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16. Abstract (Limit: 200 words)

The purpose of this research was to evaluate the safety and operational characteristics of two-way left-turn lanes (TWLTLs) compared to four-lane undivided roadways in Minnesota. Research tasks to achieve this purpose consisted of a comprehensive literature review, data collection from the identified study sites, and statistical data analysis.

Nine study sites were selected, located throughout the state of Minnesota. Operational and crash data were analyzed before and after the conversion from a four-lane undivided roadway to a three-lane roadway with a TWLTL. The results of a yoked/group comparison analysis showed statistically significant reductions in total crashes, PDO crashes and left turn crashes. The percentage reductions in total crashes, PDO crashes and left turn crashes after the conversion were approximately 37 percent, 46 percent and 24 percent, respectively. The reductions in crash rates for total crashes and PDO crashes were found statistically significant and the percentage reductions were 46 percent and 45 percent, respectively. Additionally, the change in the mean speed and 85th percentile speed were found statistically significant, but in both cases the change was less than two miles per hour.

The results of this research show that safety characteristics of a roadway are improved when a four-lane undivided roadway is converted to a three-lane roadway with a TWLTL when daily traffic volumes are less than 17,500 vehicles per day.

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SAFETY AND OPERATIONAL CHARACTERISTICS OF TWO-WAY LEFT-TURN LANES

Final Report

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EXECUTIVE SUMMARY

Introduction and Objectives

Traditional improvements to four-lane undivided and four-lane divided roadways having operational and safety problems have been limited to cross-section expansions including the addition of extra travel lanes, installing a raised median or adding a center two-way left turn lane. These improvements typically result in an increase in the roadway cross-section width. Recently, converting a four-lane undivided roadway to a three-lane roadway with a two-way left-turn lane (TWLTL), without changing the cross-section width, has been considered a viable alternative by traffic engineers to improve the safety of these roadways. Minnesota has implemented several of these four-lane to three-lane conversions; however, no Minnesota-based research has been completed to evaluate the safety and operational effects of these conversions.

There is a renewed interest in three-lane roadway cross-sections with a TWLTL in Minnesota because of documented success in other states. It is unclear if these cross-sections are safer and/or more operationally efficient when compared to the traditional four-lane roadways that they replaced. Therefore, research was needed in Minnesota to compare the operational and safety characteristics of three-lane cross-sections with TWLTLs to four-lane roadways.

The objective of this research was to evaluate the safety and operational characteristics of three-lane cross-sections with a TWLTL compared to four-lane undivided roadways. Specifically, the primary objective of this research was to compare the crash rates and operational characteristics to determine if the roadways constructed with a TWLTL are safer and/or operationally more efficient. Research tasks to achieve this purpose consisted of a comprehensive literature review, data collection from the study and comparison sites, analysis of the data, and documentation of results.

This research considers the following safety and operational impacts of the conversions:

- Change in the number of crashes;
- Change in the severity of the crashes;
- Change in the type of crashes;
- Change in operating speed (mean and 85th percentile speed); and
- Change in the ADT.

In addition to these safety and operational impacts, other relevant changes in roadway conditions and access were investigated.

A comprehensive literature review was conducted which included a summary of research findings from four-lane to three-lane with TWLTL conversions in several different states. Based on the literature, it is clear that the overall safety of a roadway can be enhanced by the conversion when the appropriate operational conditions exist. Nearly all of the published research studies found positive improvements in safety with little impact to traffic operations.

This research selected study and comparison sites in Minnesota. All the sites considered in this research were three-lane roadways with TWLTL, converted from a four-lane undivided roadway. A total of nine study sites were selected including two that were converted in 2005 where operational data were collected by visiting the sites before and after conversion.

Before and after speed data and average daily traffic (ADT) data were available for six study sites and nine study sites, respectively. Crash data analysis was conducted at the seven sites that were converted to a three-lane roadway prior to 2005. Over 20 years of crash data for the study and comparison sites were available and obtained from the Minnesota Department of Transportation (Mn/DOT) crash database, although the primary evaluation was limited to crash data five years prior to and five years after the conversion.

Operational before and after data considered in this research included ADT, mean speed, and 85th percentile speed. General information about each site and corresponding operational data were obtained by a variety of data collection methods including site visits, pneumatic traffic counters, LIDAR speed guns, photographs, and videotaping.

Crash data were categorized by severity and type. Changes in total, injury, property damage only (PDO), rear end, right angle, and left-turn crashes due to the conversion were analyzed. Fatal crashes were not considered in this research as none occurred during the study period. A ‘before’ and ‘after’ statistical modeling approach was used to analyze the data.

Results showed that the change in ADT after the cross-section conversions was not statistically significant. Traffic volumes remained consistent or grew slightly at most study sites. Change in the mean speed and 85th percentile speed before and after conversion was found to be statistically significant but not large in magnitude. The average reduction in the mean and 85th percentile speed after conversion was 1.88 miles per hour (mph) and 1.66 mph, respectively.

A yoked/group comparison analysis of crashes found the reduction in total crashes, PDO crashes and left turn crashes to be statistically significant. The percentage reductions in total crashes, PDO crashes and left turn crashes after the conversion were approximately 37 percent, 46 percent and 24 percent, respectively. The reductions in crash rates (per vehicle mile traveled) for total crashes and PDO crashes were also found to be statistically significant with percentage reductions of approximately 47 percent and 45 percent, respectively.

The crash analysis was also completed using the Empirical Bayes (EB) statistical approach. The reduction in total crashes was found to be 44 percent which compared favorable to the yoked/group comparison results. Further, simplified traditional approaches were used to determine how the results may vary based on analysis method selection. The traditional approaches found a reduction in total crashes to be between 42 and 43 percent, also consistent with the previous results. It is concluded that the four-lane to three-lane conversion was effective in reducing total, PDO, and left turn crashes.

Research results show that safety characteristics of a roadway can be improved when a four-lane roadway is converted to a three-lane roadway with a TWLTL. It is important to note that the study sites evaluated in this research had ADT values ranging from approximately 8,900 to 17,400 vpd. Existing and projected operational conditions of the roadway are significant in determining the effectiveness of the four-lane to three-lane with TWLTL conversion.

Research findings along with the literature suggest that four-lane to three-lane conversions is a recommended option if the roadway of interest is experiencing safety problems. It is recommended that four-lane to three-lane conversions be considered only if the projected ADT of the roadway is less than 17,500 vpd. For higher daily traffic volumes, additional analysis should be completed before considering a four-lane to three-lane conversion.

Chapter 1
INTRODUCTION

BACKGROUND

A widespread and growing network of urban four-lane undivided and median divided roadways exists in United States. Increasing traffic volumes on these roadways have led to escalating congestion and safety problems. An effort to accommodate the growing number of vehicles on the roadway, without compromising safety, has led transportation professionals to explore new methods in roadway design and operations.

Traditional improvements to the four-lane undivided and median divided roadways having operational and safety problems have been focused on adding travel lanes, installing raised medians, or adding a center two-way left turn lane (TWLTL) to the existing cross-section. These improvements generally result in an increased roadway cross-section width. The problem lies in locations where operational and safety improvements are needed but no additional cross-sectional space is available. To address this problem, recent efforts have explored converting a four-lane undivided roadway to a three-lane roadway with a center TWLTL, and no change in cross-section width. It is hypothesized that this new three-lane cross-section may be a viable alternative to maintain roadway operations and improve safety at appropriate locations.

Roadway cross-sections with TWLTL provide a single center lane, usually 15 to 18 feet in width that can be used by left-turn traffic in both directions to complete a left-turn maneuver. Cross-sections with a TWLTL commonly provide one through-lane in each direction with a TWLTL in the center; however, a TWLTL has also been used in cross-sections with two through-lanes in each direction. Examples of a five-lane roadway with a TWLTL and three-lane roadway with a TWLTL are presented in Figures 1.1 and 1.2.

The use of a TWLTL can improve safety by reducing vehicle speeds and interactions during lane changes, moving the left-turn vehicles out of the through lanes of traffic. Traditional TWLTL installation involves adding the TWLTL to the existing cross-section thereby adding an extra lane to the existing lane configuration. Recent installations of TWLTLs have involved a reduction in the overall number of through lanes by removing the two center through lanes and converting them into a single center TWLTL. Converting a four-lane undivided roadway into a three-lane cross-section is a relatively new concept, and is popularly referred to as a "road diet". The term "road diet" may also be used to refer to conversion of a six-lane cross-section to a five-lane section with a TWLTL. The existing pavement area of the four-lane roadway is reallocated, most often by simply changing the pavement markings. This type of conversion is particularly suitable for the sites where the existing roadway and pavement conditions are in acceptable condition. The additional pavement made available from the former fourth lane may be used to provide additional lane width or be converted to bicycle lanes or on-street parking.

Figure 1.1. Five-lane Roadway with TWLTL

Figure 1.2. Three-lane Roadway with TWLTL

Although logic would suggest that the removal of a through traffic lane would result in a roadway capacity reduction, in practice, this is generally not the case. The reason for this is because on some four-lane roadways, especially during the peak hour, the inside lanes are used by left turning vehicles only, becoming 'defacto' left-turn lanes. Through traffic avoids the inside lanes because of the potential delay and being stopped behind left-turning vehicles. Therefore, the four-lane roadways which can be considered an ideal candidate for "road diets" are the roadways that operate as a 'defacto' three lane roadways during various hours of the day.

The literature highlights several potential benefits of four-lane to three-lane conversions including (*1*, *2*):

- Left-turning vehicles are separated from the through traffic;
- Left-turning vehicles have a lane where they can stop and wait for a gap in the opposing through traffic before making the left turn maneuver;
- Left turning vehicles will no longer stop through traffic as they search for a gap;
- Left turning vehicles have to select a gap through one lane of traffic instead of having to do so through two lanes of traffic;
- Additional lane space can be made available to accommodate other modes of travel;
- Vehicle speeds may be reduced; and
- Lane interactions are reduced.

Other site-specific operational and safety benefits are possible.

PROBLEM STATEMENT

Roadway cross-sections with a TWLTL have been used extensively around the U.S., with documented success in nearly all instances. Minnesota has also implemented a number of roadway sections with a TWLTL; however, no research has been completed to evaluate the effectiveness of these installations. There is a renewed interest in TWLTLs in Minnesota because of documented success in other states. It remains unclear if these cross-sections are safer and/or more operationally efficient compared to the traditional four-lane roadways that they replaced. Therefore, research is needed in Minnesota to compare the operational and safety characteristics of three-lane cross-sections with TWLTLs to four-lane undivided roadways.

RESEARCH OBJECTIVE

The objective of this research was to determine the safety and operational effects of roadway cross-sections with TWLTLs when compared to the cross-sections they have replaced. Specifically, the primary objective of this research was to compare the crash rates and operational characteristics of three-lane roadways with a TWLTL to four-lane undivided roadways. Using appropriate statistical procedures, the results will determine if three-lane roadways with a TWLTL are safer and/or operationally more efficient. To meet this objective, each selected site was evaluated before and after the cross-sectional change. Note that the availability of study sites led this research to consider only 4-lane undivided roadway conversions.

This research considers the following safety and operational impacts of the conversions:

- Change in the number of crashes;
- Change in the severity of the crashes;
- Change in the type of crashes;
- Change in operating speed (mean and 85th percentile speed); and
- Change in the ADT.

In addition, other relevant changes in roadway conditions and access were investigated.

RESEARCH TASKS

The methodology adopted to meet the objectives of this research consists of four tasks. A brief description for each task is provided below.

Task 1. Literature Review

A comprehensive literature review was conducted which included both published and unpublished literature along with design manuals and other relevant information. The literature review was performed throughout the duration of the research to provide a state-of-the-knowledge review of the safety and operational effects of TWLTLs and to assure that the most recent information available was included. All elements of the literature review are presented in Chapter 2.

Task 2. Data Collection

This task consisted of identifying appropriate study sites and associated comparison sites across Minnesota. Each site selected required both before-and-after crash and operational data. A total of nine sites across Minnesota were identified for this research. The site selection process is described in the *Data Collection* section. Site selection was based largely on the timing of TWLTL installations and availability of before-and-after crash and operational data. Data collected consisted of crash and operational data measured before-and-after implementation of the TWLTLs. Site selection and data collection were conducted with the assistance of Mn/DOT and local officials. Background data of the study and comparison sites were collected by visiting, photographing and videotaping each site. Operational data such as speed and volume data were collected by a variety of methods. Crash data for the study and comparison sites were obtained from the Mn/DOT crash database.

Task 3. Data Analysis

Crash and operational data were collected and analyzed using appropriate statistical procedures. The statistical procedures which were used in this research are presented in the *Overview of Statistical Procedures* section.

Task 4. Reporting the Results

The findings from the previous tasks were used to generate conclusions and recommendations pertaining to the use of TWLTLs in Minnesota. The results generated by this research are presented in chapter 4. The conclusions and recommendations are presented in chapter 5.

SCOPE

The safety benefit of four-lane to three-lane with TWLTL cross-section conversions is well documented. This research considered both the safety and operational effects of TWLTLs, and was limited to analysis of nine sites located in Minnesota which had sufficient before and after safety and operational data. All the nine sites considered in this research were three-lane roadways with TWLTLs which where converted from four-lane undivided roadways. The study period was five years before and after conversion, although not all the sites had five years of 'after' data. Five years of 'before' crash data and five or less than five years of 'after' crash data from the conversion date were considered in evaluating the safety effects of the four-lane to three-lane roadway conversion.

REPORT ORGANIZATION

This report consists of five chapters that parallel the research tasks, including this introductory chapter. Chapter 2 consists of a comprehensive literature review which provides a state-of-the-knowledge review of the safety and operational effects of TWLTLs. Chapter 3 documents the data collection process and statistical analysis procedure used in this research. Chapter 4 presents the data obtained and results of the data analysis. Chapter 5 presents the conclusions and recommendations.

Chapter 2
LITERATURE REVIEW

A considerable amount of literature currently exists on four-lane to three-lane conversions and the safety and operational benefits of two-way-left-turn-lanes (TWLTL). This abundance of literature has not always been the case as many of the publications have been produced in the last few years. Most of the early TWLTL literature focused on adding a TWLTL while maintaining the existing number of through-lanes, such as conversion of a two-lane undivided road to a three-lane TWLTL, or conversion of a four-lane roadway into a five-lane roadway with a TWLTL (*4 – 18*). Such conversions resulted in either an expansion of the overall roadway cross-section, narrower lane widths, shoulder elimination, or some combination of these.

The concept of converting four-lane undivided roadways to three-lane TWLTLs by simply changing the pavement marking configuration, often referred to as a "road diet", was rather uncommon in the United States and not well-researched until the 1990's (*1 – 3, 19 – 29*). As presented in Figure 2.1, the concept of "road diet" involves modifying the cross-section of a four-lane undivided roadway to a three-lane cross-section that includes two through lanes plus a center TWLTL.

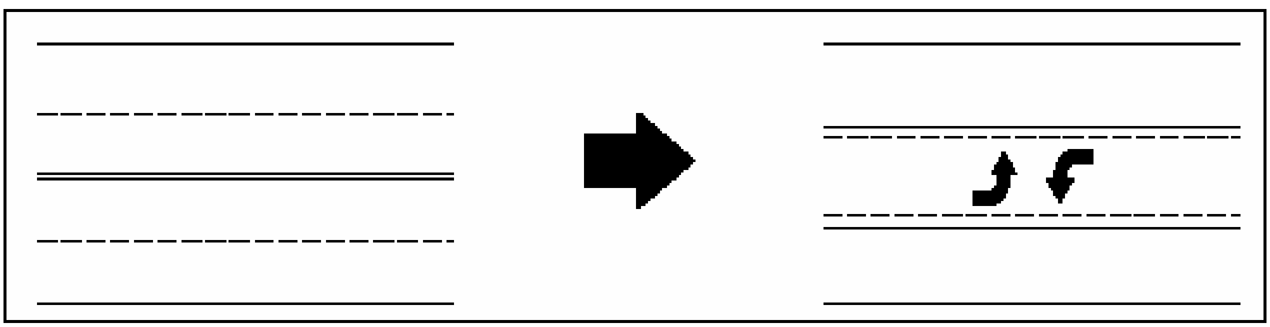

Figure 2.1. Four-lane Undivided Roadway to Three-lane Roadway with TWLTL (*20*)

The additional pavement made available from the former fourth lane may be used to provide additional lane width or be converted to bicycle lanes or on-street parking. Similarly, conversion of six-lane undivided roadways to five-lane cross-sections with a TWLTL can also be completed with a low-cost modification of an existing road cross-section. The potential benefits of these conversions (i.e., safety improvements without significant changes in capacity) were not immediately realized, likely due to the unfounded fear of capacity reduction and the associated negative public perception. Four-lane to three-lane (or six-lane to five-lane) TWLTL conversions are now commonplace in many urban/suburban areas of the United States.

EARLY TWLTL RESEARCH

Early use of TWLTLs was limited largely due to the fear of head-on conflicts and resulting crashes that would arise from competing opposing left-turns. However, a before and after analysis of crash data collected by Hoffman at four locations in Michigan in 1974 revealed that all crashes were reduced by 33 percent and there was a significant decrease in head-on collisions after the installation of a TWLTL (*4*). The hypothesis of increased head-on conflicts was further dispelled in research done by Walton and Machemehl in Texas in the late 1970's that analyzed driver maneuvering and positioning on the approach to and within TWLTLs (*5*). At sites ranging in ADT from 12,000 to 31,000 vpd, researchers found that most "anticipated" conflicts rarely occur, and when they do, are handled most often with appropriate driver judgment for avoidance. The authors concluded that the fear of conflicts and subsequent increase in head-on and other related crashes after implementation of a TWLTL was unfounded.

In 1978, Nemeth published results of research focused on the use and implementation of TWLTLs (*6*). This study included numerous before-and-after field evaluations of various cross-section conversions, including one of the first analyses of a four-lane to three-lane TWLTL conversion on US 20 in Painesville, Ohio. The 0.95 mile section of US 20 carried approximately 16,000 vehicles per day (vpd) with a posted speed limit of 45 miles per hour (mph). After the conversion, crash severity decreased, average speeds were found to have decreased by roughly seven miles-per-hour, and the roadway improved its access function. Brake applications decreased by 22 percent and although there was an observed increase in weaving maneuvers, this was corrected with proper removal of the old centerline.

Thakkar used a before and after design methodology to determine the effect of TWLTLs in Illinois considering various measures of effectiveness (*7*). The crash and traffic volume data from 15 five-lane roadways with a TWLTL and 16 three-lane roadways with a TWLTL where a TWLTL was added to the existing cross-section were collected. Total crashes, affected crashes (left turn, rear end, and sideswipe crashes), crash rates, and severity were tested for statistically significant differences from the before period to the after period. Wilcoxon and paired t-tests (at a 95 percent confidence level) were used. The author reported that for the five-lane sections ranging in ADT from 10,600 to 27,900 vpd, the left turn, rear end and sideswipe same-direction crashes were significantly reduced. For the three-lane sections ranging in ADT from 3,800 to 21,100 vpd, there was no significant reduction in any of the three crash types. Nevertheless, when the affected crashes were considered collectively, the crash reductions were statistically significant for both the five-lane and three-lane sections.

Another goal of the Illinois research was to determine the cost effectiveness of the TWLTL design (*7*). An economic analysis of the TWLTL design was done by assuming an interest rate of 8 percent, the improvement would last for a period of 15 years, and the salvage value of the improvements was zero. The two approaches considered for the economic analysis were benefit/cost (B/C) ratios and a cost effectiveness analysis. Only the savings in the crashes were considered as benefits of the improvements. Other potential benefits, such as improved mobility, driving comfort, and savings in time and fuel, were not considered in the economic analysis. The B/C ratios for five-lane roadways were found to be above the benchmark level of 1.0 for various interest rates, service lives, and salvage values. The five-lane improvements were also found to be cost effective for various interest rates, service lives, and salvage values. Three-lane improvements were found to be cost effective for interest rates less than 12 percent, service lives longer than ten years, and salvage values greater than or equal to ten percent. The author concluded that the TWLTL design was both safe and cost effective.

Early TWLTL research did not focus on the four-lane to three-lane conversion. In addition, the magnitude of the safety improvements reported are viewed with skepticism because of the study site selection biases and statistical procedures used. A more detailed look at converting four-lane to three-lane TWLTL using more robust statistical procedures was not performed until the 1990s.

RECENT TWLTL RESEARCH

Increasing the capacity of an existing urban or suburban roadway is often desirable given the steady increase in traffic volumes and vehicle miles traveled. One of the methods often used to increase capacity is to increase the width of the roadway, or in other words, add more lanes to the existing cross-section. This method may not be implemented easily in a congested urban area due to limited right-of-way and other physical constraints. In such cases, the capacity of the road can be increased by changing the cross-section or by traffic signalization improvements such as retiming, progression, and computerized control. Changes to the cross-section of the existing roadway involve the reallocating of the road width by eliminating or narrowing an existing feature such as a median, parking lane, and/or a turning lane. Adding a raised median or a turn lane to the existing lane configuration is another popularly recommended method of increasing the safety and operational characteristics of the roadway.

All the above-mentioned methods result in the widening of the road, potentially causing conflicts with non-motorized road users and difficulty due to the physical constraints. However, roadway capacity may be increased without widening the existing road by using the "road diet" concept of eliminating the two center through lanes and converting them to a single TWLTL. The advantages of this low cost alternative can be improved safety and acceptable operations. Moreover, the extra width made available from the elimination of one lane can be utilized by adding a bike or parking lane.

Harwood discussed the performance of a variety of roadway cross-sections, including three-lane TWLTLs in NCHRP Report 282 (*8*). Analysis of five years of crash history, from suburban highways on the state highway systems of California and Michigan considering the effects of nine variables (ADT, truck percentage, type of development, estimated level of left turn demand, lane width, shoulder width, speed, driveways per mile, and unsignalized intersections per mile) revealed that the three-lane TWLTLs had the lowest total crash rates (non-intersection crashes and unsignalized intersection crashes) for commercial areas. He reported that converting a two-lane undivided cross section to a three-lane TWLTL would be expected to result in an 11 to 35 percent reduction in crashes (average ADT at these study sites was approximately 14,600 vpd). Similar crash reductions were also expected for conversions of suburban four-lane undivided roadways to five-lane TWLTLs (average ADT at these study sites was approximately 26,700 vpd). Some of the advantages and disadvantages of adding TWLTLs were:

- Advantages:
    - Reduced delay to through vehicles;
    - Reduced frequency of rear-end and angle crashes;
    - Reduced frequency of head-on crashes; and
    - Increased operational flexibility.

- Disadvantages:
  - Requires greater right-of-way;
  - May eliminate shoulders;
  - May encourage strip commercial development; and
  - May cause safety problems at closely spaced driveways or intersections.

NCHRP 282 research did not quantify the safety and operational performance of the six-lane divided and seven-lane with TWLTL cross-sections. It was expected that the safety and operational performance would be similar to the four-lane undivided roadways to five-lane TWLTLs. In practice, it appears that highway agencies limit the use of the seven-lane TWLTL cross-section to residential and light commercial areas with relatively low left turn volumes since left-turns must cross three lanes of opposing traffic and there would likely be an increased volume of left turns in more heavily commercialized areas that would not be adequately served by a TWLTL. Linear regression equations developed by Squires indicated that the six-lane divided roadway would be safer than the seven-lane TWLTL roadway but under certain conditions such as low traffic volume, high driveway density, and fewer signalized intersections and approaches, the seven-lane TWLTL roadway would have lower crash rates (*9*). ADT values at the study sites used in this research ranged from approximately 23,700 to 47,700 vpd.

The Georgia Department of Transportation retrofitted a seven-lane TWLTL roadway to six-lane raised median in the 1990s as there were a high number of crashes, especially mid-block crashes, high number of pedestrian fatalities, and increasing traffic volume (*10*). The site included 4.34 miles of Memorial Drive in a commercially developed area of Atlanta with an ADT of approximately 50,000 vpd. The benefits of converting the seven-lane TWLTL roadway to six-lane raised median were immediately realized. In a year after the conversion, there was a 37 percent reduction in total crash rate and a 48 percent drop in the injury rate. A traffic volume reduction of 12 percent was observed within the project whereas a traffic volume reduction of 5.5 percent was observed outside the project. Note that other major construction projects were taking place during this research and the Memorial Drive area in general experienced some business and commercial closings or transitions during the period that may have influenced the decrease in traffic volumes.

Researchers also reported the long-term impacts of the conversion of the seven-lane section with TWLTL to six-lane raised median section on the safety and abutting business activity after eight years of the raised median (*11*). Until 1998, not a single fatality took place in the seven years after the project completion whereas in the 11.6 years preceding the project there were 15 fatalities, including six pedestrian fatalities. Recently, the magnitude of the crash rate reduction began decreasing leading researchers to question if the raised median was losing its effectiveness. Further data analysis by normalizing the data and establishing crash indices using a base of 1.00 for the county wide data revealed that the increase in the crash rate was part of an overall trend. The project did have a negative impact on the abutting businesses but there were other socioeconomic factors such as the development of a rapid rail system which could have contributed to the loss of businesses. There was also a business recession throughout the United States at the time when the median was built and opened to traffic.

NCHRP 282 research did not consider the "road diet" concept for TWLTL applications (*8*). Many of the aforementioned disadvantages of TWLTLs disappear when applying road diets.

For example, the overall size of the roadway usually remains unchanged and shoulder elimination or right-of-way addition is not likely encountered. Road diets will typically not encourage strip commercial development, since development typically has already occurred and the addition of a TWLTL is meant to relieve the operational and safety problems caused by traffic turning left into commercial developments.

Harwood expanded on his previous research in NCHRP 330 (*12*). Researchers analyzed improvement strategies for urban arterial streets that would change the geometric characteristics of the street without changing the total curb-to-curb street width. In most cases, this simply involved changing the layout and narrowing existing lanes, but did not include road diets. Seventeen sites with ADTs ranging from 8,900 to 56,900 vpd were analyzed that involved conversion from four-lane undivided to five-lane with a TWLTL. On average, this type of conversion reduced the mid-block crash rate by 45 percent. Similarly, conversion of six-lane divided with narrow medians (ADTs ranged from 24,400 to 29,200 vpd) to seven-lane TWLTLs reduced the mid-block crash rate by 32 percent. Harwood concluded that installations of TWLTLs at sites where they previously did not exist will typically reduce crashes even if the project incorporates narrower lanes.

TRAF-NETSIM micro-simulation models were developed in 1992 to study delay and fuel consumption, two broad measures of the operational effectiveness for TWLTL and non-traversable medians (*13*). Both the design alternatives had two through lanes in each direction. The variables in this simulation were driveway density (two levels- 32 driveways/mile and 64 driveways/mile), traffic volume (three levels- 600 vph, 900 vph, 1200 vph) and two alternative designs (TWLTL and non-traversable medians). It was found that the average delay and fuel consumption were greater in the case of the non-traversable medians compared to the TWLTL and the difference increased at higher levels of driveway density and through volumes.

U.S. state highway engineers completed surveys pertaining to the use of TWLTLs in 1993 (*14*). The survey questionnaire consisted of 14 questions and three case studies regarding the choice of median and TWLTLs. The results showed that the choice between implementing a TWLTL versus a median treatment was not clear cut and found to be a controversial issue. In the case of choosing an appropriate median treatment for undeveloped areas, most of the responding engineers chose a non-traversable median. Reasons for this selection focused on the fact that the non-traversable median would prevent strip development. In the case of choosing an appropriate median treatment for a developed area where commercial strip development already exists, most state highway engineers opted for a TWLTL (assuming an ADT range of 13,000 to 25,000 vpd). When queried about choosing an appropriate median treatment for a residential development, there was no consensus among the state highway design engineers. Another interesting observation that could be made from this survey was that 42 percent of the states that responded had at least one case where a non-traversable median road cross-section was changed to a TWLTL whereas only 19 percent of the states had transformed a roadway with a TWLTL into a roadway with a non-traversable median.

An analysis of Tennessee crash data in 1995 for two median designs (continuous TWLTL and raised medians) and ADTs less than 32,500 vpd was completed to determine the relative safety (*15*). The study concluded that raised medians were generally safer than a TWLTL, but under high driveway densities and medium to low traffic volumes, a TWLTL would have a more favorable safety history as driveway density was found to be an important contributor to crashes for roadways with medians, but not for roadways with TWLTLs.

In NCHRP Report 395 (1997), Bonneson and McCoy compared the operational, safety, and access impacts of TWLTL roadway sections versus raised-curb median and undivided sections (*16*). The researchers modeled the impacts of the various treatments using data collected from sites nationwide. Data collected for the model included the number of through traffic lanes, the segment length, the cross-section width, the median width, the driveway and un-signalized public street approach density, the speed limit, and the average daily traffic (AADT). Adjacent land use and the presence of parallel parking were also taken into consideration. For a wide range of traffic demand and geometric conditions, TWLTLs and raised-curb medians were found to yield similar delays to arterial drivers, while the undivided sections yielded significantly higher delays. At sites where parallel parking was allowed, the undivided cross sections had significantly higher crash frequencies than the TWLTL and raised-curb median sections. Where no parking was allowed, the difference between crash frequencies for undivided sections and TWLTLs was negligible for traffic volumes less than 25,000 vpd. The raised-curb median treatments generally had the fewest crashes of all treatments, especially where ADTs exceeded 20,000 vpd. Surveys of business owners discovered a general belief that arterial traffic conditions and business conditions will improve after conversion of an undivided cross section to either a TWLTL or raised-curb median, as long as the median openings occurred every 330 feet. Business owners also believed that the typical business may be able to overcome some reduction of access if that business offers good, reliable service.

The collision prediction empirical model developed by Bonneson and McCoy was recalibrated to predict collisions on four-lane median divided roadways and five-lane roadways with TWLTL segments in North Carolina (*16*, *17*). One hundred forty-three sites were randomly selected from the North Carolina Department of Transportation database of which 62 had a raised median and 81 had a TWLTL. The data collected from each site included volume, geometric, land use, and collision data. For each data set, 20 percent of the data were removed to validate the model and the calibration of the model was done using the remaining data set. Data analysis revealed that for business and office land uses with medium to high approach densities (25-90 approaches per mile), the TWLTL appeared to be slightly safer than the four-lane median divided roadway at low traffic volumes.

Analysis of 26 five-lane arterial roadways with a TWLTL in the state of Alabama with speed limits of 45 mph and higher was completed in 2005, with the objective to identify possible relationships between crash data and physical/traffic characteristics *(18)*. ADTs on the selected roadway ranged from approximately 12,500 to 71,400 vpd. Analysis of the original crash reports of the 48 head-on or side swipe crashes that occurred at the TWLTL sites established that driver action preceding the crash did not include intentionally crossing the median such as attempting a left-turn maneuver. Regression techniques failed to provide significant correlation and therefore analysis of the data range was conducted using the interquartile (IQR) method. Analysis of both the crash rate and crash frequency was done but the relatively small range of crash frequency did not result in meaningful IQR results. Based on the crash rate analysis, it was concluded that TWLTL arterials should be investigated for safety countermeasures when the crash rate exceeds 14.1 crashes per 100 million vehicle miles of travel (VMT).

ROAD DIET RESEARCH

The road diet concept is relatively new. Most of the early research on cross-section improvements for increased safety and operational efficiency focused on the addition of raised medians or TWLTLs resulting in the expansion of the overall roadway cross-section. Iowa was one of the first states to perform widespread implementation and evaluation of roadway conversions from four-lane undivided to three-lane TWLTLs and develop guidelines for their use. State traffic engineers analyzed and discussed some of the early Iowa conversions in 1999, referring to the idea as "another viable alternative tool to place in our urban congestion/safety toolbox" (*1*). Several advantages of a three-lane TWLTL section over a four-lane undivided roadway were cited, including:

- Increase in safety as a result in the decrease in the number of conflict points;
- Increase in pedestrian safety;
- Improvement of intersection sight distance; and
- Traffic calming.

The disadvantage of a three-lane TWLTL roadway compared to the four-lane roadway was found to be increased corridor delay, but may not be problematic if an acceptable level of service could be maintained (*1*).

In 1999, Burden and Lagerwey documented the case of Lake Washington Boulevard in Kirkland, Washington, which successfully pushed the capacity limits of four-lane undivided to three-lane TWLTL conversion by carrying 20,000 to 25,000 vpd (*19*). The conversion helped alleviate congestion problems around rush hour and allowed for easier driveway access. It was noted that at one point, a nearby road was closed for construction, forcing 30,000 vpd on the three-lane TWLTL section of Lake Washington Boulevard. The three-lane TWLTL cross-section successfully accommodated the increased volume. The authors also described a before and after study of nine four-lane to three-lane TWLTL conversions in Seattle, Washington where collisions were reduced considerably at six of the nine locations. Traffic volumes increased at each of the nine sites after the conversions to TWLTL.

Additional research was conducted on this topic in the early 2000's including a discussion of past research, case study examples, and factors related to the conversion of four-lane undivided roadways to a three-lane cross-section (*2*, *20*). Factors included roadway function, total traffic volume, turning volumes and patterns, weaving, speed and queues, crash type and patterns, pedestrian and bike activity, and right of way availability and cost. Based on the case study analyses, it was concluded that the conversion of four-lane undivided roadways to a three-lane cross-section could improve the safety of the roadway without decreasing the Level of Service (LOS) significantly. This research documented the successful conversion of four-lane undivided roadways to a three-lane cross-section in many areas of the United States. Table 2.1 summaries these results, including sites in Duluth and Ramsey County, Minnesota (*20*). It was concluded that a three-lane cross-section can easily be incorporated as a potential feasible alternative and present and future characteristics of several factors should be considered to determine the design period feasibility.

Table 2.1. Case Study Analysis Results (*20*)

Location	Approx. ADT	Safety	Operations
Montana			
Billings—17th Street West	9,200–10,000	62 percent total crash reduction (20 months of data)	No Notable Decrease**
Helena—U.S. 12	18,000	Improved**	No Notable Decrease**
Minnesota			
Duluth—21st Avenue East	17,000	Improved**	No Notable Decrease**
Ramsey County—Rice Street	18,700 Before 16,400 After	28 percent total crash reduction (3 years of data)	NA
Iowa			
Storm Lake—Flindt Drive	8,500	Improved**	No Notable Decrease**
Muscatine—Clay Street	8,400	Improved**	NA
Osceola—U.S. 34	11,000	Improved**	No Notable Decrease**
Sioux Center—U.S. 75	14,500	57 percent total crash reduction (1 year of data)	Overall travel speed decreased from 28–29 mph to 21 mph, and free-flow speed from 35 to 32 mph. There was a 70 percent decrease in speeds greater than 5 mph over the posted speed limit.
Blue Grass	9,200–10,600	NA	85th percentile speed reduction up to 4 mph (two locations increased 1 to 2 mph in one direction). The change in percent vehicles speeding depended upon location and direction (see discussion).
Des Moines (Note: This was a conversion from multiple cross sections to a three-lane)	14,000	NA	Average travel speed increased from 21 to 25 mph
California			
Oakland—High Street	22,000–24,000	17 percent in total crash reduction (1 year of data)	No notable change in vehicle speed
San Leandro—East 14th Street	16,000–19,300 Before 14,000–19,300 After	52 percent in total crash reduction (2 years of data)	Maximum of 3 to 4 mph spot speed reduction
Washington			
Seattle—Nine Locations	9,400–19,400 Before 9,800–20,300 After	34 percent average total crash reduction (1 year of data)	NA

*NA = Not Available. Safety data duration is for before/after conversion.
**Summarized results based on anecdotal information.

The increasing number of road diet installations in the late 1990's prompted the Iowa Department of Transportation (DOT) to create usage guidelines, which were developed in 2001 (*20*). The guidelines were based on an extensive review of the literature combined with data from 13 case studies along with an operational sensitivity analysis using the CORSIM software package. The results of the case study analyses showed a reduction in the mean and 85th percentile speeds (typically less than five mph), a 60 to 70 percent reduction in the percent exceeding five mph over the speed limit, and a reduction in total crashes between 17 and 62 percent.

The CORSIM analysis completed as a part of this research indicated only a slight decrease in average speed for through-vehicles for a large range of volumes, access densities, and left-turn volumes (*20*). The case study corridor evaluated was a quarter mile long arterial segment bound on each end by a signalized intersection. Synchro™ simulation software was then used to optimize the two signals and these optimized signal plans were then transferred to the corridor models in CORSIM. The four-lane and three-lane corridors were built for the 64 combinations of the above mentioned variables and five simulation runs were done for each of the models to account for the stochastic nature of the simulation. The four-lane and three-lane corridor simulation results were then evaluated using the procedures stated in the 1994 Highway Capacity Manual for arterials. Based on the simulation it was reported that the smallest difference in the arterial speed in the four-lane undivided cross-section and the three-lane with a TWLTL cross-section was when the access point density was 40 to 50 access points per mile. At lower values of access point density the difference was higher.

The simulated reduction in average speed was typically between zero and four mph. The simulation showed that the arterial level of service does not decrease when converting from four-lane to three-lane TWLTL until traffic reaches 1,750 vehicles per hour, or roughly 17,500 vehicles per day (*21*, *22*). Researchers recommended that conversion of an urban arterial from four-lane undivided to three-lane with TWLTL is a feasible option when bi-directional peak hour volumes are less than 1,500 vehicles per hour. Caution was recommended when considering conversion for arterials with volumes between 15,000 and 17,500 vehicles per day. It was also recommended that numerous other factors be considered prior to selecting alternative cross section treatments, including the roadway function and environment, turning volumes and patterns, and crash types.

Hummer and Lewis compared the safety of two-lane undivided, three-lane with a TWLTL, and four-lane undivided roadways in 2000 (*23*). The results showed that three-lane roadways had lower crash rates than four-lane undivided roadways for an ADT range of 5,000 to 20,000 vpd, development type, development density, and driveway density. In addition, it was also observed that the crash rates of the three-lane roadways did not increase with development density but the crash rates increased in the case of four-lane undivided roadways with an increase in development density. It can be inferred that driveway density is an important contributor to crash rates for four-lane undivided roadways but not for three-lane TWLTL roadways.

Sohrweide detailed two recent examples of four-lane undivided to three-lane TWLTL conversions in Minnesota and Wisconsin (*24*). Portland Avenue in Burnsville, Minnesota (ADT of 9,200 vpd) and North Main Street in River Falls, Wisconsin (ADT of 19,200 vpd) were changed to three-lane roadways in November 2000 and December 2001, respectively, with the intent of reducing crashes and lowering vehicle speeds. Each conversion led to a decrease in crashes compared to previous years, and driver speeds were lowered on average by approximately two mph at both sites. Public perception of the road conversions varied greatly. At the Minnesota location, people made unsolicited comments about the change as a positive addition to their community. However, at the Wisconsin site, a survey distributed to drivers traveling through the recently converted corridor found numerous complaints about increased stress levels in dealing with the roadway and significant increases in delay. The difference between the two groups' reaction was likely tied to the considerable difference in traffic volumes, as the Wisconsin site carried roughly twice the traffic volume as the Minnesota site.

Comparatively, researchers found generally good public reaction to road diet installations in communities throughout Iowa (*20*). Though no formal studies were performed, area residents felt that the converted roadways were operating safer without a noticeable change in capacity, although many residents were strongly opposed to the changes prior to implementation.

Huang conducted a study in 2002 to investigate the effects of road diets on motor vehicle crashes and injuries (*25*). Twelve road diet sites and 25 comparison sites in cities located in California and Washington were analyzed to evaluate crash frequency, severity, and type. Overall, approximately 10,000 crashes were analyzed between the road diet and comparison sites at roadways ranging in ADT from approximately 10,000 to 16,000 vpd. A before and after analysis found that the percent of road diet crashes occurring during the after period was six percent lower than that of the matched comparison sites. However, crash rates between the road diets and comparison sites were not significantly different, nor did road diets affect crash severity. Road diet conversion sites tended to have a slightly higher percentage of angle collisions but a lower percentage of rear-end collisions when compared to the comparison sites.

Research was conducted in 2002 to investigate the differences in traffic flow and vehicle operations by simulating four-lane undivided roadways and three-lane roadways with TWLTLs (*26*). A range of peak hour volumes, heavy vehicle percentages and bus stop activities were considered and the impacts on the side street vehicle delay and non peak hour traffic were evaluated. The simulation was done using CORSIM and the corridor developed for the simulation analysis was ¼-mile long, included two signalized intersections and five uniformly spaced four legged un-signalized access points. Peak hour traffic was assumed to be 10 percent of the ADT and the ADT volumes considered in the research were 20,000, 21,000, 22,000, 23,000, 24,000 and 25,000 vpd. The minor street volumes (at the signalized intersection) were assumed to be 40 percent of the main arterial traffic volume. A free flow speed of 30 mph was used in the simulation analysis and the two signalized intersections in the corridor were assumed to have two phases and the cycles were optimized using TRANSYT-7F. The number of bus stops on the arterial was either 1 or 2 and the locations varied accordingly. If there was only one bus stop, it was assumed to be at the mid-block and if the number of bus stops were two then they were assumed to be at the two ends of the arterial. The range of bus dwell times considered for the simulation were 30, 40, 50, and 60 seconds and the range of bus headways were 5, 10, 15, 30, and 60 minutes. Using 106 input combinations, 530 simulations were conducted and the results used to perform a sensitivity analysis for heavy vehicles with a fixed peak-hour volume of 1,500 vph. Heavy vehicle percentages ranging from 0 to 30 percent of total entering vehicles, at 5 percent intervals, were simulated.

The sensitivity analysis revealed that the operation of three-lane roadways was influenced more by the increases in the percentages of heavy vehicles than the four-lane undivided roadway. The reduction in average arterial through-vehicle travel speed was three times more for the three-lane roadway than that for the four-lane undivided roadway. Arterial level of service (LOS) of the three-lane roadway also dropped with the increase in the percentage of heavy vehicles. There was also a significant impact of the bus stops on the average arterial through-vehicle travel speeds in the case of the three-lane roadway. A decrease of 0.1 to 7.6 mph was observed when compared to no bus stop simulation.

Russell and Mandavilli used statistical analysis techniques to analyze and compare the output obtained from aaSIDRA Version 1.0 for three-lane with TWLTL roadway conditions with four-lane roadway conditions (*27*). The research site studied was the intersection of 67thAvenue and 44th Avenue in University Place, Washington where a four-lane undivided roadway was converted to a three-lane roadway with TWLTL plus bike lanes in each direction. The traffic counts were done using a video camera for two six-hour sessions from 7:00 AM to 1:00 PM and from 1:00 PM to 7:00 PM. Traffic was videotaped for five days in the four-lane condition and for five days in the three-lane conditions. A statistically significant decrease in the average queue length was found on the major approach (67thAvenue) in the three-lane condition which was attributed to the separation of left turning vehicles from the through and right turning vehicles. There was also a statistically significant decrease in the proportion of vehicles stopped for the three lane condition. However, there was an increase in the average intersection delay and degree of saturation in the case of three-lane condition but the increase was statistically insignificant proving that the three lanes were handling the traffic as well as the four lane condition. It was concluded from the above results that a "road diet" can handle traffic satisfactorily without significantly deteriorating the operational efficiency of the intersections.

A recent study was completed in Iowa to evaluate the safety impacts of the conversion of a four-lane undivided roadway to a three-lane roadway using before and after study methodologies (*28*). A yoked comparison analysis of the 11 study sites, with ADTs ranging from 2,000 to 17,400 vpd, found that the frequency of crashes dropped by 21 to 28 percent when other changes such as continuing reduction in the overall crashes across the state were taken into account. The study also evaluated the changes in the number of crashes, nature of crashes, types of injury, severity of crashes, major causes of crashes, and key age groups. The yoked sites were selected by considering factors such as roadway volume to be within 20 percent of the study site, city population within 20 percent of the study roadways city population, similar developments along the roadway and roadway segments of approximately same lengths. The crash information was collected from DOT records. For most sites, the before data were taken as five years preceding the conversion and the after data as the years following the year of conversion. Initial comparison of the number of crashes before and after conversion and the percentage of reduction that was achieved is presented in Table 2.2. The average crash reduction was 50 percent; however, the crash reduction could not entirely be correlated to the conversion. There was a corresponding statewide decrease in the number of crashes in Iowa due to the ongoing efforts to improve the safety of the roadways. Secondly, in 2001 an increase in the crash reporting threshold in Iowa ($500 to $1,000) was made along with other changes to the Iowa crash reporting form which may have resulted in less crashes being reported.

Table 2.2. Change in the Average Annual Crash Frequency (*28*)

City	Before Conversion	After Conversion	Percentage Change
Storm Lake	64	34	-47
Osceola	47	22	-53
Manchester	15	11	-27
Iowa Falls	21	8	-62
Rock Rapids	6	2	-67
Glenwood	30	15	-50
Des Moines	67	39	-42
Blue Grass	12	3	-75
Sioux Center	65	23	-65
Indianola	29	24	-17
Sioux City	5	3	-40
Average	**33**	**17**	**-50**

Two additional analyses were undertaken to account for the overall trends in crashes. The first was to compare the crash history of the study segment with the crash history of the cities in which the segments are located. The results of this analysis are presented in Table 2.3. Using this method of analysis, the average reduction in crashes after conversion was reported as 21 percent. Again, the results appear questionable given the unrealistic city-wide changes in crash frequencies reported. The second method of analysis which was adopted to account for the overall trends was yoked comparisons. Using this method, the average reduction in crashes after conversion was reported as 28 percent. The results for this method of analysis are presented in Table 2.4. An analysis of crash rates showed a similar percent reduction. Several segments showed a 50 percent unadjusted decline in crash rates and a 23 percent decline in crash rates when the overall trends were taken into account. Further analysis of the crash data, after adjusting for citywide trends, revealed that fatal crashes were reduced by 35 percent, major injury crashes by 11 percent, minor injury crashes by 34 percent and possible injury crashes by 29 percent. Overall, injury crashes were reduced by 27 percent. Analysis of the crash data considering driver age groups revealed an after period decrease in the proportion of crashes involving drivers of the age group 25 and under as well as drivers of the age group 65 to 74. Researchers also reported a significant reduction in the number of crashes related to left turns and stopped traffic. Although this research clearly showed a safety improvement with the four-lane to three-lane with TWLTL conversions, the magnitude of the improvement is suspect.

Table 2.3. TWLTL Segment vs. City Percentage Change in Crash Frequency (*28*)

City	Converted Segment	City	Difference
Storm Lake	-47	-21	-26
Osceola	-53	-13	-40
Manchester	-27	-17	-10
Iowa Falls	-62	-17	-45
Rock Rapids	-67	-23	-44
Glenwood	-50	-33	-17
Des Moines	-42	-20	-22
Blue Grass	-75	-68	-7
Sioux Center	-65	-53	-12
Indianola	-17	-24	7
Sioux City	-40	-28	-12
Average	**-50**	**-29**	**-21**

Table 2.4. Percent Change in Crashes for Study Elements, Cities, and Yoked Pairs (*28*)

City	Segment	City	Difference	Segment	Yoked	Difference
Storm Lake	-47	-21	-26	-47	-55	8
Osceola	-53	-13	-40	-53	-11	-42
Manchester	-27	-17	-10	-27	-39	12
Iowa Falls	-62	-17	-45	-62	-38	-24
Rock Rapids	-67	-23	-44	-67	-3	-64
Glenwood	-50	-33	-17	-50	-19	-31
Des Moines	-42	-20	-22	-42	-11	-31
Blue Grass	-75	-68	-7	-75	-5	-70
Sioux Center	-65	-53	-12	-65	-33	-32
Indianola	-17	-24	7	-17	-18	1
Sioux City	-40	-28	-12	-40	-5	-35
Average	**-50**	**-29**	**-21**	**-50**	**-21**	**-28**

Another study to evaluate the reduction in the crashes after the conversion of a four-lane undivided roadway to a three-lane roadway in Iowa was done using Bayesian data analysis (*3*). The monthly crash data and estimated volumes, for the 15 treatment and 15 control sites over 23 years (1982-2004), were obtained from Iowa DOT Office of Traffic and Safety (TAS) and were used in this study. Treatment and control sites ranged in ADT from approximately 2,800 to 15,300 vpd. A Hierarchical Poisson model, where the log mean rate was expressed as a function of time period, seasonal effects, and a random effect corresponding to each site, was fitted to the crash frequencies. To account for seasonality in crash rate, three smoothly evolving cyclical functions of season with different periods and frequency were included to account for the seasonal trends. Full Bayesian approach was used to estimate the model parameters. Model parameters were treated as random variables and the goal was to estimate the distribution of likely values of the parameters given prior (before conversion) data.

The study concluded that, after conversion, there was a 25.2 percent reduction in crash frequency and an 18.8 percent reduction in crash rate. The distribution of likely values of the model parameters on which all the inferences are based were depicted as joint posterior distributions. The posterior distribution of expected annual crash densities for the control sites and treatment sites were computed and are presented in the Figures 2.2 and 2.3.

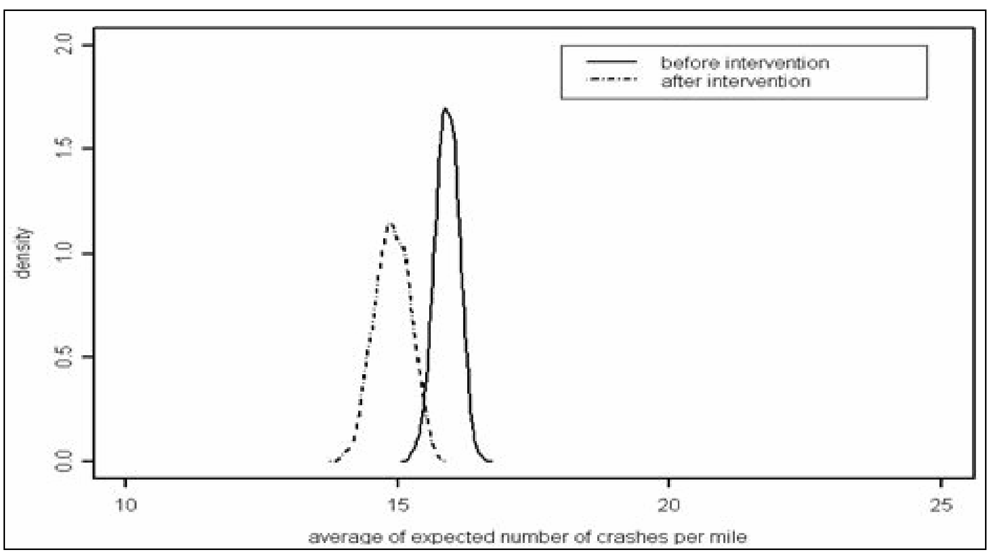

Figure 2.2. Posterior Distribution for Control Group (*3*)

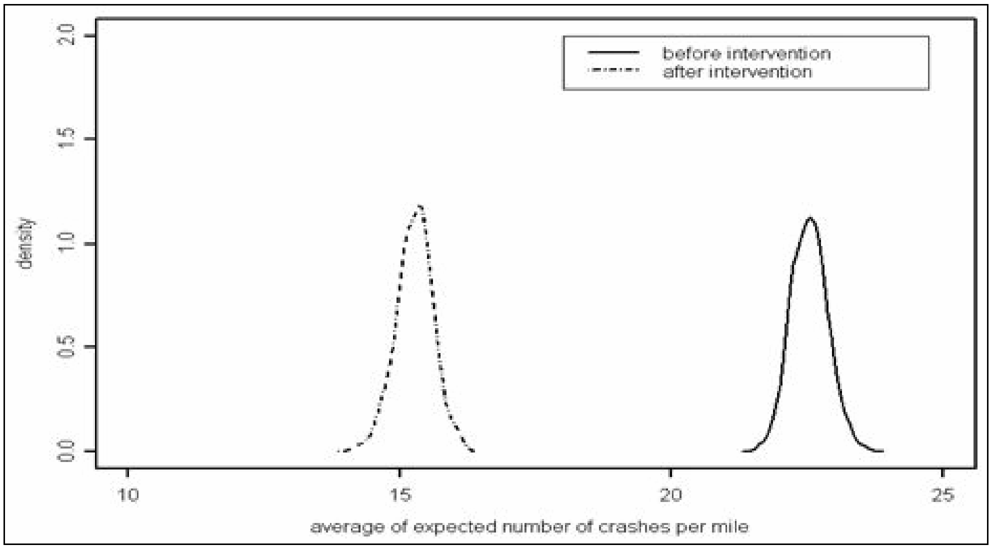

Figure 2.3. Posterior Distribution for Treatment Group (*3*)

As observed in the Figures 2.2 and 2.3, although the expected crash density decreased at all the sites, the reduction in the crash density was much more pronounced in the treatment group. An overlap in the posterior distribution was found in the case of the control group indicating that the reduction in the crash density in the after period was not large. The researchers noted that the posterior distributions were narrow which implied that the posterior mean is a reliable summary of the distribution of the likely values of expected crash frequencies.

OTHER IMPACTS OF THREE-LANE WITH TWLTL ROADWAYS

To better understand the other potential impacts of four-lane to three-lane with TWLTL conversions, public opinion surveys were conducted at five “road diet” sites in Washington, Iowa, and Georgia, and in Canada and New Zealand (*29*). The surveys evaluated the so called ‘livability’ impacts of road diet projects, addressing issues of other modes of transportation such as bicyclists, transit users and pedestrians, increased landscaping and beautification opportunities, improved quality of life and street character, and public reaction.

It was found that significant safety benefits were realized due to the road diet projects. The reduction of crashes ranged from 30 to 65 percent. Traffic speeds were also found to be reduced. Increased pedestrian and bicycle activities were also observed. Researchers concluded that road diets have resulted in several livability benefits. Some of the positive impacts identified by researchers were that streets were easier to cross, new home and business improvement projects resulted from the roadway improvements, streets were perceived to be safe and comfortable, and economic growth was observed in adjacent and nearby businesses. Based on the case studies of the five road diet projects, researchers found safety, operational and livability benefits for all modes of transportation.

TWLTL PAVEMENT MARKING AND SIGNAGE

Pavement marking and signage used with TWLTLs has been defined by the Manual on Uniform Traffic Control Devices (MUTCD). As described in the MUTCD, the yellow markings for TWLTL longitudinal lines should be placed to separate the two-way left turn lanes from other lanes (*30*). The lane line pavement markings on each side of the two-way left-turn lane should consist of a normal broken yellow line and a normal solid yellow line to delineate the edges of a lane that can be used by traffic in either direction as part of a left-turn maneuver with the broken line toward the two-way left-turn lane and the solid line towards the adjacent traffic lane as presented in Figure 2.4.

The pavement markings are supplemented with Two-Way Left Turn Only (R3-9a or R3-9b) signs as shown in Figure 2.5 to reinforce the message that the lane is reserved for the exclusive use of left-turning vehicles in either direction and is not used for passing, overtaking, or through travel. The R3-9a sign is an overhead-mounted sign and the R3-9b sign is a ground mounted sign. Another set of pavement markings associated with the TWLTL are the pavement arrows which can be used in conjunction with the two-way left-turn lane markings but are not required (Figure 2.6). The signing and the pavement arrows are helpful to drivers in areas where the two-way left turn only maneuver is new or in areas subject to environmental conditions that frequently obscure the pavement markings, and on peripheral streets with two-way left turn only lanes leading to an extensive system of routes with two-way left turn lanes.

A comprehensive study was completed in Phoenix, AZ to evaluate the effectiveness of pavement arrows for TWLTL in which the 1988 major street crash records in Phoenix having a TWLTL were analyzed (*31*). After ten years of having TWLTLs in Phoenix, the engineering staff became so comfortable with the safety and operational characteristics of a TWLTL that they discontinued installing pavement arrows. Removing pavement markings provided researchers an ideal opportunity to measure driver confusion due to the absence of pavement arrows on the TWLTL. Pavement arrows on TWLTLs are designed to improve driver recognition of the proper use of TWLTLs and eliminate possible driver confusion. Researchers assumed that if driver confusion existed on the TWLTL due to the absence of the pavement arrows, side-swipe and head-on crashes would occur. The next step in this research was to analyze the crashes and investigate the number of side-swipe and head-on crashes taking place in the City of Phoenix.

A computerized citywide search of police crash records for 1988 in Phoenix revealed that 189 crashes occurred near TWLTLs out of 31,029 crashes that occurred citywide. Another 411 crashes were classified as “other”. Since it was possible that these crashes could have been some type of head-on and side-swipe crashes, they were analyzed in detail. It was found that most of the crashes occurred in the left turn lanes approaching traffic signals and only 41 crashes were found to occur in TWLTL and none of them involved a fatality. In 37 of these crashes, no evidence was found that any of these crashes would have been influenced by or avoided had pavement arrows been used, leaving only four crashes that might have possibly benefited from the use of the pavement markings. Even this conclusion is doubtful as out of the four crashes, one involved a hit and run motorist and two involved drivers under the influence of alcohol.

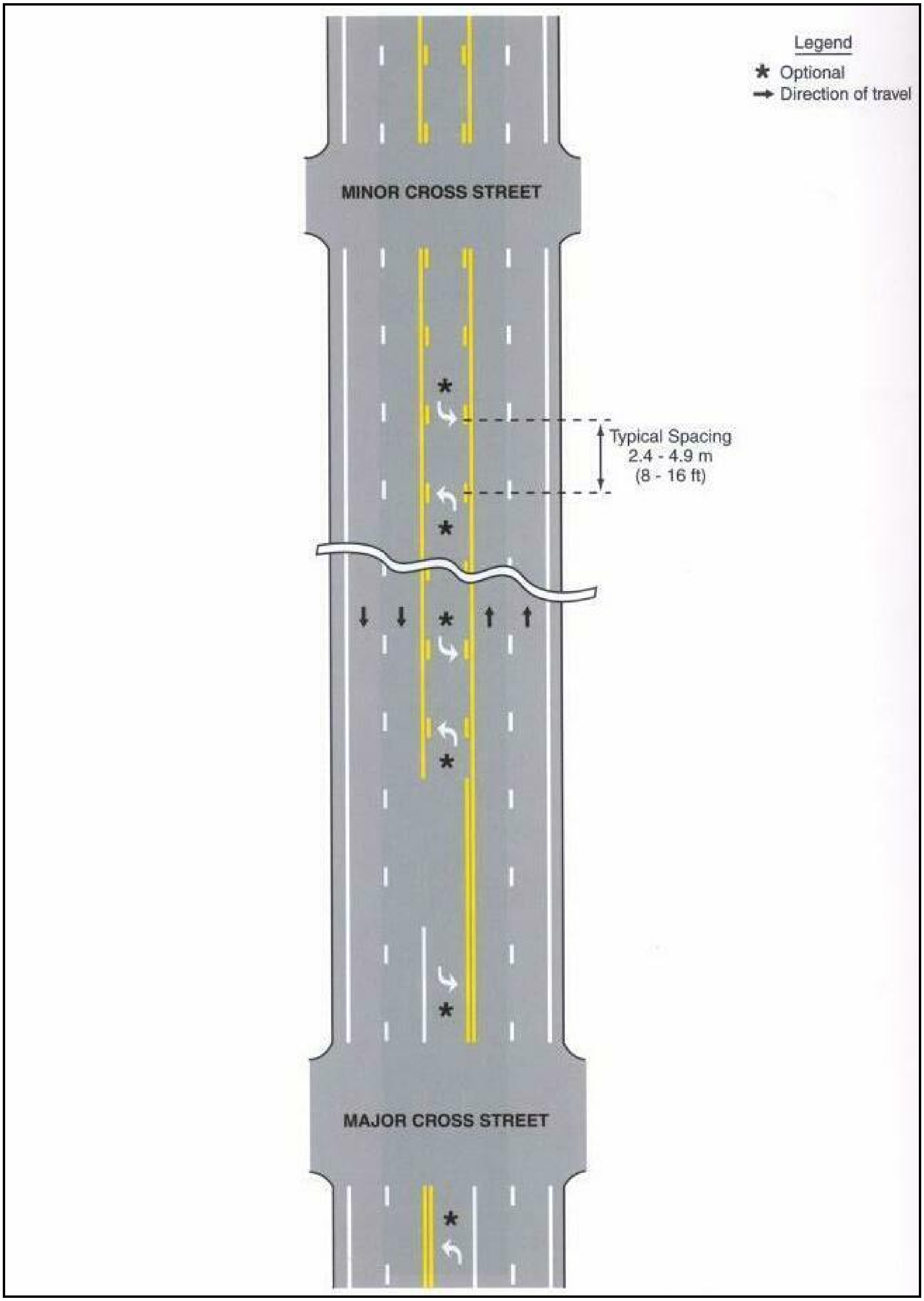

Figure 2.4. Pavement Markings for a TWLTL (*30*)

R3-9a **. R3-9b**

Figure 2.5. Signage for a TWLTL (*30*)

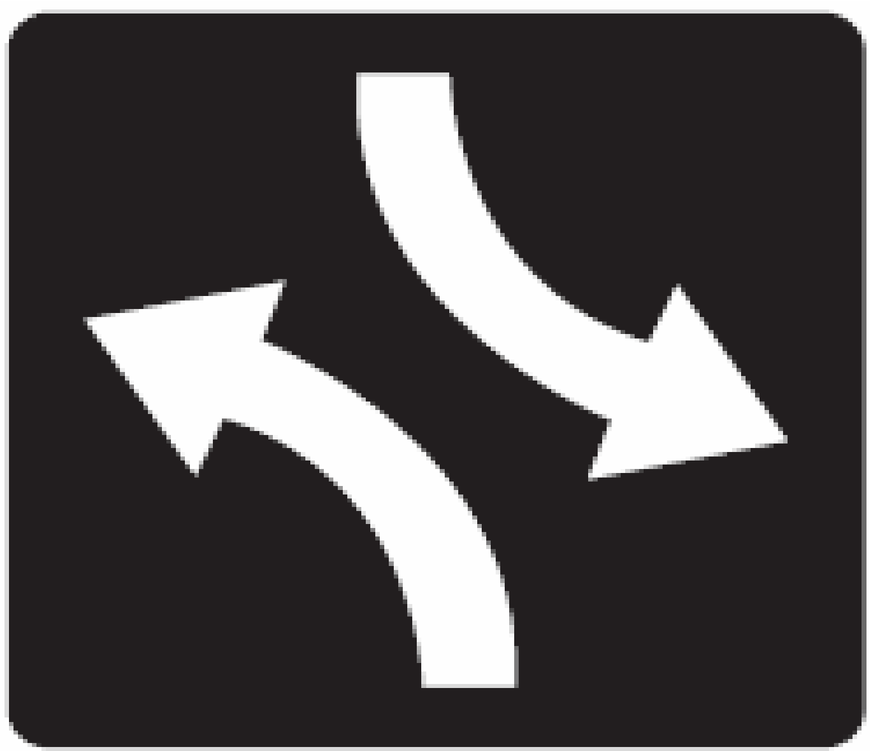

Figure 2.6. Pavement Arrows for Two-Way Left-Turn Lane (*30*)

The City of Phoenix also conducted two before and after studies to determine the differences in driver behavior with and without the use of pavement arrows on TWLTLs. The first site was a half mile segment of Camelback Road which has a high degree of commercial strip development and substantial left turn activity. The other site was 19^{th} Avenue north of Thunderbird Road which was chosen due to substantial misuse of TWLTLs by motorists entering the TWLTL early to access a one-way left-turn lane approaching a traffic signal. At the first site, the observations were conducted from an elevated platform truck located midway along the segment. It was found that during a four-hour period when the TWLTL was used extensively, a total of 60 users used the TWLTL improperly. After these observations, two sets of TWLTL pavement arrows were installed on the same segment and an after study was conducted after 45 days. The observations were conducted on the same day and time as the before study was and it was found that a total of 57 road users used the TWLTL improperly.

At the second site, the TWLTL was being used to access the left-turn pocket because of the backups in the through lane. Observations were conducted on two separate occasions during the morning peak hour for the before study and on one occasion for the after study. The percentages of motorists using the TWLTL improperly were again found to be similar.

It was concluded from these studies that there is virtually no change in driver behavior by installing the pavement arrows. The results also confirmed that extensive signing of TWLTLs is not necessary if the TWLTLs have been in use for a long period of time and with the unique striping patterns assigned by the MUTCD for the TWLTLs the need to provide further information appeared redundant. Nevertheless, pavement arrows and signs may be useful if the TWLTLs are being used at some location where they have not been used extensively. But once drivers become familiar with the TWLTLs, the continued expense of maintaining the arrows and signs may not be needed.

A survey was conducted by sending a questionnaire to 29 different states on the various facets of TWLTL. Only the responses of the agencies with TWLTL installations were considered (*32*). Based on the survey results, it was recommended that overhead signs should be installed where frequent obliteration of pavement markings can reasonably be expected due to snow in northern climates or where roadside development can camouflage ground mounted signs or if street parking exists which can obstruct the driver's view. Spacing of the overhead signs should be at the ¼ to ½ points between major intersections but not less than 1,000 feet apart for other locations. It was also recommended that TWLTL markings approaching major intersections should not be carried through the intersection but stopped at approaches and striping for an exclusive intersection left turn lane may be installed. For minor unsignalized intersections, the TWLTL markings should be extended to the intersection entrance.

SUMMARY

When comparing the safety and operational effects of roadways with TWLTLs with four-lane divided and four-lane undivided cross-sections, it is important to consider traffic volumes, roadway functions and environment, and crash types. From the above studies, these factors not only effect the safety and operational effects but also the public perception of the roadway conversions.

Based on this review of the literature, it can be concluded that the operational and safety features of a roadway with the appropriate attributes can be enhanced by the addition of a TWLTL. Addition of a TWLTL results in the reduction of delay and vehicle interactions during lane changes. The overall crash rates can be significantly reduced where parallel parking is allowed, but the reduction in the crash rate may be negligible where parking is removed. There can also be a significant decrease in delay in the roadway when a TWLTL is added to the existing lanes. Nevertheless, in conversions from a four-lane roadway to three-lane roadway with a center TWLTL, the total corridor delay and intersection delay may increase but most often at insignificant levels within acceptable levels of service (LOS).

The change from a four-lane roadway to a three-lane roadway with TWLTL can lead to a significant improvement in safety with little impact in traffic operations. This result has been consistent with ADTs less than 20,000 vpd. The exact magnitude of this safety improvement varies and in some of the literature cited is questionable due to the statistical procedures selected. Nevertheless, the fact that some improvement in safety was experienced after the conversion is clear.

Research on four-lane to three-lane with TWLTL conversions finds that the operation of three-lane roadways with TWLTLs is influenced by heavy vehicles. A reduction of average arterial through-vehicle travel speed is often observed with an increase of heavy vehicles. The presence of bus stops also impacts the operation of three-lane roadways, leading to a significant reduction of the average arterial through-vehicle travel speeds. Three-lane roadways are less affected by driveway densities and can increase in the accessibility function of the roadway. The conversion to a three-lane TWLTL from four-lane roadway may be accompanied by negative public reaction due to unfounded fear of a capacity reduction resulting from the reduction in the total number of lanes. However, numerous jurisdictions have found that once the roadway conversion is implemented and operating, a positive change in the community attitude is observed.

A study has suggested that extensive signing of TWLTLs may not be necessary if the TWLTLs have been in use for an extended period of time. With the unique striping patterns assigned by the MUTCD for TWLTLs, the need to provide further information appears to be redundant. Nevertheless, pavement arrows and signs are useful for unfamiliar drivers.

Based on the literature review, the quantitative operational and safety impacts of four-lane to three-lane conversions are summarized below:

- Crash rates can be reduced by as much as 25 percent;
- No significant affect on the operational performance of the roadway is experienced when the ADT of the roadway is below 17,500 ADT. At higher volumes, a reduction in the arterial LOS may be expected;
- Mean and 85th percentile speeds decrease, typically less than five mph; and
- Operating speed differences when compared to four-lane undivided cross-sections are the lowest when the number of access points along the roadway is high (typically 40-50 access points per mile). At lower values of access point density the difference will be greater.

Chapter 3
DATA COLLECTION and ANALYSIS PROCEDURE

The purpose of this chapter is to describe the data collection process and analysis methods completed to meet the objectives of this research. Background information on the statistical procedures, study sites and comparison sites selected are also discussed.

DATA COLLECTION

The first step in Task 2 was to identify locations where a roadway segment had been converted to a three- or five-lane cross-section with a TWLTL for which both operation and safety data were available. This step turned out to be a considerable challenge. The process began by obtaining lists of three-lane and five-lane cross-sections from the Minnesota Department of Transportation (Mn/DOT). An additional list of 100 sites was provided by Midwest Research Institute that they compiled as part of a previous research effort (*8*). The information in this list appeared to be very comprehensive, including the beginning and ending reference points of each location verified by site visits and the Mn/DOT video logs. Each of these sites was either an existing three-lane or five-lane cross-section. However, the original roadway configuration prior to the three- or five-lane conversion and much of the before data were not included and unavailable. Before data were essential for this research. The list was then compared to the list of TWLTL sites on state routes provided by Mn/DOT to determine the roadway configuration prior to the conversion and to confirm the locations of the TWLTL sections.

After comparison of the two lists, only three sites on the state trunk highways were found to be four-lane to three-lane conversions. The other 97 sites were either two-lane to three-lane or four-lane to five-lane expansions. The number of four-lane to three-lane conversions were few on the state trunk highway system and thus insufficient for a meaningful analysis. Another problem was that operational data were not available for the three sites. Therefore, the next step in the data collection task was to identify more sites where four-lane to three-lane conversions took place and before and after operational data were available.

Information was provided by Mn/DOT pertaining to certain counties and municipalities which had converted roadways from four-lanes to three-lanes. The counties were contacted through a series of telephone calls and emails. After contacting various counties and municipalities, four sites in St. Paul were identified where four-lane to three-lane conversions had occurred and before and after operational data were available.

Two additional sites were identified where four-lane undivided roads were scheduled to be converted to three-lane roadways with a TWLTL in the summer of 2005. These were ideal sites as the operational data before and after conversion could be collected, although “after” crash data would not be available for purposes of this research project. The project timeline was extended to accommodate operational data collection at these sites. Speed, volume, and other site information such as access density/driveway density information were collected both before and after conversion.

The combination of the above effects led to a total of nine sites that were used for data analysis. The details of the sites are presented in Table 3.1.

Table 3.1. Study Sites

Site	Jurisdiction	Before Condition	After Condition	Year of Conversion	Length (Mile)
MNTH 61	Mn/DOT	4 Lanes	3 Lanes	2000	0.75
MNTH 23	Mn/DOT	4 Lanes	3 Lanes	1989	0.61
MNTH 29	Mn/DOT	4 Lanes	3 Lanes	1995	0.53
Lexington Parkway	St. Paul	4 Lanes	3 Lanes	2003	0.60
Fairview Avenue	St. Paul	4 Lanes	3 Lanes	1998	2.10
W. 7th Street	St. Paul	4 Lanes	3 Lanes	2004	1.40
Pierce Butler Route	St. Paul	4 Lanes	3 Lanes	2001	2.90
E. Wentworth Avenue	St. Paul	4 Lanes	3 Lanes	2005	0.90
Grand Avenue	Duluth	4 Lanes	3 Lanes	2005	0.90

The next step in Task 2 was to collect volume, speed, geometric, and driveway/side street access data related to these sites. Volume and speed data were required to compare the change in basic traffic operations before and after conversion. Geometric and access data information were used for analysis of each site and to match the comparison sites. The need for comparison sites is described later.

Various data collection procedures were used in this research to collect the volume, speed, geometric, and access density/driveway density data. Data collection procedures included site visits, photographing and videotaping the sites, automatic traffic data recorders, measuring speed by using a LIDAR speed gun, manual counting of traffic, and discussions with local Mn/DOT and city staff.

At the seven sites where four-lane to three-lane conversion was completed prior to 2005, volume and speed data were obtained from Mn/DOT and local officials. Before and after volume data were available for all the seven sites; however, before and after speed data were available for only four sites. The two sites where four-lane to three-lane conversions took place in 2005 were Grand Avenue in Duluth and E. Wentworth Avenue in St. Paul. Before and after speed, volume, and classification data for Grand Avenue in Duluth, which was converted to a three-lane roadway in the summer of 2005, were collected by setting up automatic traffic recorders. Automatic traffic recorders were placed at the same locations for a seven-day period before conversion and a three-day period after conversion.

Before and after volume and speed data for E. Wentworth Avenue in St. Paul were collected by manual traffic counts and by a LIDAR speed gun. A minimum of 100 free-flow speed observations were obtained in each location. Volume data were collected by video recording the roadway and then analyzing the videotapes at the Traffic Operations and Safety Laboratory (TOPS) at the University of Wisconsin-Madison.

Field data such as geometric and access data were collected by visiting each site. All the study sites and comparison sites were reviewed between May, 2005 and January, 2006. Access data consisted of the number of unsignalized approaches per mile and the number of driveways per mile. The sites were driven through and videotaped so that the number of driveways and the number of unsignalized approaches opening into the roadway could be quantified. The number of signalized intersections along the roadways was also recorded.

During the site visits, suitable comparison sites were also identified in the vicinity of the study sites. Geometric and access data related to these comparison sites were collected during the site visits. The importance of comparison sites in a before-after study is explained in greater detail in the *Overview of Statistical Procedures* section of this report. The description of the identified comparison sites is provided in the ***Comparison Sites*** section.

Crash data for all the study sites and comparison sites from the years 1984 to 2004 were obtained from the Mn/DOT crash database. This range of years covered all sites with at least five years of "before" crash data. Additional years of "before" data were used to develop historical trends in crashes based on existing attributes.

Maps of the study and comparison sites are provided in Appendix A. Tabular summaries of all the background data and crash data collected from the study and comparison sites are provided in Appendix B through Appendix G.

STUDY SITES

Grand Avenue, Duluth, Minnesota

Grand Avenue is an urban collector roadway in the City of Duluth, Minnesota. Grand Avenue from 59th Avenue to 46th Avenue was previously a four-lane undivided roadway with parking lanes located on both sides. Grand Avenue is being converted to a three-lane roadway with a center TWLTL and two parking lanes from the intersection of 59th Avenue to Carlton Street in two phases. In the summer of 2005, a 0.9 mile section of Grand Avenue from the intersection of 59th Avenue to 46th Avenue was converted to a three-lane roadway (Figures 3.1 and 3.2). Please note that an additional four-lane to three-lane conversion of Grand Avenue from the intersection of 46th Avenue to Carlton Street is proposed for the summer of 2006.

The posted speed limit on Grand Avenue is 30 mph. This roadway segment has five unsignalized intersections and five signalized intersections. The number of driveways on both sides of the roadway segment is 30 and the driveway density of the roadway segment is 33 driveways per mile. The number of unsignalized approaches for the roadway segment is seven and the approach density for this roadway segment is eight approaches per mile. Grand Avenue is predominantly a commercially developed area with a variety of businesses located along the roadway.

Volume and speed data were collected at the study site using automatic traffic data recorders which were placed at an appropriate mid-block location (between the intersections of Grand Avenue and Elinor Street and Grand Avenue and Central Avenue). The data collection before the conversion was done in the last week of May, 2005. After the 4-lane to 3-lane conversion of Grand Avenue in the summer of 2005, the volume and speed data after conversion were collected using automatic traffic data recorders, which were placed at the same location. Volume and speed data after the conversion data were collected in January, 2006.

Figure 3.1. Grand Avenue Before Conversion towards Carlton Street

Figure 3.2. Grand Avenue After Conversion towards Carlton Street

East Wentworth Avenue, St. Paul, Minnesota

East Wentworth Avenue in St. Paul, Minnesota is functionally classified as a collector and is oriented in the east-west direction. A 0.9 section of this roadway was converted from a four-lane undivided to a three-lane cross-section from the intersection of Humboldt Avenue to Trunk Highway 52 in the summer of 2005 (Figures 3.3 and 3.4).

The posted speed limit for this roadway segment is 35 mph. The roadway segment has one signalized intersection and six unsignalized intersections. Two major intersections exist along this corridor including a signalized intersection at South Robert Street and a four-way stop controlled intersection at Oakdale Avenue. There are 29 driveways located along this segment and the driveway density is 32 driveways per mile. The number of unsignalized approaches is 11 and the approach density is 12 approaches per mile. Land use along the roadway segment consists of both residential as well as commercial developments.

Speed data at this site were randomly collected both for the before and after periods using a LIDAR infrared speed gun. The free flow vehicles were chosen randomly and their speed was recorded at mid-block locations. Volume data were collected by video recording the intersection of S. Robert Street and E. Wentworth Avenue and video recording was also done at the mid-block location between S. Robert Street and Marthaler Lane.

Figure 3.3. E. Wentworth Avenue Before Conversion towards Trunk Highway 52

Figure 3.4. E. Wentworth Avenue After Conversion towards Humbold Avenue

Pierce Butler Route, St. Paul, Minnesota

Pierce Butler Route is a three-lane roadway in St. Paul, Minnesota. A 2.9 mile section of Pierce Butler Route was converted from a four-lane to a three-lane cross-section from the intersection of Transfer Road to Minnehaha Avenue in the fall of 2001 (Figure 3.5). This roadway is functionally classified as a collector. The posted speed limit for this roadway segment is 40 mph. The only signalized intersection on this roadway segment is at the intersection with Minnehaha Avenue. Twenty-eight unsignalized approaches and 46 driveways open into this segment of roadway and approach density is 10 approaches per mile and the driveway density is 16 driveways per mile. Land use along Pierce Butler Route consists of industrial and commercial developments without a significant amount of residential developments.

Figure 3.5. Pierce Butler Route After Conversion towards Transfer Road

Lexington Parkway, St. Paul, Minnesota

A 0.6 mile section of Lexington Parkway in St. Paul, Minnesota was converted from a four-lane undivided to a three-lane cross-section with a TWLTL from the intersection of Lincoln Avenue to Jefferson Avenue in the fall of 2003 (Figure 3.6). This roadway is functionally classified as a collector. The posted speed limit for this roadway segment is 30 mph. There are two signalized intersections along this segment of Lexington Parkway, which are located at Jefferson Avenue and St. Clair Avenue. There are 11 unsignalized approaches and 11 driveways located along this roadway segment. Approach density and driveway density are 18 approaches per mile and 18 driveways per mile. Land use along this segment of Lexington Parkway mostly consists of residential developments.

Figure 3.6. Lexington Parkway After Conversion towards Lincoln Avenue

Fairview Avenue, St. Paul, Minnesota

A 2.1 mile section of Fairview Avenue was converted from a four-lane undivided roadway to a three-lane roadway with a TWLTL from Marshall Avenue to Ford Parkway in 1998. Fairview Avenue is functionally classified as a local road (Figure 3.7). The converted segment consists of mostly residential developments with a few commercial developments and has eight signalized intersections and 24 unsignalized intersections. There are 65 driveways and 42 unsignalized approaches along this roadway segment and the driveway density and approach density are 31 driveways per mile and 20 approaches per mile, respectively. The posted speed limit on Fairview Avenue is 30 mph.

Figure 3.7. Fairview Avenue After Conversion towards Marshall Avenue

West 7th Street, St. Paul, Minnesota

A 1.4 mile segment of West 7th Street in St. Paul was converted to a three-lane roadway with a TWLTL from a four-lane undivided roadway in 2004 from Jefferson Avenue to May Street (Figure 3.8). West 7th Street is functionally classified as a collector. This segment consists of mostly commercial developments with a few residential developments. There are four signalized intersections with 16 unsignalized intersections. There are also 43 driveways and 26 unsignalized approaches along this roadway segment and the driveway density and approach density is 31 driveways per mile and 19 approaches per mile, respectively. Posted speed limit on West 7th Street is 35 mph.

Figure 3.8. West 7th Street After Conversion towards Jefferson Avenue

MNTH 61, Duluth, Minnesota

A 0.75 mile section of MNTH 61 in Duluth was converted to a three-lane roadway with TWLTL from a four-lane undivided roadway in August, 2000 (Figure 3.9). The converted section on MNTH 61 is between the intersections with 32nd Avenue and 40th Avenue. As most of the entrances are on one side of the road the extra width from the eliminated lane was used to provide a continuous right turn lane.

Land use along this site is mostly residential with almost all the entrances on one side. Driveway density and approach density is 17 driveways per mile and three approaches per mile, respectively. Posted speed limit on this section of MNTH 61 was 40 mph.

Figure 3.9 MNTH 61 After Conversion towards 32nd Avenue

MNTH 29, Alexandria, Minnesota

A 0.53 mile section of MNTH 29 in Alexandria was converted to a three-lane roadway with a TWLTL from a four-lane undivided roadway in 1995 (Figure 3.10). The TWLTL is located between the intersections with Broadway Street and Nokomis Street.

The land use primarily consists of commercial developments. Driveway density and approach density are 28 driveways per mile and 22 approaches per mile, respectively. Posted speed limit on MNTH 29 is 30 mph. In 2004 the three-lane roadway was expanded to a five-lane roadway with a central TWLTL.

Figure 3.10. MNTH 29 After Conversion to Five-lane Section towards Broadway Street

MNTH 23, Cold Spring, Minnesota

A 0.61 section of MNTH 23 in the city of Cold Spring was converted to a three-lane roadway with a TWLTL from a four-lane undivided roadway in 1989 (Figure 3.11). The TWLTL is located between the intersections with 5th Avenue and the Sauk River Bridge. The land use consists of commercial developments. This section of MNTH 23 has one signalized intersection and three unsignalized intersections. Driveway density and approach density are 11 driveways per mile and 5 approaches per mile, respectively. Posted speed limit on MNTH 23 is 35 mph. In 2003, the three-lane roadway was expanded to a five-lane roadway with a central TWLTL.

Figure 3.11. MNTH 23 After Conversion to Five-lane Section towards 5th Avenue

COMPARISON SITES

Comparison sites were identified near the vicinity of the study sites. Comparison sites were used in the statistical analysis to account for factors which may have randomly changed with time and may have influenced the safety and/or operational characteristics of the roadway. While conducting a before and after statistical analysis to evaluate the safety and operational changes of four-lane to three-lane conversions, it is important to account for factors such as changing ADT, seasonal trends, and other natural phenomena which might have influenced the crashes occurring on the roadway in the before and after period. If the factors are not accounted for in the statistical analysis, an inflated estimate of increase/decrease in the safety of the roadway may occur. Therefore, comparison sites isolate the effect of a specific countermeasure on the computed safety of a roadway. The importance of comparison sites in the statistical analysis is explained in greater detail in the *Overview of Statistical Procedures* section of this report.

Ideally, a comparison site should have the same attributes as the study site. Nevertheless, it is often challenging to identify a site which has the same cross-section, ADT, posted speed limit, intersection and driveway density, and land use. In most cases, a site is acceptable as a comparison site if the site has similar general attributes as the study site. The acceptability of a comparison site can also be computationally evaluated in the statistical procedure.

Comparison sites that were identified for use in the analysis are described below. Each of the sites selected were near one or more of the study sites and had similar attributes to warrant their selection. Detailed information about the comparison sites such as the access density and approach density is presented in Appendix F. Crash data is provided in Appendix G.

Snelling Avenue, St. Paul, Minnesota

Snelling Avenue from the intersections of Grand Avenue to Montreal Avenue is a four-lane undivided roadway (Figure 3.12). The length of this segment is 1.9 miles and has a posted speed limit of 30 mph. Snelling Avenue has parking on one side and adjacent land use consists of both commercial and residential developments. The roadway has 71 driveways and 29 unsignalized approaches. Driveway density and the unsignalized approaches density are 37 driveways per mile and the 15 approaches per mile. ADT on the roadway is approximately 21,000 vpd.

Figure 3.12. Snelling Avenue towards Grand Avenue

Dale Street, St. Paul, Minnesota

Dale Street is a four-lane undivided roadway from Concordia Avenue to Grand Avenue (Figure 3.13). The posted speed limit on Dale Street is 30 mph. The adjacent land use consists of both commercial and residential developments. Dale Street from Concordia Avenue to Grand Avenue is 0.8 miles long with 27 driveways and 14 unsignalized approaches openings. Dale Street has on street parking and an ADT of approximately 12,800 vpd.

Figure 3.13. Dale Street towards Grand Avenue

West 7^{th} Street, St. Paul, Minnesota

A 1.0 mile segment of West 7^{th} Street was selected between the intersections of St. Clair Avenue and Kellogg Boulevard (Figure 3.14). This roadway is a four-lane undivided roadway with a posted speed limit of 30 mph. This site has 34 driveways and 14 unsignalized approaches openings. Land use adjacent to the W. 7^{th} Street consists of predominantly commercial developments. ADT of this segment of W. 7^{th} Street is approximately 15,000 vpd. Parking lanes are located on both the sides of the roadway.

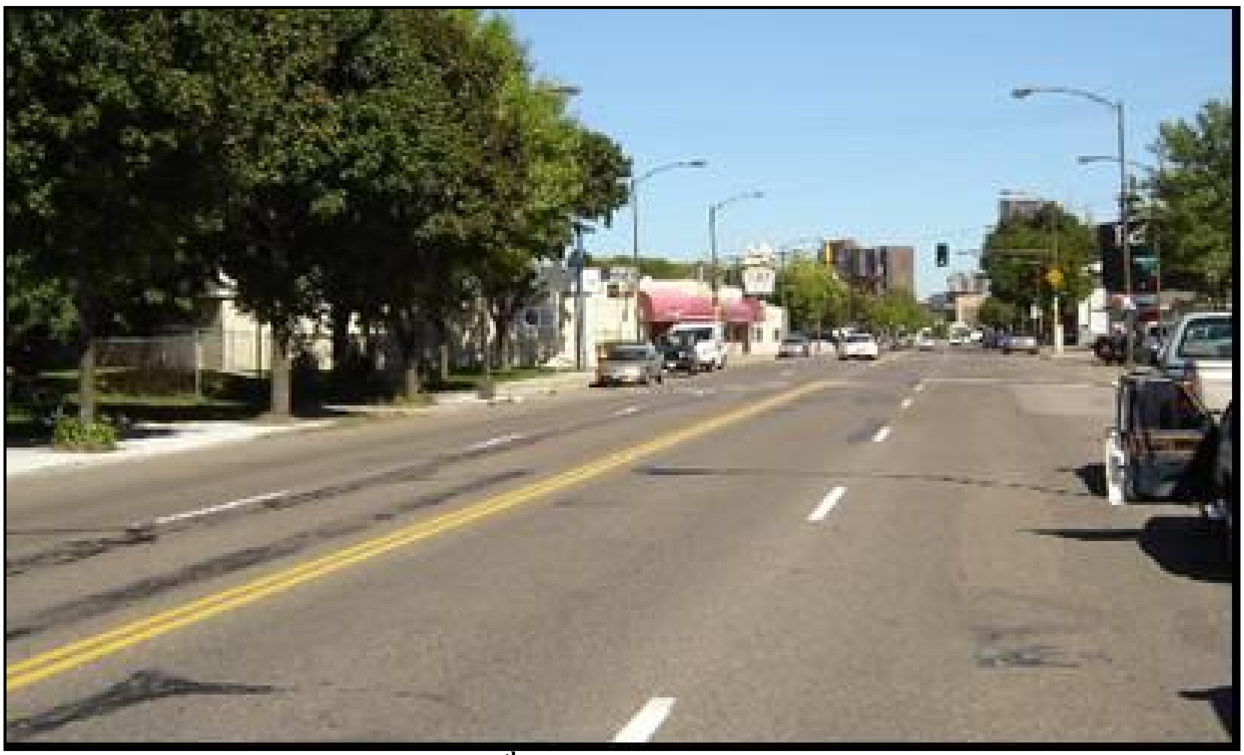

Figure 3.14. W. 7^{th} Street towards Kellogg Boulevard

Grand Avenue, Duluth, Minnesota

A 1.0 mile segment of Grand Avenue in Duluth from 46th Avenue to 34th Avenue was selected. Grand Avenue is a four-lane undivided roadway with a posted speed limit of 30 mph (Figure 3.15). This segment of roadway has 43 driveways and 11 unsignalized approaches openings and the land use adjacent to this roadway consists of commercial developments with a few residential developments. This segment of Grand Avenue does not have parking lanes and has an ADT of approximately 12,500 vpd.

Figure 3.15. Grand Avenue towards 34th Avenue

6th Avenue East, Duluth, Minnesota

A 0.3 mile four-lane undivided segment of Sixth Avenue East in Duluth was selected as a comparison site (Figure 3.16). The length of the roadway is 0.3 miles and there is no on-street parking available. Land use adjacent to the roadway consists primarily of commercial developments. The posted speed limit on the roadway is 30 mph and the driveway density and unsignalized approaches density for this roadway segment are 48 and 17, respectively. ADT on 6th Avenue East is approximately 13,400 vpd.

Figure 3.16. Sixth Avenue East towards 9th Street

Superior Street, Duluth, Minnesota

Superior Street in Duluth from Carlton Avenue to 23rd Avenue is a four-lane undivided roadway with no parking (Figure 3.17). The length of this roadway segment is 0.75 miles with a posted speed limit of 30 mph. Land use adjacent to the roadway is commercial developments. ADT of the roadway is approximately 8,000 vpd. Driveway density and unsignalized approach density are 43 driveways per mile and 14 unsignalized approaches per mile.

Figure 3.17. Superior Street towards 23rd Avenue

North 40th Avenue West, Duluth, Minnesota

A 0.3 mile segment of North 40th Avenue West from the intersection of Michigan Street to Grand Avenue in Duluth was selected as a comparison site (Figure 3.18). North 40th Avenue is a four-lane undivided roadway which has an unsignalized approach density of 10 approaches per mile and a driveway density of 27 driveways per mile. Land use adjacent to the roadway primarily consists of commercial developments. Posted speed limit on 40th Avenue is 30 mph and the current ADT is approximately 8200 vpd.

Figure 3.18. North 40th Avenue towards Michigan Street

MNTH 29, Alexandria, Minnesota

A 0.22 mile section of MNTH 29 from 6th Avenue to 3rd Avenue in Alexandria was selected as a comparison site. This section of MNTH 29 was a four-lane undivided roadway with intermittent left turn lanes (Figure 3.19). Parking lanes are provided on both the sides of the roadway. The section has a posted speed limit of 30 mph. Driveway density and the unsignalized approaches density are 27 driveways per mile and eight approaches per mile. Adjacent land use consists of commercial developments and ADT on the roadway is approximately 15,000 vpd.

Figure 3.19. MNTH 29 towards 6th Avenue

MNTH 23, Cold Spring, Minnesota

A 0.7 mile section of MNTH 23 in Cold Spring was selected as a comparison site. Limits of the comparison site were from the intersection of 14th Avenue to 5th Avenue (Figure 3.20). Previously this roadway was a two-lane undivided roadway but was expanded to a four-lane divided roadway in 2004. Land use adjacent to the roadway consists of very few commercial developments and the driveway density and the unsignalized approaches density are four driveways per mile and seven approaches per mile. Posted speed limit was 40 mph with a 2004 ADT of 11,800.

Figure 3.20. MNTH 23 towards 5th Avenue

OVERVIEW OF STATISTICAL PROCEDURES

After identifying the study and comparison sites for this research, appropriate statistical procedures were required to evaluate the safety and operational effects of the four-lane to three-lane conversions. Statistical procedures used to analyze the data are discussed in this section.

Traditional methods involve the use of simple before and after study methodologies to determine the change in safety and operational characteristics of a roadway. The underlying assumption in the traditional before and after analysis is that the only variable affecting any changes in operational or safety characteristics is the conversion itself. This methodology may fail to take into account the potential impact of other variables (e.g., citywide crash reduction) on the effects observed during the study period.

A call for a more robust statistical procedure for before and after safety analyses has led to a series of other procedures that are now commonly used. These procedures include:

- Yoked Comparisons (YC),
- Group Comparisons (GC), and
- Empirical Bayes (EB).

These statistical procedures use the traditional before and after approach but include additional procedures to evaluate the effectiveness of the conversion. Of these three approaches, the EB approach has gained wide prominence as it addresses the selection bias or 'regression to the mean' phenomena by using historic data with the observed data to predict what the crash frequency in the after period would have been had the treatment not been applied.

'Regression to the mean' is a selection bias statistical error which gives the false impression that the installed safety countermeasure was effective in reducing the crashes. It is possible that the increase in the crashes which prompted the transportation professionals to install the safety countermeasure was due to an unrelated random event. In such a case, even if no countermeasure was installed, there would likely have been a reduction in crashes in the successive years. Therefore, the result of a 'regression to the mean' bias tends to be an inaccurate (inflated) measure of the safety improvement.

YC and GC methods involve the selection of a comparable site or a group of comparison sites, with similar attributes as the study site, to account for the effects of factors which may change with time during the before and after study. The selection of comparison sites was discussed in previous sections. YC and GC methods use the comparison sites to establish a baseline for the study sites. In other words, the comparison sites provide a measure of how safety and traffic operations changed at a site that did not receive any treatment, as compared to the study sites which did receive some treatment or change. It is assumed that the effects of other factors and overall trends on study and comparison sites are similar.

Traditional, YC, GC, and EB methodologies are discussed briefly in the following sections. Note that each of the previous methods is used in this research to document how the results may vary based on the statistical methodology selected.

Traditional Before and After Analysis Methods

Traditional methods to evaluate the change in safety after implementing a safety countermeasure involve a simple comparison of before and after crashes. An assumption is made that only the variable of intent has changed. All other variables which may change with time are assumed to be constant. While evaluating the safety of a roadway, traditional methods do not consider the effect of other variables which may change with time. Examples of factors which are assumed to remain unchanged and factors not accounted for in a traditional before and after analysis are (*33*):

- Traffic, weather, and road user behavior;
- Other treatments and programs that might have been implemented during the before and after period;
- Change in the probability of reportable crashes being reported; and
- Site selection for countermeasure implementation based on unusual crash history.

Another issue associated with traditional methods is the need for a large data set of before and after crash counts. Statistically large data sets are usually difficult to acquire as crashes are rare and random events.

One traditional method of evaluating the safety of a roadway is the basic Student's t-test. In this analysis type, crash data from equal number of before and after periods are considered. The t-test is used to determine if the difference in the means of the crash counts in the before and after periods is statistically significant. If the results are statistically significant, the implemented safety countermeasure is considered effective. The difference in the means is typically tested at a 95 percent confidence level. This means that if the computed probability of the difference between sample means and population means is less than 0.05, the difference in the means is statistically significant and can be attributed to the implemented safety countermeasure. The procedure for conducting a Student's t-test is described below:

The reduction in crashes is given by:

$$Average_{Before} - Average_{After} \tag{1}$$

Where,

$Average_{Before}$: Average crashes in the before conversion period, and

$Average_{After}$: Average crashes in the after conversion period.

The percentage reduction is given by:

$$\frac{Average_{Before} - Average_{After}}{Average_{before}} \times 100 \tag{2}$$

The t-value is given by:

$$t = \frac{Average_{Before} - Average_{After}}{\sqrt{\frac{Var(Crashes_{Before})}{n_{Before}} + \frac{Var(Crashes_{After})}{n_{After}}}} \tag{3}$$

Where,

n_{Before} = Number of years before conversion, and

n_{After} = Number of years after conversion.

The degrees of freedom are given by:

$$df = n_{Before} + n_{After} - 2 \tag{4}$$

Where,

df = Degrees of freedom.

The t-distribution table is referenced and the p-value (observed significance level of the test) for the calculated t-value and degrees of freedom. If the difference in the means is tested at a 95 percent confidence level and the p-value lies below 0.05, it could be concluded that at 95 percent level of confidence, the difference in means is statistically significant. It could then be concluded that the treatment was effective in reducing the crashes, assuming all other variables remained constant.

Another form of the traditional method is described by Hauer in his book on observational before and after studies in traffic safety (*33*). In this methodology, an equal or unequal number of before and after crash data years can be used to evaluate the change in the safety of the roadway. The notations used in this method are:

p : Expected number of crashes on the roadway in the after period had the countermeasure not been implemented. This number has to be predicted using 'before' data.

l : Expected number of crashes on the roadway in the after period after the countermeasure been implemented. This value is estimated using 'after' data.

Since expected values are estimated, the estimates of p and l are denoted by $\hat{p}$ and $\hat{l}$. Estimates $\hat{p}$ and $\hat{l}$ are then compared to determine the effect on safety due to the conversion.

The reduction in the crash frequency after the implementation of the countermeasure is:

$$\hat{d} = \hat{p} - \hat{l} \tag{5}$$

The variance of $\hat{d}$ is given by:

$$\mathrm{Var}(\hat{d}) = \mathrm{Var}(\hat{l}) + \mathrm{Var}(\hat{p}) \tag{6}$$

The ratio of estimated crashes in the after period to predicted crashes in the after period is computed as:

$$\hat{q} = \frac{\hat{l}}{\hat{p}} \tag{7}$$

This value is also known as the 'index of effectiveness' and sometime referred to as a 'crash modification factor'. If $\hat{q}$ <1 then the treatment is considered to be effective. However this is a biased estimate of q. The unbiased estimate of q is given by:

$$\hat{q}^{*} = \frac{\hat{l}/\hat{p}}{1 + Var(\hat{p})/\hat{p}^{2}} \tag{8}$$

The variance of this estimate is given by:

$$Var(\hat{q}^{*}) = \hat{q}^{2}[(Var(\hat{l})/\hat{l}^{2}) + (Var(\hat{p})/\hat{p}^{2})]/[1 + Var(\hat{p})/\hat{p}^{2}]^{2} \tag{9}$$

The percentage reduction in the crash frequency is given by:

$$\text{Percent Reduction} = 100 * (1 - \hat{q}) \tag{10}$$

As mentioned, the challenge with traditional before and after methods is the assumption that all variables except for the treatment remain constant. If this is true, the results have a high level of statistical precision. If this is not true, the actual contribution of the treatment to the change observed cannot be fully determined. Any reduction in crashes could have occurred due to the joint influence of the other factors which may have changed with time. For example, it is possible that a similar citywide reduction in crashes was experienced during the 'after' period. Other influencing factors such as change in the ADT and change in weather, which could have contributed to the reduction in crashes, are not specifically accounted for. Nevertheless, the traditional before-after analysis can provide researchers with an accurate estimate of the overall increase or decrease in the safety of the roadway due to joint influence of all factors. If the uncontrolled factors provide little influence on the data, an accurate prediction of change can be made.

Yoked Comparison Method

The Yoked Comparison (YC) method is used to account for the other factors which may have influenced the safety of the roadway and isolate the safety effect of the countermeasure. YC methodology uses comparison sites which have similar attributes as a study site in terms of geometric design, location and traffic volume (*34*). Criteria to select the comparison sites are discussed in detail in the next section.

YC methodology assumes that the ratio of the crash reduction for each study site before and after is the same as the ratio for the comparison site, had the conversion not been implemented. The difference between the estimated (observed) crashes in the after period and the predicted crashes in the after period is a measure of effectiveness of the conversion. If the crashes at the comparison site before and after are denoted as **M** and **N** respectively, and observed crashes at the study site in the before and after period is **K** and **L** respectively, the predicted crashes $\hat{p}$ in the after period if no conversion took place are given as:

$$\hat{p} = \frac{N}{M} * K \tag{11}$$

The estimated crashes $\hat{l}$ after the conversion took place are the observed crashes in the after period:

$$\hat{l} = \mathrm{L} \tag{12}$$

The change in crashes in the after period is given by:

$$\hat{d} = \hat{p} - \hat{l} \tag{13}$$

The variance of $\hat{d}$ is given by:

$$\mathrm{Var}\,(\hat{d}) = \mathrm{Var}\,(\hat{l}) + \mathrm{Var}\,(\hat{p}) \tag{14}$$

If $\hat{d} < 0$, the countermeasure or change implemented is not considered to be effective. If $\hat{d} > 0$, the change is considered effective in reducing crashes.

The ratio for estimated and predicted crashes ($\hat{q}$) is another measure of effectiveness given by:

$$\hat{q} = \frac{\hat{l}}{\hat{p}} \tag{15}$$

However, this is a biased estimate of $\hat{q}$. The unbiased estimate of q is given by:

$$\hat{q}^* = \frac{\hat{l}/\hat{p}}{1+Var(\hat{p})/\hat{p}^2} \tag{16}$$

The variance of this estimate is given by:

$$Var(\hat{q}^*) = \hat{q}^2[(Var(\hat{l})/\hat{l}^2) + (Var(\hat{p})/\hat{p}^2)]/[1+Var(\hat{p})/\hat{p}^2]^2 \tag{17}$$

If $\hat{q}^* < 1$, the change is believed to have a positive effect on crash reduction. If $\hat{q}^* > 1$, the change is not considered to be effective in reducing crashes. Accordingly, the percent reduction of crashes is calculated as:

$$\text{Percent Reduction} = 100*(1-\hat{q}^*) \tag{18}$$

Selection of Comparison Sites

YC methodology uses comparison sites which have similar attributes as study sites in terms of geometric design, location, and traffic volume. Ideally, a comparison site should have the same attributes as the study site. However, it is often a challenging task to identify a site near the study site which has the same cross-section, ADT, posted speed limit, and land use. In most cases, a site is acceptable as a comparison site if the site has similar general attributes as the study site. If a similar site as the study site can not be identified, a segment of the untreated study site roadway can be selected as a comparison site.

For a site to be considered as a suitable comparison site, the following requirements should be met (*33*):

- The before and after periods for the study and comparison site should be same to avoid temporal bias;
- If there was a change in variables (speed, ADT, etc.) during the before and after period, the change in variables should be similar to both the treatment and comparison sites;
- The crash data set should be sufficiently large; and
- The sequence of sample odds ratios when calculated from historical crash data should have a sample mean close to 1 and a very small variance.

The concept of sample odds ratios is explained in greater detail later on in this section. The major assumption in traditional before and after analysis methods while evaluating the safety effect of a countermeasure is that other variables remain unchanged during the study period. The major assumption in YC methodology is that the ratio of the crash reduction for the study site before and after is the same as the ratio for the comparison site had the conversion not been implemented at the study site. In terms of mathematical notation, YC method assumes that (*33*):

$$r_C = r_T \text{ or } \frac{r_C}{r_T} = 1 \tag{19}$$

Where,

$r_C = \dfrac{N}{M}$: r_C is the ratio of the crash counts in the after and before periods for the comparison site, and

$r_T = \dfrac{p}{K}$: r_T is the ratio of the crash counts in the after and before periods for the treatment site if no safety countermeasure was implemented.

The unbiased estimate of r_C is given by:

$$\hat{r}_C = \hat{r}_T = (N/M)/(1+\frac{1}{M}) \approx N/M \tag{20}$$

The estimated value of the crash counts for the treatment site had there been no conversion is given by:

$$\hat{p} = \hat{r}_T * K \tag{21}$$

Since YC methodology assumes that $r_C = r_T$, the estimated value of the crash counts for the treatment site had there been no conversion is given by:

$$\hat{p} = \hat{r}_C * K \tag{22}$$

Since (r_C / r_T) is never exactly equal to 1 the odds ratio w which is defined as $w = r_C / r_T$ takes on different values on different occasions. Thus, for a pair of treatment and comparison sites there is a time series of w's. Any such sequence of w's has a mean E{w} and a variance Var{w}. For an acceptable comparison site the value of E{w} is equal to 1. The comparison site that should be selected for the maximum precision is the one that has the lowest value for $1/K+1/N+Var(w)$. The reason for this criterion is explained briefly below.

The variance of $\hat{p}$ is given by:

$$Var(\hat{p}) = \hat{p}^{2}[(1/K) + Var(\hat{r}_T)/r_T^{\,2}] \tag{23}$$

and the $Var(\hat{r}_T)/r_T^{\,2}$ is given by:

$$Var(\hat{r}_T)/r_T^{\,2} = 1/M + 1/N + Var(w) \tag{24}$$

Since $\hat{p} = \hat{r}_T * K$, the precision with which $\hat{p}$ is estimated depends upon $Var(\hat{r}_T)$. From eqn. (24), it can be inferred that $Var(\hat{r}_T)$ will be the lowest when $1/M+1/N+Var(w)$ attains the lowest value. When a comparison site with the lowest $1/M+1/N+Var(w)$ is chosen the estimate $\hat{p}$ will be the most precise. Therefore, a site which has the lowest value for $1/M+1/N+Var(w)$ should be chosen as a comparison site.

Group Comparison Method

Replacing the comparison site with a comparison group is another effective method to account for overall trends. Unlike the YC methodology, the Grouped Comparison (GC) statistical approach does not require strong similarity between study sites and comparison sites. The GC methodology relies on using a number of comparison sites to improve the accuracy of the reference groups. Computational procedures for the GC method are identical to YC. Crashes for the comparison group before and after periods are M and N, which are the sum of crash counts for all comparison sites.

Empirical Bayesian Analysis

The Empirical Bayes (EB) approach uses the means of the reference population along with the observed counts to predict the crashes that would have taken place at the study site in the absence of conversion. The reference population consists of sites with similar attributes. EB uses a weighted average of observed crash data and crash data from a reference population and thereby addresses the 'regression to the mean' phenomena.

As previously mentioned, 'regression to the mean' is a selection bias which occurs when the sites for the conversion have been chosen because of high crash frequency for a short period of time. There is a possibility that the number of crashes would have decreased even if no conversion took place. If a decrease in the after conversion crashes is observed, it is likely that the decrease is not entirely due to the effect of the treatment and the safety benefit of the conversion is inflated due to the regression to the mean phenomena.

While the YC approach accounts for unrelated effects such as time and travel trends, it does not address the regression to the mean phenomena. The EB approach directly addresses the regression to the mean phenomena and may provide significantly different results than those achieved by traditional statistical approaches (*35*). Nevertheless, the EB approach is more complex and the data needs for the EB approach are more than is required for the traditional methodologies.

A growing body of literature exists describing the benefits of using EB techniques in crash data analysis. Often times, safety studies are looking to quantify benefits through Crash Modification Factors/Accident Modification Factors (CMFs and AMFs, respectively) (*36*). AMFs are used to provide an estimate of the crash reductions associated with the safety improvements and are used to determine the costs and benefits of different alternatives. In a review of different safety study methodologies, researchers assigned a level of predictive certainty (LOPC) to each AMF on the basis of the reviews (*36*). This rating was an indicator of the confidence level one should have in the AMF for that treatment. The AMFs which were developed by the EB statistical approach were assigned the highest level of predictive certainty and were qualitatively defined as 'high'. Researchers considered the EB methodology to be the best available statistical approach for before and after crash analysis.

The EB approach is used in the 'before' period to estimate the safety of the four-lane roadway. However, the safety of the roadway after conversion is estimated by considering the average or sum of the crash data in the after period. The EB approach can be used to estimate the safety of the roadway in the after period by using an appropriate reference population but it would be difficult to acquire a new reference population and it is not clear if the existing reference population could be used as the reference population in the 'after' period (*37*).

The proposed step-by-step procedure for EB analysis is as follows (*38*):

1) A regression model to estimate the crashes is formulated, often using average daily traffic (ADT) and other basic roadway attributes as parameters. Other specific parameters important to the speicifc research effort, such as speed variation and unsignalized approaches per mile, could also be incorporated in the model assuming the availability of the data. Previous research has shown that crash data tends to follow a negative binomial statistical distribution. Therefore, the negative binomial statistical modeling procedure is most often employed. The model developed in this procedure is often referred to as the Safety Performance Function (SPF), and represents the 'before' conditions input to the evaluation. A typical SPF with average ADT as the parameter is presented below:

$$y_i = a \times ADT_i^{\,b} \qquad (25)$$

Where,

y_i = Number of average expected crashes per year per mile;

a *and* b = Regression parameters; and

ADT = Average Daily Traffic.

2) An overdispersion parameter is estimated which would determine how widely the crashes are distributed around the mean. The overdispersion parameter is used to generate weights in the EB methodology to estimate the safety of the change, in this case the conversion of the four-lane undivided roadway to a three lane with TWLTL roadway. The overdispersion parameter is denoted by j.

3) Weights are used to combine information from the crash record at the treatment site and the crash record at similar sites to estimate the expected crash frequency at the treatment site. If the crash records for the treatment site are available for a larger number of years, then the weight assigned to the expected crashes at similar sites decreases. This draws the estimated crash frequency at the treatment site towards the average crash frequency at the treatment site. The weights are determined by using the equation:

$$Weight = \frac{1}{1 + \frac{y_i \times n}{j}} \tag{26}$$

Where,

y_i = Number of average expected crashes per year per mile;

n = Number of years in the before period; and

j = Overdispertion parameter.

4) The estimated crashes for the road section for the before period is given by:

$$Estimate_i = Weight \times (y_i \times n \times l) + (1 - Weight) \times u_i \tag{27}$$

Where,

u_i = Total number of observed crashes during the before period;

n = Number of years in the before period; and

l = Length of the site.

The standard deviation of this estimate is given by:

$$s\,(Estimate_i) = \sqrt{(1 - Weight) \times Estimate_i} \tag{28}$$

5) To estimate the number of crashes in the after period, adjustments for the different before and after periods and for the change in the ADT should be made (*33, 39*). The different adjustment factors which should be considered in the analysis include:

   a) Adjustment factor for different before and after periods is given by:

$$r_d = \frac{m}{n} \tag{29}$$

Where,

r_d = Adjustment factor to account for different before and after period;

m = Number of years in the after period; and

n = Number of years in the before period

b) Adjustment factor to account for change in ADT in the before and after period is given by:

$$r_{tf} = \frac{ADT_{After}{}^{b}}{ADT_{Before}{}^{b}} \tag{30}$$

Where,

r_{tf} = Adjustment factor for change in ADT in the before and after period;

$ADT_{After}{}^{b}$ = Average ADT in the after period; and

$ADT_{Before}{}^{b}$ = Average ADT in the before period.

6) The predicted crashes in the after period is given by:

$$\hat{p}_i = Estimate \times r_{tf} \times r_d \tag{31}$$

7) The estimated crashes in the after period are given by:

$$\hat{l}_i = v_i \tag{32}$$

Where,

v_i = Observed crashes in the after period.

8) The index of effectiveness or crash modification factor is calculated as:

$$\hat{q}_i = \frac{\hat{l}_i}{\hat{p}_i} \tag{33}$$

If $\hat{q}_i$ < 1, then the conversion had a positive effect on safety.

9) The percentage reduction in the crashes at a site (E) is given by:

$$E_i = 100 \times (1 - \hat{q}_i) \tag{34}$$

10) The overall effectiveness of the conversion is given by:

$$\hat{q} = \frac{\sum l_i}{\sum p_i} \tag{35}$$

However, this is a biased estimate of the overall effectiveness of the conversion. The unbiased estimate of the overall effectiveness is given by:

$$\hat{q}^* = \frac{\hat{q}}{1 + \frac{Var(\hat{p})}{\hat{p}^2}} \tag{36}$$

The variance of $\hat{l}$ is given by:

$$Var\left(\hat{l}\right) = \sum \hat{l}_i \tag{37}$$

The variance of $\hat{p}$ is given by:

$$Var(\hat{p}) = \sum Var(Estimate)_i r_{tf}^2 \ r_d^2 \tag{38}$$

The variance of $\hat{q}^*$ is given by:

$$Var(\hat{q}^*) = \hat{q}^2 \frac{\left[\frac{Var\left(\hat{l}\right)}{\hat{l}^2} + \frac{Var(\hat{p})}{\hat{p}^2}\right]}{\left[1 + \frac{Var(\hat{p})}{\hat{p}^2}\right]^2} \tag{39}$$

The overall percentage crash reduction is given by:

$$E = 100 \times (1 - \hat{q}^{*}) \tag{40}$$

A typical spreadsheet for calculating EB statistics at multiple study sites is presented in Table 3.2.

Table 3.2. Proposed Layout of the Before and After Study Using the EB Methodology (*39*)

Study Site	**(u_i)**	**(p_i)**	**(l_i)**	**(q_i)**	**(E_i)**
1	u_1	p_1	l_1	q_1	E_1
2	u_2	p_2	l_2	q_2	E_2
.	.	.	.	.	.
i	u_i	p_i	l_i	q_i	E_i

Where,

u_i Observed crashes in the before implementing the safety countermeasure

p_i Predicted crashes at site 'i' in the after period without implementing the safety countermeasure (Equation 31)

l_i Estimated/Observed crashes at site 'i' in the after implementing the safety countermeasure (Equation 32)

q_i Index of effectiveness of the safety countermeasure at site 'i' (Equation 33)

E_i Percent reduction in the crashes at site 'i' after the implementation of the countermeasure (Equation 34)

SUMMARY

Nine study sites and nine comparison sites were selected for this analysis. Volume, speed, geometric data, and other relevant data pertaining to these sites were collected. Data were obtained by conducting a variety of data collection procedures.

A variety of before and after statistical methodologies were described and are employed in this research. The results obtained with each methodology will be compared and contrasted to evaluate the impact of methodology selection.

Chapter 4
RESEARCH RESULTS

The purpose of this chapter is to present the data (speed, ADT, and crash) collected from the study and comparison sites and to present the results obtained by analyzing the data.

OPERATIONAL DATA

The two types of operational data considered in this research were speed and average daily traffic (ADT). Before and after ADT data were available for all nine sites. ADTs ranged from approximately 8,300 to 17,400 vpd before conversion, to approximately 8,000 to 19,600 vpd after conversion. Tabular summary of the available ADT data one year prior to and after conversion are presented in Table 4.1. ADT data at the state highway sites were provided by Mn/DOT; thus, the data collection method is not cited.

Of the nine study sites considered in this research, before and after speed data were available for six sites. The three sites for which before and after speed data were unavailable were sites located on the state trunk highways. Before and after speed data were also collected within one year before and after the conversion. For some sites the speed data before and after conversion was collected from more than one mid-block location. The mean and 85th percentile speed at different locations along the study sites are presented in Tables 4.2 and 4.3, respectively.

Table 4.1. Summary of ADT Data Before and After Conversion

Site	From	To	Data Collected By	Data Collection Method	ADT (vpd) Before Conversion	ADT (vpd) After Conversion
MNTH 61, Duluth	32nd Avenue	40th Avenue	Mn/DOT	---	17,400	19,600
MNTH 23, Cold Spring	5th Avenue South	Sauk River Bridge	Mn/DOT	---	8,300	8,000
MNTH 29, Alexandria	Broadway Street	Nokomis Street	Mn/DOT	---	15,600	15,800
Lexington Parkway, St. Paul	Lincoln Avenue	Jefferson Avenue	City of St. Paul	Traffic Data Recorders	13,979	14,172
Fairview Avenue, St. Paul	Marshall Avenue	Ford Parkway	City of St. Paul	Traffic Data Recorders	14,741	14,183
W. 7th Street, St. Paul	Jefferson Avenue	May Street	City of St. Paul	Traffic Data Recorders	10,355	11,123
Pierce Butler Route, St. Paul	Minnehaha Avenue	Transfer Road	City of St. Paul	Traffic Data Recorders	8,961	9,166
E. Wentworth Avenue, St. Paul	MNTH 52	Humboldt Avenue	UW-Madison	Manual Traffic Counts	10,270	9,500
Grand Avenue, Duluth	59th Avenue West	46th Avenue West	UW-Madison	Traffic Data Recorders	9,952	10,016

Table 4.2. Summary of the Mean Speed Data Before and After Conversion

Street	Data Source	Data Collection Method	Location	Direction	Mean Speed Before	Mean Speed After	Reduction in mean speed
Lexington Parkway, St. Paul	City of St. Paul	Traffic Data Recorders	1	NB	38.0	34.0	4.0
				SB	37.0	34.0	3.0
			2	NB	34.0	31.0	3.0
				SB	34.0	32.0	2.0
Fairview Avenue, St. Paul	City of St. Paul	Traffic Data Recorders	1	NB/SB	33.5	31.5	2.0
W. 7th Street, St. Paul	City of St. Paul	Traffic Data Recorders	1	EB	34.0	35.0	-1.0
				WB	34.0	33.0	1.0
			2	EB	34.0	30.0	4.0
				WB	32.0	30.0	2.0
			3	EB	35.0	32.0	3.0
				WB	34.0	33.0	1.0
			4	EB	34.0	32.0	2.0
				WB	33.0	32.0	1.0
			5	EB	33.0	31.0	2.0
				WB	32.0	30.0	2.0
Pierce Butler Route, St. Paul	City of St. Paul	Traffic Data Recorders	1	EB	37.0	37.0	0.0
				WB	37.0	36.0	1.0
E. Wentworth Avenue, St. Paul	UW	LIDAR Speed Gun	1	EB/WB	36.0	34.3	1.7
Grand Avenue, Duluth	UW	Traffic Data Recorders	1	SB	32.0	30.0	2.0
				NB	34.0	32.0	2.0

Table 4.3. Summary of 85th Percentile Speed Data Before and After Conversion

Site	Data Source	Data Collection Method	Location	Direction	85th Percentile Speed		Reduction in 85th percentile speed
					Before	After	
Lexington Parkway, St. Paul	City of St. Paul	Traffic Data Recorders	1	NB	43.0	39.0	4.0
				SB	41.0	39.0	2.0
			2	NB	39.0	35.0	4.0
				SB	39.0	37.0	2.0
Fairview Avenue, St. Paul	City of St. Paul	Traffic Data Recorders	1	NB/SB	37.6	35.2	2.4
W. 7th Street, St. Paul	City of St. Paul	Traffic Data Recorders	1	EB	40.0	40.0	0.0
				WB	40.0	38.0	2.0
			2	EB	39.0	35.0	4.0
				WB	38.0	36.0	2.0
			3	EB	40.0	38.0	2.0
				WB	39.0	38.0	1.0
			4	EB	39.0	37.0	2.0
				WB	38.0	38.0	0.0
			5	EB	38.0	35.0	3.0
				WB	37.0	35.0	2.0
Pierce Butler Route, St. Paul	City of St. Paul	Traffic Data Recorders	1	EB	44.0	44.0	0.0
				WB	44.0	43.0	1.0
E. Wentworth Avenue, St. Paul	UW	Speed Gun	1	EB/WB	40.0	38.2	1.8
Grand Avenue, Duluth	UW	Traffic Data Recorders	1	SB	36.0	38.0	-2.0
				NB	38.0	38.0	0.0

OPERATIONAL DATA ANALYSIS AND RESULTS

A paired sample t-test was used to analyze the ADT changes in the before and after periods. The combined results of all study sites found no statistically significant change in ADT (p-value = 0.46) in the before and after conditions. Changes at individual sites varied, with little change at the MNTH 23, MNTH 29, Lexington Parkway, Fairview Avenue, Pierce Bulter Route, and Grand Avenue sites. MNTH 61 observed a 2,200 vpd increase, W. 7th Street observed an 800 vpd increase, and E. Wentworth Avenue observed an 800 vpd decrease. The slight decrease at E. Wentworth Avenue was not attributed to changes in the roadway cross-section.

A paired sample t-test was also used to analyze the change in the mean and 85th percentile speed before and after conversion. Speed data from individual sites were combined to evaluate the change in speed after conversion. The changes in the mean and 85th percentile speed before and after conversion were found to be statistically significant for the study sites. The average reduction in the 85th percentile speed was 1.66 mph (p-value = <0.001) after conversion. Average reduction in the mean speed was 1.88 mph (p-value = <0.001). The results from this analysis are consistent with the findings in the literature (*20*). Results are summarized in Table 4.4.

Changes in operating speeds at each study site varied from no change to a reduction of 4.0 mph. In all cases, the 'after' speed was less than or equal to the 'before' speed.

Plots of the reduction in speeds versus the unsignalized access density and ADT were completed and evaluated. Unsignalized access density was computed by summing the driveway density and the unsignalized approach density. Plots are presented in Figures 4.1 and 4.2. The plots were then fitted using a simple linear regression model to provide a visual estimate of trend. As expected, the trend lines suggest that a greater reduction in speeds is observed at higher ADT and higher unsignalized access density. This result is likely due to the increased vehicle density and slight change in flow conditions associated with the conversion. Nevertheless, since this trend is based on a limited (small) data set, it cannot be definitively concluded that this relationship holds for all cases.

Table 4.4. Results of Operational Evaluations (ADT, Mean Speed, 85th Percentile Speed)

Description	Average Reduction	p-value	Statistical Analysis Result
Change in ADT	- - -	0.46	Not significant
Change in Mean speed	1.88 mph	< 0.001	Significant
Change in 85th percentile speed	1.66 mph	< 0.001	Significant

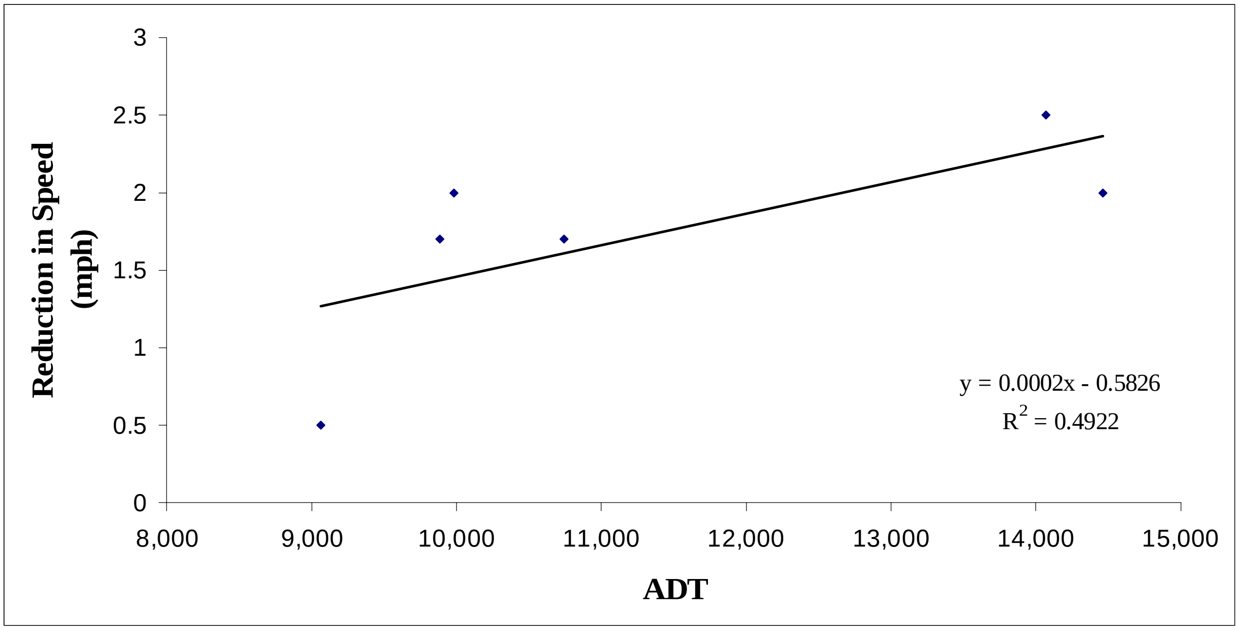

Figure 4.1. Scatterplot of Reduction in Speed and ADT

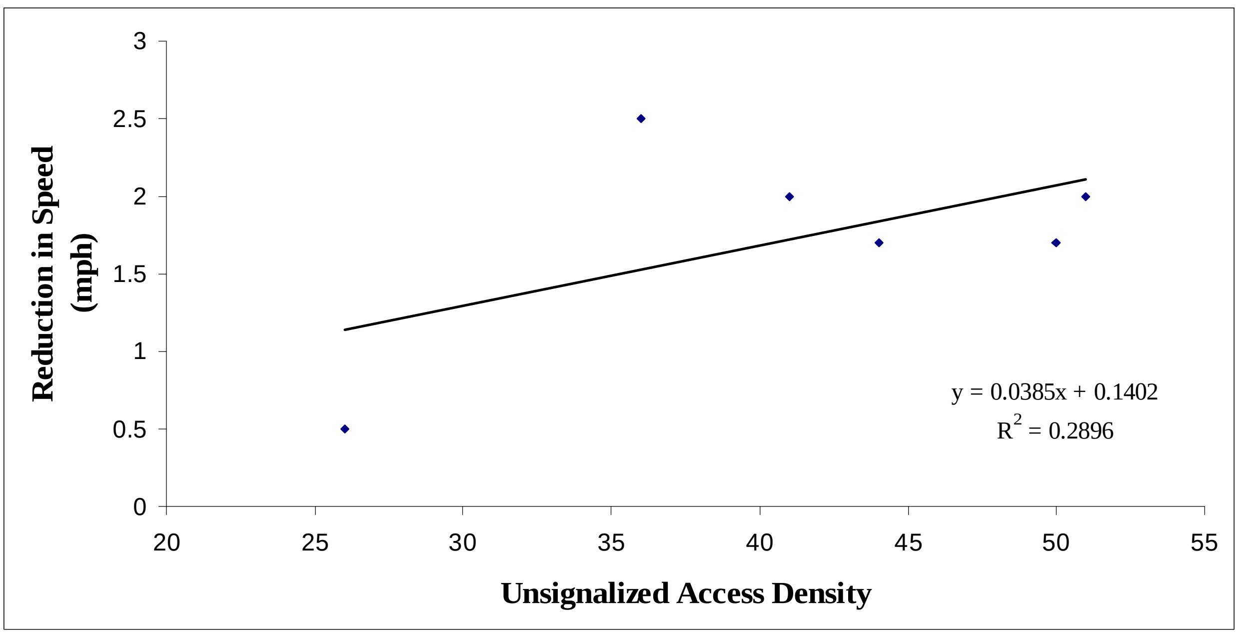

Figure 4.2. Scatterplot of Reduction in Speed and Unsignalized Access Density

Information on the percentage of vehicles traveling above the speed limit was available for the two sites in which the researchers collected data. The two sites were Grand Avenue in Duluth and E. Wentworth Avenue in St. Paul.

At Grand Avenue in Duluth, the speeds of approximately 70,000 vehicles were recorded for a seven day period in the before period. In the after period, the speeds of approximately 31,000 vehicles were recorded for a three-day period. The distribution of speeds on Grand Avenue, before and after conversion, is presented in Figure 4.3.

Before conversion, approximately 60 percent of vehicles were found to be traveling above the posted speed limit. After conversion, the percentage of vehicles traveling above the speed limit was approximately 53 percent. Therefore, a seven percent reduction in the number of vehicles traveling above the speed limit was observed.

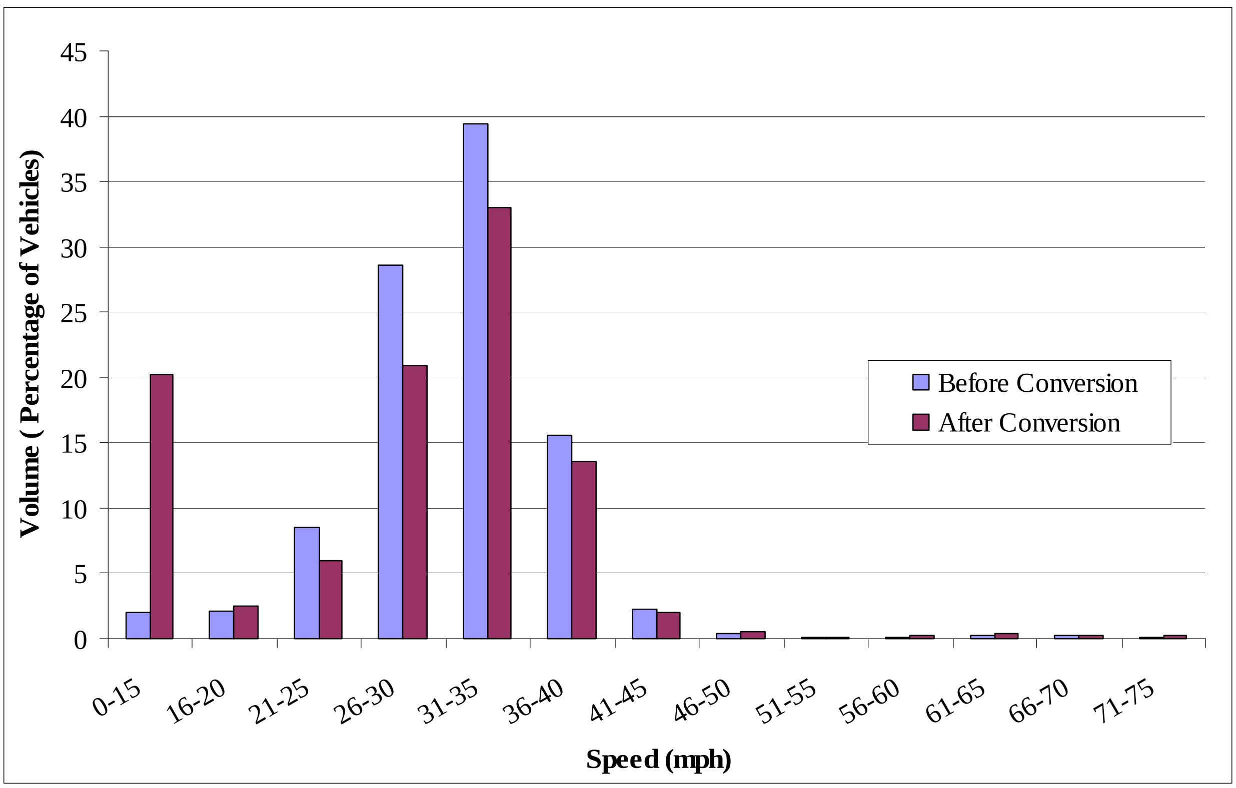

Figure 4.3. Speed Distribution at Grand Avenue, Duluth, Before and After Conversion

Fortieth Avenue in Duluth was a 'comparison site' roadway located in the vicinity of Grand Avenue. Operational data at 40th Avenue was recorded for similar durations before and after Grand Avenue was converted. A total of 51,000 speed observations were made over a seven day period before the conversion. Similarly, a total of 26,000 speed observations were made over a three day period after the conversion. The percentage of vehicles traveling above the speed limit before Grand Avenue was converted was approximately 35 percent and after conversion, approximately 41 percent. A six percent increase in the percentage of vehicles traveling above the speed limit on 40th Avenue was observed after Grand Avenue was converted. It can be inferred from these data that the conversion of Grand Avenue did lead to a reduction in operating speeds as the speeds of the vehicles traveling above the speed limit on Grand Avenue decreased after conversion compared to the increase in the percentage of vehicles traveling above the speed limit after conversion on 40th Avenue.

A much smaller sample of speeds was available at the E. Wentworth Avenue site in St. Paul. In the before period, speeds of 164 vehicles were recorded. In the after period, speeds of 123 vehicles were recorded. Both the speed counts were done between 11:00 AM and 3:00 PM. The distribution of speeds on E. Wentworth Avenue before and after conversion is presented in Figure 4.4. The percentage of vehicles traveling above the speed limit on E. Wentworth Avenue was 56 percent and 39 percent before and after conversion, respectively. Therefore, a 17 percent reduction in vehicles traveling above the speed limit after the conversion of E. Wentworth Avenue was observed.

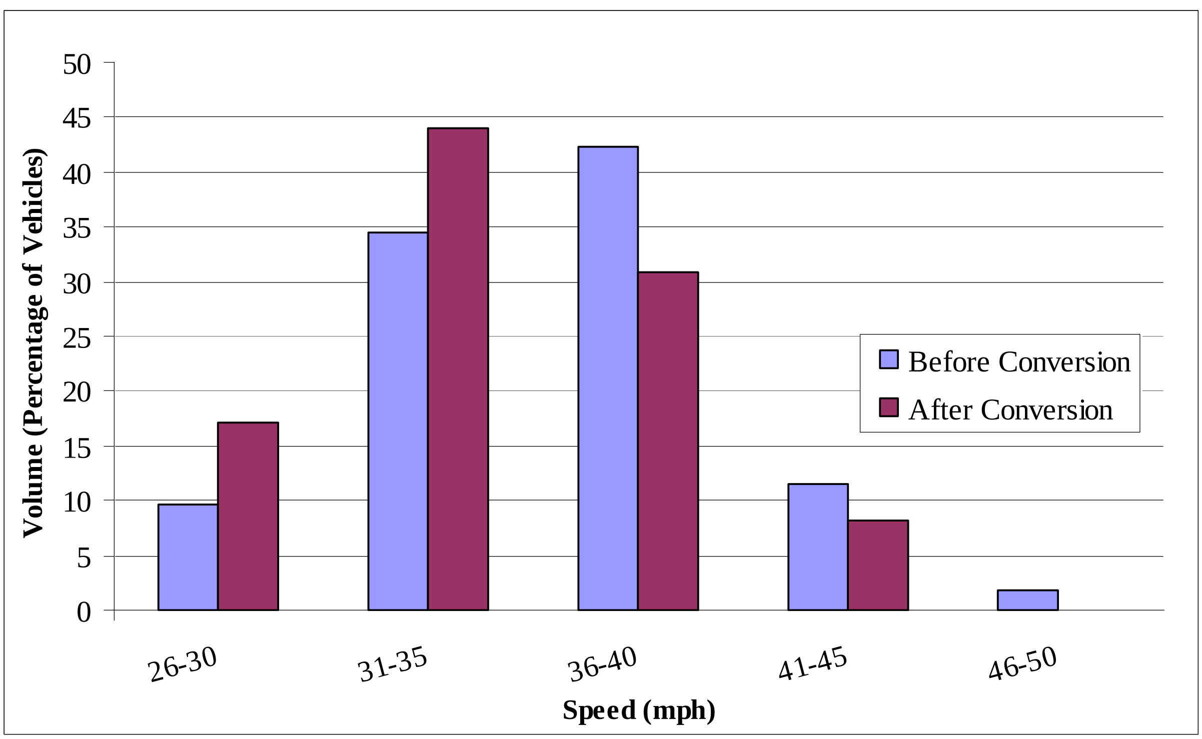

Figure 4.4. Speed Distribution at E. Wentworth Avenue, St. Paul, Before and After Conversion

CRASH DATA

Of the nine sites evaluated, only seven sites were considered for crash data analysis as E. Wentworth Avenue in St. Paul and Grand Avenue in Duluth were converted in 2005 and did not have a sufficient 'after' data set. Nevertheless, 'before' data from all nine sites were used to develop an understanding of crash history and trends. Before conversion crash data for all sites are summarized in Appendix E.

Crash data for all the study and comparison sites from 1984 to 2005 were obtained from the Mn/DOT crash database. As previously mentioned, each study site was focused on crash data obtained five years prior to five years after the conversion. However, since each study site was converted from a four-lane to a three-lane with TWLTL roadway at different times, the number of data years available both before and after the conversion varied at each site.

Crash data were analyzed by year and categorized by type and severity. Total crashes that took place before the conversion and after the conversion for each treatment site were also analyzed. Fatal crashes were not considered in this research as no fatal crashes occurred during the five-year before/after study period. Two levels of crash severity were considered in this research. They were:

- Injury Crashes; and
- Property Damage Only Crashes (PDO).

Total crashes, injury crashes, and property damage only crashes before and after the conversion are presented in Tables 4.5 and 4.6. Note that the sites without 'after' data were not included in the calculations.

Table 4.5. Total Crashes and Average Crashes in the Before and After Period

Site	Before Conversion			After Conversion			Reduction in Crashes/ Year
	Years	Total Crashes	Crashes /Year	Years	Total Crashes	Crashes /Year	
Lexington Parkway, St. Paul	5	157	31.4	2	29	14.5	16.9
Fairview Avenue, St. Paul	5	314	62.8	5	157	31.4	31.4
W. 7th Street, St. Paul	5	135	27	1	14	14	13
Pierce Butler Route, St. Paul	5	141	28.2	4	99	24.8	3.4
MNTH 61, Duluth	5	24	4.8	5	17	3.4	1.4
MNTH 23, Cold Spring	5	62	12.4	5	43	8.6	3.8
MNTH 29, Alexandria	5	290	58	5	157	31.4	26.6
Average			**32.1**			**18.3**	**13.8**

Table 4.6. Crash Data Categorized by Severity

Severity	Site	Before Conversion			After Conversion			Reduction in Crashes /Year
		Years	Crashes	Crashes /Year	Years	Crashes	Crashes /Year	
Injury Crashes	Lexington Parkway, St. Paul	5	36	7.2	2	8	4.0	3.2
	Fairview Avenue, St. Paul	5	86	17.2	5	40	8.0	9.2
	W. 7th Street, St. Paul	5	38	7.6	1	0	0.0	7.6
	Pierce Butler Route, St. Paul	5	32	6.4	4	24	6.0	0.4
	MNTH 61, Duluth	5	12	2.4	5	11	2.2	0.2
	MNTH 23, Cold Spring	5	31	6.2	5	14	2.8	3.4
	MNTH 29, Alexandria	5	70	14.0	5	37	7.4	6.6
	E. Wentworth Avenue, St. Paul	5	28	5.6	---	---	---	---
	Grand Avenue, Duluth	5	31	6.2	---	---	---	---
Property Damage Only Crashes	Lexington Parkway, St. Paul	5	121	24.2	2	21	10.5	13.7
	Fairview Avenue, St. Paul	5	228	45.6	5	117	23.4	22.2
	W. 7th Street, St. Paul	5	97	19.4	1	14	14.0	5.4
	Pierce Butler Route, St. Paul	5	109	21.8	4	75	18.7	3.1
	MNTH 61, Duluth	5	12	2.4	5	6	1.2	1.2
	MNTH 23, Cold Spring	5	31	6.2	5	29	5.8	0.4
	MNTH 29, Alexandria	5	220	44.0	5	120	24.0	20.0
	E. Wentworth Avenue, St. Paul	5	62	12.4	---	---	---	---
	Grand Avenue, Duluth	5	17	3.4	---	---	---	---

The addition of a two-way left-turn lane changes the attributes of a left-turn maneuver and may impact the frequency of left-turn maneuver crashes. Additionally, moving decelerating turning vehicles out of the through lane may affect rear-end crash frequencies. To determine the safety impact of the change in turning maneuvers, three types of crashes were further explored including:

- Rear-end crashes;
- Left-turn crashes; and
- Right-angle crashes.

Rear-end, left-turn, and right-angle crashes, before and after the conversion, are presented in Table 4.7. Note again that detailed crash data for the study and comparison sites are provided in Appendix E and Appendix G.

Table 4.7. Crash Data Categorized by Type

Type of Crash	Site	Before Conversion			After Conversion			Reduction in Crashes /Year
		Years	Crashes	Crashes /Year	Years	Crashes	Crashes /Year	
Rear End	Lexington Parkway, St. Paul	5	27	5.4	2	14	7.0	-1.6
	Fairview Avenue, St. Paul	5	61	12.2	5	56	11.2	1.0
	W 7th Street, St. Paul	5	29	5.8	1	2	2.0	3.8
	Pierce Butler Rt., St. Paul	5	10	2.0	4	24	6.0	-4.0
	MNTH 61, Duluth	5	7	1.4	5	6	1.2	0.2
	MNTH 23, Cold Spring	5	11	2.2	5	16	3.2	-1.0
	MNTH 29, Alexandria	5	117	23.4	5	61	12.2	11.2
Right Angle	Lexington Parkway, St. Paul	5	67	13.4	2	8	4.0	9.4
	Fairview Avenue, St. Paul	5	113	22.6	5	38	7.6	15.0
	W 7th Street, St. Paul	5	31	6.2	1	7	7.0	-0.8
	Pierce Butler Rt., St. Paul	5	19	3.8	4	16	4.0	-0.2
	MNTH 61, Duluth	5	2	0.4	5	3	0.6	-0.2
	MNTH 23, Cold Spring	5	6	1.2	5	5	1.0	0.2
	MNTH 29, Alexandria	5	54	10.8	5	21	4.2	6.6
Left Turn	Lexington Parkway, St. Paul	5	26	5.2	2	3	1.5	3.7
	Fairview Avenue, St. Paul	5	41	8.2	5	13	2.6	5.6
	W 7th Street, St. Paul	5	14	2.8	1	2	2.0	0.8
	Pierce Butler Rt., St. Paul	5	9	1.8	4	7	1.8	0.0
	MNTH 61, Duluth	5	1	0.2	5	0	0.0	0.2
	MNTH 23, Cold Spring	5	21	4.2	5	3	0.6	3.6
	MNTH 29, Alexandria	5	47	9.4	5	25	5.0	4.4

CRASH DATA ANALYSIS

Crash data were first analyzed using traditional approaches which involves a comparison of the before and after crashes. Crash data were also analyzed by YC, GC, and EB approaches. The reasons for considering multiple analysis techniques were both for analytical curiosity as well as to show how the results may vary based on analysis method selected.

Traditional Approach

Both the crash frequency and crash rate were considered in the before and after analysis. Therefore, ADT was selected as a normalizing measure used in calculating the crash rate. Before and after ADT was the average ADT in the study period preceding the conversion and following the conversion. The ADT values used in the crash data analysis are presented in Table 4.8.

To begin the analysis, the total number of crashes that took place before and after conversion was quantified. Average total crashes per year and crash rate (crashes per million vehicle miles traveled) were then calculated. The average crashes per year, crash rate and the percentage reduction of the average crashes are presented in Table 4.9. Note that 'before' data is provided on East Wentworth Avenue and Grand Avenue for information only as it is not included in the totals. Paired sample t-test was used to analyze the change in the average crashes and crash rate before and after conversion.

Table 4.8. Before and After Study Periods and ADT Before and After Conversion

Site	Before Period (Years)	ADT- Before Conversion	After Period (Years)	ADT – After Conversion	Difference in ADT
Lexington Parkway, St. Paul	5	13,979	2	14,172	193
Fairview Avenue, St. Paul	5	14,741	5	13,991	-750
W. 7th Street, St. Paul	5	10,355	1	11,123	768
Pierce Butler Route, St. Paul	5	8,961	4	8,233	-728
MNTH 61, Duluth	5	18,150	5	19,233	1,083
MNTH 23, Cold Spring	5	6,918	5	9,000	2,082
MNTH 29, Alexandria	5	15,266	5	15,800	534
E. Wentworth Avenue, St. Paul	5	9,762	---	10,500	738
Grand Avenue, Duluth	5	13,800	---	10,000	-3800

Table 4.9. Average Crashes, Crash Rate and Percentage Reductions

Site	Length	Average Crashes Before	Average Crashes After	Percentage Reduction	Crash Rate Before*	Crash Rate After*	Percentage Reduction
Lexington Parkway, St. Paul	0.6	31.4	14.5	53.8	10.3	4.7	54.5
Fairview Avenue, St. Paul	2.1	62.8	31.4	50.0	5.6	2.9	47.3
W. 7th Street, St. Paul	1.4	27.0	14.0	48.1	5.1	2.5	51.7
Pierce Butler Route, St. Paul	2.9	28.2	24.8	12.2	3.0	2.8	4.5
MNTH 61, Duluth	0.7	4.8	3.4	29.2	1.0	0.7	33.2
MNTH 23, Cold Spring	0.6	12.4	8.6	30.6	8.1	4.3	46.7
MNTH 29, Alexandria	0.5	58.0	31.4	45.9	19.6	10.3	47.7
E. Wentworth Avenue, St. Paul	0.9	(18.0)	---	---	(5.3)	---	---
Grand Avenue, Duluth	0.9	(9.6)	---	---	(2.5)	---	---
Total		224.6	128.1		52.6	28.1	

* Crash Rate = (Crashes*10^6)/ (365*Number of Years*Length*ADT)

Similar calculations were repeated for different crash types using the data provided in Tables 4.5 and 4.6. The results of the analysis of total crashes, injury crashes and property damage only crashes are summarized in Table 4.10. Statistically significant reductions in the frequencies and rates for total crashes, injury crashes, and property damage only crashes were observed using this approach.

Another method of evaluating the effectiveness of the conversion is by predicting the number of crashes that would have taken place had there been no conversion. The crashes that would have taken place had there been no conversion were predicted by considering both the number of before crashes along with the duration of the before and after periods. The predicted crashes are then compared to the actual crashes that took place in the after period. The procedure for conducting this analysis was provided in greater detail in the *Overview of Statistical Procedures* section in Chapter 3. Total crashes that took place in the before and after conversion period and the duration of the before and after periods considered in this analysis are presented in Table 4.11. ***K*** is used to denote the total number of crashes in the before period and ***L*** is used to denote the total number of crashes in the after period.

Table 4.10. Results of Total Crashes, Injury Crashes and Property Damage Only Crash Analysis

Severity	Description	p-value	Statistical Analysis Result	Percentage Reduction
Total Crashes	Change in average crashes	0.022	Significant	43.0
	Change in crash rate	0.028	Significant	46.5
Injury Crashes	Change in average crashes	0.017	Significant	50.2
	Change in crash rate	0.022	Significant	54.3
Property Damage Only Crashes	Change in average crashes	0.034	Significant	40.3
	Change in crash rate	0.047	Significant	44.6

Table 4.11. Total Crashes in the Before and After Periods

Site	Before Conversion		After Conversion	
	Years	Total Crashes (K)	Years	Total Crashes (L)
Lexington Parkway, St. Paul	5	157	2	29
Fairview Avenue, St. Paul	5	314	5	157
W. 7th Street, St. Paul	5	135	1	14
Pierce Butler Route, St. Paul	5	141	4	99
MNTH 61, Duluth	5	24	5	17
MNTH 23, Cold Spring	5	62	5	43
MNTH 29, Alexandria	5	290	5	157

An estimated of crashes that would have taken place had there been no conversion, the reduction in the crashes per site, and the index of effectiveness per site are computed using equations 5 and 7 outlined in Chapter 3. Results are presented in Table 4.12. The results show that crash reductions have occurred at all study sites. However, the magnitude of the reduction in crashes varied from site to site as indicated by the percentage reduction in crashes.

The net effect of four-lane to three-lane conversion on total crashes for the seven study sites is presented in Table 4.13. The results indicate that there was a combined reduction of 376.6 crashes after the four-lane to three-lane conversion. This reduction was found to be statistically significant. Similar calculations were performed for injury crashes and property damage only crashes. The percentage reductions in the total crashes, injury crashes and property damage only crashes after the conversion are presented in Table 4.14. The results indicate that a reduction of total crashes, injury crashes and property damage only crashes occurred at all study sites. Reduction in crashes varied from site to site as indicated by the percentage reduction in crashes.

The net effect of the four-lane to three-lane conversion on total crashes, injury crashes and property damage only crashes for the seven study sites is presented in Table 4.15. The results indicate that after the four-lane to three-lane conversion, there was a reduction of 112.6 injury crashes and 264 PDO crashes. These reductions in crashes were found to be statistically significant.

Table 4.12. Predicted Crashes, Reduction in Crashes, Index of Effectiveness and Percentage Reduction in Crashes (Total Crashes)

Site	**λ**	**Variance (λ)***	**r_d**	**π**	**Variance (π)**	**δ**	**θ**	**100(1- θ)**
Lexington Parkway, St. Paul	29	29	0.4	62.8	25.1	33.8	0.459	54.1
Fairview Avenue, St. Paul	157	157	1.0	314.0	314.0	157	0.498	50.2
W. 7th Street, St. Paul	14	14	0.2	27.0	5.4	13	0.515	48.5
Pierce Butler Route, St. Paul	99	99	0.8	112.8	90.2	13.8	0.871	12.9
MNTH 61, Duluth	17	17	1.0	24.0	24.0	7	0.680	32.0
MNTH 23, Cold Spring	43	43	1.0	62.0	62.0	19	0.683	31.7
MNTH 29, Alexandria	157	157	1.0	290.0	290.0	133	0.540	46.0
Total	516	516		892.6	810.8			

* By definition, λ is equal to variance λ

Where,

λ : Observed/Estimated Crashes in the after period;

r_d : Ratio of the years in the after period to the years in the before period;

π : Predicted Crashes in the after period had there been no conversion;

δ : Reduction in Crashes;

θ : Index of Effectiveness. If $\theta < 1$, the conversion was effective in reducing crashes; and

100*(1- θ): Percentage reduction in crashes.

Table 4.13. Net Effect of Four-lane to Three-lane Conversion on Total Crashes

Reduction in crashes (δ)	376.6
Index of Effectiveness $\theta = (\lambda/\pi)/\{1+Var(\pi)/\pi^2\}$	0.58
$Var(\delta) = Var(\pi) + Var(\lambda)$	1326.8
Standard Deviation $\sigma(\delta)$	36.4
$Var(\theta) = \theta^2[(Var(\pi)/\pi^2) + (Var(\lambda)/\lambda^2)]/(1+Var(\pi)/\pi^2)^2$	0.001
Standard Deviation $\sigma(\theta)$	0.031
Percentage Reduction in Crashes $100*(1-\theta)$	42.3

Table 4.14. Percentage Reductions in Crashes (Total Crashes, Injury Crashes and Property Damage Only Crashes)

Site	Percentage Reduction in Crashes		
	Total Crashes	Injury Crashes	Property Damage Only Crashes
Lexington Parkway, St. Paul	54.1	45.9	57.0
Fairview Avenue, St. Paul	50.2	54.0	48.9
W. 7th Street, St. Paul	48.5	100.0	28.6
Pierce Butler Route, St. Paul	12.9	9.1	14.8
MNTH 61, Duluth	32.0	15.4	53.8
MNTH 23, Cold Spring	31.7	56.3	9.4
MNTH 29, Alexandria	46.0	47.9	45.7

Table 4.15. Net Effect of Four-lane to Three-lane Conversion on Total Crashes, Injury Crashes and Property Damage Only Crashes

Description	Total Crashes	Injury Crashes	PDO Crashes
Reduction in crashes (δ)	376.6	112.6	264.0
Index of Effectiveness (θ)	0.58	0.54	0.59
Standard Deviation $\sigma(\delta)$	36.4	19.0	31.1
Standard Deviation $\sigma(\theta)$	0.031	0.057	0.037
Percentage Reduction in Crashes $100*(1-\theta)$	42.3	45.8	40.9

The same methodologies were also used to analyze crashes categorized by type. The results are presented in Table 4.16. Results indicate that the reduction of left-turn crashes was statistically significant. The change in the crash rate of left-turn crashes after conversion was also statistically significant. Changes in rear-end and right-angle crashes were not found to be significant.

Changes in rear-end, right-angle, and left-turn crashes after the conversion were also determined by estimating the number of crashes had there been no conversion and comparing them with the observed number of crashes in the after period. The percentage reductions in rear-end, right-angle, and left-turn crashes after the conversion are presented in Table 4.17. It can be observed that a reduction in the left turn crashes occurred at all the seven sites. Rear-end and right-angle crashes varied from site-to-site, with several sites showing modest increases in these crash types (negative value indicates increase).

Table 4.16. Results of Rear-End, Right-Angle and Left-Turn Crash Analysis

Crash Type	Description	p-value	Statistical Analysis Result	Percentage Reduction
Rear End Crashes	Change in average crashes	0.491	Not significant	- - -
	Change in crash rate	0.414	Not significant	- - -
Right Angle Crashes	Change in average crashes	0.116	Not significant	- - -
	Change in crash rate	0.093	Not significant	- - -
Left Turn Crashes	Change in average crashes	0.021	Significant	57.70
	Change in crash rate	0.052	Significant	64.66

Table 4.17. Percentage Reduction in Rear-End, Right-Angle and Left-Turn Crashes

Site	Percentage Reduction in Crashes		
	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
Lexington Parkway, St. Paul	-25.0	70.6	72.2
Fairview Avenue, St. Paul	9.6	66.6	69.0
W. 7th Street, St. Paul	66.6	-9.4	33.3
Pierce Butler Route, St. Paul	-172.7	0.0	12.5
MNTH 61, Duluth	25.0	0.0	100.0
MNTH 23, Cold Spring	-33.3	28.6	86.3
MNTH 29, Alexandria	48.3	61.8	47.9

The combined effect of four-lane to three-lane conversion on rear end crashes, right angle crashes and left-turn crashes for all seven study sites is presented in Table 4.18. It can be observed from the results that after the four-lane to three-lane conversions, there was a reduction of 41.6 rear-end crashes, 125.2 right-angle crashes and 77.4 left-turn crashes. These reductions in crashes were found to be statistically significant.

Table 4.18. Net Effect of Four-lane to Three-lane Conversion on Rear-End, Right-Angle and Left-Turn Crashes

Description	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
Reduction in crashes δ	41.6	125.2	77.4
Index of Effectiveness θ	0.808	0.437	0.403
Standard Deviation $\sigma(\delta)$	19.6	17.2	13.2
Standard Deviation $\sigma(\theta)$	0.079	0.052	0.064
Percentage Reduction in Crashes $100*(1-\theta)$	19.2	56.2	59.6

Yoked Comparison/Group Comparison Approach

A list of the study sites and the corresponding comparison site/comparison groups are presented in Table 4.19. Total crashes were analyzed and the number of crashes that took place in the comparison group during the before period and the after period were calculated. The total crashes for the study site and the comparison group are presented in Table 4.20. K and L are used to denote the total number of crashes in the before period and after period for the study site and M and N are used to denote the total crashes in the before period and after period for the comparison group.

Using the statistical procedure for the YC/GC approach, the effectiveness of the conversion was computed. While analyzing the crash data using the GC approach, the variance (ω) was assumed to be zero as the study period was less than ten years. The results of GC analysis for total crashes are presented in Tables 4.21 and 4.22.

Analyzing the change in the total crashes before and after conversion using the YC/GC approach shows that a reduction in the number of crashes after conversion was observed at five of the seven sites. At two sites, an increase in the crashes occurred after conversion (Table 4.21).

The net effect of four-lane to three-lane conversion on the total crashes using the YC/GC approach is presented in Table 4.22. The results indicate that there was a reduction of 295.5 crashes after four-lane to three-lane conversion. This reduction was found to be statistically significant.

Table 4.19. List of Study Sites and Comparison Sites

Study Site	Comparison Site
Lexington Parkway, St. Paul	W. 7th Street, St. Paul (From St. Clair Avenue to Kellogg Boulevard)
	Dale Street, St. Paul (From Concordia Avenue to Grand Avenue)
	Snelling Avenue, St. Paul (From Grand Avenue to Montreal Avenue)
Fairview Avenue, St. Paul	W. 7th Street, St. Paul (From St. Clair Avenue to Kellogg Boulevard)
	Dale Street, St. Paul (From Concordia Avenue to Grand Avenue)
	Snelling Avenue, St. Paul (From Grand Avenue to Montreal Avenue)
W. 7th Street, St. Paul	W. 7th Street, St. Paul (From St. Clair Avenue to Kellogg Boulevard)
	Dale Street, St. Paul (From Concordia Avenue to Grand Avenue)
	Snelling Avenue, St. Paul (From Grand Avenue to Montreal Avenue)
Pierce Butler Route, St. Paul	W. 7th Street, St. Paul (From St. Clair Avenue to Kellogg Boulevard)
	Dale Street, St. Paul (From Concordia Avenue to Grand Avenue)
	Snelling Avenue, St. Paul (From Grand Avenue to Montreal Avenue)
MNTH 61, Duluth	6th Avenue, Duluth (From 9th Street to 4th Street)
	Grand Avenue, Duluth (From 46th Avenue to 34 th Avenue)
	Superior Street, Duluth(From Carlton Avenue to 23rd Avenue)
MNTH 23, Cold Spring	MNTH 23, Cold Spring (From 14th Avenue to 5th Avenue)
MNTH 29, Alexandria	MNTH 29, Alexandria (From 6th Avenue to 3rd Avenue)

Table 4.20. Summary of Total Crashes for Study Sites and Comparison Groups

Study Site	Before Period (Years)	After Period (Years)	Study Site: Total Crashes Before Conversion (K)	Study Site: Total Crashes After Conversion (L)	Comparison Group: Total Crashes in the Before Period (M)	Comparison Group: Total Crashes in the After Period (N)
Lexington Parkway, St. Paul	5	2	157	29	983	330
Fairview Avenue, St. Paul	5	5	314	157	1084	897
W. 7^{th} St., St. Paul	5	1	135	14	897	164
Pierce Butler Route, St. Paul	5	4	141	99	1006	638
MNTH 61, Duluth	5	5	24	17	157	70
MNTH 23, Cold Spring	5	5	62	43	7	16
MNTH 29, Alexandria	5	5	290	157	72	63

Table 4.21. Results of Group Comparison Approach (Total Crashes)

Site	λ	Variance (λ)*	r_c	π	Variance (π)	δ	θ	100(1-θ)
Lexington Parkway, St. Paul	29	29	0.34	52.65	28.88	23.65	0.55	45.5
Fairview Avenue, St. Paul	157	157	0.83	259.59	351.91	102.59	0.60	39.8
W. 7th Street, St. Paul	14	14	0.18	24.65	8.89	10.65	0.56	44.0
Pierce Butler Route, St. Paul	99	99	0.63	89.33	77.04	-9.67	1.10	-9.8
MNTH 61, Duluth	17	17	0.44	10.63	7.05	-6.37	1.51	-50.5
MNTH 23, Cold Spring	43	43	2.00	124.00	3405.57	81.00	0.28	71.6
MNTH 29, Alexandria	157	157	0.86	250.27	2080.19	93.27	0.61	39.3
Total	516	516		811.14	5959.52	295.14		

* By definition, λ is equal to variance λ

Where,

λ : Observed Crashes in the after period (Study Site);

r_c : Unbiased Ratio of the crash counts in the after period to the crash counts in before period for the comparison group and is given by (N/M)/(1+1/M);

π : Predicted Crashes in the after period had there been no conversion;

δ : Reduction in Crashes;

θ : Index of Effectiveness. If $\theta < 1$, the conversion was effective in reducing crashes; and

100*(1- θ) : Percentage reduction in crashes.

Table 4.22. Net Effect of Four-lane to Three-lane Conversion on Total Crashes

Reduction in crashes δ	295.1
Index of Effectiveness $\theta = (\lambda/\pi)/\{1+Var(\pi)/\pi^2\}$	0.630
$Var(\delta) = Var(\pi) + Var(\lambda)$	6475.5
Standard Deviation $\sigma(\delta)$	80.4
$Var(\theta) = \theta^2[(Var(\pi)/\pi^2) + (Var(\lambda)/\lambda^2)]/(1+Var(\pi)/\pi^2)^2$	0.004
Standard Deviation $\sigma(\theta)$	0.065
Percentage Reduction in Crashes $100*(1-\theta)$	37.0

YC/GC approach was also used to analyze specific crash types. Injury crashes and property damage only crashes are presented in Table 4.23. Rear-end, right-angle and left-turn crashes are presented in Table 4.24. Note that the MNTH 23 site in Cold Spring was excluded from the analysis because the crash counts for the corresponding comparison site were insufficient.

The percent reductions in total crashes, injury crashes and property damage only crashes after the conversion are presented in Table 4.25. The net effect of the four-lane to three-lane conversion on the total crashes, injury crashes and property damage only crashes is presented in Table 4.26. Based on the results presented, it can be concluded that the conversion resulted in a reduction of 309.7 in PDO crashes. This reduction in PDO crashes was found to be statistically significant. The change in the injury crashes however was not found to be statistically significant.

The percent reductions in rear-end, right-angle, and left-turn crashes after the conversion are presented in Table 4.27. The net effect of the four-lane to three-lane conversion on rear-end, right-angle, and left-turn crashes is presented in Table 4.28. It can be observed from the results that after four-lane to three-lane conversion, there was a reduction of 63.8 rear-end, 52.8 right-angle, and 13.6 left-turn crashes. Each of these crash reductions was found to be statistically significant.

Table 4.23. Crash Data Categorized by Severity

Severity	Study Site	Before Period (Years)	After Period (Years)	Study Sites		Comparison Sites	
				Before Period	After Period	Before Period	After Period
Injury Crashes	Lexington Parkway, St. Paul	5	2	36	8	278	58
	Fairview Avenue, St. Paul	5	5	86	40	333	226
	W. 7th Street, St. Paul	5	1	38	0	226	23
	Pierce Butler Route, St. Paul	5	4	32	24	316	123
	MNTH 61, Duluth	5	5	12	11	77	44
	MNTH 23, Cold Spring	5	5	31	14	4	1
	MNTH 29, Alexandria	5	5	70	37	22	12
Property Damage Only Crashes	Lexington Parkway, St. Paul	5	2	121	21	703	272
	Fairview Avenue, St. Paul	5	5	228	117	751	670
	W. 7th Street, St. Paul	5	1	97	14	670	141
	Pierce Butler Route, St. Paul	5	4	109	75	688	515
	MNTH 61, Duluth	5	5	12	6	80	25
	MNTH 23, Cold Spring	5	5	31	29	3	15
	MNTH 29, Alexandria	5	5	220	120	50	51

Table 4.24. Crash Data Categorized by Type

Type of Crash	Site	Before Period (Years)	After Period (Years)	Study Sites		Comparison Sites	
				Before Period	After Period	Before Period	After Period
Rear End Crashes	Lexington Parkway, St. Paul	5	2	27	14	260	81
	Fairview Ave., St. Paul	5	5	61	56	248	235
	W. 7th St., St. Paul	5	1	29	2	235	41
	Pierce Butler Rt., St. Paul	5	4	10	24	259	161
	MNTH 61, Duluth	5	5	7	6	41	11
	MNTH 23, Cold Spring	5	5	11	16	1	0
	MNTH 29, Alexandria	5	5	117	61	18	24
Right Angle Crashes	Lexington Parkway, St. Paul	5	2	67	8	251	85
	Fairview Ave., St. Paul	5	5	113	38	329	224
	W. 7th St., St. Paul	5	1	31	7	224	49
	Pierce Butler Rt., St. Paul	5	4	19	16	275	162
	MNTH 61, Duluth	5	5	2	3	32	26
	MNTH 23, Cold Spring	5	5	6	5	0	1
	MNTH 29, Alexandria	5	5	54	21	17	9
Left Turn Crashes	Lexington Parkway, St. Paul	5	2	26	3	103	41
	Fairview Ave., St. Paul	5	5	41	13	105	101
	W. 7th St., St. Paul	5	1	14	2	101	13
	Pierce Butler Rt., St. Paul	5	4	9	7	100	71
	MNTH 61, Duluth	5	5	1	0	14	15
	MNTH 23, Cold Spring	5	5	21	3	0	0
	MNTH 29, Alexandria	5	5	47	25	8	1

Table 4.25. Percentage Reductions in Crashes (Total Crashes, Injury Crashes and Property Damage Only Crashes)

Site	Percentage Reduction in Crashes		
	Total Crashes	**Injury Crashes**	**Property Damage Only Crashes**
Lexington Parkway, St. Paul	45.5	-1.9	55.7
Fairview Avenue, St. Paul	39.8	32.5	42.8
W 7th Street, St. Paul	44.0	100.0	32.6
Pierce Butler Route, St. Paul	-9.8	-85.4	9.1
MNTH 61, Duluth	-50.5	-45.2	-42.6
MNTH 23, Cold Spring	71.6	1.1	82.6
MNTH 29, Alexandria	39.3	11.4	47.8

Table 4.26. Net Effect of Four-lane to Three-lane Conversion on Total Crashes, Injury Crashes and Property Damage Only Crashes

Description	Total Crashes	Injury Crashes	PDO Crashes
Reduction in crashes δ	295.1	-2.5	309.7
Index of Effectiveness θ	0.63	1.00	0.54
Standard Deviation $\sigma(\delta)$	80.5	21.3	93.7
Standard Deviation $\sigma(\theta)$	0.066	0.158	0.076
Percentage Reduction in Crashes $100*(1-\theta)$	37.0	0.0	45.7

Table 4.27. Percentage Reductions in Crashes (Rear End Crashes, Right Angle Crashes and Left Turn Crashes)

Site	Percentage Reduction in Crashes		
	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
Lexington Pkwy., St. Paul	-58.6	65.7	72.7
Fairview Ave., St. Paul	5.1	51.3	68.1
W 7th Street, St. Paul	62.7	1.9	3.2
Pierce Butler Rt., St. Paul	-249.1	-35.0	2.5
MNTH 61, Duluth	-160.1	-21.3	100.0
MNTH 29, Alexandria	62.7	34.6	-123.0

Table 4.28. Net Effect of Four-lane to Three-lane Conversion on Rear End Crashes, Right Angle Crashes and Left Turn Crashes

Description	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
Reduction in crashes δ	63.8	52.8	13.6
Index of Effectiveness θ	0.69	0.63	0.76
Standard Deviation $\sigma(\delta)$	50.6	18.8	12.8
Standard Deviation $\sigma(\theta)$	0.151	0.094	0.163
Percentage Reduction in Crashes $100*(1-\theta)$	31.3	37.0	23.6

Empirical Bayes Approach

The empirical Bayes method was used to analyze the crash data to predict the number of crashes that would have taken place had there been no conversion. The advantage of the EB approach is its ability to accurately address the regression to mean phenomena. Regression to mean phenomena was discussed in greater detail in the *"Overview of Statistical Procedures"* section in Chapter 3.

Using SAS statistical analysis software, the crash data from study and comparison sites were used to generate a negative binomial model to predict the number of crashes that could occur on a four-lane undivided roadway. Variables considered in this model were ADT, speed limit, driveway/access density, approach density, length and crash reporting threshold. The negative binomial model used to predict the number of crashes per year at a study site is presented below:

$$y_i = e^{Ln\left(\frac{ADT \times Length \times 365}{10{,}000{,}000}\right) + 8.7336 - 0.1195 \times Speed\ Limit - 0.0149 \times Driveway\ Density - 0.0118 \times Approach\ Density + 0.1809 \times (1 - Crash\ Threshold))} \quad (41)$$

Where, 'i' denotes the year in the after period.

Dispersion parameter was obtained for the negative binomial model and was used to generate the weights. The weights were given by:

$$Weight_i = \frac{1}{1 + DispersionParameter \times y_i} \quad (42)$$

The weights were then used to combine information from the crash history of the study site and the predicted crashes from the negative binomial model to estimate the crash frequency at the study site for each year in the after period had there been no conversion. The estimated crashes for each year in the after period had there been no conversion was calculated by:

$$Estimate(Crashes)_i = Weight \times y_i + (1 - Weight) \times \frac{1}{n}\sum_{k=1}^{n}\frac{Crashes_k}{ADT_k} \times ADT_i \quad (43)$$

Where, 'n' is the total number of years in the before period and 'k' denotes a year in the before period.

The total estimated crashes in the after period for each study site were obtained by adding up the estimates of crashes for each year in the after period and these crashes were then compared to the observed number of crashes in the after period. Results of this analysis are presented in Table 4.29.

Table 4.29. Percentage Reductions Achieved using Empirical Bayes Approach

Site	Before Conversion		After Conversion		Number of Crashes in the After period had there been no conversion	Percentage Reduction
	Years	Total Crashes	Years	Total Crashes		
Lexington Parkway, St. Paul	5	157	2	29	57	49.1
Fairview Avenue, St. Paul	5	314	5	157	297	47.1
W. 7th Street, St. Paul	5	135	1	14	27	48.1
Pierce Butler Route, St. Paul	5	141	4	99	158	37.3
MNTH 61, Duluth	5	24	5	17	29	41.4
MNTH 23, Cold Spring	5	62	5	43	94	54.3
MNTH 29, Alexandria	5	290	5	157	262	40.1
Total				**516**	**924**	**44.2**

RESULTS OF CRASH DATA ANALYSIS

Using traditional statistical approaches, it was found that the reductions in average crashes and crash rates for total crashes, injury crashes, and property damage only crashes were statistically significant. The change in left-turn crash frequency and rate was also statistically significant. The percentage reduction in average crashes and crash rate were 43 percent and 46.5 percent, respectively. For injury crashes, the percentage reduction in average crashes and crash rate were 50.2 percent and 54.3 percent, respectively. For the property damage only crashes, the percentage reduction in the average crashes and the crash rate were 40.3 percent and 44.6 percent, respectively. The percentage reduction for left-turn crashes was 57.7 percent.

The second traditional approach estimated that 893 crashes would have occurred in the after period based on historical data, when a total of 516 crashes actually occurred, resulting in a reduction of 377 crashes. The percentage reduction in total crashes for the seven study sites was 42.3 percent. There was also a reduction of 112.6 injury crashes and 264 property damage only crashes. The percentage reduction in injury crashes and property damage only crashes for the seven sites was 45.8 percent and 40.9 percent. There was a reduction of 77.4 left-turn crashes (59.6 percent).

The YC/GC approach showed a reduction of 295.1 crashes with the conversions. The percentage reduction in total crashes was 37 percent. The previous analysis showed a percentage reduction in total crashes of 42.3 percent. There was a reduction of 309.7 property damage only crashes (45.7 percent). An insignificant increase in injury crashes after conversion was observed. The percentage reduction in rear-end, right-angle and left-turn crashes was 31.3 percent, 37 percent and 23.6 percent, respectively.

The EB approach showed an overall reduction in the total crash frequency of 44.2 percent, which was similar to crash reductions observed using traditional and YC/GC statistical approaches. This similarity is important, because it validates the findings of the traditional and yoked/group comparison versus the highly accurate, yet difficult to perform, Empirical Bayes method. Table 4.30 provides a direct comparison of all statistical approaches.

Table 4.30. Percentage Reductions Achieved by Different Statistical Approaches

Variables	Traditional Approach (t-test)	Traditional Approach	YC/GC Approach	EB Approach
Total Crashes	**43.0**	**42.3**	**37**	**44.2**
Injury Crashes	**50.2**	**45.8**	0	
Property Damage Only Crashes	**40.3**	**40.9**	**45.7**	
Rear End Crashes	18.3	**19.2**	**31.3**	
Right Angle Crashes	51.4	**56.2**	**37**	
Left Turn Crashes	**57.7**	**59.6**	**23.6**	

*Numbers in bold indicate that the reductions achieved were statistically significant

Chapter 5
CONCLUSIONS and RECOMMENDATIONS

Two-way left turn lanes have traditionally been added to an existing roadway cross-section to enhance the operational and safety characteristics of the roadway. Recently TWLTLs are being used in "road diet" strategies which maintain the previous cross-sectional width, thereby resulting in a decrease in the total number of lanes. A road diet is achieved by removing the two central lanes and converting them into a single center TWLTL lane. TWLTL are usually used in three-lane and five-lane cross-sections.

The objective of this research was to determine the safety and operational characteristics of three-lane roadways with TWLTLs compared to the four-lane roadways they have replaced. To evaluate the safety and operational characteristics of three-lane and five-lane cross-sections with TWLTLs, an extensive literature review was completed initially that consisted of published papers, design manuals and other unpublished documentation. Along with the literature review, nine sites in Minnesota were identified which were converted to a three-lane roadway with a TWLTL. All nine sites were four-lane undivided roadways prior to conversion. Crash and operational data were collected using different data collection procedures and the safety and operational effects of a TWLTL were evaluated by analyzing the collected crash data and operational data using selected statistical approaches.

CONCLUSIONS

Conclusions from Literature Review

After completing an extensive literature review, it was found that when a TWLTL is added to the existing cross-section, the operational and safety features of a roadway are generally enhanced. Typical operational benefits are a decrease in delay and a reduction in the interactions during lane changes. Adding a TWLTL to the existing cross-section can lead to a decrease in the crash rates, especially at locations where parallel parking is allowed. At locations where parallel parking is not allowed the reduction in crash rates may not be significant.

In the case of four-lane to three-lane conversions, where the number of lanes is reduced, the total corridor delay and intersection delay can increase but most often at insignificant levels and within acceptable levels of service (LOS). However, these "road diet" conversions can significantly affect the operation of the roadway if the ADT of the roadway is greater that 17,500 vpd. Additionally, heavy vehicles can affect the operation of three-lane roadways. A reduction of average arterial through-vehicle travel speed can be observed with an increase of heavy vehicles. The presence of bus stops also impacts the operation of a three-lane roadway, leading to a significant reduction of the average arterial through-vehicle travel speeds.

Some have experienced unfavorable public reaction to the change to three-lane roadways because of the assumed decrease in operations and roadway function. Those that have reported this problem have also found a positive change in the community attitude after the new cross-section is observed. Some have also reported an increase in the pedestrian and bicycle activity as a three-lane cross-section can be easier to cross.

A decrease in the mean and 85th percentile speeds is often observed when a four-lane roadway is converted to a three-lane roadway. The decrease in the mean and 85th percentile speed is typically less than five mph. Nearly all documented literature shows that a four-lane to three-lane conversion is accompanied with a reduction in crashes. Studies in Washington and California reported a reduction of 6 percent in crash frequency. Recent studies in Iowa have reported up to a 25 percent reduction in crash frequency. Although the exact percent of improvement varies, it is fairly consistent that safety improvements are achieved with four-lane to three-lane with TWLTL conversions.

Conclusions from the Operational Effects Analysis

The analysis of before and after ADT data for all nine Minnesota study sites showed that the overall change in ADT was not statistically significant. There was no evidence to suggest that traffic diverted to other routes or that drivers changed travel behavior. A significant change in speed was found although the average speed reduction was only 1.88 mph. This speed reduction may not be practically significant, but does suggest a slight increase in vehicle density as traffic is condensed from two to one through lane. Simple linear regression analysis showed that before-after mean speed reductions increased as both the density of unsignalized intersections increased and ADT increased. This result is consistent with the expectation that an increase in ADT will lead to more operational impacts with the four-lane to three-lane conversion. The reduction in the 85th percentile speed after the conversion was consistent with the mean speed. The average reduction in the 85th percentile speed was 1.66 mph. At the two sites where speed was measured, the number of vehicles traveling above the speed limit was reduced after the four-lane to three-lane conversion. The reasons for this are consistent with the other speed changes.

The speed of vehicles on a three-lane roadway with TWLTL after it has been converted from a four-lane roadway is influenced by one of three primary factors. The speed of the vehicles on a three-lane roadway may increase because the left turning traffic is separated from the through traffic. The speed of the vehicles may decrease as right turning traffic and through traffic have to share a single lane. Lastly, the speed of the vehicles may decrease due to the reduction of lane capacity associated with the removal of two center through lanes. Reduction in capacity leads to the increase in the flow density which in turn leads to a decrease in the speed. In this research, a reduction in mean speed was observed at all study sites, which implies that the second and/or third factors had the greatest effect on speed after the conversions.

Conclusions from the Safety Analysis

Both traditional approaches and the comparison approaches were used to analyze the crash data. Crashes were categorized by severity and type and analyzed to determine if the changes were statistically significant.

Using traditional statistical approaches, reduction in crashes was observed for all crash types categorized by severity and type. The change in crash frequency and the crash rates of the total crashes, injury crashes and property damage only crashes were found to be statistically significant. After categorizing the crashes by type, only the change in the crash frequency for left-turn crashes and left-turn crash rates were found to be statistically significant. No change in rear-end crashes was likely due to the fact that right-turn traffic does not change significantly with the cross-section change. Many of the rear-end crashes observed were likely a result of vehicles that had decelerated to make a right-turn movement. Some reduction in right-angle crashes was observed, but not at a statistically significant level.

The statistical methods used in this first analysis are often criticized for the fact that they are not able to isolate the variable of interest while controlling all other variables. Furthermore, with nearly all safety studies, there is a selection bias associated with applying the safety improvements at sites that are believed to need improvement instead of at randomly selected sites. Selection bias can lead to inflated safety improvement estimates as some of the improvement experienced may be a result of random changes in crashes often associated with the 'regression to the mean' concept. Nevertheless, with the above weaknesses noted, the relative stability in the ADT and speed values, two of the important change variables, suggests that the results presented are of an acceptable quality.

To show how the results of a more robust statistical method would compare to the traditional approaches, a yoked/group comparison approach was explored. The trade-off with this methodology is that the strength of the statistics decreases, leading to larger variances in the results. As with the traditional results, a decrease in the total number of crashes was found. Significant decreases in property damage only crashes and left-turn crashes after the four-lane to three-lane conversion were also found. The percentage reductions in total crashes, PDO crashes and left turn crashes after the conversion were approximately 37 percent, 46 percent and 24 percent, respectively. Injury crashes were not found to be statistically significant, largely due to the increase in variance. Reductions in crash rates (per vehicle mile traveled) for total crashes and PDO crashes were also found to be statistically significant with percentage reductions of approximately 47 percent and 45 percent, respectively. It is concluded that the four-lane to three-lane conversion was effective in reducing total, PDO, and left turn crashes.

Finally, the recommend approach for before and after statistical analysis of safety data is the Empirical Bayes approach for reasons cited throughout this report. The results of the EB analysis showed an overall reduction in the total crash frequency of 44.2 percent, which was similar to crash reductions observed using traditional and YC/GC statistical approaches. This similarity is important, because it validates the findings of the traditional and yoked/group comparison versus the highly accurate, yet difficult to perform, Empirical Bayes method.

The results obtained by this research are consistent with the results cited in the literature and recently found with research in Iowa. Various statistical approaches used resulted in slightly different estimates of the reduction in the crashes provided by the TWLTL conversions. Nevertheless, the overall safety benefit of four-lane to three-lane conversions with the addition of a TWLTL is clear. It should be remembered that the results obtained by this research pertain only to the sites considered in this research. There is always some probability that additional sites and larger data sets may alter the results. Nevertheless, the consistency with the vast amount of published data on this topic suggests that this is not the case.

RECOMMENDATIONS

Based on this research, four-lane to three-lane conversions can improve safety with little impact to operational conditions. It is recommended that four-lane to three-lane conversions be implemented after considering the below mentioned factors:

- TWLTL use is suitable for locations where it is probable that the number of businesses along the roadway will be the same or increase with time. TWLTLs provide the advantage of separating the left-turning traffic out from the through lanes, providing better traffic flow compared to undivided four-lane sections without TWLTLs. The crash frequency on a roadway having a TWLTL is relatively insensitive to the number of accesses along the roadway, unlike four-lane divided and undivided roadways, which typically see increases in crashes as access density increases.

- Four-lane to three-lane conversions are feasible if the ADT of the roadway is less than 17,500 vpd. Although this ADT was approximately the maximum ADT observed in this research, and generated in a simulated research effort and not part of this study, observations made during this research support that additional consideration should be made when projected ADTs meet or exceed this value.

- Four-lane to three-lane conversions were found to be effective in reducing the operating speeds and crashes of the roadway with little impact on capacity. Therefore, although a roadway cross-section change is not a countermeasure for speeding problems, some speed reduction benefits can be gained with this cross-section change.

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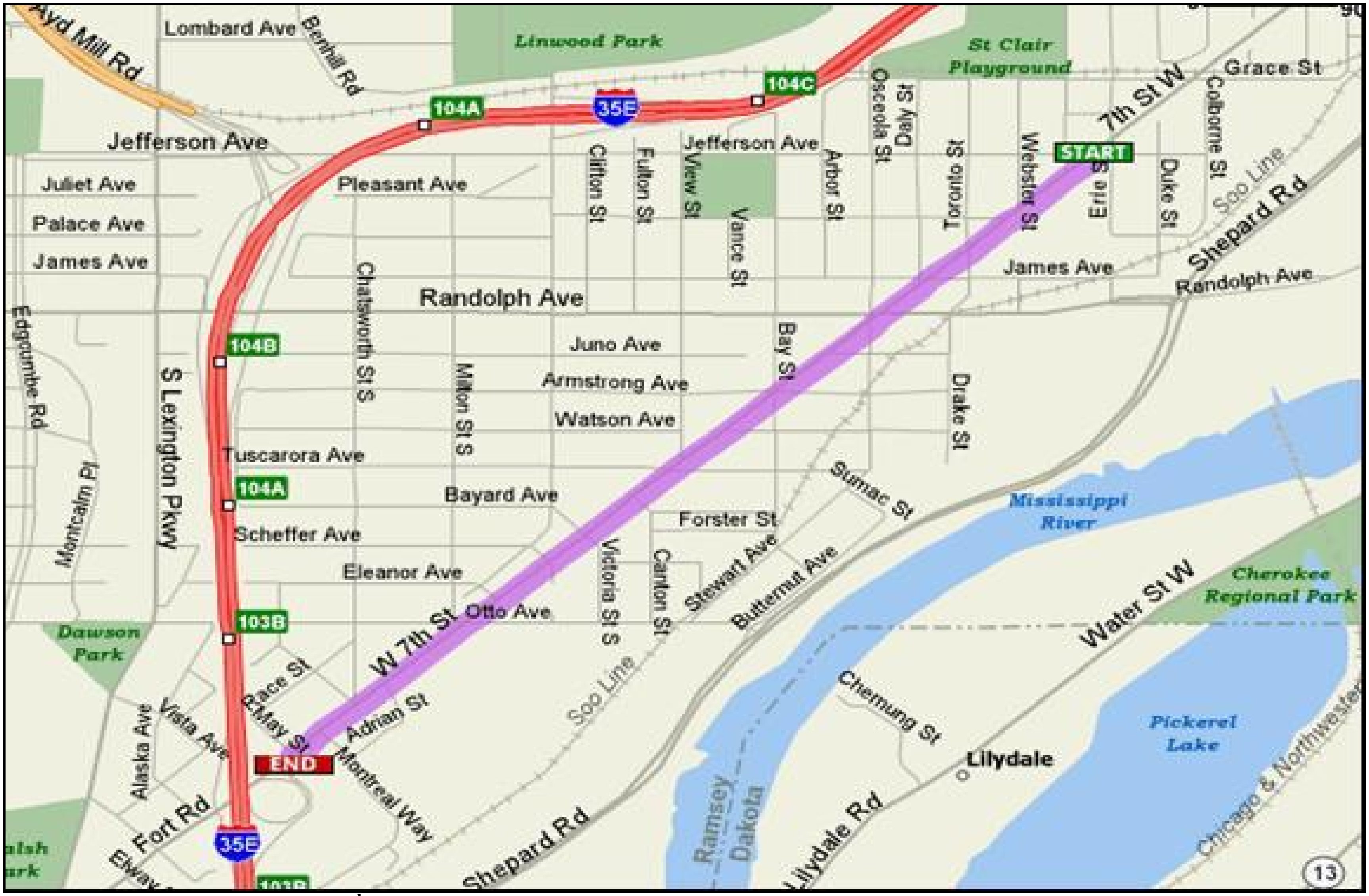
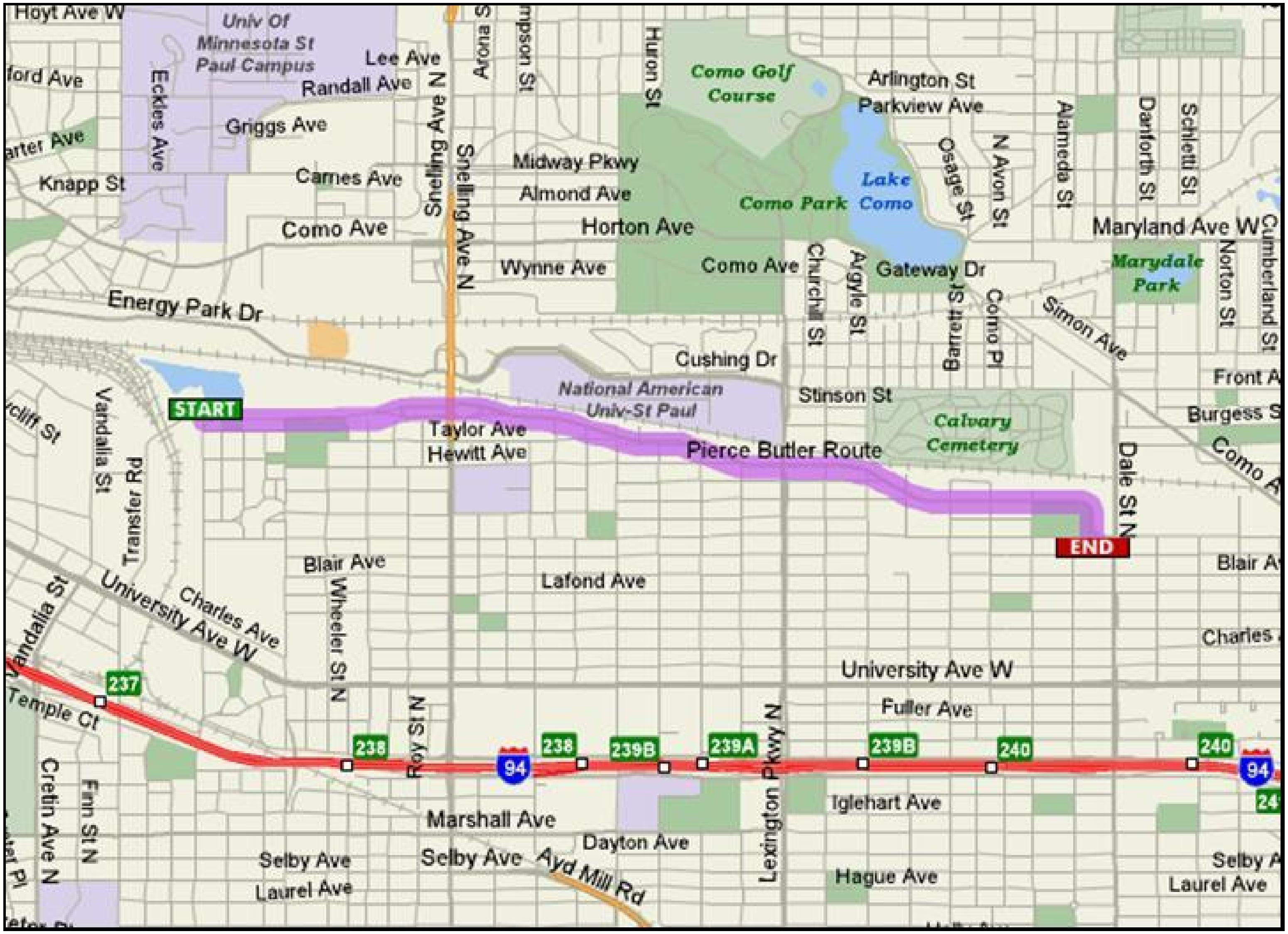
Appendix A

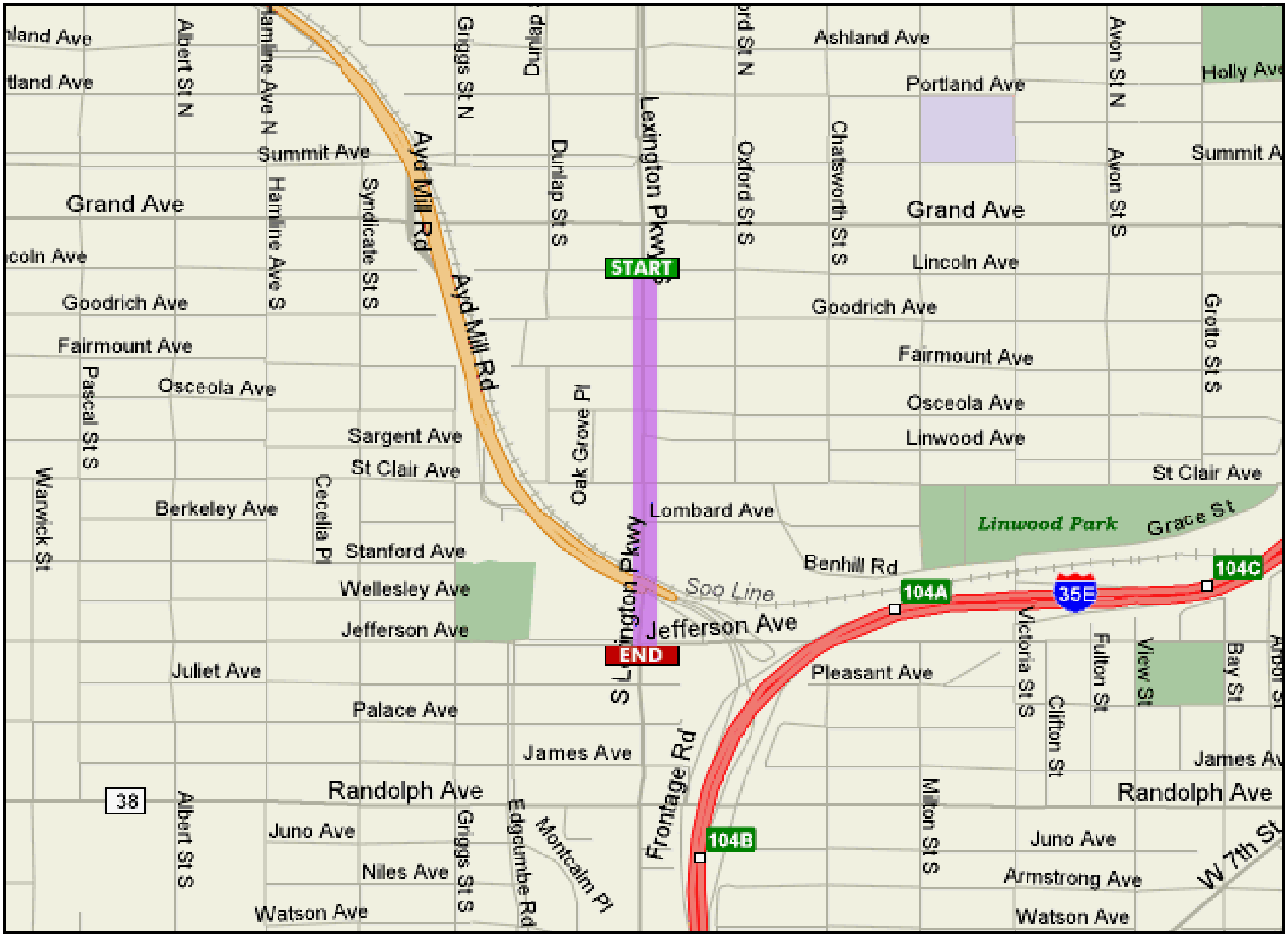
Maps of Study Sites and Comparison Sites



Study Site: W. 7th Street, St. Paul (From May Street to Jefferson Avenue) **(maps accessed from www.mapquest.com)**

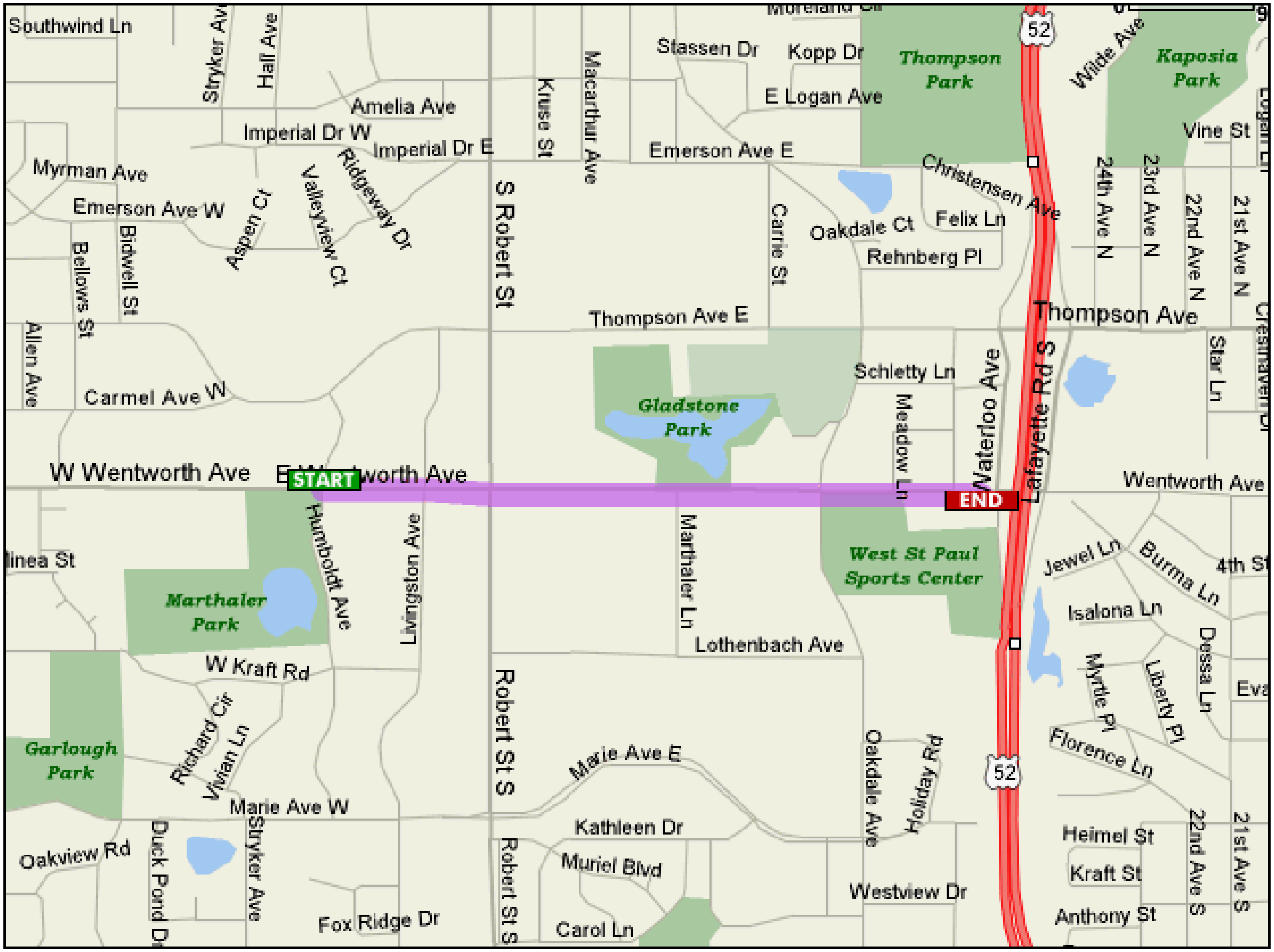


Study Site: Pierce Butler Route, St. Paul (From Transfer Road to Minnehaha Avenue)

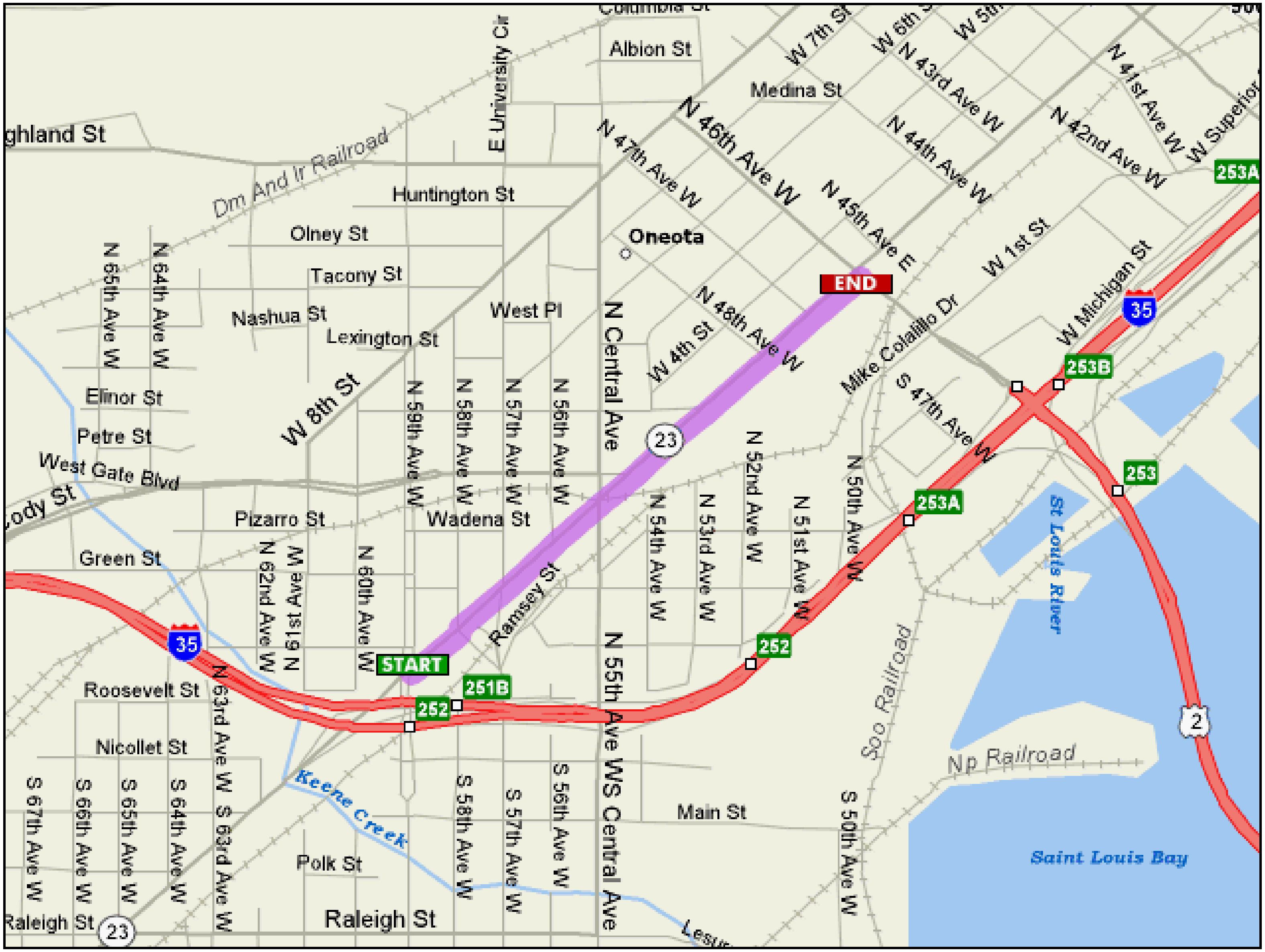


Study Site: Lexington Parkway, St. Paul (From Lincoln Avenue to Jefferson Avenue)

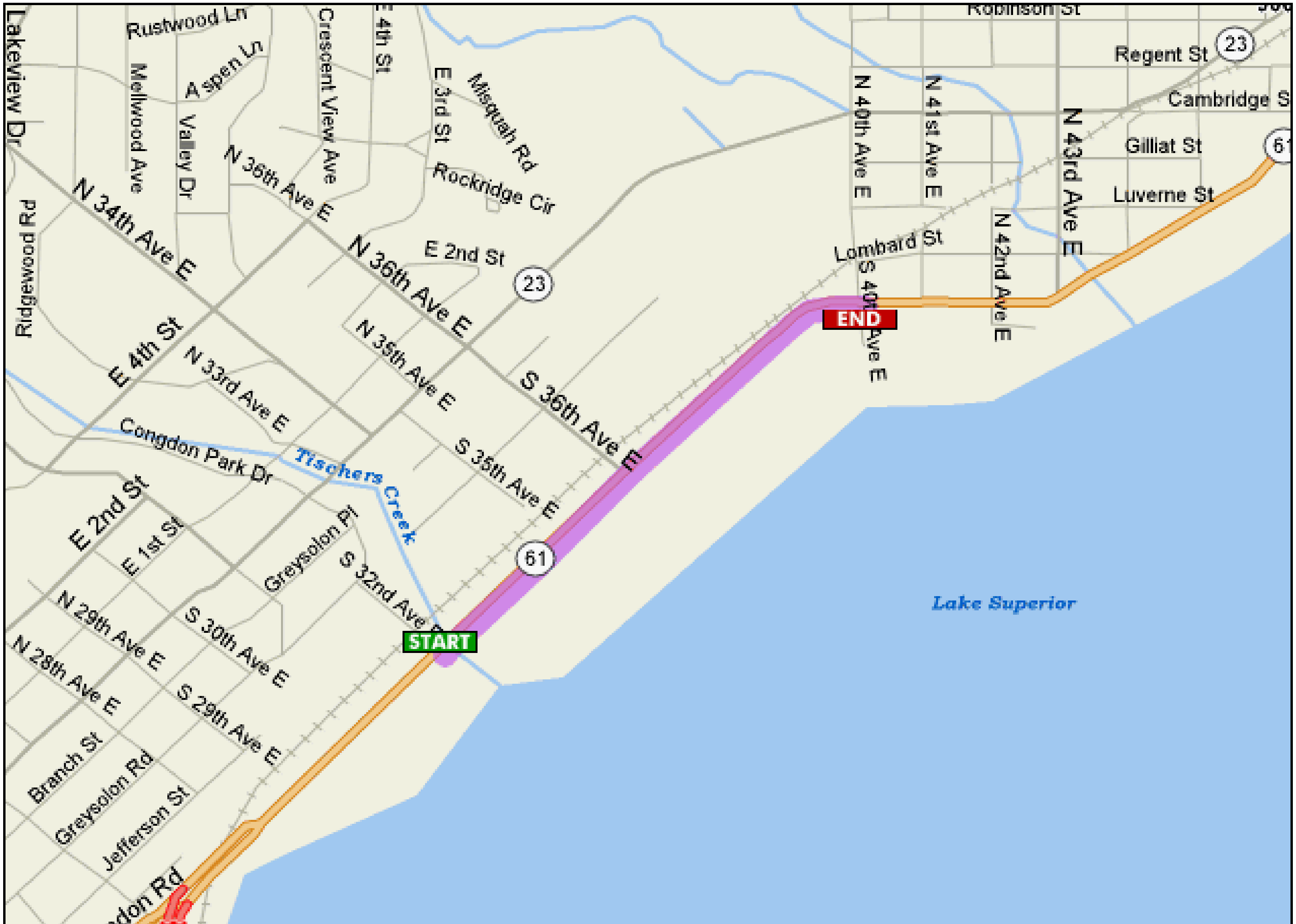
Study Site: Fairview Avenue, St. Paul (From Marshall Avenue to Ford Parkway)



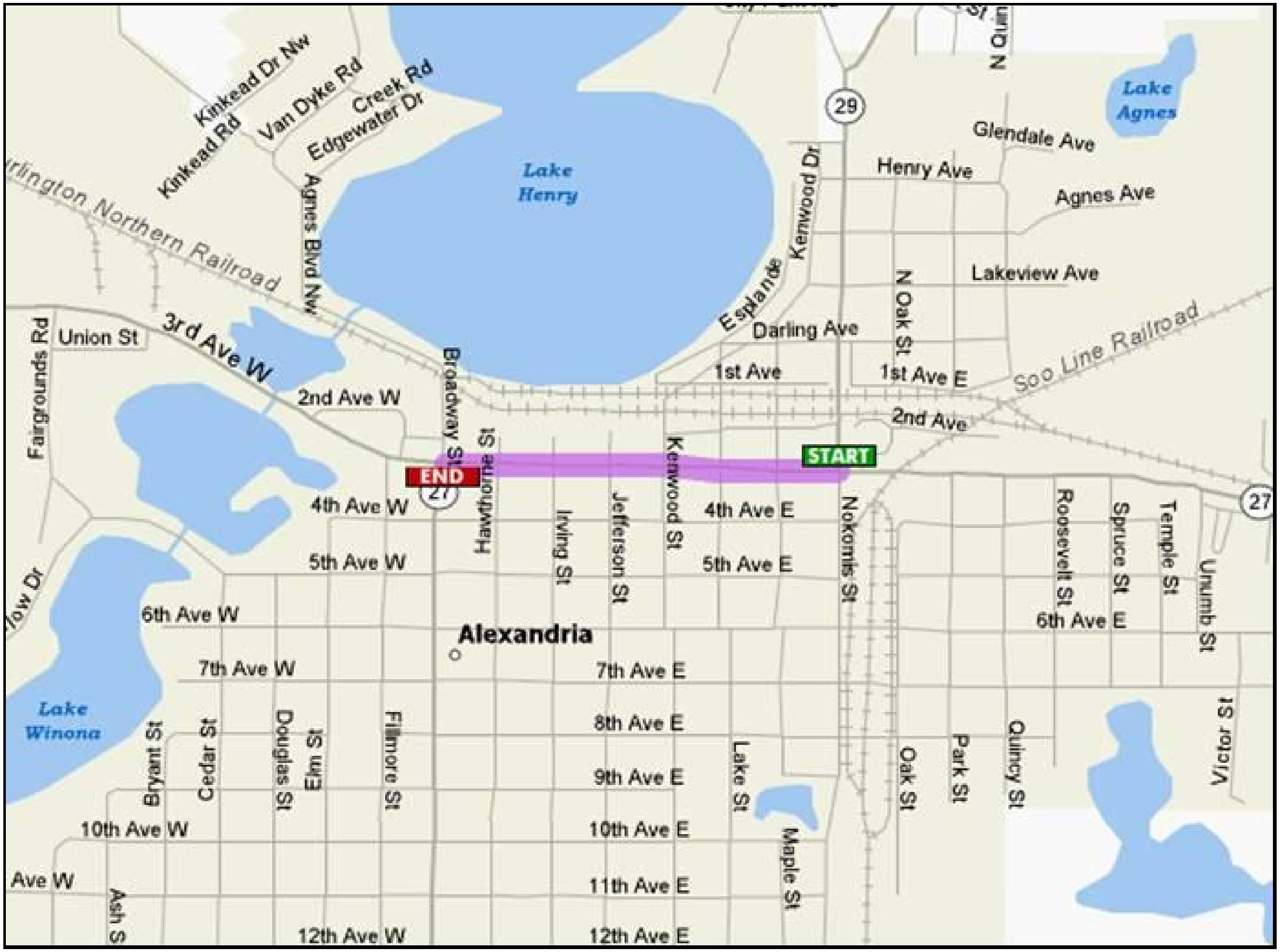
Study Site: E. Wentworth Avenue, St. Paul (From MNTH 52 to Humboldt Avenue)



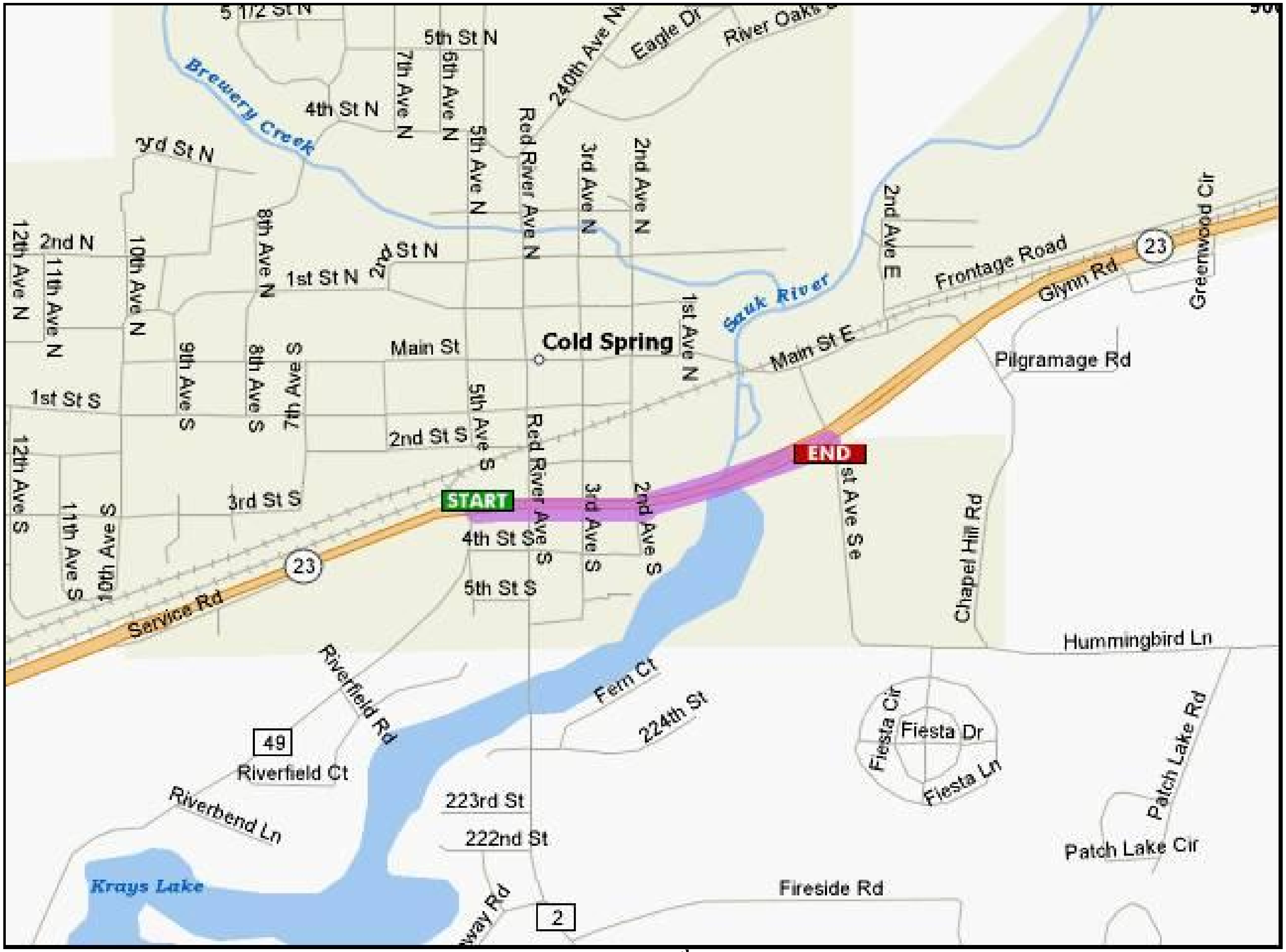
Study Site: Grand Avenue, Duluth (From N. 59th Avenue W. to N. 46th Avenue W.)



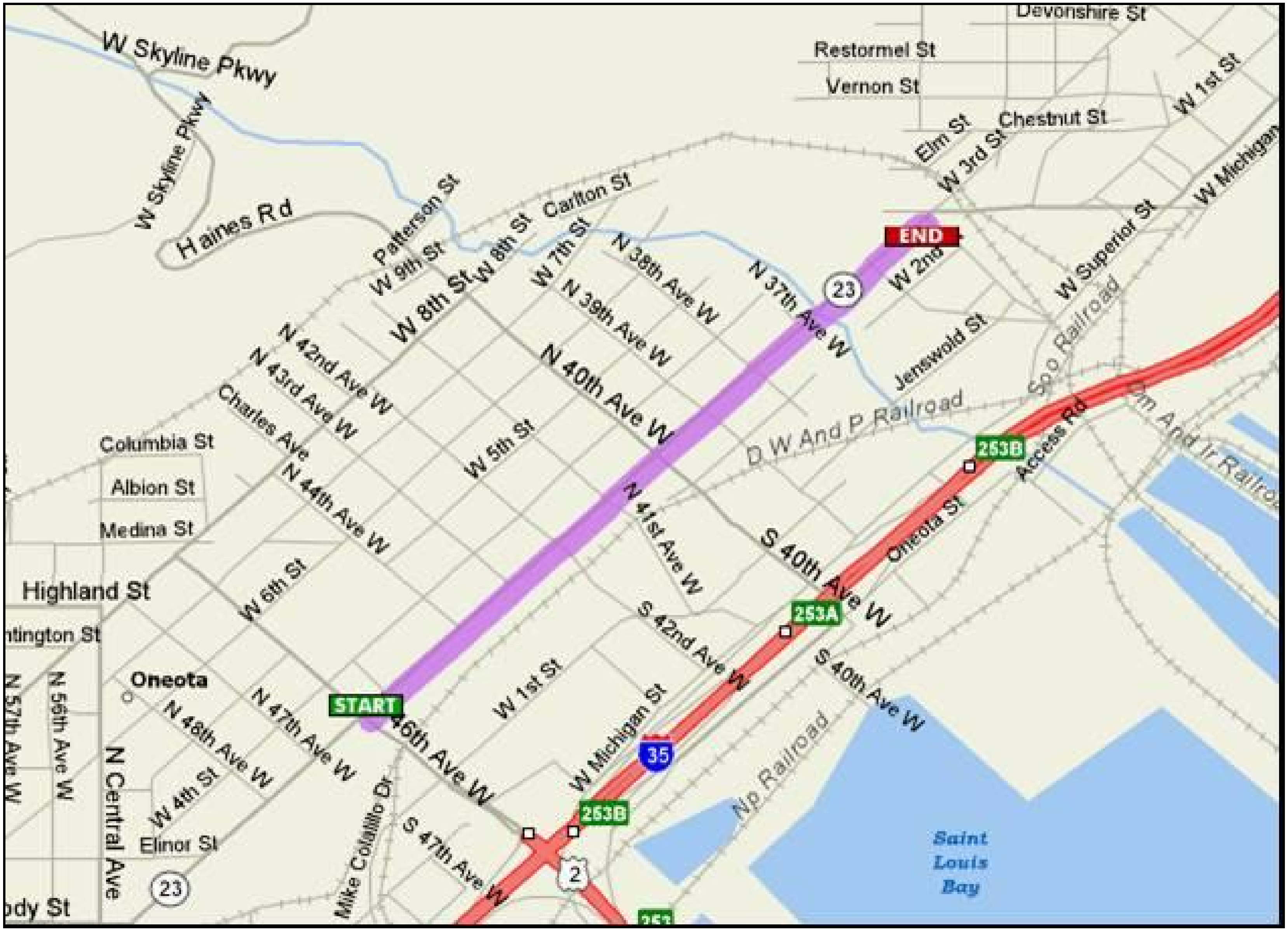
Study Site: MNTH 61, Duluth (From S. 32nd Avenue E. to S. 40th Avenue E.)



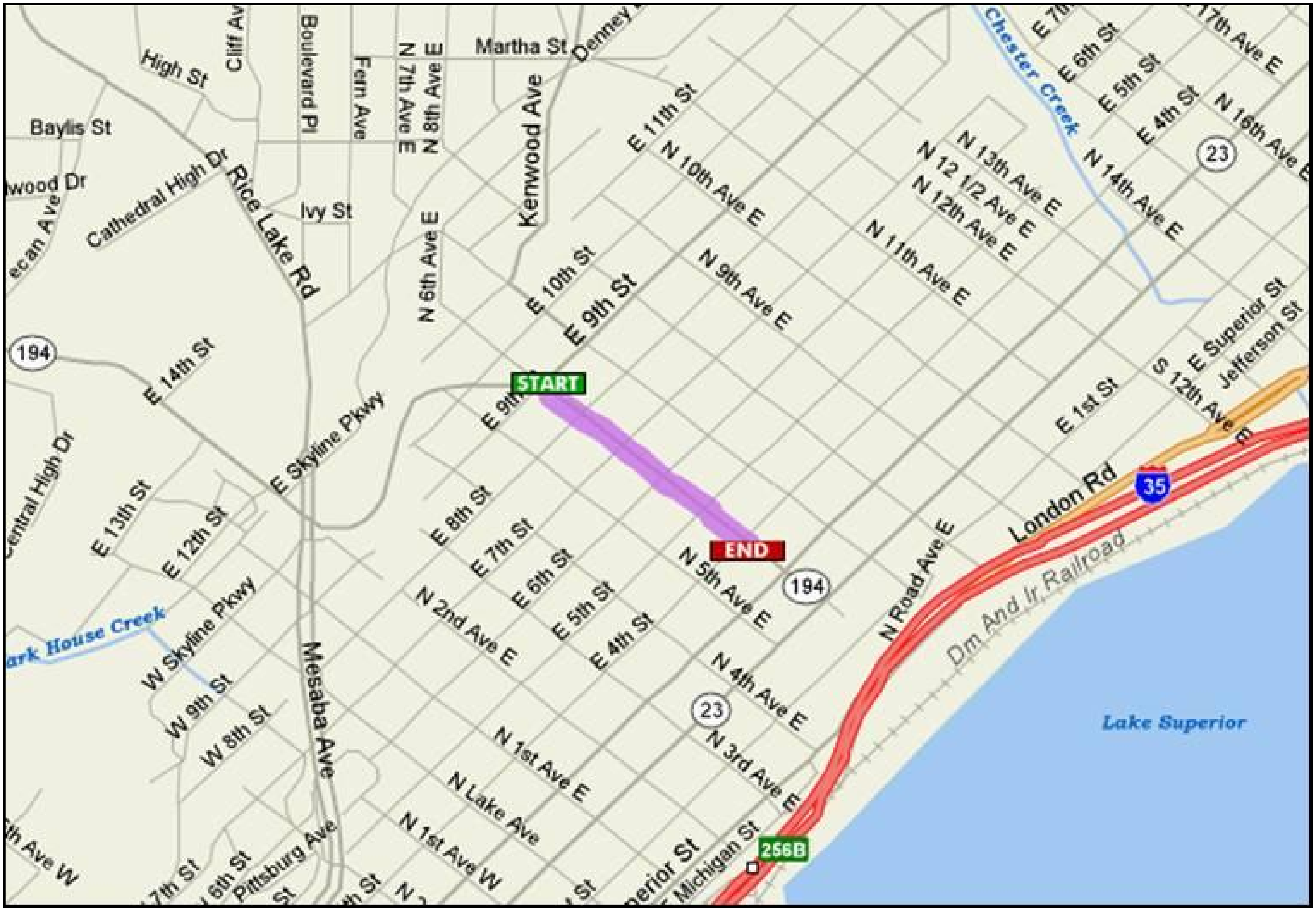
Study Site: MNTH 29, Alexandria (From Broadway Street to Nokomis Street)



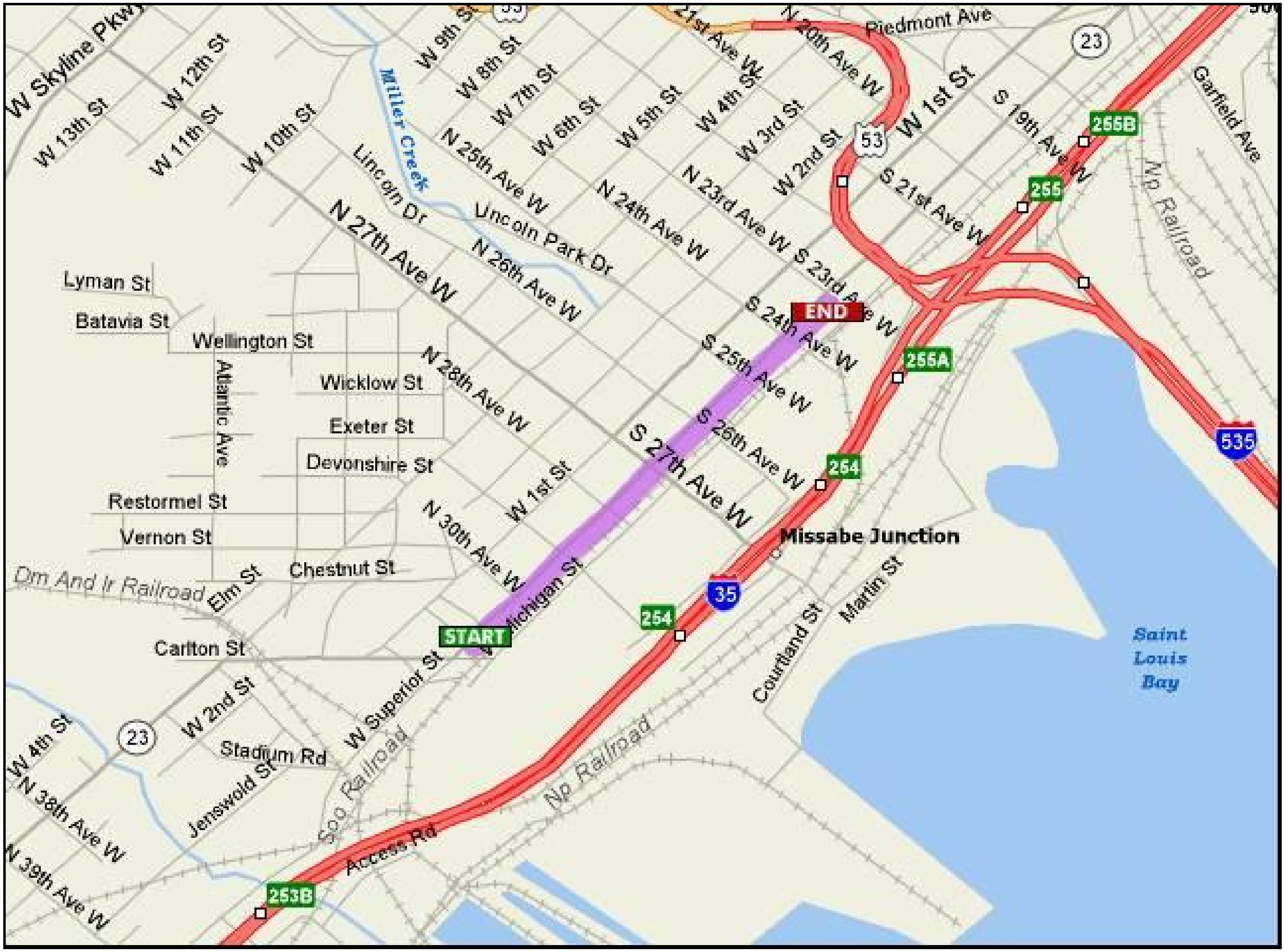
Study Site: MNTH 23, Cold Spring (5th Avenue to Sauk River Bridge)



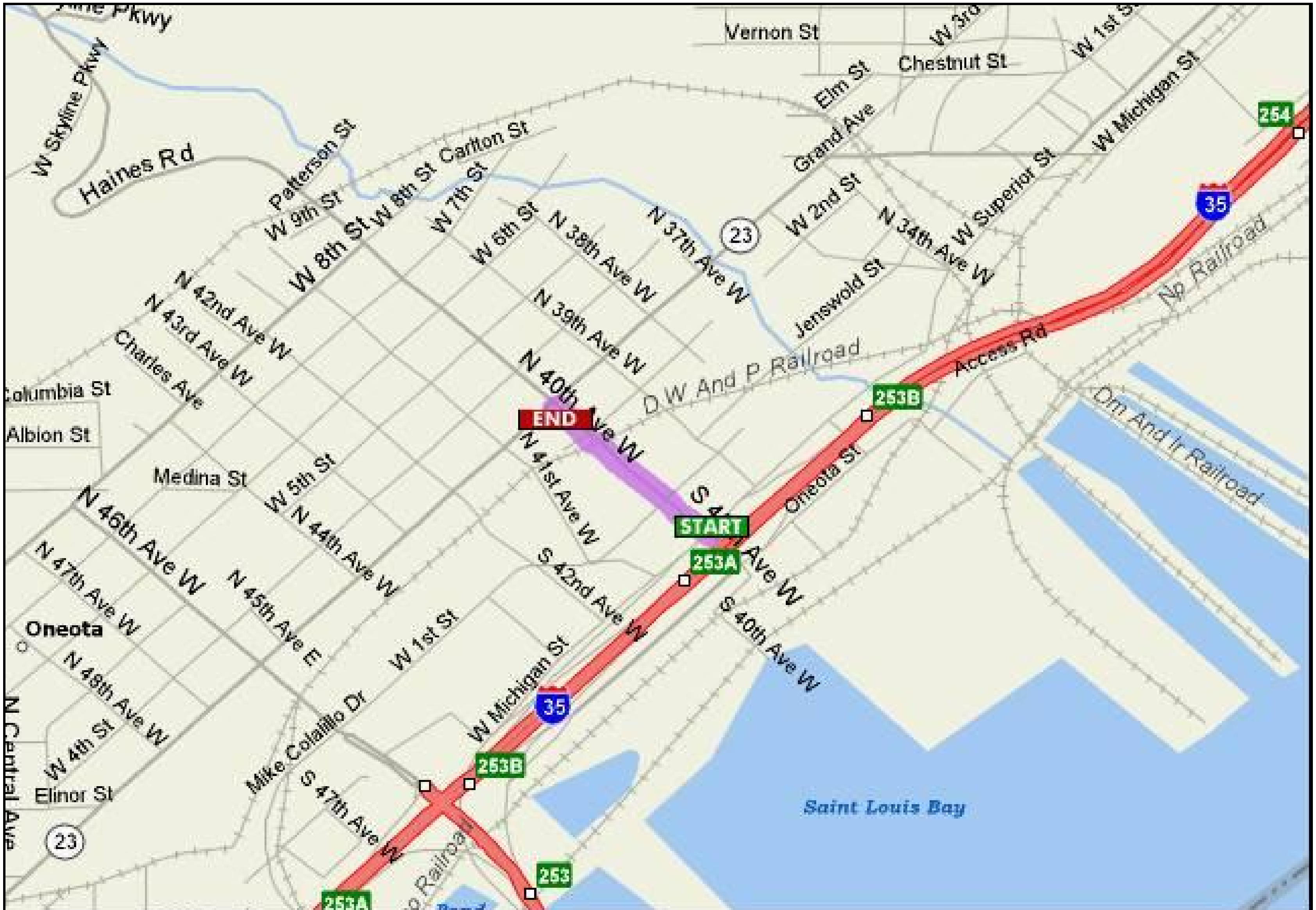
Comparison Site: Grand Avenue, Duluth (46th Avenue to 34th Avenue)



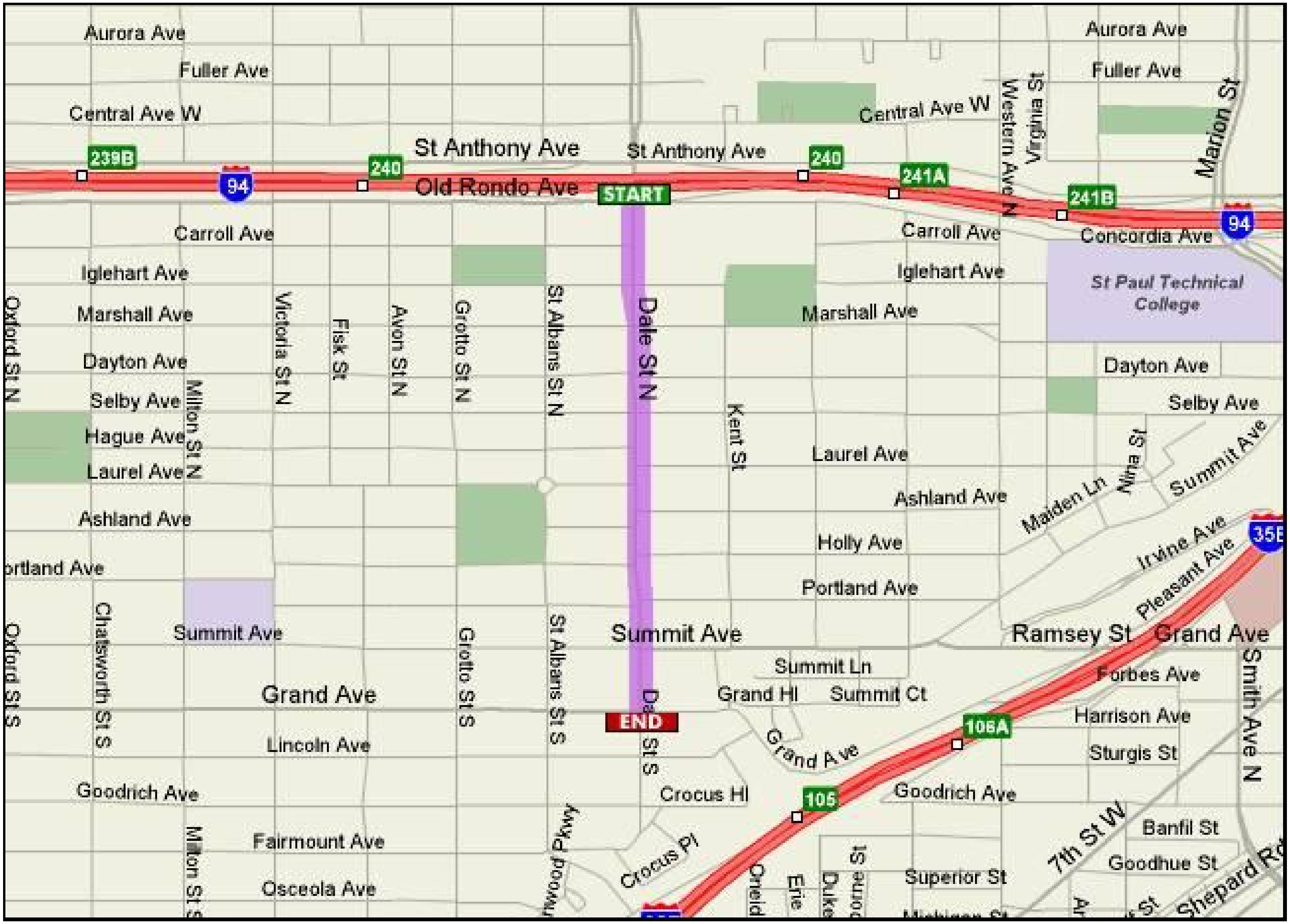
Comparison Site: 6th Avenue E., Duluth (9th Street to 4th Street)



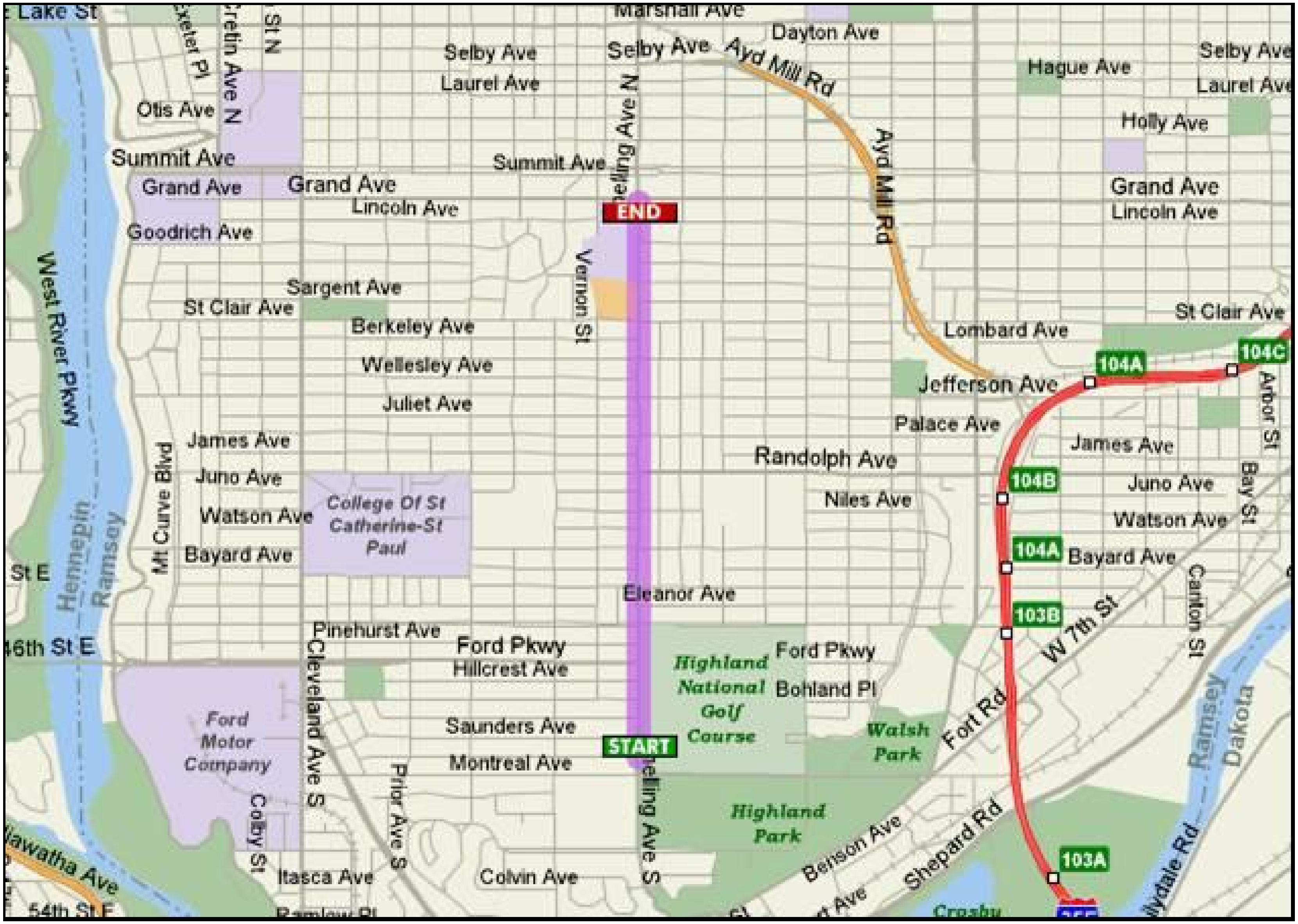
Comparison Site: W. Superior Street, Duluth (Carlton Street to 23rd Avenue)



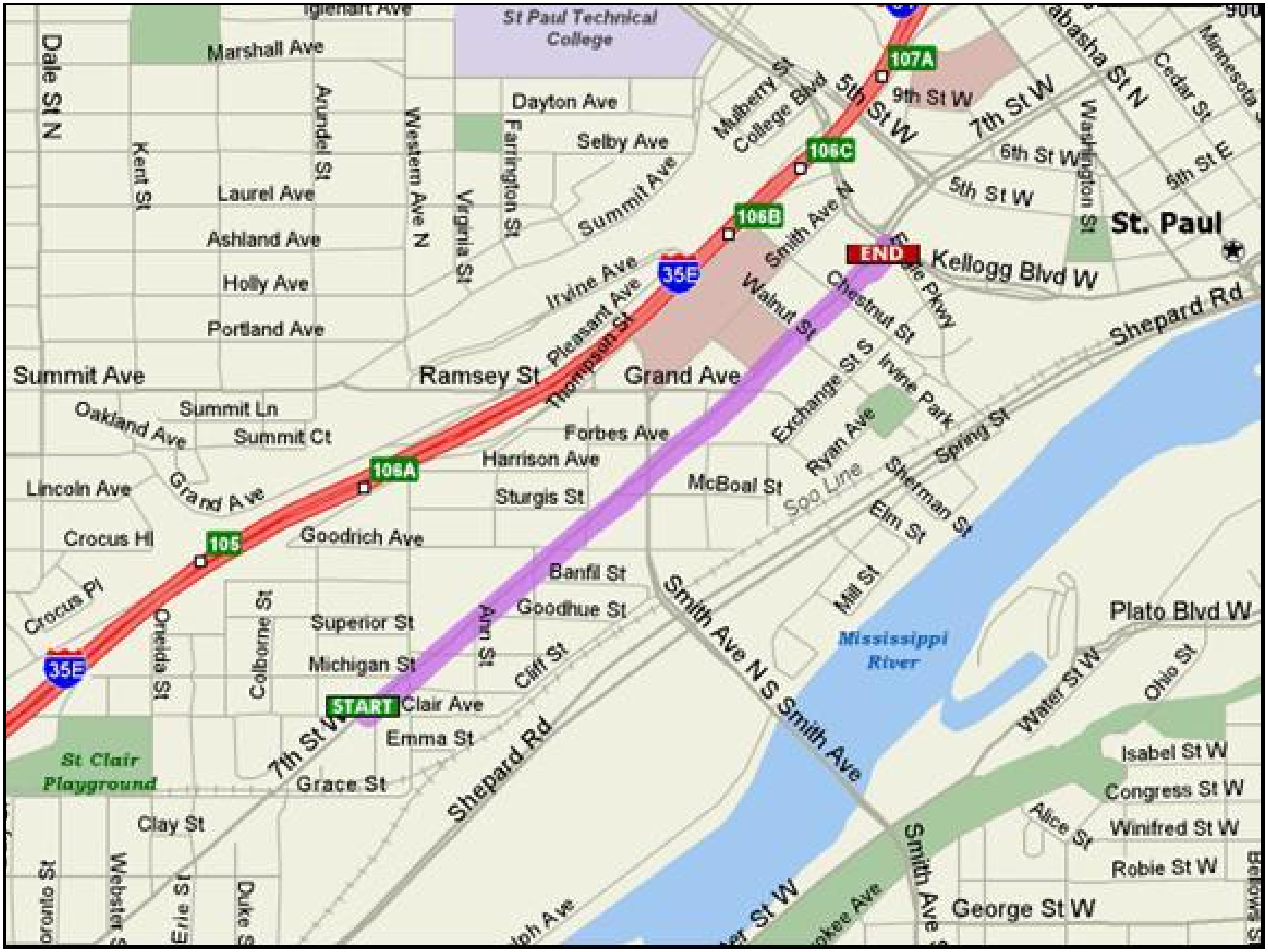
Comparison Site: 40th Avenue, Duluth (From Grand Avenue to Michigan Street)



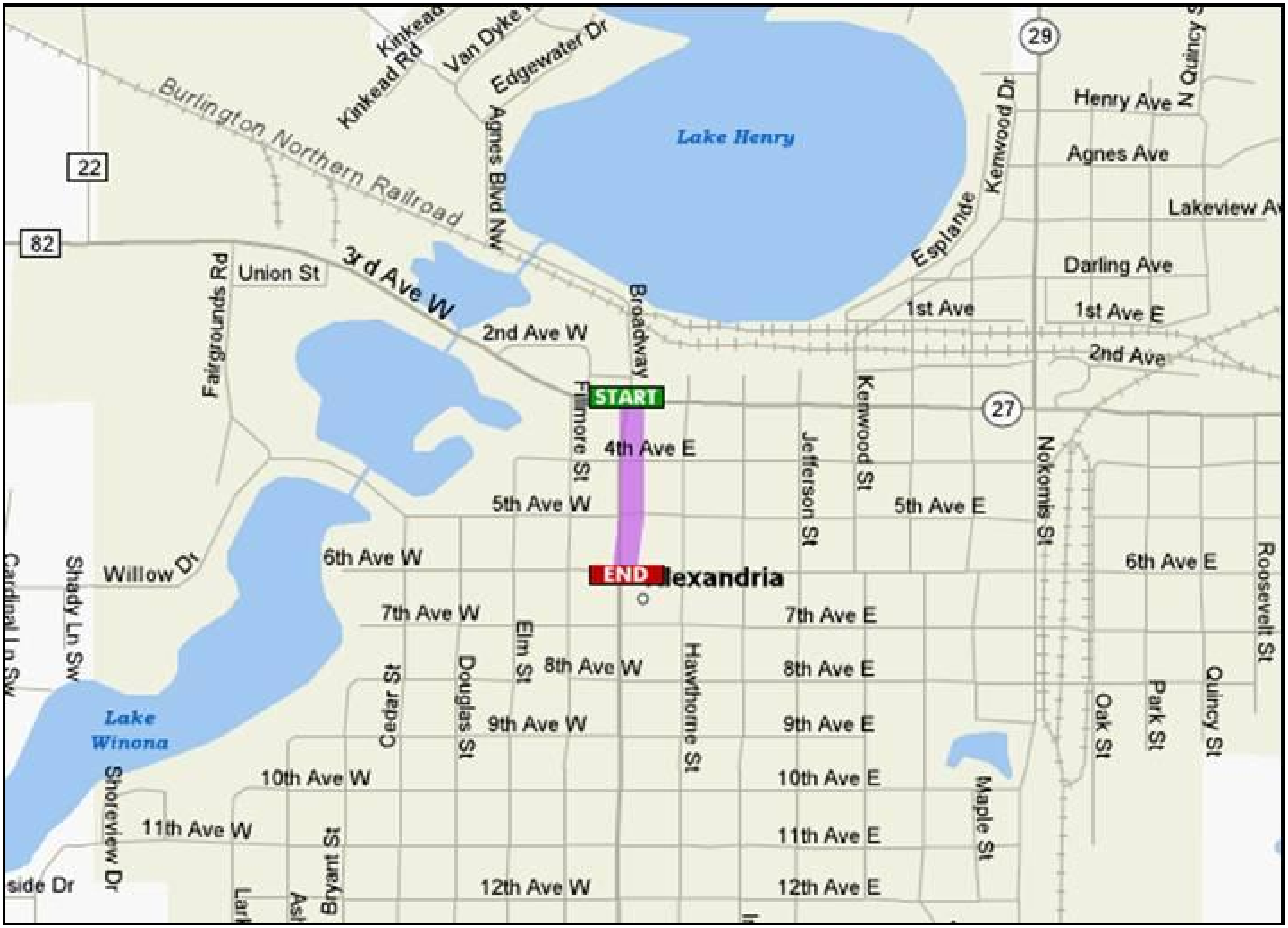
Comparison Site: Dale Street, St. Paul (Concordia Avenue to Grand Avenue)



Comparison Site: Snelling Avenue, St. Paul (Montreal Avenue to Grand Avenue)



Comparison Site: W. 7th Street, St. Paul (From St. Clair Avenue to Kellogg Boulevard)



Comparison Site: MNTH 29, Alexandria (From 6th Avenue E. to 3rd Avenue E.)

Appendix B

General Data - Study Sites

Background Data for Study Sites

Site		Length (miles)	Functional Classification	Land Use	Parking (on street parking or no parking)	Driveways per Mile	Un-signalized Approaches per mile
From	To						
St. Paul							
Lexington Parkway & Lincoln Avenue	Lexington Parkway & Jefferson Avenue	0.6	Collector	Residential developments	No	18	18
Fairview Avenue & Marshall Avenue	Fairview Avenue & Ford Parkway	2.1	Local Road	Predominantly residential developments	Yes	31	20
W. 7th Street & Jefferson Avenue	W. 7th Street & May Street	1.4	Collector	Predominantly commercial developments	Yes	31	19
Pierce Butler Route & Minnehaha Avenue	Pierce Butler Route & Transfer Road	2.9	Collector	Predominantly Industrial and commercial developments	No	16	10
E. Wentworth Avenue & Humboldt Avenue	E. Wentworth Avenue & MNTH 52	0.9	Collector	Predominantly commercial developments	No	32	12

Background Data for Study Sites

Site		Length (miles)	Functional Classification	Land Use	Parking (on street parking or no parking)	Driveways per Mile	Un-signalized Approaches per mile
From	To						
Duluth							
N. 32nd Avenue E. & MNTH 61	N. 40th Avenue E. & MNTH 61	0.7	Arterial	Residential developments	No	17	3
Grand Avenue & 59th Avenue	Grand Avenue & 46th Avenue	0.9	Collector	Predominantly commercial developments	No	33	8
Cold Spring							
MNTH 23 & 5th Avenue	MNTH 23 & Sauk River Bridge	0.6	Arterial	Predominantly commercial developments	No	11	5
Alexandria							
MNTH 29 & Nokomis Street	MNTH 29 & Broadway Street	0.5	Arterial	Predominantly commercial developments	Yes	28	22

Appendix C

Speed Data

Speed Data for Study Sites

Site		Posted Speed Limit	Mean Speed		85th Speed	
From	To		Before	After	Before	After
St. Paul						
Lexington Parkway & Lincoln Avenue	Lexington Parkway & Jefferson Avenue	30	35.0	32.5	39.7	37.2
Fairview Avenue & Marshall Avenue	Fairview Avenue & Ford Parkway	30	33.6	31.6	37.7	35.2
W. 7th Street & Jefferson Avenue	W. 7th Street & May Street	35	33.5	31.8	38.8	37.0
Pierce Butler Route & Minnehaha Avenue	Pierce Butler Route & Transfer Road	40	37.0	36.5	44.0	43.5
E. Wentworth Avenue & Humboldt Avenue	E. Wentworth Avenue & MN 52	35	36.0	34.3	40.0	38.2
Duluth						
Grand Avenue & 59th Avenue	Grand Avenue & 46th Avenue	30	33.0	31.0	37.0	38.0

Speed Data on E. Wentworth Avenue, St. Paul Before Conversion

Speed (mph)	Frequency	Cumulative Frequency	Cumulative Percent	Speed Percentile
27	1	1	0.6	
28	4	5	3.0	
29	5	10	6.1	
30	6	16	9.7	
31	6	22	13.3	
32	10	32	19.4	
33	12	44	26.7	
34	18	62	37.6	
35	11	73	44.2	50th Percentile
36	18	91	55.1	
37	12	103	62.4	
38	18	121	73.3	
39	10	131	79.4	85th Percentile
40	12	143	86.7	
41	9	152	92.1	
42	5	157	95.1	
43	4	161	97.6	
45	1	162	98.2	
47	2	164	99.4	
50	1	165	100.0	

Speed Data on E. Wentworth Avenue, St. Paul After Conversion

Speed (mph)	Frequency	Cumulative Frequency	Cumulative Percent	Speed Percentile
27	5	5	4.1	
28	4	9	7.3	
29	5	14	11.4	
30	7	21	17.1	
31	11	32	26.0	
32	12	44	35.8	
33	11	55	44.7	50^{th} Percentile
34	13	68	55.3	
35	7	75	61.0	
36	9	84	68.3	
37	9	93	75.6	
38	10	103	83.7	85^{th} Percentile
39	7	110	89.4	
40	3	113	91.9	
41	7	120	97.6	
42	2	122	99.2	
43	1	123	100.0	

Appendix D

Volume Data

Volume Data for Study Sites (Numbers in Parentheses Indicate Year of the ADT)

Study Site	Before Conversion			After Conversion		
Lexington Parkway, St. Paul	---	---	13,979 (2003)	14,172 (2004)	---	---
Fairview Avenue, St. Paul	---	---	14,741 (1997)	14,183 (1999)	13,800 (2001)	---
W. 7th Street, St. Paul	---	---	10,355 (2004)	11,123 (2005)	---	---
Pierce Butler Route, St. Paul	---	---	8,960 (2001)	9,166 (2003)	7300 (2004)	---
E. Wentworth Avenue, St. Paul	---	---	10,270 (2004)	9,500 (2005)	---	---
MNTH 61, Duluth	18,900 (1996)	17,400 (1998)	16,600 (2000)	19,600 (2002)	19,600 (2003)	18,500 (2004)
Grand Avenue, Duluth	---	---	13,800 (2004)	10,000 (2005)	---	---
MNTH 23, Cold Spring	5,605 (1984)	6,850 (1986)	8,300 (1988)	8,000 (1990)	9,700 (1992)	9,300 (1994)
MNTH 29, Alexandria	15,000 (1990)	15,200 (1992)	15,600 (1994)	15,800 (1998)	15,800 (2000)	---

Appendix E

Crash Data – Study Sites

Crash Data Summary for Study Sites

(Note – Total of all annual crash types shown and shaded cells indicate the year of conversion)

St. Paul: Lexington Avenue - From Jefferson Avenue to Lincoln Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	4	4	0	0
1985	6	6	0	0
1986	35	9	26	0
1987	26	12	14	0
1988	26	9	17	0
1989	39	12	27	0
1990	24	8	16	0
1991	19	5	14	0
1992	23	4	19	0
1993	27	8	19	0
1994	20	7	13	0
1995	29	14	15	0
1996	32	8	24	0
1997	20	4	16	0
1998	29	8	21	0
1999	37	9	28	0
2000	35	6	29	0
2001	30	7	23	0
2002	26	6	20	0
2003	3	1	2	0
2004	15	3	12	0
2005	14	5	9	0

St. Paul: Lexington Avenue - From Jefferson Avenue to Lincoln Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	1	2	0
1985	1	1	2
1986	9	7	9
1987	5	4	9
1988	4	5	8
1989	10	5	6
1990	7	5	6
1991	3	3	6
1992	2	8	6
1993	7	8	2
1994	2	10	4
1995	9	7	6
1996	5	12	5
1997	4	6	3
1998	4	12	8
1999	10	10	10
2000	5	18	3
2001	4	17	3
2002	4	10	2
2003	2	1	0
2004	9	6	0
2005	5	2	3

St. Paul: Fairview Avenue - From Ford Parkway to Marshall Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	18	18	0	0
1985	20	20	0	0
1986	54	11	43	0
1987	47	12	34	1
1988	56	9	47	0
1989	70	15	55	0
1990	43	16	27	0
1991	64	17	47	0
1992	53	13	40	0
1993	57	19	38	0
1994	65	19	46	0
1995	72	24	48	0
1996	66	10	56	0
1997	54	14	40	0
1998	44	7	37	0
1999	29	7	22	0
2000	35	12	23	0
2001	36	9	27	0
2002	33	6	27	0
2003	24	6	18	0
2004	25	2	23	0
2005	24	8	16	0

St. Paul: Fairview Avenue - From Ford Parkway to Marshall Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	4	7	3
1985	4	5	6
1986	9	9	10
1987	8	10	7
1988	7	21	10
1989	13	20	15
1990	5	17	8
1991	9	21	9
1992	14	11	9
1993	5	21	13
1994	13	22	14
1995	16	25	6
1996	10	27	5
1997	17	18	3
1998	10	14	8
1999	9	9	1
2000	7	14	1
2001	17	6	3
2002	11	7	6
2003	12	2	2
2004	11	6	1
2005	9	5	1

St. Paul: W. 7th Street - From May Street to Jefferson Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	9	8	0	1
1985	7	7	0	0
1986	46	12	34	0
1987	51	12	39	0
1988	42	10	32	0
1989	44	10	34	0
1990	38	14	24	0
1991	28	10	18	0
1992	38	13	25	0
1993	36	12	24	0
1994	33	8	25	0
1995	24	4	19	1
1996	25	4	21	0
1997	24	4	20	0
1998	37	14	23	0
1999	31	10	21	0
2000	27	6	21	0
2001	24	6	18	0
2002	34	10	24	0
2003	19	6	13	0
2004	23	3	20	0
2005	14	0	14	0

St. Paul: W. 7th Street - From May Street to Jefferson Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	3	1	1
1985	0	1	1
1986	11	7	3
1987	9	7	5
1988	10	10	3
1989	14	9	4
1990	12	7	5
1991	7	6	2
1992	10	10	4
1993	8	4	5
1994	6	5	3
1995	2	6	3
1996	5	3	3
1997	4	3	5
1998	13	11	1
1999	5	8	4
2000	7	5	3
2001	6	3	3
2002	6	8	3
2003	5	7	1
2004	6	3	2
2005	2	7	2

St. Paul: Pierce Butler Route - From Transfer Road to Minnehaha Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	1	1	0	0
1985	8	8	0	0
1986	27	6	21	0
1987	29	8	21	0
1988	38	9	29	0
1989	29	7	22	0
1990	27	8	19	0
1991	31	9	22	0
1992	18	5	13	0
1993	23	9	14	0
1994	34	8	26	0
1995	15	0	15	0
1996	27	5	22	0
1997	21	4	17	0
1998	20	6	14	0
1999	34	7	27	0
2000	39	10	29	0
2001	22	7	15	0
2002	23	5	18	0
2003	22	5	17	0
2004	30	9	21	0
2005	24	5	19	0

St. Paul: Pierce Butler Route - From Transfer Road to Minnehaha Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	1
1985	2	2	4
1986	1	2	13
1987	2	1	18
1988	2	5	22
1989	5	1	16
1990	5	0	17
1991	2	0	13
1992	4	0	3
1993	3	1	7
1994	1	4	10
1995	3	1	3
1996	1	2	6
1997	2	1	0
1998	0	2	2
1999	3	1	5
2000	4	3	6
2001	8	0	4
2002	6	3	3
2003	8	2	3
2004	5	1	9
2005	5	1	1

St. Paul: E. Wentworth Avenue - From Humboldt Avenue to MNTH 52

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	3	3	0	0
1985	3	3	0	0
1986	23	11	12	0
1987	12	2	10	0
1988	10	3	7	0
1989	16	5	11	0
1990	12	1	11	0
1991	18	7	11	0
1992	16	4	12	0
1993	24	10	14	0
1994	16	4	12	0
1995	16	4	12	0
1996	29	10	19	0
1997	20	11	9	0
1998	19	10	9	0
1999	13	6	7	0
2000	16	6	10	0
2001	23	4	19	0
2002	23	9	14	0
2003	14	3	11	0
2004	14	6	8	0
2005	14	5	9	0

St. Paul: E. Wentworth Avenue - From Humboldt Avenue to MNTH 52

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	1
1985	1	2	0
1986	2	13	0
1987	2	5	0
1988	4	6	0
1989	1	11	3
1990	3	5	2
1991	2	6	0
1992	1	9	1
1993	1	17	4
1994	2	6	2
1995	1	9	2
1996	1	13	9
1997	4	7	3
1998	3	12	2
1999	5	6	1
2000	2	9	2
2001	3	9	4
2002	0	12	8
2003	1	8	3
2004	6	4	1
2005	1	12	1

Duluth: Grand Avenue - From 59th Avenue to 46th Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	2	2	0	0
1985	5	5	0	0
1986	12	5	7	0
1987	9	1	8	0
1988	6	3	3	0
1989	9	4	5	0
1990	7	1	6	0
1991	18	7	11	0
1992	21	6	14	1
1993	21	7	14	0
1994	23	9	14	0
1995	20	11	9	0
1996	7	3	4	0
1997	13	4	9	0
1998	15	12	3	0
1999	17	8	9	0
2000	17	10	7	0
2001	9	8	1	0
2002	7	4	3	0
2003	9	7	2	0
2004	6	2	4	0
2005	3	1	2	0

Duluth: Grand Avenue - From 59th Avenue to 46th Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	1	0
1985	0	1	0
1986	0	2	2
1987	3	1	0
1988	0	2	0
1989	2	2	0
1990	1	2	2
1991	4	9	1
1992	1	8	8
1993	0	9	5
1994	3	8	2
1995	5	8	3
1996	2	2	1
1997	2	1	2
1998	3	8	0
1999	4	3	1
2000	2	4	1
2001	0	9	0
2002	2	2	0
2003	1	2	4
2004	2	1	2
2005	0	1	0

Duluth: MNTH 61 - From 32nd Avenue to 40th Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	1	1	0	0
1985	1	1	0	0
1986	5	4	1	0
1987	7	2	5	0
1988	1	1	0	0
1989	13	6	6	1
1990	5	2	3	0
1991	6	1	5	0
1992	2	1	1	0
1993	8	3	5	0
1994	5	4	1	0
1995	9	4	5	0
1996	5	2	3	0
1997	5	3	2	0
1998	3	1	2	0
1999	2	2	0	0
2000	8	3	5	0
2001	3	1	2	0
2002	5	5	0	0
2003	1	1	0	0
2004	6	3	3	0
2005	2	1	1	0

Duluth: MNTH 61 - From 32nd Avenue to 40th Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	0
1985	0	0	0
1986	1	1	2
1987	1	0	1
1988	1	0	0
1989	5	1	2
1990	1	0	1
1991	1	1	0
1992	0	0	0
1993	4	0	0
1994	2	1	0
1995	4	0	0
1996	1	1	0
1997	0	1	0
1998	1	0	1
1999	1	0	0
2000	4	0	0
2001	0	0	0
2002	1	1	0
2003	1	0	0
2004	4	1	0
2005	0	1	0

Cold Spring: MNTH 23 - From 5th Avenue to Sauk River Bridge

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	4	4	0	0
1985	6	6	0	0
1986	27	11	16	0
1987	8	2	6	0
1988	17	8	9	0
1989	11	1	10	0
1990	3	0	3	0
1991	12	6	6	0
1992	11	1	10	0
1993	10	5	5	0
1994	7	2	5	0
1995	9	2	7	0
1996	16	3	13	0
1997	10	3	7	0
1998	13	5	8	0
1999	3	0	3	0
2000	11	3	8	0
2001	5	1	4	0
2002	15	4	11	0
2003	13	6	7	0
2004	17	5	12	0
2005	12	3	9	0

Cold Spring: MNTH 23 - From 5th Avenue to Sauk River Bridge

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	1	0
1985	0	0	5
1986	1	3	14
1987	2	1	1
1988	8	1	1
1989	5	1	1
1990	0	0	0
1991	4	2	3
1992	4	1	0
1993	4	2	0
1994	4	0	0
1995	2	2	2
1996	7	2	0
1997	2	2	0
1998	4	2	2
1999	0	1	0
2000	2	5	0
2001	0	1	0
2002	5	4	1
2003	3	2	2
2004	6	5	0
2005	3	2	0

Alexandria: MNTH 29 - From Broadway Street to Nokomis Street

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	13	13	0	0
1985	13	13	0	0
1986	47	20	27	0
1987	47	15	32	0
1988	71	21	50	0
1989	52	12	40	0
1990	55	13	42	0
1991	58	11	47	0
1992	37	10	27	0
1993	73	18	55	0
1994	67	18	49	0
1995	52	14	38	0
1996	28	4	24	0
1997	34	7	27	0
1998	27	7	20	0
1999	30	9	21	0
2000	38	10	28	0
2001	32	10	22	0
2002	26	3	23	0
2003	23	9	14	0
2004	7	1	6	0
2005	23	2	21	0

Alexandria: MNTH 29 - From Broadway Street to Nokomis Street

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	6	0	1
1985	2	2	4
1986	18	6	8
1987	15	7	8
1988	30	11	5
1989	22	8	6
1990	23	9	10
1991	22	9	11
1992	21	1	5
1993	32	16	9
1994	19	19	12
1995	11	13	8
1996	6	4	5
1997	15	5	4
1998	12	3	6
1999	11	4	5
2000	17	5	5
2001	12	5	4
2002	9	7	1
2003	8	8	2
2004	1	6	0
2005	8	4	1

Appendix F

General Data –Comparison Sites

Background Data for Comparison Sites

Site		Length (miles)	Roadway Cross-section	Functional Classification	Land Use	Parking	Driveways per Mile	Un-signalized Approaches per mile
From	To							
St. Paul								
W. 7th Street & St. Clair Avenue	W. 7th Street & Kellogg Boulevard	1.0	Undivided 4-Lane	Collector	Predominantly commercial developments	Yes	34	14
Dale Street & Concordia Avenue	Dale Street & Grand Avenue	0.8	Undivided 4-Lane	Collector	Commercial and Residential Developments	Yes	34	17
Snelling Avenue & Grand Avenue	Snelling Avenue & Montreal Avenue	1.9	Undivided 4-Lane	Collector	Commercial and Residential Developments	Yes	37	15
Duluth								
40th Avenue & Michigan Street	40th Avenue & Grand Avenue	0.3	Undivided 4-Lane	Collector	Predominantly commercial developments	No	27	10

Background Data for Comparison Sites

Site		Length (miles)	Roadway Cross-section	Functional Classification	Land Use	Parking	Driveways per Mile	Un-signalized Approaches per mile
From	To							
Duluth								
Grand Avenue & 46th Avenue	Grand Avenue & 34th Avenue	1.0	Undivided 4-Lane	Collector	Predominantly commercial developments	No	43	11
6th Avenue & 9th Street	6th Avenue & 4th Street	0.3	Undivided 4-Lane	Collector	Predominantly commercial developments	No	48	17
Superior Street & Carlton Avenue	Superior Street & 23rd Avenue	0.8	Undivided 4-Lane	Collector	Predominantly commercial developments	No	43	14
Cold Spring								
MNTH 23 & 14th Avenue	MNTH 23 & 5th Avenue	0.7	Divided Roadway	Arterial	Very few Commercial Developments	No	4	7
Alexandria								
MNTH 29 & 3rd Avenue	MNTH 29 & 6th Avenue	0.2	Four-lane undivided with left turn lanes	Arterial	Predominantly commercial developments	Yes	27	8

Appendix G

Crash Data –Comparison Sites

Crash Data Summary for Comparison Sites
(Note – total of all annual crash types shown)
St. Paul: W. 7th Street - From St. Clair Avenue to Kellogg Boulevard

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	12	12	0	0
1985	17	17	0	0
1986	74	21	53	0
1987	93	24	69	0
1988	119	29	90	0
1989	77	23	54	0
1990	97	32	65	0
1991	74	24	50	0
1992	88	24	64	0
1993	72	22	50	0
1994	71	19	52	0
1995	63	17	46	0
1996	58	19	39	0
1997	60	20	40	0
1998	63	22	41	0
1999	49	18	31	0
2000	61	16	44	1
2001	70	15	55	0
2002	55	13	42	0
2003	36	5	31	0
2004	35	9	26	0
2005	45	6	39	0

St. Paul: W. 7th Street - From St. Clair Avenue to Kellogg Boulevard

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	3	3	1
1985	6	4	1
1986	22	6	9
1987	20	24	9
1988	33	31	13
1989	20	18	10
1990	27	28	12
1991	15	18	9
1992	19	22	10
1993	16	20	9
1994	14	15	10
1995	18	15	13
1996	18	14	12
1997	18	21	5
1998	16	19	8
1999	12	6	6
2000	20	12	6
2001	18	9	13
2002	17	11	6
2003	10	8	6
2004	9	7	5
2005	7	17	5

St. Paul: Dale Street - From Grand Avenue to Concordia Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	9	9	0	0
1985	4	4	0	0
1986	26	8	18	0
1987	25	9	16	0
1988	35	11	24	0
1989	36	12	24	0
1990	16	5	11	0
1991	70	20	50	0
1992	54	17	37	0
1993	64	16	48	0
1994	56	14	42	0
1995	72	21	51	0
1996	60	27	33	0
1997	50	14	36	0
1998	63	22	41	0
1999	41	10	31	0
2000	44	10	34	0
2001	55	22	33	0
2002	42	7	35	0
2003	34	6	28	0
2004	57	12	45	0
2005	57	6	51	0

St. Paul: Dale Street - From Grand Avenue to Concordia Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	1	4	0
1985	2	0	2
1986	8	4	5
1987	6	3	7
1988	12	4	8
1989	13	6	5
1990	4	3	2
1991	13	22	4
1992	14	10	6
1993	4	26	5
1994	10	18	2
1995	8	26	4
1996	7	24	4
1997	11	9	7
1998	12	18	1
1999	7	13	7
2000	7	16	2
2001	12	18	7
2002	5	10	2
2003	4	13	3
2004	10	16	6
2005	14	14	7

St. Paul: Snelling Avenue - From Montreal Avenue to Grand Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	26	26	0	0
1985	25	25	0	0
1986	111	34	76	1
1987	135	43	92	0
1988	116	26	90	0
1989	111	24	87	0
1990	96	35	61	0
1991	95	30	65	0
1992	89	35	54	0
1993	88	30	58	0
1994	86	28	58	0
1995	93	29	64	0
1996	95	25	70	0
1997	96	32	64	0
1998	85	33	51	1
1999	80	23	57	0
2000	101	25	76	0
2001	88	22	66	0
2002	86	20	66	0
2003	55	14	41	0
2004	74	14	60	0
2005	62	11	51	0

St. Paul: Snelling Avenue - From Montreal Avenue to Grand Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	10	4	1
1985	7	5	4
1986	29	17	12
1987	31	29	21
1988	35	29	16
1989	30	17	19
1990	30	17	22
1991	31	25	14
1992	17	34	8
1993	23	28	9
1994	24	28	5
1995	26	34	6
1996	26	27	7
1997	25	24	7
1998	30	22	9
1999	19	25	7
2000	31	25	12
2001	29	23	11
2002	25	24	6
2003	19	11	7
2004	21	13	17
2005	20	18	1

Duluth: Grand Avenue - From 46th Avenue to 34th Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	2	2	0	0
1985	1	1	0	0
1986	1	1	0	0
1987	2	1	1	0
1988	5	3	2	0
1989	1	0	1	0
1990	3	2	1	0
1991	24	7	17	0
1992	20	6	14	0
1993	27	9	18	0
1994	33	12	21	0
1995	19	10	9	0
1996	17	8	9	0
1997	20	5	15	0
1998	23	15	8	0
1999	16	9	7	0
2000	10	8	2	0
2001	7	5	2	0
2002	9	6	3	0
2003	12	9	3	0
2004	14	7	7	0
2005	7	6	1	0

Duluth: Grand Avenue - From 46th Avenue to 34th Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	1
1985	0	0	0
1986	0	0	0
1987	0	0	1
1988	1	2	0
1989	0	1	0
1990	0	3	0
1991	7	4	2
1992	1	9	6
1993	5	7	7
1994	8	7	6
1995	2	4	6
1996	5	2	0
1997	2	3	2
1998	4	10	1
1999	5	5	3
2000	1	3	1
2001	1	2	2
2002	1	4	2
2003	1	4	6
2004	3	5	3
2005	1	2	2

Duluth: 40th Avenue - From Michigan Street to Grand Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	1	1	0	0
1985	0	0	0	0
1986	2	1	1	0
1987	2	1	1	0
1988	1	0	1	0
1989	8	2	6	0
1990	7	2	5	0
1991	5	2	3	0
1992	3	1	2	0
1993	0	0	0	0
1994	4	0	4	0
1995	2	1	1	0
1996	0	0	0	0
1997	2	0	2	0
1998	5	5	0	0
1999	2	1	1	0
2000	7	4	3	0
2001	2	0	2	0
2002	3	3	0	0
2003	3	1	2	0
2004	1	1	0	0
2005	1	0	1	0

Duluth: 40th Avenue - From Michigan Street to Grand Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	1	0
1985	0	0	0
1986	0	1	0
1987	0	1	0
1988	0	1	0
1989	0	5	0
1990	1	4	1
1991	0	3	0
1992	0	1	1
1993	0	0	0
1994	0	1	1
1995	0	0	1
1996	0	0	0
1997	0	1	0
1998	1	4	0
1999	0	2	0
2000	0	4	2
2001	0	1	0
2002	1	2	0
2003	0	2	0
2004	0	1	0
2005	0	1	0

Duluth: 6th Avenue - From 9th Street to 4th Street

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	8	8	0	0
1985	4	4	0	0
1986	23	5	18	0
1987	23	8	15	0
1988	15	6	9	0
1989	23	6	17	0
1990	0	0	0	0
1991	10	4	6	0
1992	17	4	13	0
1993	15	5	10	0
1994	15	6	9	0
1995	16	6	10	0
1996	10	6	4	0
1997	19	8	11	0
1998	3	1	2	0
1999	7	4	3	0
2000	2	0	2	0
2001	3	1	2	0
2002	1	0	1	0
2003	2	1	1	0
2004	7	3	3	1
2005	2	1	1	0

Duluth: 6th Avenue - From 9th Street to 4th Street

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	3	1	0
1985	1	1	0
1986	4	8	1
1987	4	1	5
1988	5	3	3
1989	5	8	1
1990	0	0	0
1991	1	4	0
1992	1	6	1
1993	3	2	7
1994	2	4	2
1995	5	1	2
1996	4	1	0
1997	7	4	0
1998	2	0	0
1999	4	1	0
2000	0	0	0
2001	1	0	0
2002	0	0	0
2003	1	1	0
2004	1	3	0
2005	0	1	0

Duluth: Superior Street - From Carlton Avenue to 23rd Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	2	2	0	0
1985	0	0	0	0
1986	2	1	1	0
1987	2	2	0	0
1988	0	0	0	0
1989	4	2	2	0
1990	6	1	5	0
1991	2	2	0	0
1992	3	1	2	0
1993	1	1	0	0
1994	0	0	0	0
1995	0	0	0	0
1996	1	1	0	0
1997	1	0	1	0
1998	3	3	0	0
1999	2	1	1	0
2000	3	3	0	0
2001	3	2	1	0
2002	0	0	0	0
2003	2	2	0	0
2004	1	1	0	0
2005	0	0	0	0

Duluth: Superior Street - From Carlton Avenue to 23rd Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	0
1985	0	0	0
1986	0	2	0
1987	0	1	0
1988	0	0	0
1989	2	1	1
1990	0	4	1
1991	0	2	0
1992	0	0	0
1993	0	0	0
1994	0	0	0
1995	0	0	0
1996	0	0	0
1997	0	0	0
1998	1	0	0
1999	0	1	0
2000	0	2	0
2001	1	2	0
2002	0	0	0
2003	0	2	0
2004	0	0	0
2005	0	0	0

Cold Spring: MNTH 23 - From 14th Avenue to 5th Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	1	1	0	0
1985	0	0	0	0
1986	1	0	1	0
1987	2	1	1	0
1988	3	2	1	0
1989	3	0	3	0
1990	4	1	3	0
1991	2	0	2	0
1992	3	0	3	0
1993	3	0	3	0
1994	4	0	4	0
1995	3	2	1	0
1996	3	2	1	0
1997	0	0	0	0
1998	0	0	0	0
1999	4	2	2	0
2000	2	1	1	0
2001	2	1	1	0
2002	3	1	2	0
2003	1	0	1	0
2004	2	0	2	0
2005	1	0	1	0

Cold Spring: MNTH 23 - From 14th Avenue to 5th Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	0
1985	0	0	0
1986	0	0	0
1987	0	0	0
1988	1	0	0
1989	0	0	0
1990	0	0	0
1991	0	1	0
1992	0	0	0
1993	0	0	0
1994	1	0	0
1995	1	0	0
1996	2	1	0
1997	0	0	0
1998	0	0	0
1999	0	0	0
2000	0	1	0
2001	1	0	0
2002	2	0	0
2003	1	0	0
2004	0	1	0
2005	0	0	0

Alexandria: MNTH 29 - From 6th Avenue to 3rd Avenue

Year	Total Crashes	Injury Crashes(A-C)	PDO Crashes	Fatal Crashes
1984	2	2	0	0
1985	3	3	0	0
1986	14	5	9	0
1987	16	6	10	0
1988	27	8	19	0
1989	9	2	7	0
1990	21	8	13	0
1991	13	1	12	0
1992	16	6	10	0
1993	11	2	9	0
1994	11	5	6	0
1995	11	5	6	0
1996	11	4	7	0
1997	12	2	10	0
1998	10	1	9	0
1999	15	2	13	0
2000	15	3	12	0
2001	10	1	9	0
2002	22	4	18	0
2003	16	1	15	0
2004	16	5	11	0
2005	13	4	9	0

Alexandria: MNTH 29 - From 6th Avenue to 3rd Avenue

Year	Rear End Crashes	Right Angle Crashes	Left Turn Crashes
1984	0	0	0
1985	0	0	1
1986	3	1	1
1987	2	2	2
1988	4	4	3
1989	2	1	1
1990	6	9	1
1991	3	1	3
1992	3	3	3
1993	2	1	0
1994	4	3	1
1995	3	1	0
1996	5	1	0
1997	1	2	1
1998	6	1	0
1999	6	5	0
2000	6	3	0
2001	3	1	1
2002	4	7	1
2003	4	5	1
2004	3	5	3
2005	6	1	3