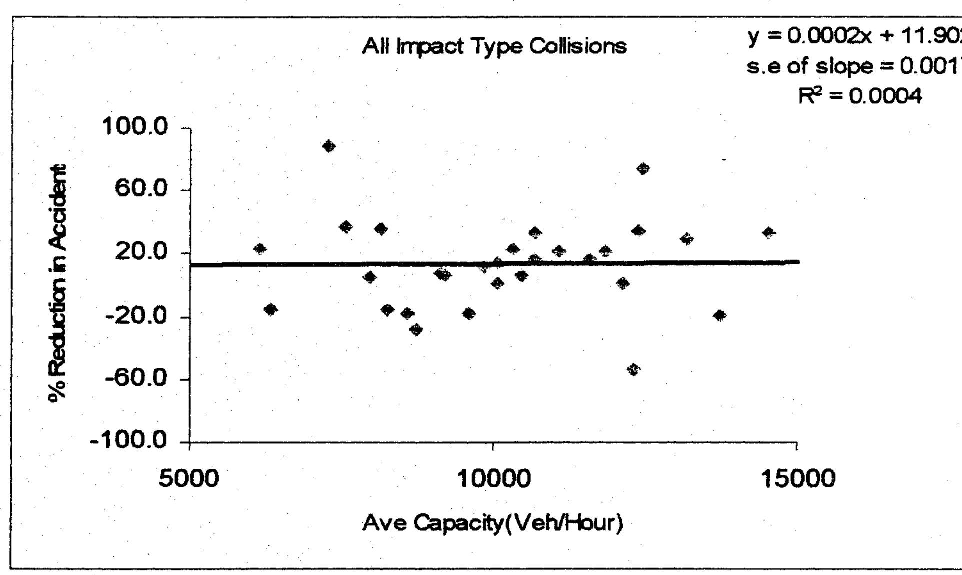

Figure 17: Safety effect vs. rush period capacity for all impact type collisions/year

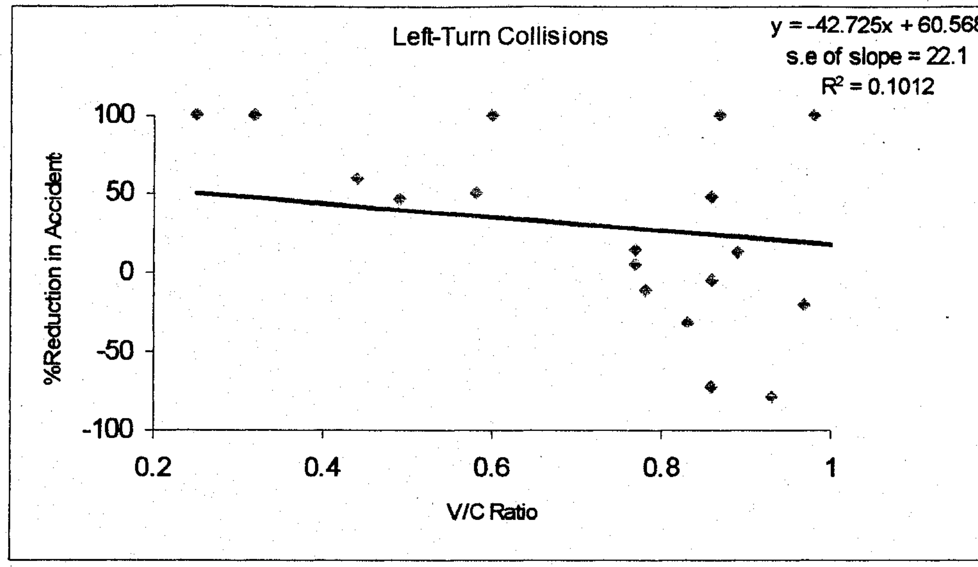

Figure 18: Safety effect and average rush period v/c ratio for left-turn collisions/year

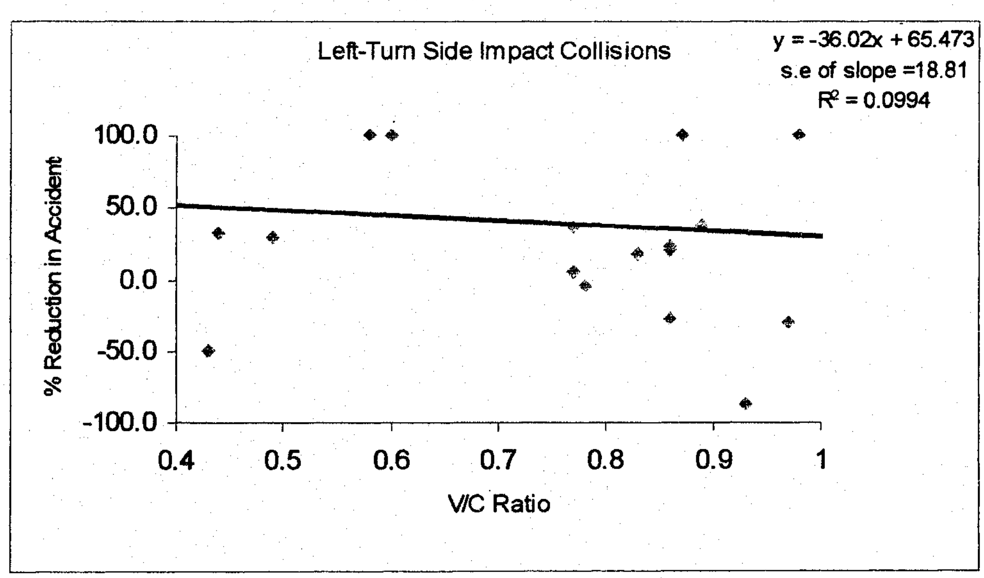

Figure 19: Safety effect vs. rush period v/c ratio for left-turn side impact collisions/year

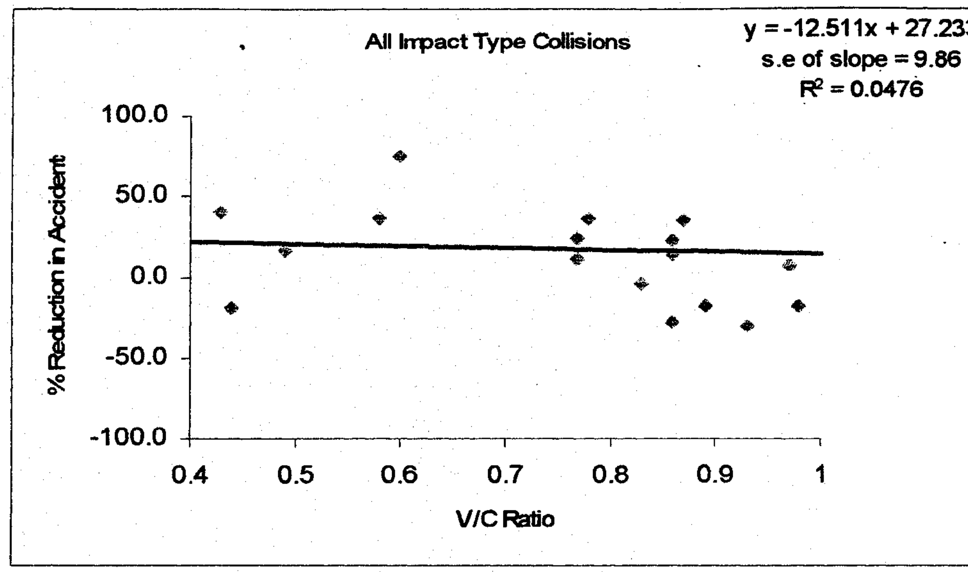

Figure 20: Safety effect and average rush period v/c ratio for all impact type collisions/ye

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The fundamental task of this analysis was to evaluate the safety effect of left-turn phasing using the empirical Bayesian methodology. This methodology is considered to be the most advanced evaluation methodology for examining changes in collisions following implementation of a safety treatment.

Some valuable insights into the reduction of collisions were gained following the application of left-turn priority treatment at 35 signalized intersections. The safety treatment applied consisted of addition of some form of priority phasing at one or more approaches of an intersection during some peak period (morning or after) of the day. This analysis was confined to injury (fatal and severe injuries) collisions. (PDO and pedestrian injury accidents were not considered)

Following are the highlights of the results.

- Left-turn green arrow phasing is relatively safer compared to flashing advance green phase when analyzed for left-turn side impact collisions. These results and difference between results (25% reduction in accidents for LTGA compared with 12% for FAG) are statistically significant (at the 5% level).
- Flashing advance green phase is comparatively safer compared to left-turn green arrow phasing when analyzed for all impact types combined collisions. The results and difference between these results (15% reduction in accidents for FAG compared with 10% reduction in accidents for LTGA) are statistically significant (at the 5% level).
- There is no apparent relationship between the safety effect of left-turn priority phasing and the expected annual number of collisions in the before period.

- There is an apparent trend that suggests that, as the control delay in seconds (calculated by HCM procedure) increases, and safety benefits of left-turn phasing decreases. In other words, the worse the level of service (HCM), the less likely it is for safety benefit to be achieved by introducing left-turn priority phasing.

In summary, it can be concluded that evaluating the safety effects of installing left-turn phasing at Toronto intersections using the latest methodology was a valuable exercise. Even though the safety benefits were small, it is nevertheless reassuring that treatments to improve level of service can be implemented without a sacrifice in safety.

6.2 Recommendations

Given the value and promise of this study, a few recommendations are in order:

- The safety effectiveness of left-turn priority phasing should be considered by highway agencies and cities in evaluating potential improvements at intersections.
- The City of Toronto should continue the evaluation process by amalgamating the results of this study with data from additional left-turn priority phasing installations. The availability of a larger sample of conversions could mean that trends will emerge that will better define the conditions under which left-turn priority phasing would be more safety beneficial.
- In the light of the difficulties experienced in assembling the data for this evaluation study, it is strongly recommended that the City's data and information bases be refined to make it easier to access information required for safety evaluation of all types of traffic engineering measures. Flow and accident data should be updated and error free. Missing fields in the data should be filled with accurate information

- The empirical Bayes approach should be implemented as the preferred approach for observational before-after evaluation of safety improvements.

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