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Left-turn treatment and safety at high speed signalized intersections

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To Appa, Amma, Usha, Balaji

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Left-turn traffic is a major source of conflicts at intersections. Though an average of only ten to fifteen percent of all approaching traffic turns left, left-turning vehicles are involved in approximately 45 percent of all accidents (1). Left-turns at a signalized intersection can be controlled by a left-turn phase in the signal, and by having an exclusive left-turn lane. This thesis addresses issues related to the safety of left-turn treatments at signalized intersections that have approaches with speed limits 35 miles per hour or higher.

Importance of Research

Left-turn treatments at signalized intersections include left-turn lanes, and left-turn signal phasing. Left-turn treatment design decisions are usually made based on an engineer's experience and judgment, and locally derived standards. A Federal Highway Administration study notes:

> Traffic engineers have no clear-cut guidelines concerning the need for either left-turn lanes or left-turn signal phasing. This uncertainty results from a lack of agreement as to what constitutes unreasonable delay, congestion or danger to a left-turning vehicle. To compound the problem, there are numerous ways to signalize the intersection once the decision is made to install left-turn phasing (2).

There are no quantitative methods for estimating the safety impacts of left-turn design decisions. For instance, when an engineer considers changing the left-turn treatment at an intersection approach, a quantitative model would be useful to estimate the effect of this change on the intersection based on conditions existing at that intersection.

This research has developed quantitative models to estimate accident implications of a change in left-turn treatment based on conditions existing at high speed signalized intersections. High speed signalized intersections are defined as those having approaches with speed limits of 35 miles per hour or higher. High speed signalized intersections are selected for this study because of their significant facility costs and larger traffic volumes.

Quantitative models for estimating the safety impacts of left-turn treatments are developed by performing statistical analysis on data collected from intersections across Iowa. The data collected included intersection geometrics, traffic volumes, and traffic signal operating characteristics. The models estimate the accident rate or the number of accidents based on conditions at the intersection. The next few paragraphs briefly discuss left-turn treatments.

Background Information

The left-turn maneuver at an intersection is associated with traffic conflicts because the left-turning vehicle has to cross the opposing lanes while turning. Left-turning vehicles take longer to clear an intersection than through vehicles (3). Therefore, left-turning vehicles reduce the capacity of an intersection (4).

The effect of left-turning vehicles at an intersection is summarized by the Federal Highway Administration report:

> Left-turning vehicles cause few problems at signalized intersections that are operating under low volume conditions. Drivers of left-turning vehicles may be delayed by opposing vehicles for a few moments, but normally they and all other drivers who wish to pass through the intersection will be accommodated during the green time available to that approach. However, as the traffic volume nears capacity, fewer opportunities for left-turning maneuvers exist and both the left-turning vehicles and

> any non-turning vehicles queued behind them will suffer long delays before clearing the intersection.
>
> Drivers will sometimes become impatient and make hazardous maneuvers when they suffer long delays at an intersection. Left-turning drivers may suddenly turn in front of oncoming traffic forcing the drivers of the opposing vehicles to slow down or even brake to a stop in order to avoid an accident. If the opposing vehicle is being followed by another vehicle, a rear-end collision may result. At intersections without left-turn lanes, drivers of non-turning vehicles may become impatient and attempt a dangerous lane change or passing-on-the-right maneuver (2).

Left-turns at an intersection can be controlled by the left-turn signal phase, and by providing left-turn lanes. The next few paragraphs deal with left-turn lanes and left-turn signal phasing.

Left-Turn Lanes

A left-turn lane is an auxiliary lane for storing left-turning vehicles, thus clearing the way for through traffic (2). The presence of a left-turn lane at a signalized intersection improves intersection safety and efficiency of operation (5), and the visibility for left-turning motorists (2). The overall traffic capacity of the intersection is improved by providing a left-turn bay, which may decrease delay, fuel consumption, and probably decrease the number of accidents at the intersection (6). An exclusive left-turn lane may facilitate future installation of protected only left-turn phasing by separating left-turning traffic from through traffic. Constraints on the addition of a left-turn lane are space and the cost of installation.

Left-Turn Signal Phasing

Left-turn signal phasing is added to reduce left-turn conflicts at intersections. Glen Etelamaki notes that the "primary purpose of left-turn phasing is to minimize accidents attributable to left-turn movements" without substantially increasing overall delay at the intersection. A left-turn phase generally requires longer cycle lengths." As the number of phases increases, delay and fuel consumption at the intersection increase." The capacity of the intersection is reduced with an additional phasing because, with the "addition of left-turn phases to a signalized operation, the amount of green time available for all other phases is reduced." Increased delays result because of additional lost time associated with "starting delays, additional yellow intervals", and longer cycle lengths (7).

Permitted, Protected, and Protected/Permitted Left-Turn Phasing

Left-turn phasing can be categorized into the following three types: (i) permitted left-turn phasing; (ii) protected left-turn phasing; and, (iii)protected/permitted left-turn phasing (2). Permitted left-turn phasing exists whenever a separate left-turn phase is not provided for left-turns (2). Left-turns are made on the green ball when a driver finds an acceptable gap in the opposing traffic. Protected only left-turn phasing provides an exclusive phase for left-turns without any conflicting movements (2). This is indicated by a green arrow. Left-turns are prohibited during the rest of the cycle. Protected/permitted phasing is a combination of protected and permitted phasing. Left-turn signal phasing provides a protected phase for turning during one interval and allows turns to be made through gaps in the opposing traffic during another interval (2).

Accidents Associated with Different Types of Left-Turn Phasing

Protected left-turn phasing has the drawback of increasing delay for left-turning vehicles because motorists turning left have to wait for a green arrow (protected turn) even though there may be gaps in the opposing traffic stream. While protected-only phasing reduces the number of left-turn accidents, it may increase the number of rear-end accidents (2).

Permitted left-turn phasing does not allow an exclusive phase for turning left. Left-turning vehicles may turn in front of opposing traffic, resulting in left-turn accidents (2). Permitted phasing reduces intersection delay at the cost of increasing accidents.

Protected/permitted left-turn phasing occurs when the left-turners are first provided with a protected phase and then also allowing traffic to make left-turns through gaps in on-coming traffic during the through traffic phase. Protected/permitted phasing gives the motorists more freedom to make left-turns than protected left-turn phasing. In comparison to protected phasing, protected/permitted phasing decreases the delay but it also increases the number of left-turn accidents. Less delay results in fewer rear-end accidents. Generally, protected/permitted is safer than permitted only phasing (2).

Research Objective

The objective of this research is to quantify the relationships between intersection and traffic characteristics, and accident reduction potential of modified left-turn treatment. Characteristics included in the analysis are

- Intersection geometry,
- Traffic volumes,
- Traffic signal phasing, and
- Approach speed

Relationships between left-turn accidents and left-turn treatments are found using inferential statistics. These relationships will provide traffic engineers with a quantitative framework in which to assess the tradeoffs between accident potential and left-turn treatments.

Methodology

The research involved the following steps:

- Literature review: A detailed review of research in the field of left-turn treatments, their safety, and to determine gaps in the literature.

- Data collection: This involved collecting intersection geometry and traffic control information from city traffic engineers and the Iowa Department of Transportation. Accident reports were obtained from Iowa Department of Transportation.

- Database development: Data collected were coded into two microcomputer databases. One database contains information on intersection geometrics and traffic volumes. The other database is comprised of the accident data.

- Data analysis: The database was transferred to Iowa State University's mainframe computer for statistical analysis. The statistical analysis was performed using the computer package, Statistical Analysis System (SAS). Linear and Poisson models were developed to estimate the relationships between accident rates, traffic volumes, and left-turn treatments.

- Findings: The findings of the statistical analysis were interpreted so that the relations developed could be used for field applications.

Part of the research for this thesis was done as a research project for the Iowa Highway Research Advisory Board titled "Impacts on Safety of Left-Turn Treatments at High Speed Signalized Intersections" (8).

Thesis Organization

A detailed literature review and gaps identified in existing research are presented in Chapter 2. Intersection geometry, traffic volumes, and traffic control information data were collected by sending questionnaires to City Traffic Engineers as discussed in Chapter 3.

Linear models developed for left-turn accident rates are presented in Chapter 4. Chapter 5 involves the development of a Poisson Regression model for left-turn accidents. An example problem demonstrating the use of the models developed is solved and presented in Chapter 6. A comparison of linear and Poisson models is also made in this chapter. Conclusions and recommendations for future research are in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

The objective of the literature review is to examine past research on left-turn treatment and accident reduction, and to identify gaps in literature. A computerized literature review was conducted using the Transportation Research Information Service (TRIS) database. Articles dealing with safety/accidents, signalized intersections, left turns, and left-turn phasing were reviewed. *Transportation Research Record*s served as a valuable source of articles on left-turn treatment and accidents. Some of the articles included reports generated by both federal and state departments of transportation.

The literature review revealed that although some research on left-turn treatment has been conducted, none has produced a model predicting the accident implications of modifying left-turn treatments. No research on left-turn treatments using data from intersections in Iowa was found.

Some research have focused on before-and-after studies. Although these provide information on the impact of a specific change on accident rates, they do not offer an analysis of the trade-offs among specific treatments, intersection characteristics, traffic volumes, and accident potential. Some research has been conducted to develop warrants for left-turn phasing. There are no uniform warrants and guidelines for left-turn treatments.

Studies on Left-Turn Treatment

There have been several studies on the safety of left-turn treatments. The different types of studies on left-turn treatments can be classified into the following groups:

- Before-and-after studies,
- Comparison of intersections, and
- Warrant/Guidelines development studies

Before-and-after studies are those for which a time-series of data is collected before and after a specific change is made to the geometry or signalization of an intersection. To gain statistically significant estimates of the accident rate before and after the change requires data for up to three years before and three years after the change. Due to data requirements of before-and-after studies, a limited number of intersections are considered.

Comparison studies investigate accident rates at similar intersections with different left-turn treatments using cross-sectional data. In comparison studies, data are collected for a large number of intersections over a short period of time.

Studies on the Safety Effects of Left-Turn Lanes

In order to investigate the safety impacts of adding a left-turn lane Hammer conducted a before-and-after study of 53 urban and rural intersections . He found the installation of left-turn lanes resulted in significant reduction in accidents. The installation of a left-turn lane resulted in a 54 percent reduction in left-turn accidents and 17 percent reduction in total number of accidents at signalized intersections (9).

Foody and Richardson analyzed accident experiences over a two year period on 363 intersection approaches on rural state highways in Ohio to evaluate the safety effects of left-turn lanes . They classified approaches with respect to signalization, number of lanes, presence of left-turn lanes, and intersection types. At signalized approaches with left-turn lanes, the left-turn accident rate was found to be 39 percent lower with a total accident rate reduction of 9 percent. These differences were not statistically significant at the five percent level (10).

Five years of accident data reported for intersections in Lexington, Kentucky, were used to compare accident rates at intersections with and without left-turn lanes. The study defined left-turn related accidents as follows: "(a) a left-turning vehicle turns into the path of an oncoming vehicle, (b) a left-turning vehicle that is struck from behind while waiting to turn left, and (c) a vehicle that weaves around a vehicle stopped waiting to make a left-turn and is involved in an accident". The study determined that the left-turn accident rate is significantly lower for intersections with left-turn lanes when compared to intersections without left-turn lanes. For signalized intersections with left-turn lanes, the left-turn accident rate was 54 percent lower. The left-turn accident rate dropped further with the addition of a left-turn phase (11,12).

In their study to determine the relation of accidents to geometric features of highways, David and Norman used data from 558 intersections. They concluded that left-turn lanes primarily serve the purpose of improving capacity at an intersection. They did not find left-turn lanes serve as an accident reduction measure. In fact, they found that accidents at intersections with left-turn lanes were significantly more frequent when compared with intersections without left-turn lanes. The decrease in left-turn accidents is more than offset by the increase in accidents involving through traffic. These results conflict those of previous studies showing left-turn lanes significantly reduce accident rates (13).

McCoy and Malone studied the safety effects of "Left-Turn Lanes on Urban Four-Lane Roadways" . Their objective was to develop a definitive guide recommending when left-turn lanes should be implemented at intersections on urban roadways in Nebraska with projected daily hourly volumes (DHV's) between 600 and 1800 vehicles per hour (vph). Accident rates for approaches with left-turn lanes were compared to those without left-turn lanes. The types of accidents that were compared were: (i) right angle, (ii) rear-end, (iii) sideswipe (same direction), (iv) sideswipe (opposite direction), (v) head-on, (vi) left-turn, and (vii) right-turn. The presence of left-turn lanes was not found to be associated with a statistically significant reduction in the number of sideswipe (opposite direction), head-on, or right-turn accidents. The presence of left-turn lanes on signalized approaches, on the other hand, was associated with statistically significant reductions in rear-end, sideswipe (same direction), and left-turn accident rates (14).

Studies on Safety Effects of Medians

Squires and Parsonson conducted a study on accident comparisons of raised median and two-way left turn lane median treatments. They found that raised medians have lower accident rates for most conditions. Two-way left-turn lanes, however, had lower accident rates where a few concentrated areas of turns existed. Approaches with raised medians have accident rates which are about 40 percent lower than approaches with painted medians. This was attributed to the fact that 44 percent of approaches with raised medians have left turn lanes. The reduction in accidents may be partly explained by the presence of the left turn lane (15).

Studies on Left-Turn Phasing

Agent conducted a study of protected/permitted phasing for the state of Kentucky. In a before-and-after accident analysis, he found that protected/permitted phasing resulted in a reduction in average total accidents per year per approach compared with the previously used left-turn treatment. Left-turn accidents, however, depended upon the type of phasing present before the protected/permitted phasing was added. For a new signal installation, or when protected/permitted phasing was the first left-turn treatment (where previously there was no left-turn signal), there was little effect on left-turn accidents, and there was a reduction in the number of total accidents. There was, however, a large increase in left-turn accidents when protected/permitted phasing replaced protected-only phasing. Analysis also showed that protected/permitted phasing was more effective in reducing the accident rate for approaches without a separate left-turn lane than for approaches with a left-turn lane. For speed limits of 35 miles per hour or less, the number of left-turn and total accidents decreased slightly after the installation of protected/permitted phasing. For speed limits of 40 and 45 miles per hour, the "after" data showed an increase in accidents, especially left-turn accidents. For speed limits above 45 miles per hour, there was a dramatic increase in accidents. A comparison of approaches with and without the regulatory sign " LEFT-TURN YIELD ON (GREEN BALL)" revealed that the presence of the sign did not decrease the related accident rate. In fact, intersections without the sign actually had fewer related accidents than intersections having the regulatory sign (16).

Upchurch, Radwan, and Dean conducted a study on different types of left-turn signal phasing. Their study offered recommendations for comparing different types of left-turn phasing with respect to relative safety and operating characteristics. Safety performance and delay costs were evaluated for different types of left-turn phasing for a particular intersection. The traffic engineer is then allowed to make the judgment on the safety and delay tradeoff to select the best left-turn treatment for the intersection. The left-turn accident rate, according to the study, is the most appropriate accident rate for comparison of different left-turn phasing. Operating characteristics that could be used to compare different types of left-turn phasing were suggested as follows: (i) delay to all the vehicles approaching the intersection, (ii) delay to through and right-turning vehicles, (iii) delay to left-turning vehicles, (iv) average or maximum queue length, (v) number of stops per vehicle, (vi) vehicle operating cost, (vii) fuel consumption, and (viii) vehicle emission. The costs for each of these factors could be calculated using output from NETSIM. They suggest that an analysis of the various costs, mentioned above, be done for each type of left-turn phasing for a particular intersection. The costs and safety performance of each left-turn phasing should be evaluated and the engineer should be allowed to make a judgment on the safety and delay tradeoffs to select the best left-turn treatment (17).

Before-and-After Studies

Agent studied the effect of replacing protected left-turn phasing with protected/permitted phasing at four trial intersections. A before-and-after study was conducted for intersection delay and accidents. He concluded that protected/permitted left-turn phasing resulted in a 50 percent reduction in left-turn delay when compared with protected phasing. Left-turn accidents, however, increased with a change from protected to protected/permitted. For opposing volume of more than 1,000 vehicles per hour on a four lane street, few left-turns are made during the permitted phase. A benefit cost analysis "using the average annual cost for a three year after period" showed that all four locations had benefit-to-cost ratios greater than 1 (18).

Warren conducted an accident analysis of left-turn phasing for intersections in the metropolitan area of Washington, D.C. He evaluated two types of left-turn control changes listed below:

- Change from protected to protected/permitted.
- Introduction of protected/permitted phasing at signalized intersections that previously had no left-turn signals.

He analyzed the number of accidents before and after the change and compared them with the number of accidents at similar intersections that were not changed. The results of the study show that protected/permitted left-turn phasing affects the type of accidents. The change in the type of accidents depending upon the type of left-turn phasing before the change to protected/permitted phasing. At intersections that previously did not have a left-turn phase (permitted phasing), rear-end and total accidents decreased while left-turn accidents increased by less than one per year. At intersections that had protected phasing and were converted to protected/permitted phasing, rear-end and total accidents decreased. Left-turn accidents, however, increased by 50 percent. Warren concluded that protected/permitted left-turn phasing was a better left-turn treatment than protected phasing. He justified this by showing that the slight rise in the increase in the number of overall accidents is insignificant when compared to the savings in delay (19).

Upchurch compared left-turn accident rates for five types of left-turn phasing: (i) permitted; (ii) leading protected/permitted; (iii) lagging protected/permitted; (iv) leading protected; and (v) lagging protected. Data collected at 523 intersection approaches in Arizona were used in his analysis. Left-turn accident rates were compared to determine the relative safety of different types of left-turn phasing. He made the following observations:

- The leading protected phase has the lowest left-turn accident rates.
- When there are two opposing lanes, lagging protected/permitted has the worst accident rate.
- For permitted, leading protected/permitted, lagging protected/permitted, and leading protected with opposing lanes of traffic, the accident rate decreases as the left-turn volume increases.

A before-and-after study was also conducted. Upchurch observed that conversions resulting in decreases in left-turn accident rates were:

- From permitted to leading protected,
- From permitted to lagging protected/permitted.
- From leading protected/permitted to lagging protected/permitted.
- From leading protected/permitted to protected.

The conversions that resulted in increases in the left-turn accident rate were:

- From permitted to leading protected/permitted.
- From leading protected to leading protected/permitted.
- From leading protected/permitted to permitted (20).

Warrants/Guidelines for Left-Turn Treatment

Members of the Colorado/ Wyoming Section of the Institute of Transportation Engineers (ITE) conducted a questionnaire-type survey to determine the techniques used to decide when a left-turn phase should be installed at a signalized intersection. One thousand two hundred questionnaires were mailed to ITE members. Of approximately 300 responses that were returned, 164 indicated that a warrant for left-turn phasing had been adopted. The specific warrants used by each of the 164 respondents were classified into 30 different categories. Most warrants were based on delay, accident experience, and turning volumes. This study demonstrated the need for a national standard for left-turn phasing (21) .

Upchurch and Matthias studied the signal warrants for the state of Arizona. The research was conducted because there was no uniform method for application of left-turn phasing in Arizona. A warrant was developed to choose the appropriate type of left-turn signal phasing. Six arterial signalized intersections in the Phoenix metropolitan area were observed. Traffic volume and delay were determined using time-lapse photography. The effect of the type of left-turn signal phasing on left-turn delay and through delay was analyzed. For intersections with two opposing lanes protected phasing has higher left-turn delays than permitted phasing. They also found that through delay is small for permitted phasing when compared with protected/permitted and protected phasing. Protected/permitted phasing was found to decrease the delay for through vehicles by about four to eight seconds as compared with protected phasing. A warrant was developed on the basis of left-turn volume (hourly) during the peak hour, cycle length, opposing volume during the peak hour, number of opposing lanes, speed of opposing traffic, available sight distance, and accident history. This warrant applies only to intersections with separate left-turn lanes (22).

Agent recommends that protected/permitted phasing should not be used if any of the following conditions exist:

- Speed limit is over 45 miles per hour.
- Protected-only phasing is currently in operation and speed limit is over 35 miles per hour.
- Left-turn movement must cross three or more opposing through lanes.
- Intersection geometrics force the left-turn lane to have a separate signal head.
- Dual left-turn lanes exist on the approach.
- A left-turn accident problem exists at the intersection.

He recommends that when protected/permitted phasing is used, the signal head for left-turn traffic should be located above the line separating the left-turn lane from the adjacent through lane so that left-turning traffic does not have a separate signal head. No regulatory sign was found to be necessary (23).

A similar set of guidelines is found in a Florida study. Some of the guidelines are:

- Protected/permitted phasing should be used whenever a left-turn phase is required unless there is a strong reason for using another type of left-turn phasing.
- Protected left-turn phasing should be used for an approach if any one of the following conditions exist:
    - Double left-turn lanes
    - Geometric restrictions
    - Sight distance restrictions
    - Approach is lead portion of lead/lag phasing sequence (24).

High Speed Signalized Intersections

Washington et al. identified characteristics at some California high-speed signalized intersections that relate to accident rates. Effects of advance warning, signal timing and phasing, channelization, signal equipment configurations, shoulder widths and types, median widths and types, and approach speeds were studied. Data was collected at high-speed isolated signalized intersections in California were coded into a database. Two variables in the database which deal with left-turn movements on an approach were the presence or absence of a left turn phase and the presence or absence of left-turn lane. The presence of a separate left-turn phase appeared to reduce accidents at high speed isolated intersections. Vehicles on an approach without a separate left-turn phase were more likely be involved in left-turn accidents with opposing traffic. The existence of both left turn lane and left-turn phase resulted in a 70 percent decrease in the approach accident rate as compared to approaches without them. Rear-end accidents, directly associated with the existence of a left-turn lane were 37 percent lower. Left-turn accidents, related to the existence of a left-turn phase, were observed to be 85 percent less frequent. The study recommends that if a left turn lane is added to an intersection, a separate left-turn phase should also be added. Washington et al. concluded that the presence of an advance warning sign with a flashing beacon, presence of a separate left-turn phase, presence of a raised median, and wide paved shoulders result in lower accident rates (25).

Agent conducted research on traffic control and accidents at rural high speed intersections. Three objectives of the study were to determine: (i) the type of traffic control at rural high speed intersections, (ii) types of accidents occurring there, and (iii) the factors that contribute to the accidents. A fourth objective was to recommend traffic control measures that would decrease accident potential at these intersections. Sixty five intersections were included in this study. Forty-six of these were signalized. Others were stop sign controlled. Accident analysis was done to compare the three types of right-of-way control: (i) a stop sign with no intersection beacon, (ii) a stop sign with intersection beacon, and (iii) a traffic signal. The combined accident rates at intersections with either a traffic signal or a stop sign (with or without an intersection beacon) were very similar. Intersections with traffic signals and a high accident rate also have a large number of opposing left-turn accidents. The percentage of angle accidents was much lower at signalized intersections when compared with stop sign controlled intersections. The study concluded that providing drivers with adequate warning of the intersection is of primary importance. At signalized intersections, providing a proper change interval and maximizing the visibility of signal heads are essential. A separate left-turn phasing is also recommended (26, 27).

Conclusions of Literature Review

The review of literature demonstrates diversity in guidelines being used for left-turn treatments. The criteria used most frequently for the choice of a left-turn phase are delay, traffic volume, and accident experience. Other factors, such as, intersection geometry, whether the intersection is part of a signal system, type of control, approach grades are not usually considered. There are no quantitative models for estimating the safety of left-turn treatments based on conditions existing at the intersection.

The gaps in the literature can be summarized as:

- There is no empirical model for estimating left-turn accidents based on left-turn treatment and characteristics specific to an intersection.
- No left-turn study using data from Iowa has been found.

CHAPTER 3

DATA COLLECTION AND ANALYSIS

Data Collection

Intersection Data

Four types of data were collected for this research. These data include, (i) intersection geometry, (ii) traffic volumes, (iii) signal phasing, and (iv) accident data. Intersection geometry, traffic volume, and signal phasing data were collected by sending questionnaires to municipalities across Iowa. A sample questionnaire is included in Appendix A. One hundred and fifty questionnaires were sent to Iowa municipalities. Data for 109 intersections were obtained. Geometric and signal data were obtained for all intersections. Traffic volumes, however, were available for only 63 intersections.

Accident Data

Accident data for five years (1987 -1991) were obtained for each intersection from the Accident Location and Analysis System (ALAS) database. ALAS is an accident database maintained by the Iowa Department of Transportation. It is comprised of accident reports submitted by law enforcement officers that are coded into the database.

The ALAS database contains the following information for each accident:

- Direction of travel of each vehicle involved in the accident.
- Vehicle action/maneuver.
- Age and gender of the drivers involved.
- Accident severity.

- Time of day that the accident occurred.
- Day of the week.
- Roadway conditions.
- Driver condition: inebriated or sober.
- Possible cause of the accident, for example: failure to yield right-of-way while making a left-turn.

Database Development

Questionnaire data were coded by intersection into a microcomputer LOTUS 1-2-3 spreadsheet. They included intersection geometrics, signal characteristics, and traffic counts. All data were converted to a standard form before coding. For example, some turning movement counts were reported as evening peak hour and some were reported as 24-hour volumes. The peak hour turning movement counts were converted to annual average daily traffic (AADT) using procedures defined in the Iowa Department of Transportation's "Automatic Traffic Recorders: 1982-1991." A sample of calculations to convert peak hour volumes to AADT is shown in Appendix B.

Summary of accident data for five years was coded into a second database. Left-turn accidents were identified from individual accident reports and entered in the database. Left-turn accident, for the purpose of this research, is defined as any accident involving a left-turning vehicle.

Data Analysis

Left-turn treatment is specific to an approach and not to an intersection. For example, the northbound approach of an intersection may have a left-turn lane and have protected left-turn phasing, and the eastbound approach may have permitted phasing without a left-turn lane. Therefore, analysis was performed by approach.

The characteristics included in the analysis are: (i) presence or absence of median, (ii) left-turn lane, (iii) number of lanes, (iv) lane width, (v) left-turn lane width, (vi) approach volume, (vii) left-turn volume, (viii) right-turn volume, (ix) through volume, (x) number of accidents in five years, (xi) number of left-turn accidents in five years, (xii) whether the signalized intersection was part of a signal system or an isolated signal, (xiii) speed limit, and (xiv) alignment of opposing left-turn lanes. All relevant data were available for 63 intersections resulting in 248 approaches.

Two kinds of accident rates were developed for the analysis: the left-turn accident rate and the approach accident rate. The left-turn accident rate is defined as the number of left-turn accidents on the approach per million left-turning vehicles on the approach. The left-turn accident rate measures the safety of left-turns. Approach accident rate is the number of accidents per year on an approach per million entering vehicles. A model is determined for approach accident rate to find the effect of left-turn treatment on other kinds of accidents as well.

Statistical Modeling

The database developed in LOTUS 1-2-3 was converted to ASCII format and downloaded to the mainframe computer for analysis on the Statistical Analysis System (SAS). The following independent variables were considered for the regression model:

- MEDIAN: Whether a raised or painted median is present. If a median is present, the value of the variable was 1, and 0 if not.

- SYSTEM: Whether the intersection is part of a signal system or not. If the intersection was a part of a system, the value of the variable is 1, and 0 if not.

- LANES: The number of lanes on an approach excluding the left-turn lane. The values ranged from 1 to 3.

- LLANES: The number of left-turn lanes. It is either 0 or 1. Dual left-turn lanes were not studied in this research project.

- WIDTH: The average width of through lanes. Values range from 9 to 15 feet.

- LWIDTH: The average width of left-turn lane. Values range from 9.5 to 12.5 feet.

- ALIGN: The alignment of opposing left-turn lanes. If opposing left-turn lanes are aligned the value is 1, and 0 if not. A value of 2 is assigned where a left-turn lane is not present.

- SPEED: The speed limit on the approach. Values range from 35 to 55 miles per hour.

- PERMIT: This variable indicates the presence of permitted phasing. The value of this variable is 1 for permitted phasing and protected/permitted phasing. It is 0 for protected phasing.

- PROTECT: This variable indicates the presence of protected phasing. The value of this variable is 1 for protected phasing and protected/permitted phasing, and 0 for permitted phasing.

- LVOL: The annual average daily approach left-turn volume. Values range from 0 to 11,000.

- TVOL: The annual average daily through volume on the approach. Values range from 0 to 13,265.

- RVOL: The annual average daily right turning volume on the approach. Values range from 0 to 8,820.

- TOTVOL: The annual average daily approach volume. This is the sum of left-turning, through and right-turning volumes. Values range from 369 to 18,061.

- ACC: Number of accidents on an approach in five years.
- LACC: Number of left-turn accidents on an approach in five years.

The independent variables are:

- LACCRATE: The left-turn accident rate. This is the number of left-turn accidents per million left-turning vehicles on the approach.
- ACCRATE: The approach accident rate. This is the number of accidents on an approach per million vehicles on the approach.

Various graphs were plotted to inspect the nature of relationship between the dependent and independent variables. This process was also used to determine outlying data points. Outlying data points, also known as outliers, are extreme data that are far removed from the rest of the data. The outlying data points were removed from the data set because they may distort the results. The outliers removed had high left-turn accident rates (greater than 10 left-turn accidents per million left-turning vehicles). Also approaches with speed limits less than 35 miles per hour were removed because this research focuses on high speed approaches.

A Pearson's Correlation analysis was performed to determine which variables are correlated. Correlated variables could lead to multicollinearity. Multicollinearity violates the basic assumption of regression that regression coefficients measure marginal effects of independent variables (28). Also, the standard deviation of the parameter estimates of the correlated variables is very high. Therefore, correlated variables were removed. TVOL and RVOL were removed from the regression model because they are correlated with TOTVOL.

Regression was performed to fit linear and non-linear models, including a logit function. None of the attempted non-linear functions provided better results than a linear model. Therefore, a linear model was applied. Models that assume accidents as Poisson processes were also developed. These are models are discussed in detail in Chapter 6.

The number of independent variables were reduced because large models are difficult to understand and interpret (28). Independent variables for the model were reduced by using engineering judgment and using automatic selection procedures on SAS. After selection of the variables using forward, backward, and stepwise selection procedures, one linear model was obtained for all left-turn volumes. Left-turn volumes ranged from 0 to 11,000. The R^2 obtained from the model is very low: between 0.1 and 0.15. Due to the large variation in left-turn volumes, the data were divided into five groups of approximately similar sizes based on left-turn volumes. The groups are:

- Left-turn volumes of 0 to 500, which includes 38 data cases
- Left-turn volumes of 500 to 1,000, which includes 33 data cases
- Left-turn volumes of 1,000 to 1,500, which includes 29 data cases
- Left-turn volumes of 1,500 to 2,000, which includes 24 data cases
- Left-turn volumes over 2,000, which includes 33 data cases

The forward, backward and stepwise selection procedures were repeated to obtain models for both the dependent variables in each group of left-turning volumes. The findings are discussed in the next chapter.

CHAPTER 4

LINEAR REGRESSION MODELS

Linear Regression models for accident rates are discussed in this chapter. Dependent variables for the linear regression models are the left-turn and approach accident rates. The left-turn accident rate represents the number of left-turn accidents on approach per million left-turning vehicles. Approach accident rate is defined as the number of accidents on an approach per million vehicles on the approach.

Initially, one model was estimated for all volumes. This single model has a very low R^2. Therefore, the data set is divided into five groups based on left-turning volumes as explained in the previous chapter.

In each group of left-turn volumes, a model for left-turn accident rate and another model for approach accident rate were estimated. The "best" results, in terms of R^2 and statistically significant parameter estimates, were obtained for the group that has left-turn volumes between 500 and 1,000 per day. Models estimated in other volume ranges resulted in parameter estimates that were not statistically significant and have very low R^2 values. These models are presented only for purposes of illustration. The researcher only has confidence in the results of the models for the 500 to 1,000 vehicles per day range. For comparison purposes, the same independent variables were used for all groups.

The left-turn accident rate and approach accident rate models for the group with daily left-turn volumes between 500 and 1,000 are explained first. This is followed by models for the group with daily left-turn volumes of 1,500 to 2,000. The models for this group are similar to the models in the 500 to 1,000 group. The models for the other groups are presented for illustration only, and can be found near the end of this chapter.

Linear Regression Models for Daily Left-Turn Approach Volumes 500 and 1,000

Left-Turn Accident Rate Model

A linear regression model is developed for the left-turn accident rate for daily left-turn approach volumes between 500 and 1,000. The dependent variable is the left-turn accident rate which is the number of left-turn accidents per million left-turning vehicles on the approach. The model is:

$$\text{LACCRATE} = 3.78 - \underset{(0.043)}{2.24}\ \text{SYSTEM} - \underset{(0.012)}{6.48}\ \text{LLANES} + \underset{(0.021)}{0.50}\ \text{LWIDTH} + \underset{(0.133)}{1.74}\ \text{PERMIT} - \underset{(0.064)}{2.29}\ \text{PROTECT} + \underset{(0.006)}{0.00047}\ \text{TOTVOL} \qquad \text{(Model 1)}$$

Number shown in parenthesis is the level of significance of the parameter estimate.

Thirty-two data cases were used to estimate Model 1. The parameter estimates for SYSTEM, LLANES, LWIDTH, PROTECT, and TOTVOL are significant at the 10 percent level. The parameter estimate for PERMIT, however, is only significant at the 15 percent level. MEDIAN was not significant for use in this model. The R^2 for this model is 0.442.

This model shows that permitted phasing results in the highest left-turn accident rate as compared to protected and protected/permitted phasing. Protected phasing has a significantly lower left-turn accident rate as compared with protected/permitted and protected phasing. Figure 1 shows the effect of the three different types of left-turn phasing on left-turn accident rate. This figure is a graph of left-turn accident rate versus total approach volume. Figure 1 is constructed for a two lane approach with a 12 foot left-turn lane and the approach leads to an isolated intersection.

The effect of a left-turn lane and whether a signal is a part of a signal system can also be shown using this model. Figure 2 shows the effect of a left-turn lane in reducing the left-turn accident rate for a two lane approach with and without a left-turn lane. Presence of a left-turn lane will reduce the number of left-turn accidents because protected and protected/permitted phasing are not normally used unless a left-turn lane is present. A left-turn lane separates left-turning vehicles from through vehicles and, therefore, reduces the left-turn accident rate.

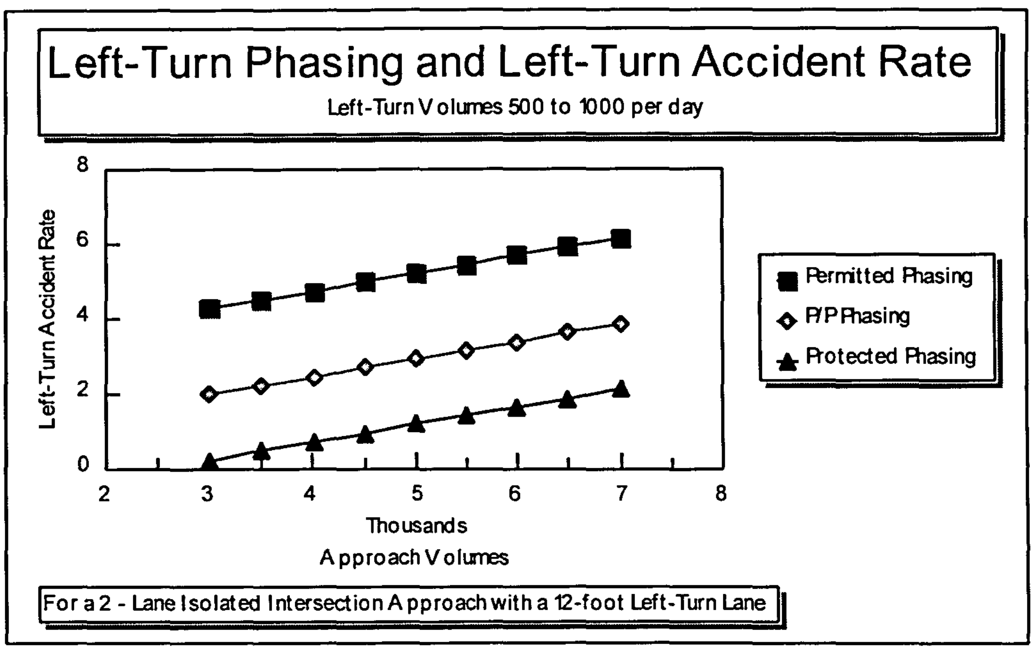


Figure 1: Effect of left-turn phasing on left-turn turn accident rate

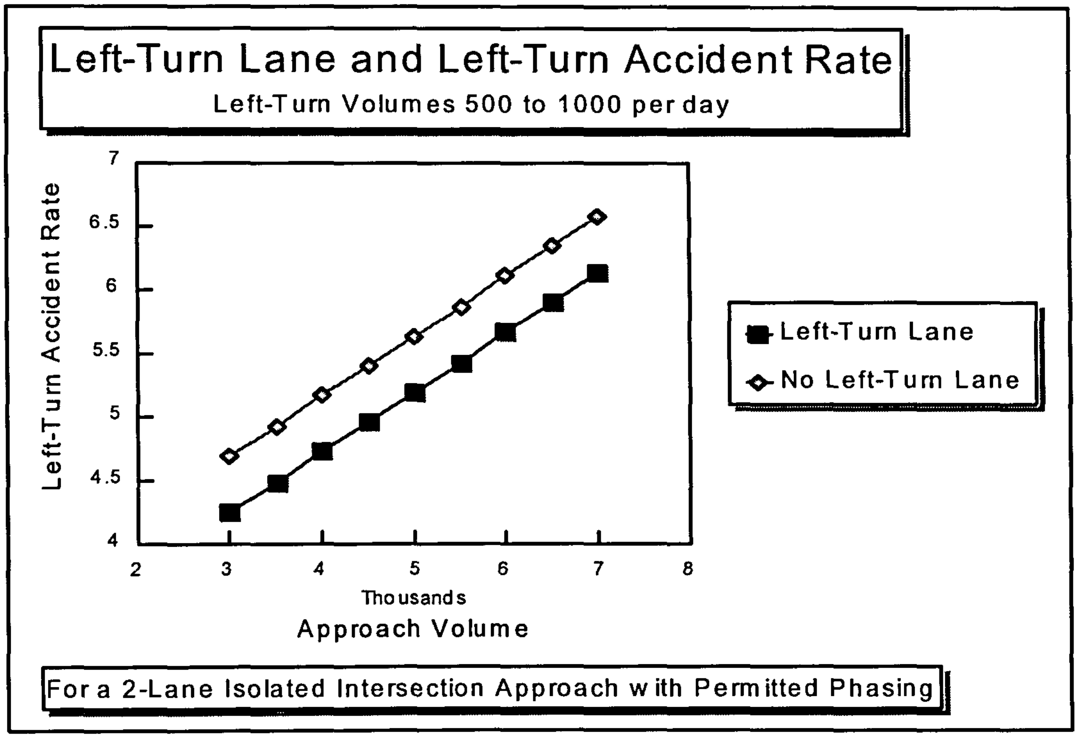


Figure 2: Effect of left-turn lane on left-turn accident rate

Figure 3 shows the effect of a signalized intersection being in a signal system. This graph is constructed for a two lane approach with a 12 foot left-turn lane and permitted phasing. Signalized intersections that are part of a signal system exhibit significantly lower left-turn accident rates than intersections that are not part of a system. This may be due to the fact that a coordinated signal system can create a platooning effect reducing the randomness of vehicle arrivals, thereby promoting an efficient flow in the corridor.

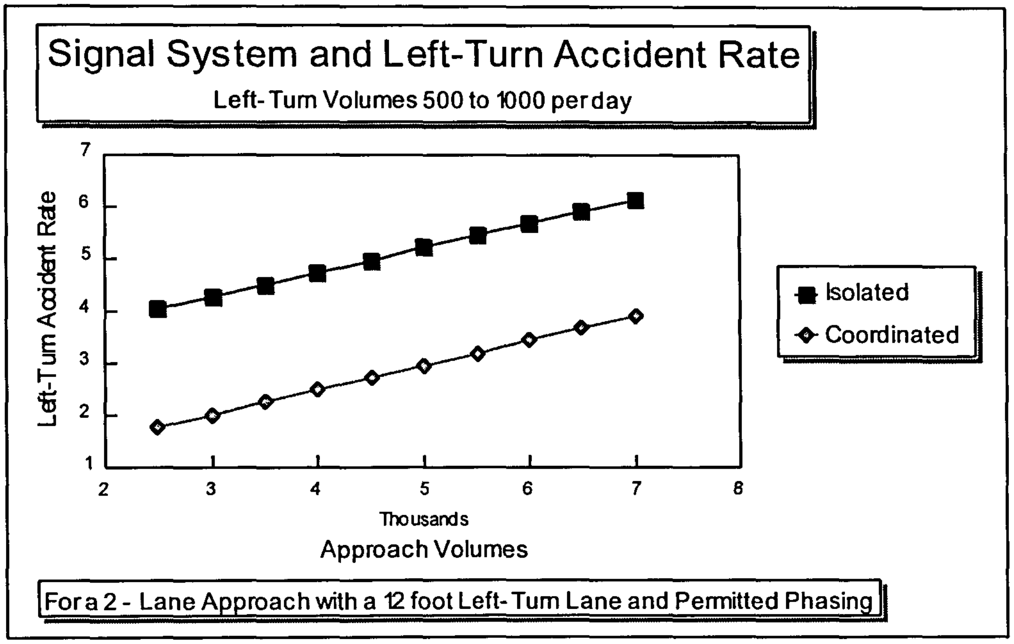


Figure 3: Effect of being in a system on left-turn accident rate

Approach Accident Rate Model

A linear regression model was developed for approach accident rate for daily left-turn volumes between 500 and 1,000. The dependent variable is approach accident rate which is the number of accidents on the approach per million vehicles. The model is:

ACCRATE = 1.14 + 0.90 MEDIAN - 0.17 LANES - 3.09 LLANES + 0.26 LWIDTH
(0.0017) (0.3868) (0.0001) (0.0001)
+ 0.11 PERMIT - 0.28 PROTECT - 0.000085 TOTVOL
(0.6816) (0.2949) (0.0117)
(Model 2)

The parameter estimates for MEDIAN, LLANES, LWIDTH, and TOTVOL are significant at the 10 percent level. The parameter estimates for PERMIT and PROTECT, however, are not significant at the 10 percent level. They have been included in the model to determine the effects of left-turn phasing on approach accident rate. However, because of the low level of statistical confidence in some of the parameter estimates, little confidence is held for the overall model. The R^2 for this model is 0.678.

In the model, there are two variables representing the left-turn lane. One is the number of left-turn lanes on an approach, LLANES, and the other is , the width of the left-turn lane, LWIDTH. The width of the left-turn lane was included in the analysis because there is variability in the width of the left-turn lane when it was present. The left-turn lane width ranged from 9.5 feet to 12.5 feet. When either of the variables, LLANES and LWIDTH, is removed due to their correlation, the models are not significant and the parameter estimates could not be interpreted. Best results were obtained by including both variables in the model.

Model 2 shows that permitted phasing results in the highest accident rate as compared with protected and protected/permitted phasing. Thus, protected left-turn phasing helps reduce left-turn accidents rate as well as the overall accident rate on an approach. These results are similar to those for left-turn accident rate. Figure 4 shows the effect of left-turn phasing on the approach accident rate. It contains a graph of approach accident rate with approach volume. The graph is constructed for a two lane approach with a 12 foot left-turn lane, and a median. It can be seen that the approach accident rate decreases at a modest rate with increasing approach volumes. The decrease in accident rate with increased approach volumes seems counter intuitive. The modest decrease may be due to a correlation between higher approach volumes and the use of improved left-turn treatments. For example, permitted left-turn phasing is more likely to be used on lower volume approaches while protected phasing is more likely to be used on high volume approaches.

As with the left-turn accident rate, a left-turn lane significantly lowers the approach accident rate. Figure 5 shows the effect of a left-turn lane on the approach accident rate. The model shows that a left-turn lane decreases accident rate. However, the width of the left-turn lane also needs to be considered. Figure 5 is constructed for a two lane approach with a median and having permitted phasing.

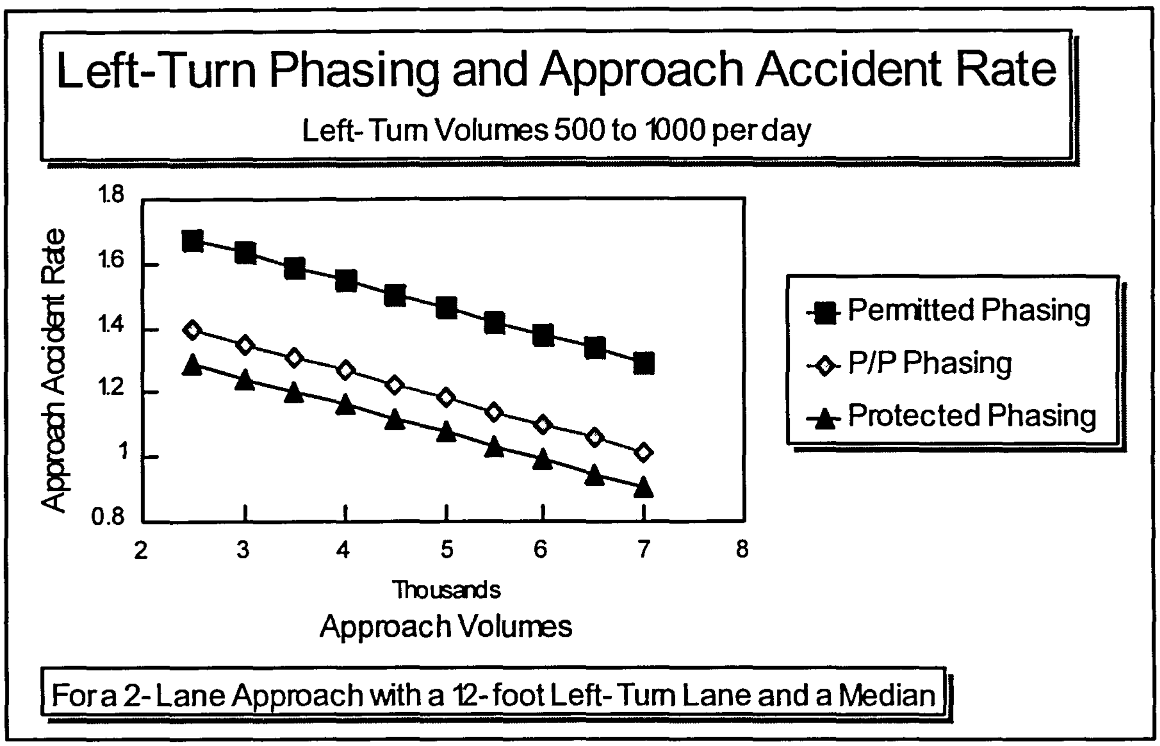


Figure 4: Effect of left-turn phasing on approach accident rate

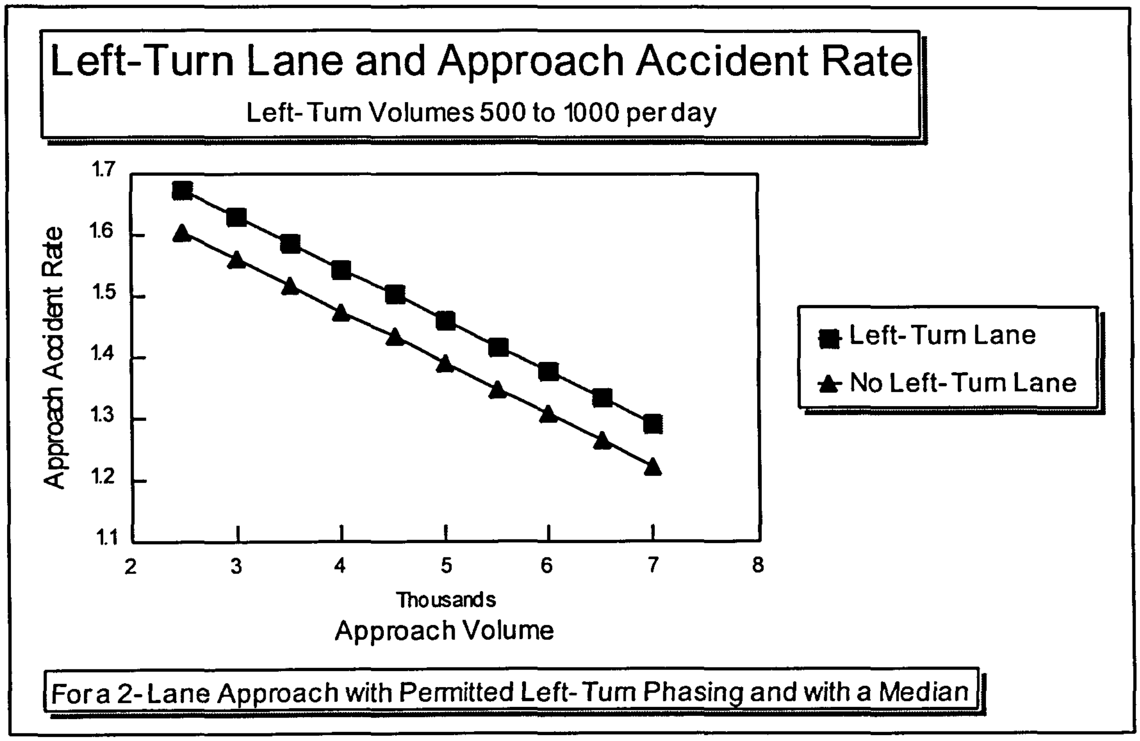


Figure 5: Effect of left-turn lane on approach accident rate

Figure 6 shows the effect of the number of through lanes on approach accident rates. The approach accident rate is lower for approaches with two through lanes compared to approaches with one through lane. This figure is constructed for a two lane approach with no left-turn lane, permitted phasing and no median.

Figure 7 shows the effect of a median on the approach accident rate. It can be seen that the presence of a median increases the approach accident rate. This may be due the limitations of statistical modeling.

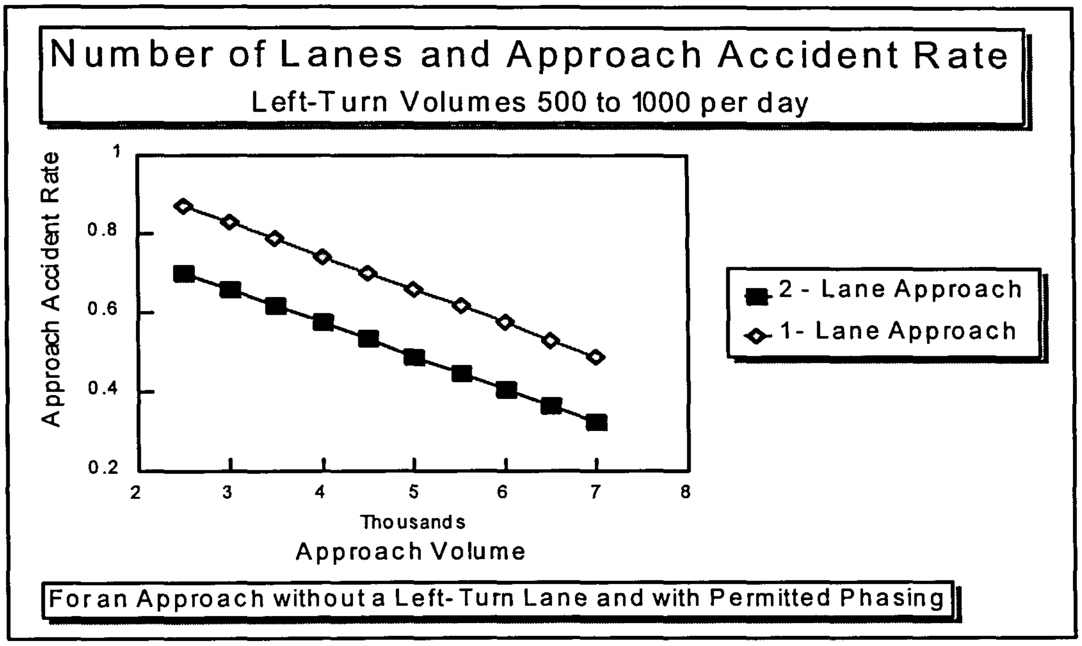


Figure 6: Effect of number of lanes on approach accident rate

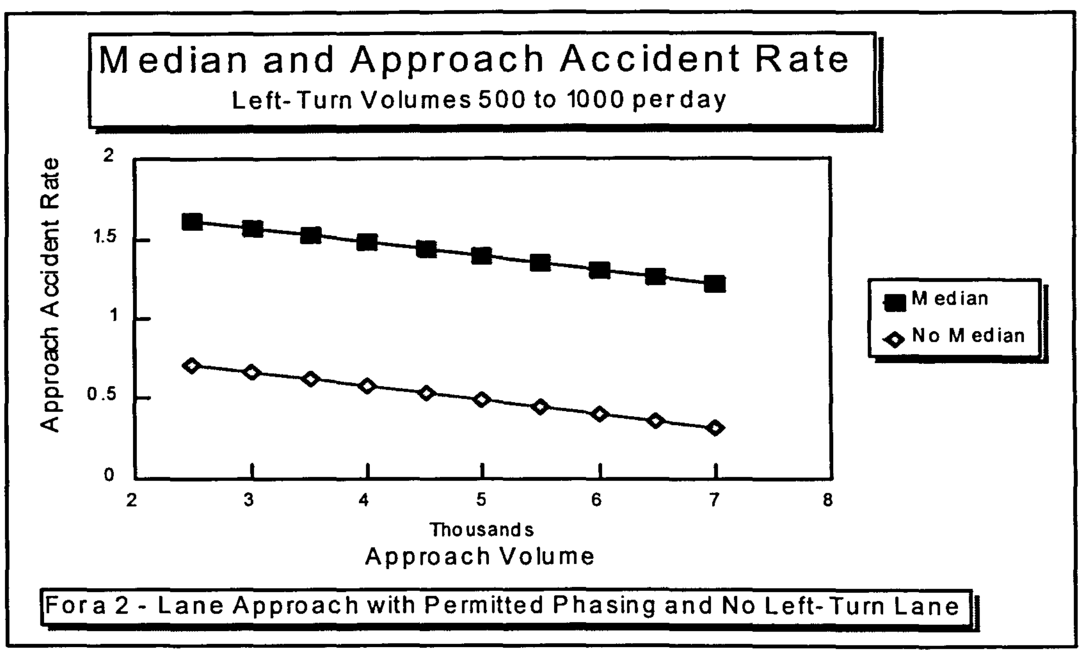


Figure 7: Effect of median on approach accident rate

Linear Regression Models for Daily Left-Turn Approach Volumes 1,500 and 2,000

Left-Turn Accident Rate Model

A linear regression model was developed for the left-turn accident rate for daily left-turn approach volumes between 1,500 and 2,000. The data set included 28 data cases. The dependent variable is the left-turn accident rate, which is the number of left-turn accidents per million left-turning vehicles on an approach. The model is:

$$\begin{aligned} LACCRATE = 2.37 &+ 0.98\ SYSTEM - 12.55\ LLANES + 0.85\ LWIDTH \\ &\quad (0.2410) \qquad\quad (0.1472) \qquad\quad (0.2344) \\ &+ 0.158\ PERMIT - 0.48\ PROTECT + 0.00017\ TOTVOL \\ &\quad (0.8538) \qquad\quad (0.6963) \qquad\quad (0.1018) \end{aligned} \qquad \text{(Model 3)}$$

None of the parameter estimates established for the variables are significant at the 10 percent level. The parameter estimates, with the exception of the parameter for the signal systems, are, on the other hand, consistent with Model 1. The R^2 for Model 3 is 0.365. Because of the low statistical confidence in the parameter estimates, little confidence is held for the overall model. *The model results are nonetheless, indicative of overall trends.*

Figure 8 contains a graph of left-turn accident rate and total approach volume. Permitted phasing has the highest left-turn accident rate and protected phasing the lowest left-turn accident rate among the three kinds of left-turn phasing. These results are similar to those found for left-turn volumes between 500 and 1,000. The graph is constructed for a two lane approach with a 12 foot left-turn lane, and the approach leads to an intersection that is part of a signal system.

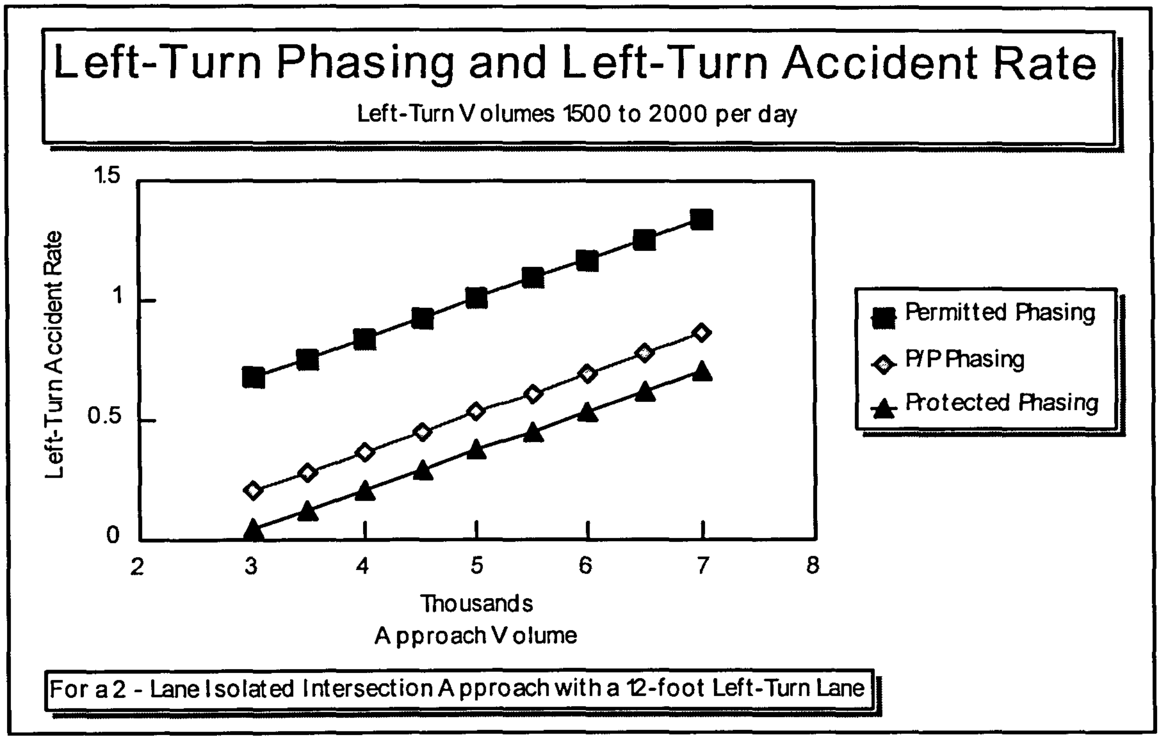


Figure 8: Effect of left-turn phasing on left-turn accident rate

The effect of the presence of a left-turn lane and being part of a signal system were examined. Figure 9 illustrates the effect of a left-turn lane on the left-turn accident rate. Figure 9 is constructed for an approach with two lanes, protected/permitted phasing, and the approach leads to an intersection that is part of a signal system. The figure shows that approaches with left-turn lanes have lesser left-turn accident rates. This result is consistent with Model 1.

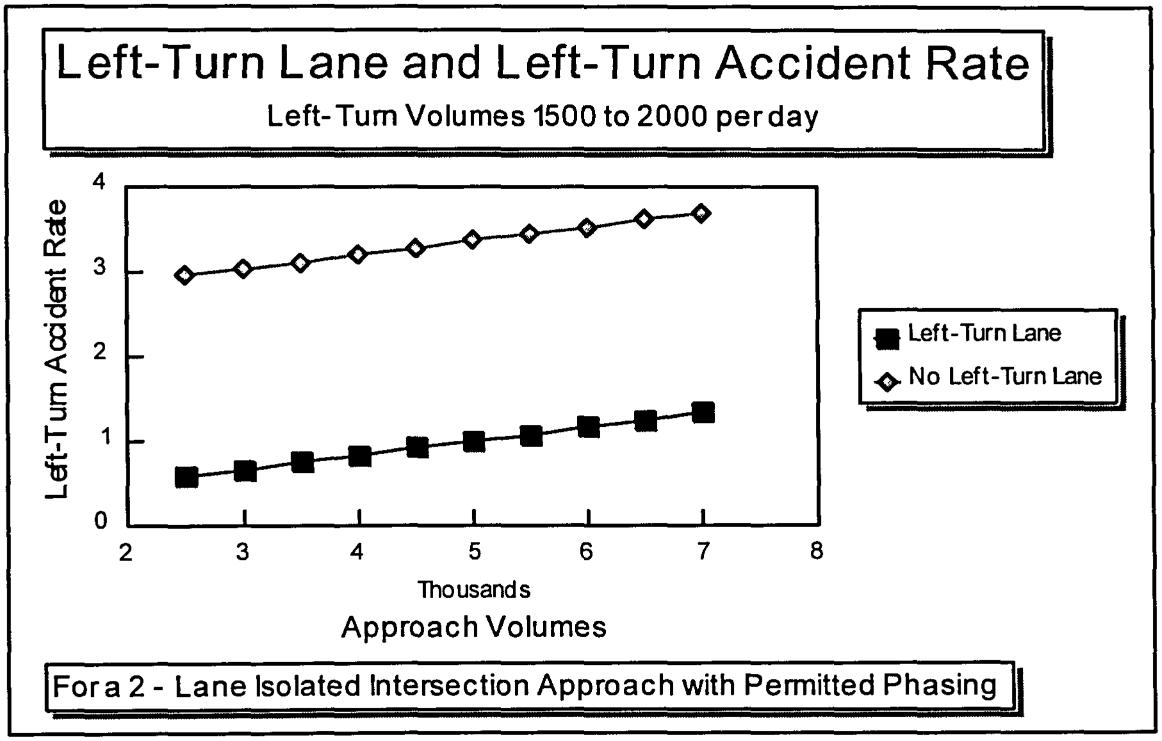


Figure 9: Effect of left-turn lane on left-turn accident rate

The effect on accident rate for signals in a system was also investigated. In this model, the left-turn accident rates are higher for approaches that are in a system as compared with those not in a system (See Figure 10). This is not consistent with the results for the same variable in Model 1. One of the reasons for this could be that the parameter estimate is not significant at the 10 percent level in this model, but it is significant in Model 1.

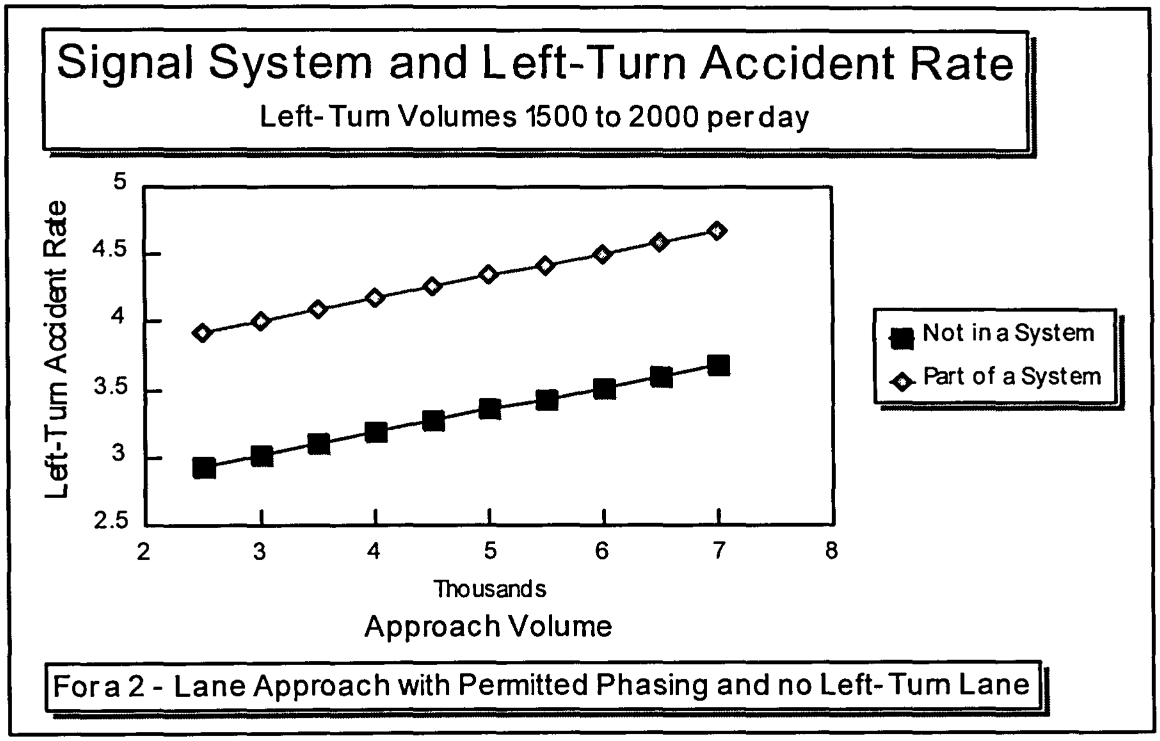


Figure 10: Effect of being in a coordinated signal system on left-turn accident rate

Approach Accident Rate Model

A linear model was developed for approach accident rate for daily left-turn volumes between 1,500 and 2,000. The dependent variable is approach accident rate which is the number of accidents on the approach per million vehicles on the approach. The model is:

$$\begin{aligned} ACCRATE = \ & 2.22 + \underset{(0.6047)}{0.23}\ MEDIAN + \underset{(0.9222)}{0.03}\ LANES - \underset{(0.6111)}{2.23}\ LLANES + \underset{(0.9211)}{0.04} LWIDTH \\ & - \underset{(0.4863)}{0.024}\ PERMIT - \underset{(0.5066)}{0.31}\ PROTECT + \underset{(0.3958)}{0.000044}\ TOTVOL \end{aligned}$$

(Model 4)

None of the parameter estimates for Model 4 are statistically significant at the 10 percent level. The R^2 for this model is 0.402. Some of the parameter estimates in this model are not consistent with the parameter estimates in Model 2. The parameter estimates for LANES, PERMIT and TOTVOL are of opposite sign when compared with Model 2. This may be explained by the fact that these parameter estimates are significant in Model 2.

Other Linear Regression Models

All of the other regression models estimated for the remaining traffic volumes are shown in Table 1. The remaining regressions provided models with parameter estimates lacking statistical significance.

Table 1: Other Linear Regression Models

<u>Volume Interval 0 to 500</u>

ACCRATE = 1.62 - 0.19 MEDIAN - 0.25 LANES + 0.33 LLANES - 0.03 LWIDTH - 0.45 PERMIT + 0.25 PROTECT - 0.000029 TOTVOL
R^2 = 0.263
(Model 5)

LACCRATE = 1.54 - 0.25 SYSTEM + 2.46 LLANES - 0.27 LWIDTH + 0.86 PERMIT + 3.54 PROTECT + 0.000027 TOTVOL
R^2 = 0.234
(Model 6)

<u>Volume Interval 1,000 to 1,500</u>

ACCRATE = 0.49 + 0.58 MEDIAN + 0.11 LANES - 0.24 LLANES - 0.04 LWIDTH + 0.13 PERMIT + 0.60 PROTECT - 0.000043 TOTVOL
R^2 = 0.244
(Model 7)

LACCRATE = 1.50 + 1.43 SYSTEM - 0.64 LLANES + 0.01 LWIDTH + 0.55 PERMIT + 0.97 PROTECT - 0.000037 TOTVOL
R^2 = 0.137
(Model 8)

<u>Volume Interval 2,000 or greater</u>

ACCRATE = 0.99 + 0.15 MEDIAN + 0.27 LANES - 0.37 LLANES - 0.01 LWIDTH + 0.22 PERMIT - 0.08 PROTECT - 0.000034 TOTVOL
R^2 = 0.39
(Model 9)

LACCRATE = 0.98 - 0.003 SYSTEM + 0.06 LLANES - 0.05 LWIDTH + 0.40PERMIT + 1.80 PROTECT - 0.000095 TOTVOL
R^2 = 0.15
(Model 10)

CHAPTER 5

POISSON REGRESSION

In Chapter 4, linear models for accident rates are presented. Since the best linear model could not account for majority of the variability in left-turn accident rates, an alternative approach, a Poisson regression, is developed. A Poisson regression is a regression in which the dependent variable is a Poisson process. Accidents, in general, can be described as Poisson processes. In this chapter, a Poisson process is explained and Poisson regression models are developed. A comparison of linear and Poisson models can be found in the next chapter.

Poisson Process

An experiment of chance that continues in time and is observed is called a process (29). A Poisson process is used to describe events such as arrival of customers at a service counter, failure of a piece of equipment, or arrivals of vehicles at intersections (29).

Let $N(t, t+h)$ denote the number of events occurring between times t and $t+h$ and $P[N(t, t+h)]$ the probability of occurrence of events in that interval. Taylor and Karlin postulate:

1. The numbers of events occurring in disjoint intervals are independent variables; that is for $t_1<t_2<...<t_m$,

$$P[N(t_1,t_2)=k_1, N(t_2,t_3)=k_2, ..., N(t_{m-1},t_m)=k_{m-1}] = P[N(t_1,t_2)=k_1]P[N(t_2,t_3)=k_2]... P[N(t_{m-1},t_m)=k_{m-1}]$$

2. Probability structure is time invariant; that is, Probability distribution of $N(t, t+h)$ depends on h but not on t.

3. The probability of at least one event happening in time interval of length h is

$$P\,[N(t, t+h) \geq 1] = \lambda h + o(h) \qquad \text{as } h \to 0 \text{ and } \lambda > 0$$

and $o(h)$ stands for any function of h such that

$$\lim_{h \to 0} \frac{o(h)}{h} = 0$$

4. The probability of two or more events occurring in an interval of length h is

$$P\,[N(t, t+h) \geq 2] = o(h) \qquad \text{as } h \to 0 \quad (30)$$

Postulate 3 is called the Law of Rare Events.

Poisson Random Variable

Define random variable X as

$X = N(0, t)$ = number of events in an interval of width t.

Then the probability function for this random variable such that the probability of X being equal to n in time interval t is

$$P\,[X = n] = \frac{(\lambda t)^n \exp(-\lambda t)}{n!}$$

by the Law of Rare Events. The mean of X is λt and variance is λt (30).

Accidents as Poisson Processes

Accidents may also be defined as Poisson processes since an accident is a discrete event and each accidents is independent of those that have occurred in an independent interval. Probability of occurrence of an accident in a small interval of time is very small.

Define Y_i as the number of accidents in t for approach i. The probability of Y_i being equal to k is

$$P[Y_i = k] = \frac{(\lambda t)^k \exp(-\lambda t)}{k!} \qquad \text{for } k = 0, 1, 2, \ldots$$

where

Y_i = Number of accidents in t years

λ_i = Average yearly number of accidents for approach i.

Poisson Regression

A regression with the dependent variable as a Poisson Random Variable may be defined as Poisson Regression. In this case, the dependent variable is the number of accidents, Y_i. The independent variables are the same as those used for the linear model. The model may be formulated as:

$$\lambda_i = \exp[\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_p X_{pi}]$$

λ_i = Average yearly number of accidents for approach i

$\boldsymbol{X}_i = (1, X_{1i}, X_{2i}, \ldots, X_{pi})'$, a (p+1)×1 vector of independent variables.

$\boldsymbol{X}_i'$ = Transpose of the $\boldsymbol{X}_i$ vector

β_j = Regression coefficients for variable X_{ji}

β = Vector of β_j's

i = 1,..., n

n = number of approaches

j = 0,..., p

p = number of independent variables

$$E[Y_i] = \lambda t = \exp(\boldsymbol{X}_i'\beta)t$$

$$V[Y_i] = \lambda t = \exp(\boldsymbol{X}_i'\beta)t$$

Maximum Likelihood Method

The likelihood function of β is defined to be the joint probability distribution for $Y_1, ..., Y_n$ (28). For n independent observations $Y_1, ..., Y_n$ the likelihood function is

$$\text{Likelihood} = P[Y_1 = y_1, ..., Y_n = y_n] = \prod_{i=1}^{n} \left[\frac{(\lambda_i t)^{y_i} \exp(-\lambda_i t)}{y_i!} \right]$$

where $\prod$ stands for product of independent probabilities (28). The objective is to develop a model such that the likelihood of each observation Y_i being equal to y_i is maximized. The ideal would be a likelihood of 1. It is often simpler to maximize the logarithm of the likelihood function or log-likelihood function:

$$\begin{aligned}\text{LogLike} = L(\beta) &= -\sum_{i=1}^{n} \lambda_i t + \sum_{i=1}^{n} y_i \ln(\lambda_i t) - \sum_{i=1}^{n} \ln(y_i!) \\ &= -\sum_{i=1}^{n} \exp(\mathbf{X}_i'\beta)t + \sum_{i=1}^{n} y_i \ln\lambda_i + \sum_{i=1}^{n} y_i \ln t - \sum_{i=1}^{n} \ln(y_i!) \\ &= -\sum_{i=1}^{n} \exp(\mathbf{X}_i'\beta)t + \sum_{i=1}^{n} y_i \mathbf{X}_i'\beta + \text{constant}\end{aligned}$$

The log-likelihood function can be maximized by taking derivatives with respect to β and setting them to 0.

$$\frac{\partial L(\beta)}{\partial \beta} = -\sum_{i=1}^{n} \exp(\mathbf{X}_i'\beta)t \,.\, \mathbf{X}_i' + \sum_{i=1}^{n} y_i \mathbf{X}_i' \approx 0$$

This is a set of (p+1) nonlinear equations and (p+1) unknowns (β). These equations may be solved iteratively. However, software limitations prevented the solution of these equations to obtain regression models. Alternatively, a solution is obtained by transforming the data and using iterative weighted lease squares on SAS.

Estimation of Regression Coefficients

In this section, the logarithms of the Y_i's is shown to follow approximately, a linear regression model with non-constant variance. Logarithm of Y_i's can be approximated as

$$\ln Y_i \approx \ln(\lambda_i t)$$

By first order Taylor Series expansion

$$\ln Y_i \approx \ln(\lambda_i t) + \left.\frac{\partial \ln Y_i}{\partial Y_i}\right|_{Y_i=\lambda_i t} (Y_i - \lambda_i t)$$

The mean and the variance of the transformed random variable are

$$\mathrm{E}(\ln Y_i) = \ln \lambda_i t + \left.\frac{\partial \ln Y_i}{\partial Y_i}\right|_{Y_i=\lambda_i t} .0 = \ln \lambda_i t$$

$$\mathrm{V}(\ln Y_i) = \left[\left.\frac{\partial \ln Y_i}{\partial Y_i}\right|_{Y_i=\lambda_i t}\right]^2 .\lambda_i t = \left[\frac{1}{\lambda_i t}\right]^2 \lambda_i t = \frac{1}{\lambda_i t}$$

Thus,

$$\ln Y_i \approx \mathbf{X}_i'\beta + \ln t + error,$$

or

$$\ln Y_i - \ln t \approx \mathbf{X}_i'\beta + error$$

where the error has mean 0 and variance $\frac{1}{\lambda_i t} = \frac{1}{t}\exp(-\mathbf{X}_i\beta)$. The error terms, thus, have non-constant variance. Regression coefficients β can be obtained by least squares estimation. The estimated regression coefficients are unbiased and consistent. However, these estimates are not minimum variance unbiased estimators because of the non-constant error variance (28).

A weighted least squares estimation procedure can be used when error terms have non- constant variance (28). A weighted least squares procedure is a modification of the ordinary least squares procedure in which weights are assigned to the least square criterion. The weights usually assigned are inversely proportional to the error variance (28). In this case, the error variance is proportional to the regression coefficients.

Note that in the equation

$$(\ln Y_i)\ \exp\left(\frac{\mathbf{X}_i'\beta}{2}\right)t^{\frac{1}{2}} \approx \exp\left(\frac{\mathbf{X}_i'\beta}{2}\right)t^{\frac{1}{2}}(\mathbf{X}_i'\beta + \ln t + \text{error}),$$

the rescaled error has constant variance.

To obtain the regression coefficient an iterative method was used. An iterative weighted least squares procedure is used to obtain improved weighted least squares estimates. This procedure involves initially estimating weights from the data, and performing a weighted least squares regression. The residuals from this regression are used to obtain the weights for the next iteration. The process is continued till the values converge. One or two iterations are usually sufficient (28). In this case, the first step was to find the ordinary least square estimates of the regression coefficients. These values are used as the starting values for weights in the weighted least square procedure. The iterative weighted least squares procedure used for developing Poisson regression models involves the following steps:

Step 1:

Obtain the estimate $\beta^{(i)}$ by Ordinary Least Squares: Regress $\ln Y_i$ - $\ln t$ on $\mathbf{X}_i$. Set i=0.

Step 2:

Obtain the estimate $\beta^{(i+1)}$ by weighted least squares: Regress $\ln Y_i$ - $\ln t$ on $\mathbf{X}_i$ using $\exp(\mathbf{X}_i'\beta^{(i)})t$ as weights.

Step 3:

Check for convergence; if not converged, go to Step 2; else stop.

The results of the regression are transformed to obtain a model for the number of accidents. The weighted least squares regression procedure estimates the regression coefficients for the dependent variable $\ln Y_i - \ln t$.

$$\text{Pred}\,[\ln Y_i - \ln t] = \mathbf{X}_i'\hat{\beta}$$

$$\text{Pred}\,[\ln Y_i] = \mathbf{X}_i'\hat{\beta} + \ln t$$

$$\hat{Y}_i = t.\exp\left(\mathbf{X}_i'\hat{\beta}\right)$$

where Pred stands for predicted value,

and $\hat{\beta}$ and $\hat{Y}_i$ are estimates of regression coefficients and predicted value of the number of accidents on approach *i* respectively. The predicted values of the dependent variable are biased because of the nonlinear transformation.

Poisson Regression Results

Regression was performed using the above method for the five groups classified by left-turn volumes. The left-turn accident count was the dependent variable and the and independent variables were the ones used for the linear model. As with the linear model, the "best" model, in terms of R^2 and statistically significant parameter estimates is obtained for the group with daily left-turn volumes 500 to 1000.

Poisson Regression Model for Left-Turn Accidents for Left-Turn Volumes 500 to 1000

The starting values for the parameter estimates were obtained from an ordinary least square estimation. The dependent variable in the regression was a transformed variable of the number of left-turn accidents on an approach in five years. The weighted least square estimation was performed three times to obtain the solution:

$$LACC = \exp\left(\begin{array}{l} -0.43 - \underset{(0.0207)}{0.88 SYSTEM} - \underset{(0.0011)}{1.74 LLANES} + \underset{(0.0026)}{0.14 LWIDTH} + \underset{(0.5935)}{0.19 PERMIT} \\ -\underset{(0.0055)}{1.04 PROTECT} + \underset{(0.0074)}{0.000145 TOTVOL} + \ln 5 \end{array} \right)$$

(Model 11)

The numbers shown in parenthesis is the level of significance of the parameter estimate. The R^2 for the model is 0.5. All the parameter estimates were significant at the 5% level except for PERMIT. The correlation between the left-turn accident rate predicted by the model and the observed left-turn accident rates is 0.7.

A graph of the number of left-turn accidents over 5 years is plotted against total approach volume in Figure 11. The graph shows the effect of left-turn phasing on the number of accidents in 5 years. The graph is constructed for an approach that has two lanes and a 12 foot left-turn lane and the approach is part of an intersection that is isolated.

Compare this Figure 11 with Figure 1. The lines for protected/permitted and protected phasing are close in this Figure 11, whereas they are well spaced out in Figure 1. One of the reasons could be that Figure 1 shows the left-turn accident rate while Figure 11 shows the number of left-turn accidents. Another reason is that the data set contained three points that had no left-turn accidents in five years. These points were considered in the linear model. In the Poisson model, however, the number of accidents had to be converted to their natural logarithm before performing the regression. Since natural logarithm of 0 does not exist, these points were not considered for regression. Examination of the data showed that the left-turn phasing for the three approaches was different. One of them had permitted phasing, one of them had protected phasing, and the third had protected/permitted phasing. A comparison of the linear and Poisson models is made later in Chapter 6.

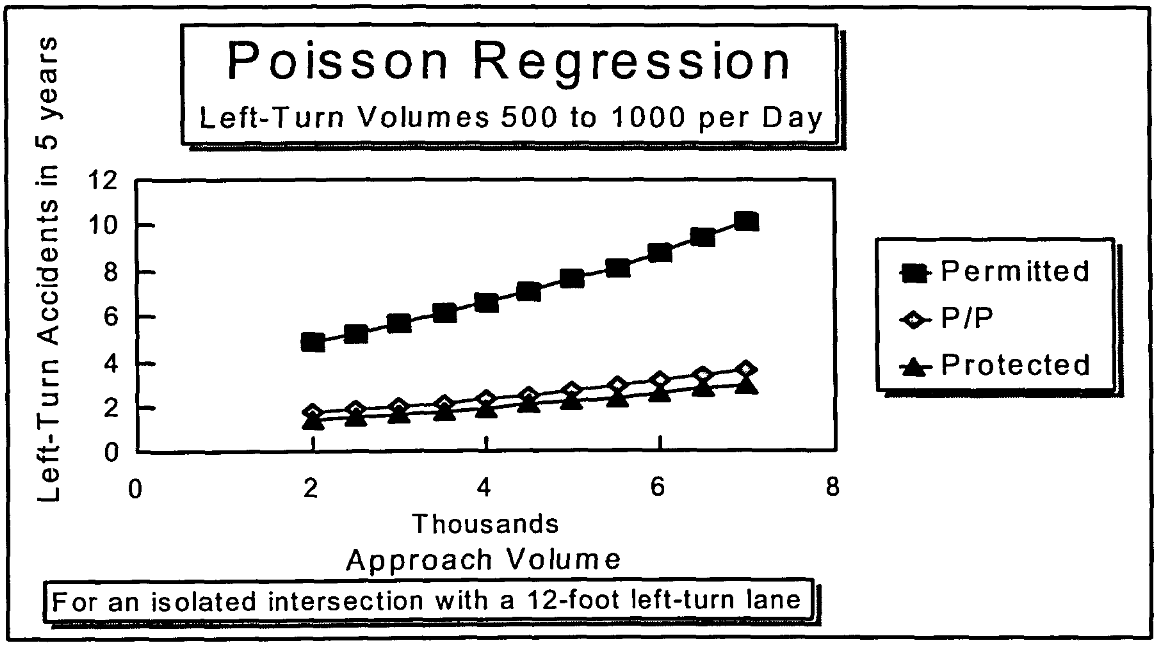


Figure 11: Left-turn phasing and left-turn accidents

Figure 12 shows the effect of a left-turn lane on the number of left-turn accidents in five years. The graph is constructed for a two lane approach with permitted phasing and the approach leads to an intersection that is part of a system. The Poisson predicts that the left-turn lane reduced the number of left-turn accidents. This result is similar to that of the linear model.

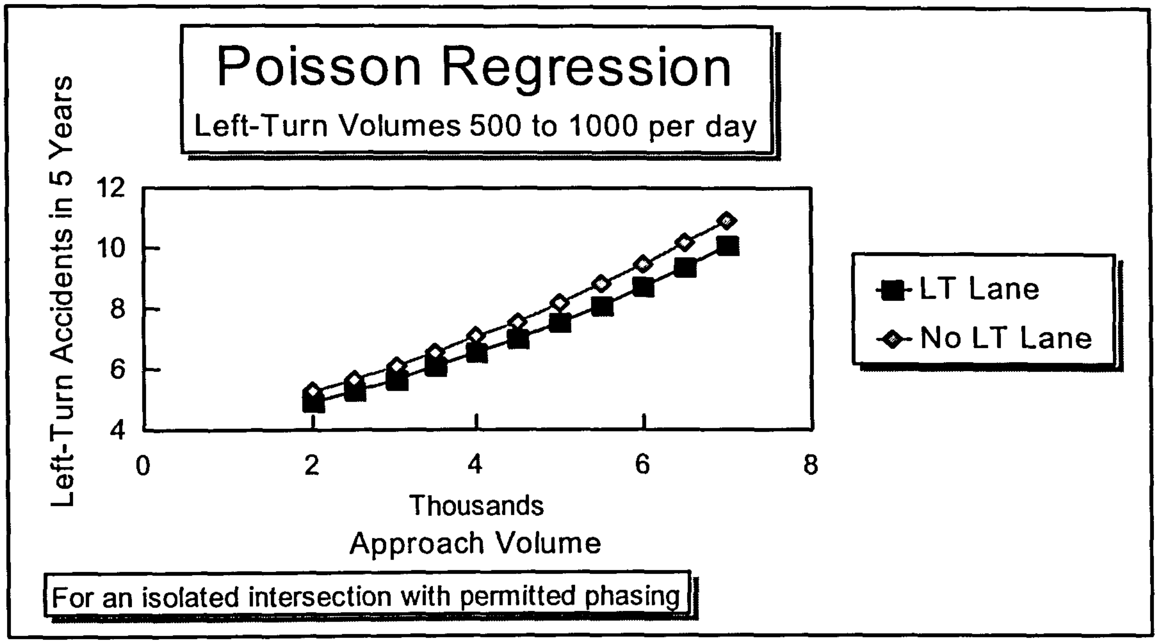


Figure 12: Left-turn lane and left-turn accidents

Other Poisson Models

Poisson Regression models for other groups is shown in Table 2. Unfortunately, the regression models provided insignificant parameter estimates. The models are shown for illustration purposes.

Limitations of Estimation Techniques

The Poisson regression models underestimate the R^2 because of bias in non-linear transformation. The estimation technique is not the best possible because of limitations of availability of software.

Table 2: Other Poisson Regression Models

Daily Left-Turn Volumes 0 to 500

$$LACC = \exp\begin{pmatrix} -0.52 + 0.11SYSTEM - 0.43LLANES + 0.04LWIDTH - 0.35PERMIT \\ -0.11PROTECT - 0.000014TOTVOL + \ln 5 \end{pmatrix}$$

$R^2 = 0.06$

Daily Left-Turn Volumes 1000 to 1500

$$LACC = \exp\begin{pmatrix} -0.72 + 0.12SYSTEM - 0.62LLANES + 0.01LWIDTH + 0.47PERMIT \\ +0.65PROTECT + 0.000016TOTVOL + \ln 5 \end{pmatrix}$$

$R^2 = 0.10$

Daily Left-Turn Volumes 1500 to 2000

$$LACC = \exp\begin{pmatrix} -0.24 + 0.53SYSTEM - 7.92LLANES + 0.56LWIDTH - 0.02PERMIT \\ -0.32PROTECT + 0.00008464TOTVOL + \ln 5 \end{pmatrix}$$

$R^2 = 0.37$

Daily Left-Turn Volumes 2000 and more

$$LACC = \exp\begin{pmatrix} -1.03 + 0.27SYSTEM + 1.22LLANES - 0.17LWIDTH + 0.29PERMIT \\ +1.18PROTECT - 0.0000051TOTVOL + \ln 5 \end{pmatrix}$$

$R^2 = 0.3$

CHAPTER 6

APPLICATION OF MODELS

Unfortunately, a majority of the statistical analysis performed in this research resulted in models with statistically insignificant parameter estimates. This was, however, not necessarily unexpected. Variation in intersection accident rates is caused by intersection attributes not accounted for in the database. For example, elderly drivers are known to be more involved in left-turn accidents than younger drivers. A high proportion of elderly drivers approaching an intersection could potentially increase the accident rate more than the other factors included in the intersection database. Such factors resulted in the inability to develop good models for all volume ranges.

The fact that reasonably good models were developed for some volume ranges illustrates the validity of the approach. The acceptable models are consistent with observations taken from the literature and from the researcher's engineering judgment. Therefore, in the future, with additional research, and better data it is reasonable to expect that acceptable models could be developed over all volume ranges.

This chapter illustrates the use of models developed. Given that acceptable models were developed and the assumption that acceptable models could be developed over all ranges of volumes, the next section explores use of the acceptable models. Also, linear and Poisson models are compared in this chapter.

Application

The primary purpose for the development of the models is to provide traffic engineers with a tool to make trade-offs between the costs of intersection improvements, intersection delay, and potential accident costs. The acceptable models developed in the prior section allow the traffic engineer to simultaneously consider delay, safety, and construction costs when estimating the costs and benefits of various design alternatives.

The accident implications of a change in intersection design can be estimated using a model to estimate the accident rate with existing traffic conditions and a new intersection geometry and/or signal phasing. Consider, for example, an approach at an intersection that has permitted phasing. If the opposing traffic volumes are high, then it may be difficult for left turning traffic to find suitable gaps for making left-turns. As a result, left-turning vehicles may experience long delays and left-turn accident rates may be high. At such an approach, a change in left-turn phasing could be a solution to reduce left-turn delay and accidents. The phasing may be changed to protected/permitted and a left-turn lane added. The change in the number of accidents can be estimated using the model. The economic benefits and costs of reducing the accident rate, construction costs of intersection modifications, cost of modifying signalization, and the delay benefits and costs can be compared to select the most cost effective alternative.

Example Problem Illustrating the Use of the Research

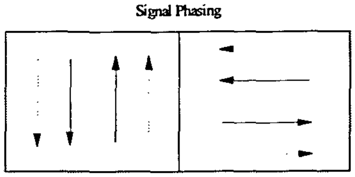
The results of the research described in the previous sections have been incorporated into an example problem to illustrate their use. This example involves a signalized intersection in Iowa. The intersection has experienced a high number of accidents involving left-turning vehicles.

The intersection has four approaches with two lanes on each approach as shown in Figure 13. It has a two phase operation and an 80 second cycle length is assumed for the analysis. The turning movement counts are shown for the evening peak hour and an average weekday. The approach speed limits are 35 miles per hour on the Main Street and 25 miles per hour on the Side Street.

Existing Signal Timing

	Main Street	Side Street
Green	45	25
Yellow + All Red	5	5
Total	50	30

Signal Phasing



Approach Speed Limits

Approach	Speed Limit
NB	35
SB	35
EB	25
WB	25

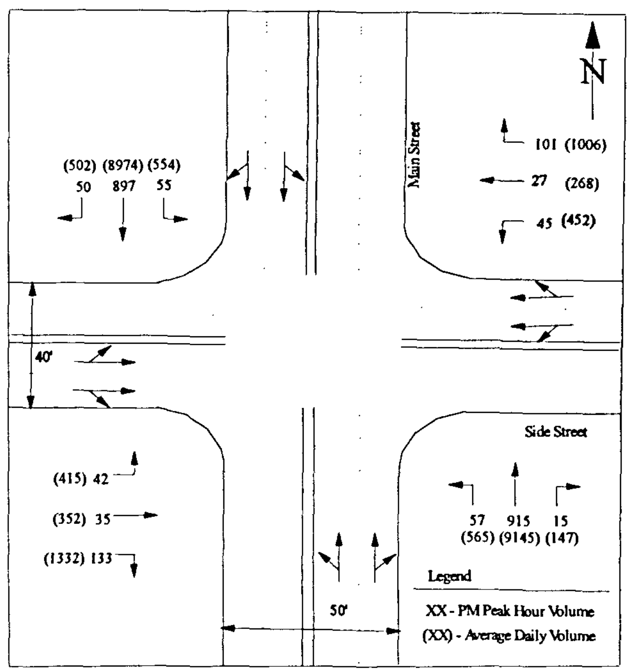


Figure 13: Intersection Characteristics

The accident history for this intersection was obtained from the Iowa Department of Transportation Accident Location and Analysis System (ALAS). A summary of accidents for northbound and southbound approaches for 1989 through 1991 is shown in Table 3. There was a total of 15 accidents on the northbound approach and 19 on the southbound approach during the three year period. The northbound approach had 8 accidents involving left-turning vehicles and the southbound approach 15. Clearly, a majority of accidents at this intersection involve left-turning vehicles. There is a need for improving the safety of left-turns at this intersection.

Linear Model

The left-turn accident rate (LACCRATE) is calculated for the northbound and southbound approaches using Model 1. Results are presented in Table 4A. For the northbound approach, Model 1 predicts a left-turn accident rate of 7.93 accidents per million left turning vehicles. For the southbound approach, the model estimates an accident rate of 8.02.

Model 1 is also used to develop left-turn accident rate estimates for four alternative left-turn treatments. The estimated accident rate for each alternative treatment is shown in Table 4A.

Poisson Model

The predicted number of left-turn accidents is calculated using Model 11. Table 4B shows the estimated number of left-turn accidents for each alternative.

Table 3: Accident Summary for Northbound and Southbound Approaches for 1989 through 1991

	Accident Type	1989	1990	1991	Total
N	Angle	2			2
O	Left Turn	4		4	8
R	Rear End	2	1	2	5
T	Head On				0
H	Sideswipe				0
B	Fixed Object				0
O	Pedestrian				0
U	Bicycle				0
N	Other				0
D	Total	8	1	6	15
S	Angle			2	2
O	Left Turn	6	3	6	15
U	Rear End		1	1	2
T	Head On				0
H	Sideswipe				0
B	Fixed Object				0
O	Pedestrian				0
U	Bicycle				0
N	Other				0
D	Total	6	4	9	19

Table 4: Predicted Left-Turn Accident Rate

A: Linear Regression Model

	Variables	Existing Conditions	Alternatives: Protected Phasing w/o LT Lane	Alternatives: Permitted Phasing with LT Lane	Alternatives: Protect/Perm Phasing with LT Lane	Alternatives: Protected Phasing with LT Lane
NORTH BOUND	SYSTEM	0	0	0	0	0
	LLANES	0	0	1	1	1
	LWIDTH	0	0	12	12	12
	PERMIT	1	0	1	1	0
	PROTECT	0	1	0	1	1
	TOTVOL	9857	9857	9857	9857	9857
	LACCRATE	7.93	3.9	7.49	5.2	3.46
SOUTH BOUND	SYSTEM	0	0	0	0	0
	LLANES	0	0	1	1	1
	LWIDTH	0	0	12	12	12
	PERMIT	1	0	1	1	0
	PROTECT	0	1	0	1	1
	TOTVOL	10030	10030	10030	10030	10030
	LACCRATE	8.02	3.98	7.57	5.28	3.54

Table 4 (continued)

B: Poisson Regression Model

	Variables	Existing Conditions	Alternatives: Protected Phasing w/o LT Lane	Alternatives: Permitted Phasing with LT Lane	Alternatives: Protect/Perm Phasing with LT Lane	Alternatives: Protected Phasing with LT Lane
NORTH BOUND	SYSTEM	0	0	0	0	0
	LLANES	0	0	1	1	1
	LWIDTH	0	0	12	12	12
	PERMIT	1	0	1	1	0
	PROTECT	0	1	0	1	1
	TOTVOL	9857	9857	9857	9857	9857
	LACC in 3 years	9.92	2.91	9.17	3.25	2.69
SOUTH BOUND	SYSTEM	0	0	0	0	0
	LLANES	0	0	1	1	1
	LWIDTH	0	0	12	12	12
	PERMIT	1	0	1	1	0
	PROTECT	0	1	0	1	1
	TOTVOL	10030	10030	10030	10030	10030
	LACC in 3 years	10.18	2.98	9.4	3.33	2.76

Left-Turn Treatment Alternatives

Four alternatives were selected for evaluation. Each alternative, based on standard traffic engineering practice, was selected because it could reduce the probability of left-turn accidents. The reduced likelihood of left-turn accidents reduces future traffic accidents costs and, therefore, provides a quantifiable safety benefit. On the other hand, each improvement implies increased construction costs and may increase intersection delay. For each of the four alternatives, all of these costs were evaluated in a single benefit-cost ratio, allowing the traffic engineer to select the most cost effective alternative. The four alternative left-turn treatment improvements include:

1. Changing the northbound and southbound approaches from permitted phasing to protected phasing without adding a left turn lane (split phasing);

2. Adding a left turn lane to both approaches with the existing permitted left-turn phasing;

3. Adding a left-turn lane to both approaches with protected/permitted phasing; and,

4. Adding a left-turn lane to both approaches with protected phasing.

Accident implications of each of the alternatives is determined using linear and Poisson models and is shown in Table 4. The linear model predicts that left-turn accident rates are lowest when there is protected left-turn phasing with a left-turn lane for both northbound and southbound approaches. Similarly, the Poisson model also shows that the number of left-turn accidents is least for alternative four. Based on this analysis, protected phasing with added left turn lane would be the best alternative for reducing accidents.

Benefit/Cost Analysis

A benefit/cost analysis was conducted to determine the overall effects of the alternatives. The analysis includes the potential for the alternatives to reduce accidents, the change in the approach delay associated with each alternative, and the construction costs for each alternative. First, the predicted number of accidents was calculated for all of the alternatives using Model 1 to determine how the proposed changes would affect the accident potential at the intersection (see Table 5). The predicted values of accidents are higher for the Poisson model when compared to the linear model. In both cases, the largest predicted reductions in accidents are produced by the two alternatives that involve protected phasing.

The approach delay was calculated using the Highway Capacity Manual software to compare the effect of each alternative (see Table 6). Cycle length was assumed to be the same for each of the alternatives. The only alternative reducing delay uses permitted phasing with a left turn lane (alternative two).

Construction costs were estimated for each of the alternatives (see Table 7). The lowest cost alternative is to add protected phasing without a left turn lane. All other alternatives include the cost of adding a left-turn lane and are assumed to cost the same amount.

Table 5: Predicted Accident Reduction

A: Linear Regression Model

		Alternative	LACCRATE	Predicted Number of Left-Turn Accidents/ Year	Predicted Left-Turn Accident Reduction/ Year	Percentage Reduction
N	B	Existing Conditions	7.93	1.63	0	0
O	O	Protected Phasing w/o LT Lane	3.9	0.8	0.83	50.81
R	U	Add LT Lane with Permit. Phasing	7.49	1.54	0.09	5.55
T	N	Protect/Perm Phasing with LT Lane	5.2	1.07	0.56	34.43
H	D	Protected Phasing with LT Lane	3.46	0.71	0.92	56.37

		Alternative	LACCRATE	Predicted Number of Left-Turn Accidents/ Year	Predicted Left-Turn Accident Reduction/ Year	Percentage Reduction
S	B	Existing Conditions	8.02	1.62	0	0
O	O	Protected Phasing w/o LT Lane	3.98	0.8	0.82	50.37
U	U	Add LT Lane with Permit. Phasing	7.57	1.53	0.09	5.61
T	N	Protect/Perm Phasing with LT Lane	5.28	1.07	0.55	34.16
H	D	Protected Phasing with LT Lane	3.54	0.72	0.9	55.86

Table 5 (continued)

B: Poisson Regression Model

		Alternative	Predicted Number of Left-Turn Accidents/ Year	Predicted Left-Turn Accident Reduction/ Year	Percentage Reduction
N	B	Existing Conditions	3.31	0	0
O	O	Protected Phasing w/o LT Lane	0.97	2.34	70.69
R	U	Add LT Lane with Permit. Phasing	3.06	0.25	7.56
T	N	Protect/Perm Phasing with LT Lane	1.08	2.23	67.37
H	D	Protected Phasing with LT Lane	0.9	2.41	72.81
S	B	Existing Conditions	3.39	0	0
O	O	Protected Phasing w/o LT Lane	0.99	2.4	70.8
U	U	Add LT Lane with Permit. Phasing	3.13	0.26	7.67
T	N	Protect/Perm Phasing with LT Lane	1.11	2.28	67.26
H	D	Protected Phasing with LT Lane	0.92	2.47	72.86

Table 6: Approach Delay for Alternatives

Alternative	Northbound Approach Predicted Delay (sec/veh)	Northbound Approach Predicted Change (sec/veh)	Southbound Approach Predicted Delay (sec/veh)	Southbound Approach Predicted Change (sec/veh)
Existing Conditions	8.3	0	8.3	0
Protected Phasing w/o LT Lane	65.6	-57.3	74.5	-66.2
Add LT Lane with Permit. Phasing	5.2	3.1	5.3	3
Protect/Perm Phasing with LT Lane	12.9	-4.6	13.1	-4.8
Protected Phasing with LT Lane	13.5	-5.2	13.7	-5.4

Table 7: Estimated Construction Cost for Each of the Alternatives

Alternative	Construction Cost
Protected Phasing w/o LT Lane	$540
Add LT Lane with Permit. Phasing	$114,431
Protect/Perm Phasing with LT Lane	$114,431
Protected Phasing with LT Lane	$114,431

Finally, a benefit/cost analysis was conducted incorporating all factors into the analysis. The benefit/cost ratio was calculated under three scenarios to show the sensitivity of the predictions to assumptions of delay and accident costs. The benefit/cost analyses also illustrate the use of the model in making trade-offs between a reduced potential for accidents, delay costs, and construction costs. In all scenarios an interest rate of eight percent was used for discounting future costs and benefits. The project was assumed to have a life of 20 years.

Accidents that occurred at this particular intersection in the past were property damage only accidents. An average accident value, however, is used for the cost of future accidents. This is an average accident cost of $11,500. Eleven thousand five hundred dollars was the average cost of all accidents throughout Iowa for 1991 (31). It would be preferable to have an average accident cost for a highway facility with similar characteristics (i.e., high speed signalized intersections). Such data are not available. The reason for the use of average accident costs can best be envisioned by supposing, through random misfortune, one of the accidents resulted in a fatality. The State of Iowa estimates the average cost of a fatal accident is $500,000. If it is then assumed accidents in the future would result in fatalities (very high cost accidents), almost any measure to improve the safety of the intersection would be justified. Instead an average accident cost is used so that very high cost accidents, and similarly very low cost accidents, do not unduly bias the left-turn treatment utilized. Because the extent of damage resulting from an accident is random, the average cost of accidents over a large number of accidents at similar facilities is a better predictor of future costs than a small sample at one location.

In the first scenario, the value for delaying the driver and vehicle is assumed to have a cost of $11.65 per hour. This value is based on the value of time used in a study of capacity improvements to the U.S. Highway 20 corridor and assumes the driver is on a business trip and that there are no passengers in the automobile (32). Clearly, the value of time can vary depending on the amount of time saved (individuals value more highly a minute saved from a ten minute delay than they would a minute saved from a two minute delay), and the type of trip being made.

Table 8 shows annual delay savings for the northbound the southbound approaches. Changing the left-turn phasing to permitted an adding a left-turn lane is the only alternative that reduces delay costs. In Table 9 are the results of discounting future costs and future benefits (reduced delay and/or reduced accidents) using linear and Poisson models. In Table 9A, only the second alternative provides positive benefits (combined delay and accident costs savings) and, therefore, a benefit to cost ratio is calculated only for alternative two. The others provide estimates of negative benefits. Based on this calculation alternative two is the most cost effective alternative and should be selected. When a similar analysis is performed using the Poisson model, positive benefit to cost ratio is obtained only for the second alternative.

Table 10 and 11 illustrate the second scenario. The second scenario assumes a very low value for delay time, $3.25. This value is selected because it illustrates the importance of the value of a motorists time and the consideration of delay. When the value of delay time is high, the alternative that most greatly reduces delay dominates the analysis (alternative two). Table 11A shows the benefit to cost ratios with the linear model when the value of delay time is low. Only alternative two has a positive benefit to cost ratio. With the Poisson model, however, positive ratios are obtained for alternatives three and four because the savings in accidents offset the negative savings in delay. Alternative two still has the best benefit to cost ratio.

Table 8: Annual Delay Cost Savings for Northbound and Southbound Approaches
Assuming a Delay Cost of $11.65 per Hour

	Alternative Alternative	Predicted Delay (Sec/Veh)	Predicted Change (Sec/Veh)	Annual Delay (Hours)	Annual Delay Savings
N B	Existing Condition	8.3	0	0	$0
O O	Protected Phasing w/o LT Lane	65.6	-57.3	-57,265	-$667,137
R U	Add LT Lane With Permitted Phasing	5.2	3.1	3,098	$36,092
T N	Protected/Permitted Phasing with LT Lane	12.9	-4.6	-4,597	-$53,557
H D	Protected Phasing With LT Lane	13.5	-5.2	-5,197	-$60,543
S B	Existing Condition	8.3	0	0	$0
O O	Protected Phasing w/o LT Lane	74.5	-66.2	-67,321	-$784,287
U U	Add LT Lane With Permitted	5.3	3	3,051	$35,541
T N	Protected/Permitted Phasing with LT Lane	13.1	-4.8	-4,881	-$56,866
H D	Protected Phasing With LT Lane	13.7	-5.4	-5,491	-$63,975

Table 9: Benefit to Cost Analysis Assuming a Delay Cost of $11.65 per Hour and an Accident Cost of $11,500 per Accident

A: Linear Model

Alternative	Total Annual Delay Savings	Total Annual Accident Savings	Present Worth of Benefits	Present Worth of Costs	Benefit to Cost Ratio
Existing Condition	$0	$0	$0	$0	0
Protected Phasing w/o LT Lane	-$1,451,424	$18,975	-$65,491,614	$540	N.A.
Add LT Lane with Permitted Phasing	$71,633	$2,070	$3,372,741	$114,431	29.47
Protected/Permitted Phasing with LT Lane	-$110,423	$12,765	-$4,468,876	$114,431	N.A.
Protected Phasing with LT Lane	-$124,518	$20,930	-$4,740,187	$114,431	N.A.

B: Poisson Model

Alternative	Total Annual Delay Savings	Total Annual Accident Savings	Present Worth of Benefits	Present Worth of Costs	Benefit to Cost Ratio
Existing Condition	$0	$0	$0	$0	0
Protected Phasing w/o LT Lane	-$1,451,424	$54,510	-$63,922,785	$540	N.A.
Add LT Lane with Permitted Phasing	$71,633	$5,865	$3,546,308	$114,431	30.99
Protected/Permitted Phasing with LT Lane	-$110,423	$51,865	-$2,679,614	$114,431	N.A.
Protected Phasing with LT Lane	-$124,518	$56,120	-$3,129,892	$114,431	N.A.

Table 10: Annual Delay Cost Savings for Northbound and Southbound Approaches Assuming a Delay Cost of $3.25 per Hour

		Alternative	Predicted Delay (Sec/Veh)	Predicted Change (Sec/Veh)	Annual Delay (Hours)	Annual Delay Savings
N	B	Existing Condition	8.3	0	0	$0
O	O	Protected Phasing w/o LT Lane	65.6	-57.3	-57,265	-$186,111
R	U	Add LT Lane With Permitted	5.2	3.1	3,098	$10,068
T	N	Protected/Permitted Phasing with LT Lane	12.9	-4.6	-4,597	-$14,940
H	D	Protected Phasing With LT Lane	13.5	-5.2	-5,197	-$16,889
S	B	Existing Condition	8.3	0	0	$0
O	O	Protected Phasing w/o LT Lane	74.5	-66.2	-67,321	-$218,793
U	U	Add LT Lane With Permitted	5.3	3	3,051	$9,916
T	N	Protected/Permitted Phasing with LT Lane	13.1	-4.8	-4,881	-$15,863
H	D	Protected Phasing With LT Lane	13.7	-5.4	-5,491	-$17,846

Table 11: Benefit to Cost Analysis Assuming a Delay Cost of $3.25 per Hour and an Accident Cost of $11,500 per Accident

A: Linear Model

Alternative	Total Annual Delay Savings	Total Annual Accident Savings	Present Worth of Benefits	Present Worth of Costs	Benefit to Cost Ratio
Existing Condition	$0	$0	$0	$0	0
Protected Phasing w/o LT Lane	-$404,904	$18,975	-$17,660,134	$540	N.A.
Add LT Lane with Permitted Phasing	$19,984	$2,070	$1,009,202	$114,431	8.82
Protected/Permitted Phasing with LT Lane	-$30,804	$12,765	-$825,442	$114,431	N.A.
Protected Phasing with LT Lane	-$34,736	$20,930	-$631,763	$114,431	N.A.

B: Poisson Model

Alternative	Total Annual Delay Savings	Total Annual Accident Savings	Present Worth of Benefits	Present Worth of Costs	Benefit to Cost Ratio
Existing Condition	$0	$0	$0	$0	0
Protected Phasing w/o LT Lane	-$404,904	$54,510	-$16,034,052	$540	N.A.
Add LT Lane with Permitted Phasing	$19,984	$5,865	$1,182,862	$114,431	10.34
Protected/Permitted Phasing with LT Lane	-$30,804	$51,865	$963,774	$114,431	8.42
Protected Phasing with LT Lane	-$34,736	$56,120	$978,532	$114,431	8.55

To illustrate the sensitivity of the solution to the cost assigned to future accidents, the analysis conducted in scenario three uses an average accident value of $40,000 and a time value of delay of $3.25 per hour. A value of $3.25 per hour is used as the time value of delay because the alternatives increase or decrease the delay only by a few seconds per vehicle. Most people may not even perceive this change (32). A value of $11.65 per hour may be too high a value for small time increments. The annual delay savings for this scenario are the same as those for the second scenario (Table 10). Benefit to cost ratios with linear and Poisson models are shown in Table 12. By increasing the cost of accidents, the benefits of reducing accidents are increased. This increases the attractiveness of alternatives which most greatly reduce the potential of accidents (Alternatives three and four). Alternative four has the highest benefit to cost ratio because it results in maximum accident reduction. The benefit to cost ratios for alternatives three and four as predicted by the Poisson model are higher those predicted by the linear model. This happens because the Poisson model predicts a much higher accident reduction for the two alternatives. Both linear and Poisson models predict that alternative four has the best benefit to cost ratio.

The example problem illustrates the use of the models developed for performing benefit/cost analyses. It also brought out difference between linear and Poisson models. The next section in this chapter is the comparison of linear and Poisson models.

Table 12: Benefit to Cost Analysis Assuming a Delay Cost of $3.25 per Hour and an Accident Cost of $40,000 per Accident

A: Linear Model

Alternative	Total Annual Delay Savings	Total Annual Accident Savings	Present Worth of Benefits	Present Worth of Costs	Benefit to Cost Ratio
Existing Condition	$0	$0	$0	$0	0
Protected Phasing w/o LT Lane	-$404,904	$66,000	-$15,508,293	$540	N.A.
Add LT Lane with Permitted Phasing	$19,984	$7,200	$1,243,940	$114,431	10.87
Protected/Permitted Phasing with LT Lane	-$30,804	$44,400	$622,153	$114,431	5.44
Protected Phasing with LT Lane	-$34,736	$72,800	$1,741,809	$114,431	15.22

B: Poisson Model

Alternative	Total Annual Delay Savings	Total Annual Accident Savings	Present Worth of Benefits	Present Worth of Costs	Benefit to Cost Ratio
Existing Condition	$0	$0	$0	$0	0
Protected Phasing w/o LT Lane	-$404,904	$189,000	-$9,852,357	$540	N.A.
Add LT Lane with Permitted Phasing	$19,984	$20,400	$1,847,972	$114,431	16.15
Protected/Permitted Phasing with LT Lane	-$30,804	$180,400	$6,845,513	$114,431	59.82
Protected Phasing with LT Lane	-$34,736	$195,200	$7,342,833	$114,431	67.17

Comparison of the Linear and Poisson Models

From the benefit-cost analysis, it can be seen that both the linear and Poisson models lead the similar results when it comes to choosing the best alternative. The Poisson model, however, predicts a higher number of accidents.

The dependent variable in the linear model was the left-turn accident rate whereas in the Poisson model the dependent variable is a transformed left-turn accident count for five years. The best models in both cases were obtained for the group with left-turn volumes 500 to 1000 per day. The R^2 for the linear model was 0.44. The Poisson model had an R^2 of 0.5. The two values cannot be compared because they are for different dependent variables. In the Poisson model, left-turn accident rate was calculated using left-turn volumes and the correlation of the observed left-turn accident rate and the predicted left-turn accident rate was determined. The correlation was 0.7. The R^2 for the model may thus be calculated as 0.49.

The Poisson model has several advantages:

- The number of accidents predicted will always be positive because of the nature of the formulation.
- It incorporates the random nature of accidents.
- The R^2 for the Poisson model is greater than the R^2 for the linear model.

The linear model also has its advantages:

- Predicts the left-turn accident rate which is the standard measure of intersection safety rather than the number of accidents per year.

  Easier to understand and use.

It is recommended that Poisson model be used. More research, however, is necessary to validate the models developed in this study.

CHAPTER 7

CONCLUSIONS

Left-turn accidents are over-represented by a factor of three in the total accident population. Because left-turn maneuvers are more hazardous than other traffic movements, the design of the most effective left-turn treatment is crucial. The purpose of this research has been to develop statistical models to allow engineers to make trade-offs during the design and evaluation of alternatives. Traditionally, there have been excellent tools for the analysis of capacity and delay considerations while designing intersections. There have not been acceptable methods for including predicted accident costs in the economic analysis of alternative left-turn treatments. In the past, engineers have used engineering judgment or locally developed warrants for left-turn treatments.

In this research, a database was generated for the statistical estimation of relationships between accident experience, intersection traffic characteristics, and left-turn treatments. Linear and non-linear models have been developed to estimate the number of accidents given the intersection geometry, traffic signal phasing and turning movement counts. Much of the statistical analysis resulted in models with poor statistical properties. A few of the models developed did, however, provide acceptable statistical results. An example of the models' use and the sensitivity of the models to changes in input parameters is provided

The data were divided into data sets based on the left-turn volumes; 0 to 500 left-turning vehicles per day, 500 to 1,000, 1,000 to 1,500, 1,500 to 2,000, and 2,000 or greater. Each data set contained information regarding accidents, intersection geometry, and traffic volumes from intersections within the left-turn volume interval. Satisfactory linear and Poisson models were developed only for the 500 to 1,000 vehicle per day interval and reasonable models for the 1,500 to 2,000. The results are interpreted to mean that there are relationships between left-turn accident rates, traffic characteristics, and left-turn treatments. The models with acceptable statistical results seem reasonable and logical. More investigation is recommend to develop higher fidelity models. However, in future research, better data collection procedures are recommended.

The specific recommendations include:

- It is recommended that traffic accident and traffic volumes cover the peak hour rather then the entire day. Typically, intersections are designed to satisfy peak hour traffic volumes.

- City traffic engineers were asked to provide intersection geometry and traffic volume data only for intersections that had not been reconstructed or had significant modification over the last five years. Current traffic volumes and signal phasing may nor necessarily be indicative of conditions every year. It is recommended that the data collected for intersections should include a time series of traffic data and signal operation for every year in the database.

- Accident data was obtained from the state level accident reporting system. Although the state accident database id the most comprehensive reporting system in Iowa, not all jurisdictions are equally judicious in their reporting of accidents to the Iowa Department of Transportation. It is recommended that accident record keeping practices of the cities and counties be examined for consistency

The example problem in Chapter 6 illustrates the use of one of the models in the selection of an alternative design of an intersection. Model 11 may be used in similar situations, in the design of intersections with left-turn volumes of 500 to 1,000 vehicles per day, with reasonable confidence in the results. It is even reasonable to use the model for design of intersections with left-turn volumes outside of the 500 to 1,000 vehicles per day range to provide an initial estimate of the implications of various left-turn treatment. More work, however, is required to develop operational models for common intersection evaluation purposes. The most important contribution of the work reported here is to illustrate that such models may be developed.

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APPENDIX A

QUESTIONNAIRE

Intersection number or ID *PLEASE ANSWER ALL THAT APPLIES*

Name of north-south street:

Name of east-west street:

1. Signal head type & Position:

	yes	no	not sure
Mast-arm overhead			
Side mounted			
Span wire overhead			
Monotube			

Other / comment

2. Signal lens visor/visibility: ✓ *the type you have!*

Type → Approach ↓	tunnel	cut-off	programmable visibility	other please explain
North thru				
North left				
South thru				
South left				
East thru				
East left				
West thru				
West left				

Other / comment

3. Back plates? ✓ *if you have it!*

Approach ↓	yes	no	not sure
North thru			
North left			
South thru			
South left			
East thru			
East left			
West thru			
West left			

Other / comment

About information on this page

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Intersection nimber or ID	page 2 of 12	*PLEASE ANSWER ALL THAT APPLIES*
Name of north-south street:		
Name of east-west street:	82	

4. Signal lens size? ✓ *the appropriate size!*

Approach ↓	8 inches	12 inches	not sure
North thru	○	○	○
North left	○	○	○
South thru	○	○	○
South left	○	○	○
East thru	○	○	○
East left	○	○	○
South thru	○	○	○
South left	○	○	○

Other / comment

5. Is there a raised median/island?	**yes**	**no**	**not sure**
North leg	○	○	○
South leg	○	○	○
East leg	○	○	○
West leg	○	○	○

Other / comments:

6. Is there a painted median/island?			
North leg	○	○	○
South leg	○	○	○
East leg	○	○	○
West leg	○	○	○

Other / comments:

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Name of **north-south street:**

Name of **east-west street:** 83

	yes	no	not sure
7. System information?			
Isolated?	○	○	○
Coordinated	○	○	○

Other/comments:

8. If coordinated:
What is the means of coordination?

	yes	no	not sure
Hard wire	○	○	○
Radial	○	○	○
External time clock	○	○	○
Internal time clock	○	○	○
None	○	○	○

Other/Comment

9. If coordinated:
What is the control system/supervision type?

	yes	no	not sure
Closed-loop	○	○	○
Central	○	○	○
Master supervision only	○	○	○
No supervision	○	○	○

10. If coordinated:
Does your timing plan change by:

	yes	no	not sure
Time of day?	○	○	○
Time of year?	○	○	○
Day of week?	○	○	○
Special events?	○	○	○
Traffic responsive algorithm?	○	○	○

Other/comments:

11. Type of control?

	yes	no	not sure
Actuated	○	○	○
Semi-actuated	○	○	○
Pretimed	○	○	○
Preemption	○	○	○

Other/Comment

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Name of **north-south street:**

Name of **east-west street:**

12. Type of controller?

- Electro-mechanical ○ ○ ○
- Pre-NEMA solid state ○ ○ ○
- NEMA ○ ○ ○
- Type 170 ○ ○ ○

Other / comment

Please enclose all the timing, phasing, and other signal information that you might have *on computer disk or paper!*

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Intersection nimber or ID	page 5 of 12	*PLEASE ANSWER ALL THAT APPLIES*
Name of north-south street:	85	
Name of east-west street:		

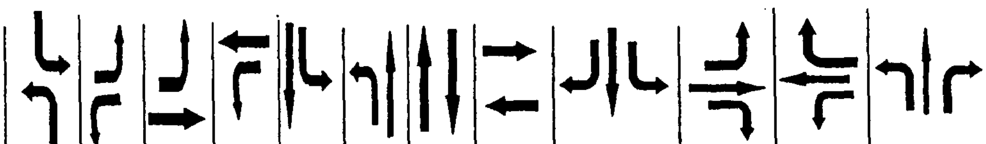
13. (GOOD LUCK):

Pretimed Check the movement in the signal phase sequence.

Actuated: If known, check the predominant movement in the signal phase sequence and note the time period for it.
Use additional sheets for multiple time periods.
TIME PERIOD:____________________

Time: Please write the corresponding green, and yellow + all red times at the bottom of the table.

	yes	no	may be so!
Actuated?	○	○	○
Pretimed?	○	○	○
Semi-actuated	○	○	○
Times shown below are in seconds	○	○	○
Times shown below are in percents	○	○	○



1st phase	○	○	○	○	○	○	○	○	○	○	○	○
2nd phase	○	○	○	○	○	○	○	○	○	○	○	○
3rd phase	○	○	○	○	○	○	○	○	○	○	○	○
4th phase	○	○	○	○	○	○	○	○	○	○	○	○
5th phase	○	○	○	○	○	○	○	○	○	○	○	○
6th phase	○	○	○	○	○	○	○	○	○	○	○	○
7th phase	○	○	○	○	○	○	○	○	○	○	○	○
8th phase	○	○	○	○	○	○	○	○	○	○	○	○
Pretimed Green:												
Actuated Avg. Green												
Yel. + all red												
Left turn Permitted?							○	○				

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Intersection number or ID *PLEASE ANSWER ALL THAT APPLIES*

Name of north-south street:

Name of east-west street: 86

14 Number of timing plans:

	1	2	3	4	5
How many timing plans are you running?	◯	◯	◯	◯	◯
Corresponding cycle length	___	___	___	___	___

Other/comment:

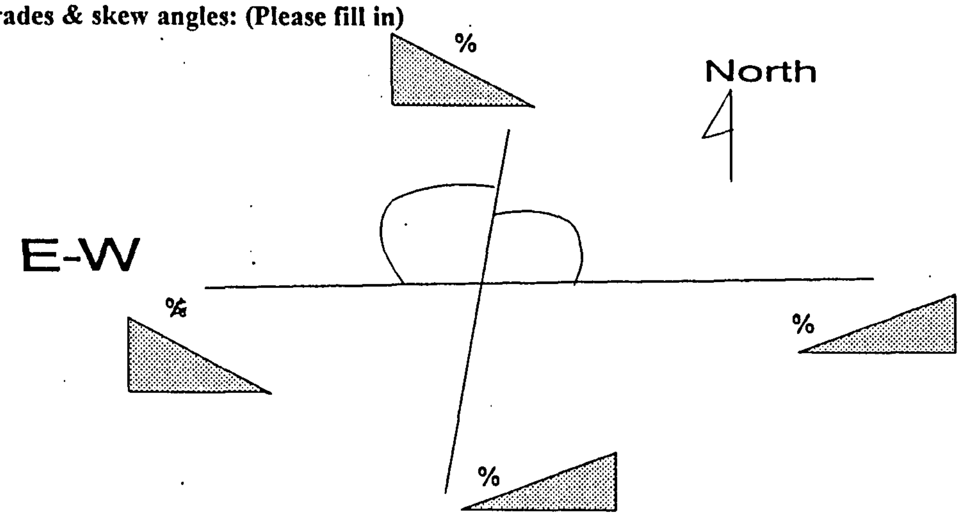
15. Number of lanes, lane widths and storage capacity

Lane use → *Approach ↓*	**Right only**	**Right and thru.**	**Thru only**	**Thru and left**	**Left only**	**Right and left and thru**
N. bound (No. of lanes)						
S. bound (No. of lanes						
E. bound (No. of lanes						
W. bound (No. of lanes						

Aerage Lane Width (ft)						

Storage Capacity, If Applicable (ft)						
Other / Comment						

16. Approach grades & skew angles: (Please fill in)



17. How close to the intersection is on street parking permitted?

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Intersection nimber or ID	page 7 of 12	*PLEASE ANSWER ALL THAT APPLIES*
Name of north-south street:		
Name of east-west street:		

0 ft	10 ft	20 ft	30 ft	40 ft	50 ft	60 ft
◯	◯	◯	◯	◯	◯	◯

Other / comment

18. Type of parking

Type of parking:	parallel	angled	none	other
	◯	◯	◯	________

19. Posted speed limit (M.P.H.):

N. bound	
S. bound	
E. bound	
W. bound	
Other / comment	

IF POSSIBLE PLEASE IDENTIFY THE GEOMETRIC DETAILS OF THE INTERSECTION, SUCH AS SHOWN ON FIGURE 1, ON A ROUGH SKETCH

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Name of north-south street:

Name of east-west street:

20. Left turn movement treatment

type → *Approach* ↓	permissive left turns	protected left turns	permissive/ protected	permissive / protected (protection activated only by certain length of queue.)	other
N. bound					
S. bound					
E. bound					
W. bound					

other/comment

21. Street (intersection) lighting

Approach ↓	yes	no	not sure
N. bound	◯	◯	◯
S. bound	◯	◯	◯
E. bound	◯	◯	◯
W. bound	◯	◯	◯

other/comment

22. Lane alignment

Do opposing left turn lanes line up

Approach ↓	yes	no	not sure	alignment with	N/A
N. bound	◯	◯	◯		◯
S. bound	◯	◯	◯		◯
E. bound	◯	◯	◯		◯
W. bound	◯	◯	◯		◯

other/comment

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Name of north-south street:

Name of east-west street:

23. Restriction/Regulation facing the approaching traffic

Regulation → *Approach* ↓	no left turns	no right turns.	do not enter	other
N. bound				
S. bound				
E. bound				
W. bound				
other/comment				

24. Advance warning signs?

Approach ↓	yes	no	not sure	if yes: what is it
N. bound	◯	◯	◯	
S. bound	◯	◯	◯	
E. bound	◯	◯	◯	
W. bound	◯	◯	◯	
other/comment				

25. Dilemma zone protection:

Approach ↓	yes	no	not sure	N/A
N. bound	◯	◯	◯	◯
S. bound	◯	◯	◯	◯
E. bound	◯	◯	◯	◯
W. bound	◯	◯	◯	◯

other/comment

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Name of north-south street:

Name of east-west street: 90

26.

Pedestrian signal information

✓ THE ITEM IF IT EXISTS

Across↓	pedestrian signal head	pedestrian push button	not sure	walk time (seconds)	flashing don't walk time (seconds)	other
North leg	◯	◯	◯			
South leg	◯	◯	◯			
East leg	◯	◯	◯			
West leg	◯	◯	◯			

other/comment

27. Changes, Changes, changes

Changes in ↓	✓ here if yes	date of change	explain
traffic generation (new commercial developments, closings, etc.)	◯		
intersection layout or road construction	◯		
signal hardware and equipment	◯		
timing, phasing, etc.	◯		
other/comment			

28. Area Type: ✓ one:

C.B.D ◯ **OTHER** ◯

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☐ **contact me.**

Name of **north-south street:**

Name of **east-west street:**

PLEASE DO NOT FORGET TO ENCLOSE THE MOST RECENT TRAFFIC VOLUME COUNTS AND INFORMATION

ON PAPER, DISK, OR OTHERWISE!

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Intersection Geometry

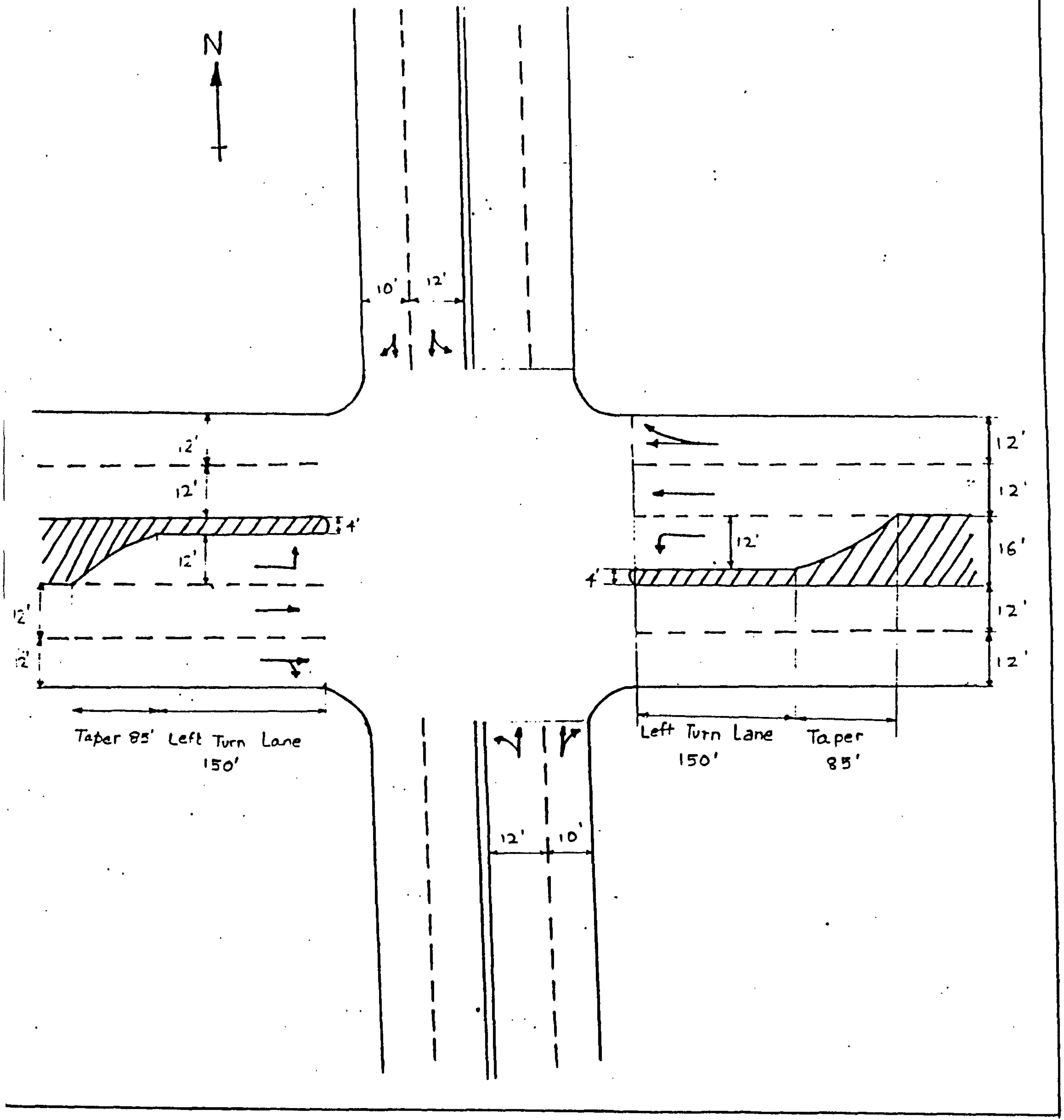

Figure 1

APPENDIX B

CALCULATION OF ACCIDENT RATES

Annual Average Daily Traffic

The traffic volumes obtained from the different agencies were in the form of peak hour turning movement counts, or annual average daily turning movement counts. The database was developed using AADT, so evening peak hour turning movement counts needed to be converted to AADT. In this appendix, the calculation used to make this conversion is shown. Conversion of peak hour traffic counts and average daily traffic to AADT was done using the reference, "Automatic Traffic Recorders 1982 - 1991," prepared by the Iowa Department of Transportation.

Assume that a traffic volume on a street during the evening peak hour (4:30 PM to 5:30 PM) on an average weekday is "X." An average weekday is typically considered to be a Tuesday, Wednesday, or Thursday when there was no unusual events or weather. Figure 1 contains a graph showing the hourly distribution of daily traffic on municipal streets in Iowa during 1991. Traffic during the evening peak represented about 8% of daily traffic. The factor for converting the evening peak hour traffic to average daily traffic (ADT) was determined as follows:

$$ADT = X / 0.08$$
$$ADT = 12.5\ X$$

With this value of ADT, the AADT can be estimated from Figure 2. From the graph in Figure 2 , ADT is about 103% of AADT. To determine the yearly traffic, the following calculations were necessary:

$$ADT = 103\%\ \text{of}\ AADT$$
$$12.5\ X = 1.03\ AADT$$
$$AADT = 12.5\ X / 1.03$$
$$AADT = 12.1\ X$$
$$\text{Number of vehicles in one year} = 365\ AADT$$

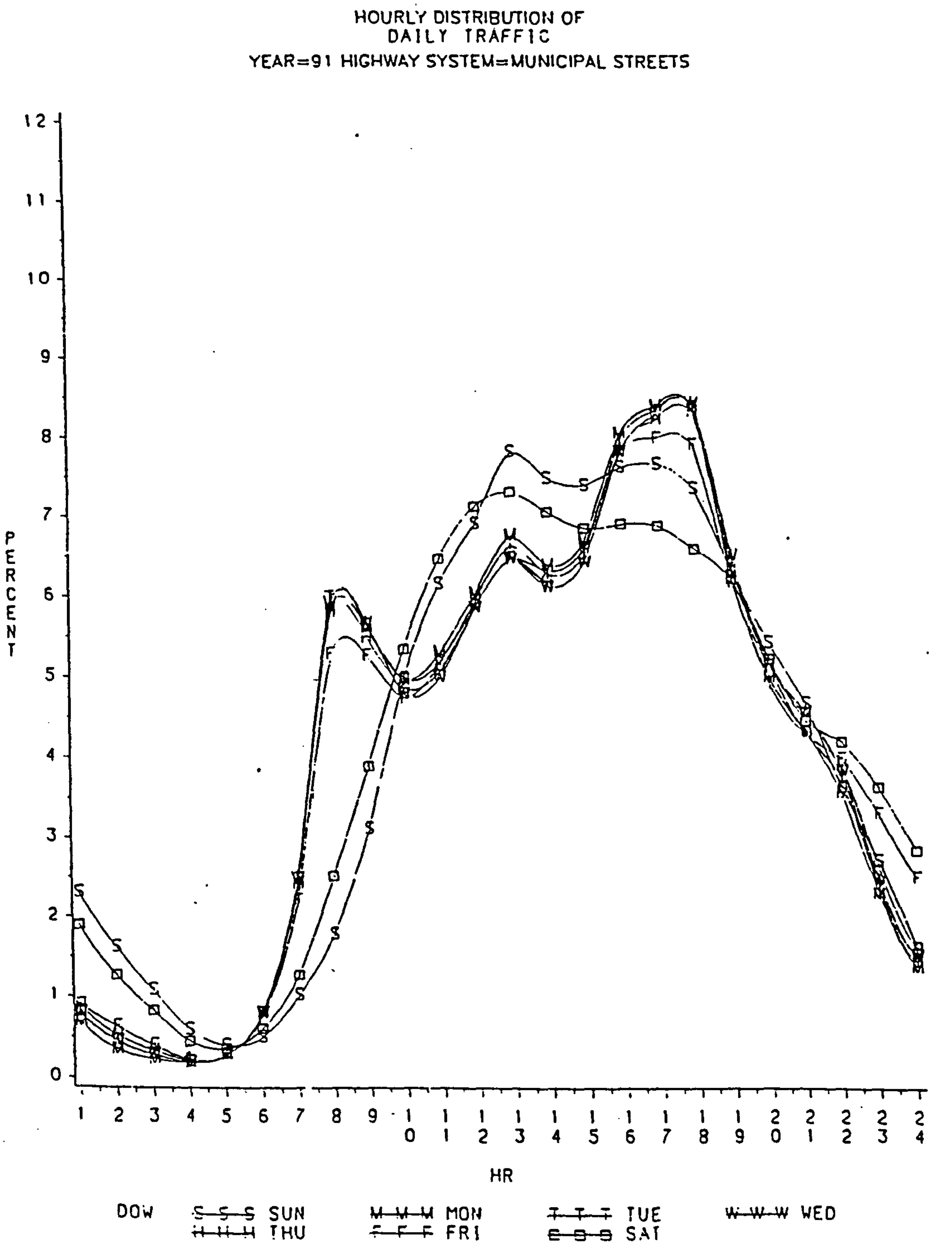

Figure 14: Hourly Distribution of Daily Traffic on Municipal Streets in Iowa During 1991
Source: Automatic Traffic Recorders 1982 - 1991 (Iowa Department of Transportation)

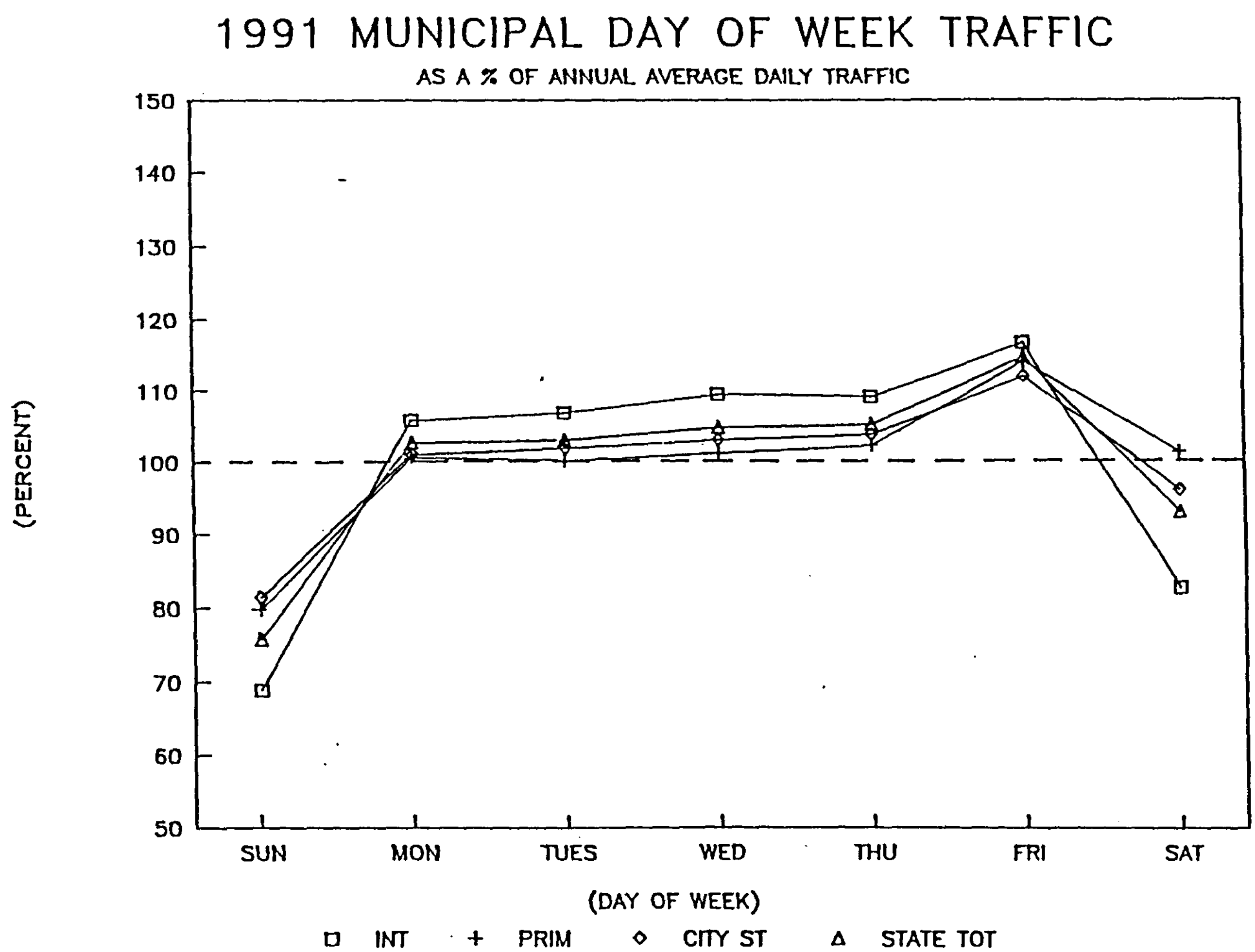

Figure 15: 1991 Municipal Day of Week Traffic in Iowa
Source: Automatic Traffic Recorders 1982 - 1991 (Iowa Department of Transportation)

Accident Rates

For the calculation of accident rates, the number of left-turn accidents, and other accidents on an approach in five years were obtained from the ALAS report. The "Left-Turn Accident Rate" (LACCRATE) is the number of left-turn accidents per million left-turning vehicles on the approach. It is calculated as follows:

$$\text{LACCRATE} = \text{No. of Left-Turn Accidents / No. of Left-Turning Vehicles} \times 10^{-6}$$

The "Approach Accident Rate" (ACCRATE) is the number of accidents on an approach per million vehicles on the approach. It is calculated as follows:

$$\text{ACCRATE} = \text{No. of Approach Accidents / No. of Approach Vehicles} \times 10^{-6}$$