# Guidelines for the Conversion of Urban Four-Lane Undivided Roadways to Three-Lane Two-Way Left-Turn Lane Facilities

Final Report

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# GUIDELINES FOR THE CONVERSION OF URBAN FOUR-LANE UNDIVIDED ROADWAYS TO THREE-LANE TWO-WAY LEFT-TURN LANE FACILITIES

Final Report

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## EXECUTIVE SUMMARY

Four-lane undivided roadways in urban areas can experience a degradation of service and/or safety as traffic volumes increase. In fact, the existence of turning vehicles on this type of roadway has a dramatic effect on both of these factors. The solution identified for these problems is typically the addition of a raised median or two-way left-turn lane (TWLTL). The mobility and safety benefits of these actions have been proven and are discussed in the "Past Research" chapter of this report along with some general cross section selection guidelines. The cost and right-of-way impacts of these actions are widely accepted.

These guidelines focus on the evaluation and analysis of an alternative to the typical four-lane undivided cross section improvement approach described above. It has been found that the conversion of a four-lane undivided cross section to three lanes (i.e., one lane in each direction and a TWLTL) can improve safety and maintain an acceptable level of service. These guidelines summarize the results of past research in this area (which is almost nonexistent) and qualitative/quantitative before-and-after safety and operational impacts of case study conversions located throughout the United States and Iowa. Past research confirms that this type of conversion is acceptable or feasible in some situations but for the most part fails to specifically identify those situations. In general, the reviewed case study conversions resulted in a reduction of average or 85th percentile speeds (typically less than five miles per hour) and a relatively dramatic reduction in excessive speeding (a 60 to 70 percent reduction in the number of vehicles traveling five miles per hour faster than the posted speed limit was measured in two cases) and total crashes (reductions between 17 to 62 percent were measured). The 13 roadway conversions considered had average daily traffic volumes of 8,400 to 14,000 vehicles per day (vpd) in Iowa and 9,200 to 24,000 vehicles per day elsewhere.

In addition to past research and case study results, a simulation sensitivity analysis was completed to investigate and/or confirm the operational impacts of a four-lane undivided to three-lane conversion. First, the advantages and disadvantages of different corridor simulation packages were identified for this type of analysis. Then, the CORridor SIMulation (CORSIM) software was used

to investigate and evaluate several characteristics related to the operational feasibility of a four-lane undivided to three-lane conversion. Simulated speed and level of service results for both cross sections were documented for different total peak-hour traffic, access densities, and access-point left-turn volumes (for a case study corridor defined by the researchers). These analyses assisted with the identification of the considerations for the operational feasibility determination of a four-lane to three-lane conversion.

The results of the simulation analyses primarily confirmed the case study impacts. The CORSIM results indicated only a slight decrease in average arterial speed for through vehicles can be expected for a large range of peak-hour volumes, access densities, and access-point left-turn volumes (given the assumptions and design of the corridor case study evaluated). Typically, the reduction in the simulated average arterial speed (which includes both segment and signal delay) was between zero and four miles per hour when a roadway was converted from a four-lane undivided to a three-lane cross section. The simulated arterial level of service for a converted roadway, however, showed a decrease when the bi-directional peak-hour volume was about 1,750 vehicles per hour (or 17,500 vehicles per day if 10 percent of the daily volume is assumed to occur in the peak hour). Past research by others, however, indicates that 12,000 vehicles per day may be the operational capacity (i.e., level of service E) of a three-lane roadway due to vehicle platooning.

The simulation results, along with past research and case study results, appear to support following volume-related feasibility suggestions for four-lane undivided to three-lane cross section conversions. It is recommended that a four-lane undivided to three-lane conversion be considered as a feasible (with respect to volume only) option when bi-directional peak-hour volumes are less than 1,500 vehicles per hour, but that some caution begin to be exercised when the roadway has a bi-directional peak-hour volume between 1,500 and 1,750 vehicles per hour. At and above 1,750 vehicles per hour, the simulation indicated a reduction in arterial level of service. Therefore, at least in Iowa, the feasibility of a four-lane undivided to three-lane conversion should be questioned and/or considered much more closely when a roadway has (or is expected to have) a peak-hour volume of more than 1,750 vehicles. Assuming that 10 percent of the daily traffic occurs during the peak-hour, these volume recommendations would correspond to 15,000 and 17,500 vehicles per day, respectively. These suggestions, however, are based on the results from one idealized case

study corridor analysis. Individual operational analysis and/or simulations should be completed in detail once a four-lane undivided to three-lane cross section conversion is considered feasible (based on the general suggestions above) for a particular corridor. All of the simulations completed as part of this project also incorporated the optimization of signal timing to minimize vehicle delay along the corridor.

A number of determination feasibility factors were identified from a review of the past research, before-and-after case study results, and the simulation sensitivity analysis. The existing and expected (i.e., design period) statuses of these factors are described and should be considered. The characteristics of these factors should be compared to each other, the impacts of other potentially feasible cross section improvements, and the goals/objectives of the community. The factors discussed in these guidelines include

- roadway function and environment
- overall traffic volume and level of service
- turning volumes and patterns
- frequent-stop and slow-moving vehicles
- weaving, speed, and queues
- crash type and patterns
- pedestrian and bike activity
- right-of-way availability, cost, and acquisition impacts
- general characteristics, including
    - parallel roadways
    - offset minor street intersections
    - parallel parking
    - corner radii
    - at-grade railroad crossings

The characteristics of these factors are documented in these guidelines, and their relationship to four-lane undivided to three-lane cross section conversion feasibility identified. This information is summarized along with some evaluative questions in this executive summary and Appendix C.

In summary, the results of past research, numerous case studies, and the simulation analyses done as part of this project support the conclusion that in certain circumstances a four-lane undivided to three-lane conversion can be a feasible alternative for the mitigation of operational and/or safety concerns. This feasibility, however, must be determined by an evaluation of the factors identified in these guidelines (along with any others that may be relevant for a individual corridor). The expected benefits, costs, and overall impacts of a four-lane undivided to three-lane conversion should then be compared to the impacts of other feasible alternatives (e.g., adding a raised median) at a particular location.

## Table ES.1 Feasibility Determination Factor Characteristics and Sample Evaluative Questions

| Factor | Characteristics | Sample Evaluative Questions |
|---|---|---|
| Roadway Function and Environment | • Actual, Expected, and Desired Primary Function (Access, Mobility, or a Combination of the Two)<br>• Community Objectives/Goals for the Roadway<br>• Available Right-of-Way<br>• Current and Expected Adjacent Land Use | • What is the primary current, expected, and desired function of the roadway?<br>• Is the roadway primarily a collector or minor arterial roadway?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section?<br>• Is the goal for the roadway improvement increased safety with somewhat lower mobility?<br>• Is the right-of-way limited?<br>• Will the adjacent land use remain relatively stable throughout the design period?<br>• Will the proposed cross section match the desired function of the roadway?<br>• Will the answers to the above questions remain the same throughout the design period of the project? |
| Overall Traffic Volume and Level of Service | • Total Daily Volume<br>• Peak-Hour Volume (Morning/Noon/Evening)<br>• Directional Split<br>• Intersection and Arterial Level of Service<br>• Side Street and Driveway Vehicle Delay<br>• Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Signal Timing/Phasing<br>• Arterial Travel Speeds and Vehicle Delays<br>• Existence of Turn Lanes | • What is an acceptable increase in minor street or signal-related delay due to the conversion?<br>• Is a decrease in arterial travel speed of 5 miles per hour or less acceptable?<br>• What is an acceptable reduction in intersection level of service?<br>• What level of daily traffic volume exists (for Iowa roadways and assuming a 50/50 split and 10 percent of daily volume occurs during peak-hour):<br>≤ 15,000 vpd (feasibility probable)<br>15,000 to 17,500 vpd (exercise caution)<br>≥ 17,500 vpd (feasibility less likely)<br>• Does the signal timing/phasing need to be changed?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Turning Volumes and Patterns | • Number and Location of Turn Volumes and Access Points<br>• Peak time period of Turn Volumes<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Design of Access Points and Intersections<br>• Turn Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Minor Street and Access Point Vehicle Delay<br>• Signal Timing/Phasing | • Does the signal timing/phasing need to changes/optimized?<br>• How important is it that right-turn vehicles quickly enter/exit the roadway?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• Does the proposed marking allow the design vehicle (e.g., tractor-trailer) to turn properly?<br>• What is an acceptable increase in minor street and/or left-turn vehicle delay?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section? |
| Frequent-Stop and/or Slow-Moving Vehicles (e.g., agricultural vehicles, mail carriers, school buses, tractor-trailers, and buggies) | • Volume, Location, and Time of Frequent-Stop and/or Slow-Moving Vehicles<br>• Type, Design (Length, Width, Turning Radius, etc.) and Speed of Vehicles<br>• Arterial Travel Speeds and Vehicle Delays<br>• Level of Enforcement for Proper TWLTL Use (i.e., No Passing Allowed) | • What is acceptable delay with respect to frequent-stop or slow-moving vehicles?<br>• Can these vehicles turn properly at the access points and intersections?<br>• Can no passing of these vehicles be enforced?<br>• Are there locations for pull-outs for these vehicles?<br>• Can some or all of the stop locations for the frequent-stop vehicles be combined? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Weaving, Speed, and Queues | • Signal Timing/Phasing<br>• Number of Existing Lane Changes<br>• Turn Volume and Location<br>• Arterial Travel Speeds and Vehicle Delays<br>• Level of Enforcement for Proper TWLTL Use (i.e., No Passing Allowed)<br>• Number and Location of Turn Volumes and Access Points<br>• Peak Time Period of Turn Volumes<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Design of Access Points and Intersections<br>• Turn Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Minor Street and Access Point Vehicle Delay<br>• Queue Length<br>• Number of Speeders (i.e., greater than 5 mph over the posted speed limit) | • Does the signal timing/phasing need to changes/optimized?<br>• How important is it that right-turn vehicles quickly enter/exit the roadway?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• What is an acceptable increase in minor street and/or left-turn vehicle delay?<br>• Is a decrease in arterial travel speed of 5 miles per hour or less acceptable?<br>• What is an acceptable change in queues?<br>• Are there safety concerns related to weaving?<br>• Can no passing be enforced?<br>• Can drivers be educated about proper use of TWLTL?<br>• Is a reduction in speeders and speed variability preferred?<br>• Can all the old markings be completely removed?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section? |
| Crash Types and Patterns | • Type of Crashes<br>• Location of Crashes<br>• Number and Location of Pedestrians and Bicyclists<br>• Parallel Parking Need | • Can the crashes that are occurring be reduced with a conversion?<br>• Will a reduction in speed and speed variability increase safety?<br>• Are there safety concerns related to parallel parking maneuvers?<br>• Do pedestrians and bicyclists have safety concerns? |
| Pedestrian and Bike Activity | • Number and Location of Pedestrians<br>• Number and Location of Bicyclist Use<br>• Characteristics of Pedestrians and Bicyclists (e.g., Age)<br>• Bike and Pedestrian Friendliness of Roadway<br>• Cross Section Width<br>• Parallel Parking Need | • What is the pedestrian and bicyclist friendliness of the roadway?<br>• Do pedestrians and bicyclists have safety concerns?<br>• Will the addition of a TWLTL assist pedestrians and bicyclists?<br>• How will pedestrians and bicyclists interact with parallel parking?<br>• Can a bike lane be added after the conversion? |

## Table ES.1 Continued

| | | |
|---|---|---|
| Right-of-Way Availability, Cost, and Acquisition Impacts | • Available Right-of-Way<br>• Cost of Right-of-Way<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Design of Access Points and Intersections<br>• Number of Properties Needed and Environmental Impacts (e.g., Tree Removal)<br>• Cross Section Width<br>• Parallel Parking Need | • Is the right-of-way limited?<br>• Will the cost of right-of-way acquisition be significant?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• What is necessary in the cross section (e.g., bike lane, parallel parking)? |
| **General Characteristics** | | |
| Parallel Roadways | • Roadway Network Layout<br>• Volume and Characteristics of Through Vehicles Diverted<br>• Impact of Diversion on Parallel Roadways | • Is a decrease in arterial travel speed of 5 miles per hour or less acceptable?<br>• Does the signal timing/phasing need to changes/optimized?<br>• Will conversion divert through vehicles to parallel roadways?<br>• Is it possible to avoid or reroute the diverted traffic?<br>• What is the impact on the parallel roadway environment? |
| Offset Minor Street Intersections | • Volume and Time of Left Turns<br>• Queue Lengths<br>• Distance between Minor Street Approaches | • Do left turns occur into both minor street/access point approaches at a similar time?<br>• Are the left-turn volumes significant?<br>• Will the left-turn volumes produce queues in the through lanes of a three-lane roadway? |
| Parallel Parking | • Parallel Parking Need<br>• Number of Parking Maneuvers<br>• Operational and Safety Impacts of Parallel Parking<br>• Design of Existing/Proposed Parallel Parking | • Does parallel parking exist?<br>• How many parking maneuvers occur during peak travel times?<br>• What are the safety and delay concerns related to parallel parking maneuvers?<br>• Is it possible to design these spaces for easy enter/exit (i.e., to minimize delay)?<br>• Will it be necessary to reduce the number of parking spaces?<br>• Does parallel parking reduce the ability of vehicles to turn in and out of minor streets and access points? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Corner Radii | • Design of Access Points and Intersections<br>• Number and Location of Turn Volumes and Access Points<br>• Peak time period of Turn Volumes<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Turn Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Minor Street and Access Point Vehicle Delay | • How important is it that right-turn vehicles quickly enter/exit the roadway?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• Does the proposed marking allow the design vehicle (e.g., tractor-trailer) to turn properly?<br>• Do parallel parking spaces need to be removed to allow proper turning? |
| At-Grade Railroad Crossing | • Volume, Location, and Time of Train Crossing<br>• Length of Crossing Train<br>• Delay Impacts of Train Crossing<br>• Queue Impacts of Train Crossing<br>• Total Daily Vehicle Volume<br>• Peak-Hour Vehicle Volume (Morning/Noon/Evening)<br>• Directional Split of Vehicles | • Do trains cross during peak travel periods? What is the typical delay from train crossing?<br>• Is double the current queue length (with four-lane undivided cross section) at a railroad at-grade crossing acceptable?<br>• Would the delay impacts of double the current queue be acceptable? |

## INTRODUCTION

There are a large number of four-lane undivided roadways in the urban areas of Iowa and the United States. Many of these roadways operate at acceptable levels of service and safety. In other cases, however, changes in volume levels, traffic flow characteristics (e.g., excessive speed), and/or the corridor environment have changed the service and/or safety of the roadway to such an extent that concerns develop and a cross section improvement appears to be necessary.

Improvements to the cross section of an urban four-lane undivided roadway are often limited to alternatives that increase its existing curb-to-curb width. For example, a typical recommendation to improve the operation and/or safety of an urban four-lane undivided roadway is the addition of a raised median or two-way-left-turn-lane (TWLTL). A schematic of this approach is shown in Figure 1. The safety and operational benefits of this type of improvement are generally accepted and are discussed in this report.

More recently, an alternative to widening the cross section of an urban four-lane undivided roadway has been considered in Iowa and throughout the United States. In certain situations, it has been shown that the conversion of an urban four-lane undivided roadway to a three-lane cross section (i.e., one lane in each direction and a TWLTL) can have lower overall impacts than a widening option, be completed for a relatively low cost, and result in acceptable operations and improved safety. A schematic of this approach is shown in Figure 2. However, unlike the addition of a raised median or TWLTL, there is little guidance available to determine the locations where a conversion of this type (see Figure 2) might be feasible and/or successful. This report provides some qualitative and quantitative guidelines related to the feasibility of four-lane to three-lane conversions and their expected impacts.

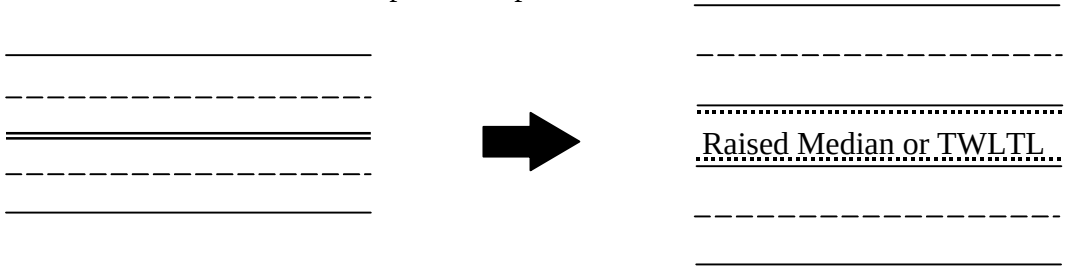


**Figure 1 Four-Lane Undivided Roadway Conversion to a Divided Cross Section**

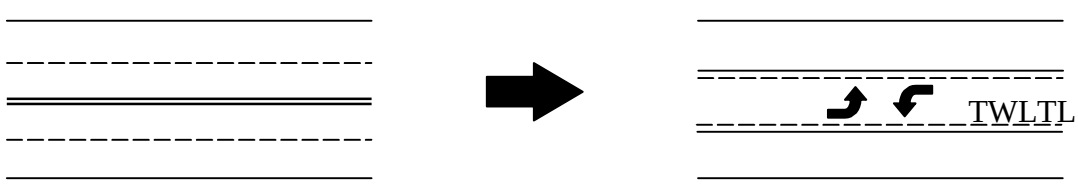


**Figure 2 Four-Lane Undivided Roadway Conversion to a Three-Lane Cross Section**

**Project Purpose and Scope**

The purpose of this project was to investigate the impacts and factors related to the feasibility of urban four-lane undivided to three-lane cross section conversions. Past research and case study experiences (in Iowa and the United States) are documented, and factors related to the feasibility of converting a four-lane undivided roadway to a three-lane cross section (see Figure 2) are also identified and discussed. Some of the guidelines provided for these factors are qualitative in nature, but others are more quantitative. For example, a sensitivity analysis of simulated traffic flow along a case study roadway was completed to evaluate and document the expected operational impacts (i.e., speed and level of service [LOS]) of an urban four-lane to three-lane conversion. The results from this sensitivity analysis are included in this report.

The focus of this report is limited to the discussion of one possible mitigation measure (i.e., a three-lane cross section) for urban four-lane undivided roadways being considered for a cross section improvement. In other words, the operation and/or safety conditions along a particular urban four-lane undivided roadway have degraded enough that several different cross section improvements are being evaluated. This report provides guidelines to assist transportation professionals in their consideration of the four-lane undivided to three-lane conversion alternative. Factors that should be considered for conversion feasibility are identified and their characteristics discussed. If it is determined that this type of conversion is feasible for a particular location, a more detailed engineering alternative analysis would need to be completed.

**Objectives**

The primary objective of this research project was to develop a set of guidelines to assist in the selection of candidate roadways for urban four-lane undivided to three-lane cross section

conversions. The authors evaluated and assessed the physical, operational, and safety characteristics that appear to be compatible with the consideration and/or feasibility of this type of conversion. These characteristics were evaluated qualitatively, with simulation software, and through an interpretation of subjective and objective before-and-after study results from four-lane undivided to three-lane conversions throughout the United States and Iowa. Some of the roadway characteristics investigated include roadway function and environment, overall traffic volume and LOS, turning volumes and patterns, weaving/speed/queues, crash types and patterns, pedestrian and bicycle activity, right-of-way availability/cost/acquisition, and several other general characteristics (e.g., parallel parking).

**Report Organization**

There are several subjects discussed in this report. First, the results of past research and the safety and operational benefits of TWLTLs or raised medians are discussed. A suggested approach to the selection of cross section improvements is also presented. Then, the results from several case study conversions (within the United States and Iowa) are described, and the output of a traffic flow sensitivity analysis presented. Based on this information, a number of feasibility determination factors are identified and discussed. The authors believe that these factors should be investigated and evaluated before an urban four-lane undivided to three-lane cross section conversion can be considered a feasible improvement alternative. The feasibility determination factors discussed in this report include

- roadway function and environment
- overall traffic volume and LOS
- turning volumes and patterns
- frequent-stop and/or slow-moving vehicles
- weaving, speed, and queues
- crash types and patterns
- pedestrian and bicycle activity
- right-of-way availability, cost, and acquisition impacts
- general characteristics, including

- parallel roadways
- offset minor street intersections
- parallel parking
- corner radii
- at-grade railroad crossings

A discussion of these factors, their characteristics, and the qualitative and/or quantitative changes they may experience due to an urban four-lane undivided to three-lane conversion are documented. The last chapter of this report is a summary of the conclusions and recommendations from this research. The results from a Sioux Center resident survey, the simulation analyses, and a checklist of the feasibility determination factor are included in the appendices.

Unlike many past efforts, these guidelines do include a discussion of the simulation sensitivity analysis done as part of research to investigate the operational impacts of an urban four-lane undivided to three-lane conversion. Simulation software was applied to a case study corridor to determine the changes in average arterial travel speed and LOS (arterial and signalized intersection) for different combinations of total volume, access point left-turn volumes, and access density. The objectives of this simulation sensitivity analysis were to evaluate the impact of a four-lane undivided to three-lane conversion on roadway operation, and attempt to identify the combinations of total peak-hour volume, access point left-turn volume, and access point density that define the operational feasibility of this type of conversion. The results of these simulation sensitivity analyses are presented, evaluated, and described in this report.

## PAST RESEARCH

There has been little formal research into the traffic flow or safety impacts of urban four-lane undivided to three-lane cross section conversions. In fact, many of the recommendations related to this type of conversion have been qualitative in nature. For example, in *National Cooperative Highway Research Program (NCHRP) Report 282* Harwood suggests that "[i]n some situations, with high left-turn volumes and relatively low through volumes, restriping of a four-lane undivided (4U) facility as a [three-lane] facility may promote safety without sacrificing operational efficiency" (*1*). The opposite is true, however, with respect to the safety and operational impacts of adding a TWLTL or raised median to a previously undivided two- or four-lane roadway. Past research about all three subjects is discussed in the following paragraphs.

### Conversion of Four-Lane Undivided Roadways to a Three-Lane Cross Section

Two studies that evaluated the impacts of converting urban four-lane undivided roadways to a three-lane cross section were referenced by Harwood in *NCHRP Reports 282* and *330* (*1*, *2*). The results from one of these studies were published and are discussed in the following paragraph. The unpublished material, on the other hand, documented the analysis of a converted roadway in Billings, Montana. Its contents are discussed in the next chapter of this report with the other before-and-after case study results.

In the late 1970s, Nemeth completed a research study about TWLTLs and their implementation (3). As part of this study several before-and-after field studies of different cross section conversions were done. At one field study location a roadway within a commercial area with an average daily traffic (ADT) of approximately 16,000 vehicles per day (vpd) was converted from a four-lane undivided to a three-lane cross section. Nemeth concluded that the reduction in through lanes increased delay, but that the access function of the roadway was improved. Overall, the average speed in both directions decreased by approximately seven miles per hour (mph) while traffic increased by about seven percent (3). It was also observed that traffic congestion and queuing during the peak periods was significant enough that some drivers used the TWLTL as a passing lane (3). In addition, the conversion reduced brake applications by about 22 percent but appeared to increase weaving (3). The weaving issue, however, was the result of some nonuse or

misuse of the TWLTL, and some of this problem was eventually corrected by the proper removal of the old centerline (3). The use of TWLTLs was also still relatively new in the 1970s. It is expected that the issue of nonuse or misuse of these facilities is less of a problem now.

In the past, there has also been at least one suggestion about the ADT volumes that are most appropriate for a three-lane cross section (4). In their study of the operational and safety impacts of TWLTLs, Walton et al. referenced a set of guidelines that suggested a 5,000 to 12,000 ADT range was appropriate for three-lane roadways (4). However, this suggestion appears to be based on what was considered acceptable for new construction rather than for an urban four-lane undivided to three-lane conversion. The case study analyses and anecdotal information discussed in the next chapter of this report show that there have been successful conversions of urban four-lane undivided roadways to three-lane cross sections with daily traffic volumes much higher than the range suggested.

Recently, Hummer and Lewis of North Carolina State University also produced a report that compared the safety of two-lane undivided, three-lane, and four-lane undivided roadways (*5*). Their safety data indicated that three-lane roadways had lower crash rates than four-lane undivided roadways in the medium and high-density residential and commercial land use areas (*5*). In addition, unlike the two-lane and four-lane undivided roadways, the crash rates of the three-lane roadways did not seem to increase with development density.

In addition to a safety comparison, Hummer and Lewis also calculated the "operational capacity" (i.e., the traffic flow at which the roadway segment goes from LOS D to E) of two-lane undivided, three-lane, and four-lane undivided roadways (*5*). The roadway segment (i.e., between signals) levels of service reported by Hummer and Lewis were based on the traffic flow data collected, a through-vehicle delay model, and a slightly adjusted version of the commonly accepted approach to determining LOS (*5*).

The LOS for three-lane and four-lane undivided roadways were determined to be about the same until an ADT of 15,000 to 20,000 vpd (based on 10 percent of this ADT occurring during the peak hour) (*5*). The difference in roadway segment LOS, however, became especially obvious at

20,000 vpd as driveway density increased (*5*). Based on through-vehicle delay, a roadway segment LOS E (and using the researchers approach) occurred for three-lane roadways when volume and driveway densities were very high (i.e., 20,000 vpd and 30 or 40 access points per mile per side), but the four-lane undivided roadways considered were never predicted to experience lower than a LOS C for the inputs considered (*5*). The researchers concluded, however, that LOS E (i.e., the operational capacity) along a three-lane roadway would be reached at a lower ADT of 12,000 vpd due to platooning (i.e., a level, 100 percent no-passing, two-lane rural roadway with a volume to capacity ratio of 0.57) rather than through-vehicle delay. Based on this definition of platooning, the operational capacity of four-lane undivided roadway segments was determined to be about 27,000 vpd.

The research documented in this report focused on the use of three-lane roadways in urban areas that may not have mobility as their primary function. The acceptable volume to capacity ratio (i.e., the platooning operational capacity) for this type of roadway may be much higher than 0.57 assumed in Hummer and Lewis's research.

**Safety Benefits of TWLTLs and Raised Medians**

Most of the research related to the selection of a roadway cross section or left-turn treatment (e.g., raised median or TWLTL) has focused on the impacts of their addition to an existing cross section. Several investigators have summarized the research done on this subject, and/or modeled the expected safety benefits of TWLTLs and raised medians (1, 2, 6, 7).

In the mid-1980s Harwood investigated the safety impacts of several cross section improvements to suburban highways (1). He found that the addition of a TWLTL to a two-lane undivided roadway could be expected to decrease overall crash rates by 11 to 35 percent (1). On average, he also found that crash rates decreased 19 to 35 percent when a TWLTL was added to a suburban four-lane undivided roadway. For urban four-lane undivided streets, however, the addition of a TWLTL (even when the roadway lanes were narrowed) reduced total crashes by approximately 44 percent, but the data varied substantially (2). The conversion of an urban two-lane undivided cross section to four lanes, on the other hand, typically produced a substantial increase in total crashes (2). Overall, angle, sideswipe, rear-end, and head-on crash rates are also typically

reduced the most by the addition of a TWLTL. The results of the previously described Hummer and Lewis research confirm the safety benefits of a TWLTL (5).

Two reports recently released by the NCHRP also address the safety benefits of TWLTLs and raised medians (6, 7). In *NCHRP Report 395,* Bonneson and McCoy model annual crash frequency for undivided roadways and also those with a raised-curb median or TWLTL (6). They found a significant correlation between annual crash frequency and ADT, driveway density, the density of unsignalized public street approaches, left-turn treatment or median type, and adjacent land use (6). It can be expected that crashes will be more frequent along roadways with higher daily traffic demands, higher driveway and public street densities, and adjacent business and office land uses (versus residential and industrial land uses) (6). In business and office areas, the model predicts that undivided roadways with parallel parking will have more crashes than cross sections with a TWLTL or raised median. When the parking is removed, however, the crash rate difference between undivided roadways and roadways with a TWLTL is relatively small (6). This similarity in crash rates was also found for residential and industrial areas, but only for an ADT less than 25,000 vpd (6). Above 25,000 vpd, undivided roadways (with or without parking) were predicted to have more crashes (6). In most cases, the model predicts the fewest crashes along roadways with a raised median (6).

*NCHRP Report 395*, along with *NCHRP Report 420,* also summarized the results of past crash prediction models (6, 7). Most of these models produce similar results. For example, roadways with an undivided cross section are expected to have the highest crash rates (6, 7). In addition, roadways with TWLTLs are predicted to have a lower crash rate than undivided roadways, and a higher rate than those roadways with a raised median (7). Harwood's model is an exception. It predicts the lowest crash rates on roadways with a TWLTL rather than roadways with a raised median (1, 7). A summary of the results produced by past crash models (with the exception of Harwood's) are shown in Table 1 (6, 7). Some of the crash reductions shown in the table are quite large.

**Table 1 Average Annual Crashes per Mile Predicted by Various Models (*6*, *7*)**

| Average Daily Traffic | Undivided Cross Section | Cross Section with TWLTL | Cross Section with Raised Median |
|---|---|---|---|
| 10,000 | 48 | 39 | 32 |
| 20,000 | 126 | 60 | 55 |
| 30,000 | 190 | 92 | 78 |
| 40,000 | 253 | 112 | 85 |

**Operational Benefits of TWLTLs and Raised Medians**

Many of the studies previously described have also modeled and/or summarized the operational benefits of TWLTLs and raised medians. For example, Harwood concluded that a reduction in through vehicle delay results from the addition of a TWLTL to a previously undivided roadway (1). Harwood found that the through vehicle delay reduction was primarily due to the removal of left-turn vehicles from the through lanes of the roadway (1). More specifically, it was shown that the delay reduction per left-turn vehicle increased as total hourly volumes increased but decreased as the number of driveways per mile decreased (1). The recent research by Hummer and Lewis into the operational capacity of roadways with TWLTLs generally supports these conclusions, and previous work by Harwood and St. John also found that the left-turn vehicle delay reduction effectiveness of TWLTLs was correlated to left-turn volume, through volume, opposing volume, and percent platooned traffic in the opposing direction (5, 8). Opposing volume, however, had the strongest relationship with delay reduction per left-turn vehicle (8).

NCHRP Reports 395 and 420 have also quantified or discussed the operational impacts of a raised median or TWLTL (6, 7). In NCHRP Report 395, Bonneson and McCoy studied and modeled the through and left-turn vehicle delay expected for undivided and divided (i.e., TWLTL and raised-curb median) roadways (6). One model describes average through delay per roadway approach as a function of left-turn and right-turn volumes per access point, total volume in subject direction, opposing through-lane flow rate, number of through lanes, and type of median treatment (e.g., undivided, TWLTL, or raised-curb) (6). Average total left-turn delay per approach, on the other hand, was related to opposing volume, average left-turn volume per access point, and number of through lanes (6). The models produced by Bonneson and McCoy have

been described as ". . . a sound basis for assessing the through and left-turn approach delays associated with various median alternatives" (7). In fact, Hummer and Lewis used a combination of North Carolina data and a Bonneson model to estimate vehicle delay (5).

Tables were provided in NCHRP Report 395 that indicated the through, major street left-turn, and annual delays for different left-turn treatments (6). Table 2 is part of the annual delay tables for the different left-turn treatments (6, 7). These tables were also summarized in NCHRP Report 420 (6, 7). As expected, delays generally increase with higher ADT, percent major-street left turns, and access point density. Delays are also typically larger for undivided roadways versus those with a TWLTL or raised median.

NCHRP Report 420 also summarized the simulation and regression models developed (since 1982) for the operational analysis of median alternatives (7). In general, these models produce results similar to the Bonneson and McCoy models. For example, lower delays are expected on roadways with TWLTLs or nontraversable medians versus undivided roadways (7). In high-volume situations, however, roadways with TWLTLs are typically expected to have lower delays than roadways with raised medians (7). This appears to be the result of modeled left-turn lane blockages, and the additional travel that may be necessary for traffic that would like to turn left at locations no longer provided a median opening (7). Usually, the modeled differences in delay along high-volume roadways with TWLTLs and raised medians are not significant (7).

**Table 2 Annual Delay to Major-Street Left-Turn and Through Vehicles (*6, 7*)***

| Access Points/Mile | Undivided Cross Section | | Cross Section with TWLTL | | Cross Section with Raised Median | |
|---|---|---|---|---|---|---|
| | 10 Percent Left Turns | 15 Percent Left Turns | 10 Percent Left Turns | 15 Percent Left Turns | 10 Percent Left Turns | 15 Percent Left Turns |
| **Average Daily Traffic = 22,500** | | | | | | |
| 30 | 2,200 | 2,900 | 1,300 | 1,700 | 1,300 | 1,700 |
| 60 | 2,200 | 3,000 | 1,400 | 1,800 | 1,400 | 1,800 |
| 90 | 2,200 | 3,000 | 1,400 | 1,800 | 1,400 | 1,800 |
| **Average Daily Traffic = 32,500** | | | | | | |
| 30 | 7,100 | 9,100 | 3,000 | 4,000 | 3,100 | 4,000 |
| 60 | 7,800 | 10,200 | 3,200 | 4,200 | 3,500 | 4,800 |
| 90 | 8,000 | 10,800 | 3,200 | 4,200 | 3,400 | 4,700 |

*Delay is in seconds per vehicle per approach, and percent left-turns is for one direction of travel and a 1,320-foot roadway segment. Table is for four through lanes (both directions).

**Cross Section Selection Guidelines**

All of the information discussed in the previous paragraphs is only useful if transportation professionals evaluating cross section design alternatives take it into account. In 1990, Harwood suggested the following eight-step process for the selection of cross section design alternatives (for an existing curb-to-curb width) on urban arterial roadways (*2*):

Step 1. Determine existing conditions
Step 2. Determine projected future conditions
Step 3. Identify constraints
Step 4. Identify feasible design alternatives
Step 5. Eliminate alternatives that do not address existing problems
Step 6. Examine possible geometric variations
Step 7. Determine benefits and disbenefits
Step 8. Select the preferred improvement strategy

This document discusses the factors that determine whether or not a three-lane cross section could be a feasible design alternative to improve the operations and/or safety of an existing urban four-lane undivided roadway (i.e., steps 4 and 5 above). These discussions should also help transportation professionals determine how some of these factors might change with the subject conversion (i.e., step 7 above).

The selection of an appropriate cross section design alternative is complex process, especially in urban areas. In *NCHRP Report 282* and *NCHRP Report 330*, Harwood discussed the many advantages and disadvantages of different urban and suburban roadway cross sections (*1*, *2*). In addition, Bonneson and McCoy have created tables to help transportation professionals with the proper selection of appropriate left-turn treatments (i.e., undivided, TWLTL, or a raised median). These tables are based on a benefit-cost analysis, and they suggest different left-turn treatments (i.e., conversions) for different combinations of total through lanes, ADT, access point density, land use (i.e., commercial and business or industrial and residential), and percent left-turns per 1,320 foot roadway segment (*6*). The results from *NCHRP Report 395* and other past research reports are summarized in *NCHRP Report 420* and recreated in Table 3 (*6*, *7*). Based on the findings and opinions expressed in the source research documents, the table identifies the "preferred" left-turn treatment for specific conversion alternatives and factors (*6*, *7*).

**Table 3 Comparison of Left-Turn Treatment Types (*Adapted from 6, 7*)**

| Comparison Factor | "Preferred" Midblock Left-Turn Treatment* | | |
|---|---|---|---|
| | **Raised Median vs. TWLTL** | **Raised Median vs. Undivided** | **TWLTL vs. Undivided** |
| **Operational Effects** | | | |
| Major –Street Through Movement Delay | n.d. | Raised Median | TWLTL |
| Major-Street Left-Turn Movement Delay | n.d. | Raised Median | TWLTL |
| Minor-Street Left & Through Delay (Two Stage Entry) | n.d. | Raised Median | TWLTL |
| Pedestrian Refuge Area | Raised Median | Raised Median | n.d. |
| Operational Flexibility | TWLTL | Undivided | n.d. |
| **Safety Effects** | | | |
| Vehicle Crash Frequency | Raised Median | Raised Median | TWLTL |
| Pedestrian Crash Frequency | Raised Median | Raised Median | n.d. |
| Turning Driver Misuse/Misunderstanding of Markings | Raised Median | Raised Median | Undivided |
| Design Variations Can Minimize Conflicts (e.g., islands) | Raised Median | Raised Median | TWLTL |
| Positive Guidance (communication to motorist) | Raised Median | Raised Median | n.d. |
| **Access Effects** | | | |
| Cost of Access (access management tool) | Raised Median | Raised Median | n.d. |
| Direct Access to all properties along the arterial | TWLTL | Undivided | n.d. |
| **Other Effects** | | | |
| Cost of Maintaining Delineation | n.d. | Undivided | Undivided |
| Median Reconstruction Cost | TWLTL | Undivided | Undivided |
| Facilitate Snow Removal (i.e., impediment to plowing) | TWLTL | Undivided | n.d. |
| Visibility of Delineation | Raised Median | Raised Median | n.d. |
| Aesthetic Potential | Raised Median | Raised Median | n.d. |
| Location for Signs and Signal Poles | Raised Median | Raised Median | n.d. |

*The "preferred" left-turn treatment is based on the findings of the source research and the more commonly found opinions from a review of the literature by the authors of the source research. n.d. = negligible difference or lack of consensus found in the literature on this factor.

## Summary of Findings

In general, past research has typically focused on the operational and safety benefits of different cross sections, or the construction of TWLTLs or raised medians along previously undivided roadways. Although there has been some recent research about the conversion of urban four-lane undivided roadways to a three lanes, the subject of these guidelines is usually only considered indirectly. Fortunately, the research results, information, and selection guidelines/tools discussed in the previous paragraphs and documented in past studies were still very helpful with the identification of the feasibility determination factors described later in this report. For example, it was concluded that crash type and patterns are important factors to consider for conversion feasibility because the expected crash reduction benefits of a TWLTL should occur whether there are one, two, or three lanes of traffic in each direction. Additional information was also gathered

from several case study conversion locations. The results of these case study conversions are discussed in the next chapter of this report.

## CASE STUDY RESULTS

Many jurisdictions have converted urban four-lane undivided roadways to a three-lane cross section. The following paragraphs describe and document the qualitative and quantitative impacts of conversions both outside and within Iowa. Vehicle speeds and crash rates before and after the conversions are reported if available, and the anecdotal reactions to a conversion at several locations are documented. The case study locations outside of Iowa are discussed first and were identified through an extensive literature review and personal contacts. The same information for conversion locations within Iowa is then presented. In particular, the impacts and reaction to the recent four-lane to three-lane conversion in Sioux Center, Iowa, are extensively documented.

### Case Studies Outside Iowa

*Montana Case Studies*

An unpublished before-and-after study report from Billings, Montana, was referenced in several previous studies (1, 2, 9). In 1979, the City of Billings, Montana, restriped 17th Street West from a four-lane undivided roadway to a three-lane cross section. The roadway was 40 feet wide and had a 35 mph posted speed limit and an ADT of 9,200 to 10,000 vpd (9). A study of the conversion impacts indicated that there was no noticeable increase in delay after the roadway was converted, but that there was a decrease in vehicle crashes (9). There were 37 reported crashes in the 20 months before the conversion, and 14 for the same time period after the conversion. The city traffic engineer of Billings, Montana, has concluded that the conversion significantly decreased crashes with no notable increase in delay (9, 10).

The city of Helena, Montana, has also converted one of its urban roadways (i.e., U.S. 12). U.S. 12 is 48 feet wide and has a posted speed limit of 35 mph. The roadway is located in a commercial area and has numerous access points and an ADT of 18,000 vpd (10). The conversion of this roadway to a three-lane cross section was suggested by the Montana Department of Transportation for increased safety. It did not have a high overall crash rate, but the crashes that did occur were primarily of the rear-end and sideswipe type. When the

conversion was initially proposed there was apprehension initially, but the change resulted in better operations and safety along the roadway. This fact alleviated most of the concerns previously expressed by city and some state officials. There also appears to be support for the conversion from the general public. The state traffic engineer for Montana indicated that the number of crashes has decreased along the roadway segment, traffic flow has been maintained, and that the public prefers the new three-lane cross section (10).

*Minnesota Case Studies*

Like the case studies in Montana, there has been a similar change in community acceptance and understanding for a four-lane undivided to three-lane conversion in Duluth, Minnesota. Many people, and the local newspaper in Duluth, were initially opposed to the conversion of 21st Avenue East from a four-lane undivided roadway to a three-lane cross section. The roadway had an ADT of 17,000 vpd, and they felt traffic flow or mobility would suffer. This attitude changed, however, when the conversion was completed and the newspaper reported what appeared to be a reduction in congestion and vehicle speed and a subsequent improvement in safety (*10*).

The safety impacts of converting a roadway from a four-lane undivided cross section to three lanes have also been investigated in Ramsey County, Minnesota (*11*). In 1992, Rice Street (T.H. 49) was milled, overlayed, and restriped as a three-lane cross section from Hoyt Avenue to Demont Avenue.

Three years of before-and-after crash data from Rice Street have been analyzed, and the following results were found. During the three years before the conversion the ADT on Rice Street was 18,700 vpd, and 162 crashes were reported (excluding those at the signalized intersections). During the three years after the construction the ADT on Rice Street decreased to 16,400 vpd, and there were 117 crashes reported (excluding those at the signalized intersections) (*11*). In other words, average daily volumes decreased by approximately 12 percent while the number of reported crashes decreased by approximately 28 percent. These changes equal a decrease of about 18 percent in the crash rate for the Rice Street roadway segments. Some of this decrease (possibly the majority) can be attributed to the conversion of the cross section.

*California Case Studies*

In the last two years, four four-lane undivided roadways in Oakland, California, have been converted to three-lane cross sections (*12*). A preliminary before-and-after comparison of vehicle speeds and crashes has been done by the city for one of the roadways, High Street, which had an ADT between 22,000 and 24,000 vpd (*12*). The other converted roadways had an ADT of 6,000 vpd or 12,000 vpd.

The speeds of 100 vehicles on High Street were measured with a radar gun before-and-after the cross section was restriped. An analysis of this data did not show any significant change in vehicle speed (*12*). However, it has been concluded that this may have been due to the methodology used to collect the data (i.e., radar gun), the sample size, and/or the ability of a data collector to get more than one or two vehicles per platoon (*12*). The residential community adjacent to High Street believes that the cross section conversion has reduced speeds and unsafe lane-change maneuvers (*12*). In addition, city transportation staff believes that the traffic has been "calmed" (*12*).

A preliminary analysis of the crashes along High Street has also been completed, and results are encouraging. There was an annual average of 81.5 reported crashes in the four years before the 1997 remarking of High Street, but in the year after the conversion there have been only 68 crashes reported (*12*). This is a 17 percent reduction in total crashes and may be partially attributable to the change in cross section. This conclusion would be consistent with the impacts experienced at the other previously discussed case study locations. However, additional analysis of a longer time period of crashes is needed.

The City of San Leandro, California, has also converted two four-lane undivided roadways to three-lane cross sections (*13*). The operation and safety of one roadway, East 14th Street, have been studied (*13*). First, it was found that spot speeds along this roadway decreased a maximum of three to four mph after the conversion. Daily volumes, on the other hand, ranged from approximately 16,000 to 19,300 vpd before the conversion to approximately 14,000 to 19,300 vpd after the conversion (*13*). Two years of before-and-after crash data also indicated that the total number of crashes along the roadway decreased by 52 percent, and that sideswipe and rear-

end crashes decreased by over 60 percent (*13*). In addition, pedestrians said they felt safer. City staff believes that this feeling is a significant benefit because the roadway passes through a downtown area and is adjacent to several schools (*13*). Expected and perceived increases in delay at the unsignalized intersections along East 14th Street were a concern, but at the same time it was recognized that crossing or turning maneuvers had become less complex (*13*). The high volumes along the roadway did require the city to widen East 14th Street to two lanes in each direction at one intersection, and this capacity-related widening maintained the intersection LOS, but also produced some safety and operational concerns related to the lane transition areas (*13*).

*Washington Case Studies*

In their paper, Burden and Lagerwey documented the before-and-after ADT and collision rates of nine four-lane undivided to three-lane cross section conversions in the Seattle, Washington, area (*14*). The ADT along these roadways was between 9,700 and 19,400 vpd before their conversion and 9,800 and 20,300 vpd after their conversion. The total collision rate reduction observed at these nine locations (one-year before and after the conversions) ranged from no change to 61 percent. Overall, the average total collision rate reduction for the nine locations was approximately 34 percent. In addition, Huang et al. have completed a more statistically intense safety evaluation of a portion of these locations, along with several sites in California, and found a decrease in monthly crashes and crash severity, but no change in crash type (*15*). In their paper Burden and Lagerwey also documented the before and after ADT for conversions in California, Washington, Pennsylvania, Michigan, and Canada (*14*). The ADT on these roadways was between 11,000 and 23,000 vpd before their conversion and 11,000 and 25,900 vpd after their conversion.

**Case Studies Within Iowa**

Several jurisdictions in Iowa have also converted urban four-lane undivided roadways to a three-lane TWLTL cross section. Some of these cities include Storm Lake, Muscatine, Osceola, Sioux Center, Blue Grass, and Des Moines. Other jurisdictions, usually due to safety concerns, have also begun to consider the feasibility of converting some of their four-lane undivided roadways to a three-lane TWLTL cross section. It is expected that these guidelines will assist these jurisdictions and the Iowa Department of Transportation (Iowa DOT) in this feasibility

determination. The following paragraphs discuss the anecdotal comments about several Iowa case study four-lane to three-lane conversions, the characteristics of the roadways converted, and the available quantitative operational and safety impacts of these conversions.

*Storm Lake, Muscatine, and Osceola Case Studies*

The three cities above have had positive experiences with the conversion of four-lane undivided roadways to a three-lane cross section. In 1993, the city of Storm Lake, Iowa, converted a portion of Flindt Drive. This roadway was 40 feet wide and had an ADT of 8,500 vpd. No formal before-and-after analysis has been done, but there has generally been a positive public response to the conversion, and city officials are also pleased with the traffic flow and increased safety of the roadway (10). Clyde Bartel, the Iowa DOT Resident Engineer indicates that there has been a ". . . very positive community reaction . . ." to the conversion in Storm Lake. There were 162 crashes on this converted section of Flindt Drive during the three years before the cross section change and 80 crashes during the three years following the conversion. This change represents a 51 percent reduction in crashes.

The Cities of Muscatine and Osceola have had similar experiences with the conversion of Clay Street (ADT of 8,400 vpd) and U.S. 34 (ADT of 11,000 vpd), respectively. Muscatine City Engineer, Ray Childs, has reported a large reduction in crashes due to the Clay Street conversion, and the reaction to the U.S. 34 conversion in Osceola has changed from skepticism to general support (*10*). In addition, the capacity of U.S. 34 does not appear to be impacted and there is a general sense that the roadway has become safer. Overall, both conversions are considered a success.

*Sioux Center Case Study*

In July 1999, the Iowa DOT and Sioux Center converted a portion of U.S. 75, a four-lane undivided roadway, to a three-lane cross section. The conversion was completed for a segment of U.S. 75 within the commercial business district, and the roadway continued to a four-lane undivided cross section at each end of the conversion. This is somewhat unique for a four-lane undivided to three-lane cross section conversion. In many cases, for expectancy, functional, safety, and operational purposes, a four-lane undivided to three-lane conversion is completed for

an entire corridor, and three-lane to four-lane (or visa versa) transitions are limited. In addition, the parallel parking along the corridor was continued after the conversion. Maneuvers in and out of these spaces, with a three-lane cross section (i.e., only one lane in each direction), have a greater potential to produce more through vehicle delay, and the parking space design took this fact into account.

The Sioux Center conversion was studied rather extensively as part of this project. First, a LOS analysis of the corridor with each cross section was done before the conversion. Then, before and after vehicle delay, vehicle speed, and overall crash frequencies were collected, and an opinion survey of Sioux Center citizens completed. The results of these activities are presented in the following paragraphs, and the comments from Sioux Center citizens and public officials summarized.

**Expected LOS and Delay.** Prior to the conversion, the Iowa DOT used *Highway Capacity Manual* procedures to compare the possible operational impacts of two alternative cross section improvements along U.S. 75 in Sioux Center. An arterial LOS analysis was done for both three-lane and five-lane cross section designs (*10*). The ADT along this roadway was 14,500 vpd, and the arterial analysis for the corridor indicated that total delay would increase from 20.5 to 29.4 seconds when the roadway was converted from a four-lane undivided to a three-lane cross section. In addition, average speeds were expected to decrease from 16.0 to 14.3 mph, but the overall arterial level of service would remain at LOS C (*10*). As expected, the analysis showed that a conversion to a five-lane cross section would lower total delay from 20.5 to 15.8 seconds or increase average speed from 16.0 to 17.1 mph. Again, however, it was estimated that the overall arterial level of service would remain at LOS C (*10*). The city and the Iowa DOT compared the estimated operational impacts of a five-lane cross section to its expected physical impacts, and decided to implement a three-lane roadway.

**Measured Before and After Speeds and Delays.** Vehicle delay and speed measurements were collected before and after the conversion of U.S. 75 to a three-lane cross section. Not unexpectedly, it was found that travel times along U.S. 75 (from 4th Street North to 3rd Street

South) increased during the morning and evening peak travel periods from about 50 seconds to 68 seconds. This corresponds to a reduction in overall average travel speeds (including signal delays) for the entire segment from 28 or 29 mph to 21 mph. The average free-flow speed (collected between 1st Street and 2nd Street South), or the average speed chosen by drivers unrestricted by congestion, was reduced from approximately 35 mph to about 32 mph. A large portion of the decrease in overall average travel speed appears to be from increased stop delay at signals and due to vehicles turning right or parking. The percentage of vehicles traveling more than five mph over the posted speed limit (i.e., 35 mph) also decreased from about 43 percent to 13 percent. This is about a 70 percent decrease in the number of drivers observed that were speeding excessively.

Overall, the stop delay at the signalized intersection along U.S. 75 appears to have increased, and noon peak travel period delays appear to be longer than those measured during either the morning or evening. Side street delays were measured before and after the conversion, but they were highly variable with respect to the vehicle maneuver (e.g., right- or left-turn), intersection location and/or design, and time of day.

**Measured Before and After Crashes.** A preliminary analysis of the crash data along U.S. 75 was also done. During the one year prior to the conversion there were 20 property damage and 10 personal injury crashes within the converted roadway segment. However, during the one year following the conversion there were only 13 total crashes. This is a total crash reduction of about 57 percent for a period of one year. The analysis of safety data from a longer period of time before and after the conversion is still required, but the conversion of U.S. 75 appears to have improved its safety. These results also coincide with those of other case studies.

**Opinion Survey Results.** An opinion survey about the U.S. 75 conversion was also distributed to the citizens of Sioux Center. Respondents were asked their opinion about several subjects, whether they supported the conversion before and after it occurred, and whether they believed that the conversion was in the best interest of the majority of Sioux Center residents. The subjects and questions in the survey are listed below.

- Traffic safety along U.S. 75 has been improved
- Traffic calming along U.S. 75 has occurred (less speeding vehicles, less aggressive driving)
- Pedestrian crossings are safer
- I experience more delay entering or exiting the side streets
- Did you support the 4 to 3 lane conversion when it was first proposed?
- Do you support the 4 to 3 lane conversion now?
- Was the conversion in the best interest of a majority of the residents of Sioux Center?

Nearly 2,000 surveys were distributed, and over 930 responses were received. This is about a 47 percent response rate. Included with these responses were over 500 written comments, and some of these are included in the next section of this report. The responses to the subjects or questions listed above are discussed and summarized in the following paragraphs. Graphical summaries of the results are shown in Appendix A.

In general, the survey results indicate that most respondents believed that the conversion had achieved its intended goal of reducing speeds and increasing pedestrian safety. About 60 percent of the respondents agreed or strongly agreed that traffic safety has improved along U.S. 75, and about 66 percent had a similar feeling that the conversion resulted in fewer speeding vehicles and less aggressive driving. The before-and-after speed and crash data quantitatively support these conclusions (see the previous sections of this discussion). Fifty percent of the respondents believed that the pedestrian crossings of U.S. 75 were safer after the conversion, but about 32 percent did not agree with this conclusion. These responses are summarized in the figures presented in Appendix A.

The survey results also showed that many respondents believed they were experiencing more delay. Unfortunately, but not unexpectedly, about 86 percent of the respondents reported that they sometimes to always experience more delay entering/exiting the side streets than theydid before the conversion. These results represent the tradeoff that is often, but not always, required

after the conversion of a four-lane undivided roadway to a three-lane cross section. The decision to convert a four-lane undivided roadway to a three-lane cross section is expected to decrease crashes, but often requires the acceptance of a decrease (sometimes insignificant) in LOS during peak hours along the roadway. The Iowa DOT and the City of Sioux Center will implement several minor signalization and geometric improvements that are expected to decrease the delays currently being experienced.

In general, the survey results also showed a change in public opinion once the conversion was implemented. Some of the survey respondents reported they were either neutral or in opposition to the decision to implement the conversion but are now supporters. The survey results indicated that about 18 percent supported the conversion when it was proposed, 37 percent were neutral, and 45 percent did not support the conversion. These percentages changed to 45, 15, and 40 percent after the conversion was complete (see Appendix A). A number of people that were neutral about the conversion now appear to support it. About five percent of the respondents shifted from complete disagreement to support of the conversion. Overall, about 44 percent of the respondents believed that the conversion was in the best interest of the majority of Sioux Center residents, about 21 percent were neutral, and about 35 percent did not believe it was in the best interest of the majority of Sioux Center residents. The results appear to indicate that some respondents still did not support the conversion, but they are neutral with respect to whether it was in the best interest of the majority of the Sioux Center residents. In April 2000 the Sioux Center City Council reviewed the results of this survey and the operational impact data discussed, and decided to retain and extend the three-lane cross section along U.S. 75.

**General Comments.** There have been many comments, both positive and negative, from the survey respondents and Sioux Center City officials about the four-lane to three-lane conversion of U.S. 75. Both types of comments are included in the following list:

- Harold Schiebout (Sioux Center City/Utilities Manager): Mr. Schiebout thanked the Iowa DOT for helping Sioux Center "…improve pedestrian and vehicular safety on Highway 75, while at the same time trying to maximize traffic movements."

- Paul Adkins (Sioux Center Police Chief ): Chief Adkins was quoted by the Sioux Center News in an article entitled “Police Pleased with Three-Lane Traffic” (September 15, 1999). Chief Adkins indicated that the conversion “. . . had a calming effect on the traffic and that was the goal when the city council agreed to make the change.” He believed that people were “. . . driving slower and that reduces crashes.”

- In the same September 15, 1999 Sioux Center News article (see previous comment), Chief Adkins did acknowledge that vehicle queues on the roadway had been a concern, “[e]specially when there are a number of trucks that need to get going after coming to a complete stop.” In addition, turning left at the signalized intersections has been an issue because there are no left-turn arrow phases. Chief Adkins also indicated that there may be more local drivers using the parallel streets in the downtown area to bypass some of the delays experienced on U.S. 75. Fortunately, with respect to emergency vehicles, Chief Adkins said that on the three-lane U.S. 75 “[t]here seems to be enough room for drivers to pull off to the side and still allow the emergency vehicles through.”

- Overall, Chief Adkins is “. . . convinced that for pedestrians, Highway 75 is safer than it was . . .”, and that pedestrians “. . . see traffic better on the three-lane plan and drivers see pedestrians better.” He believes that it has “. . . been a positive experience. It’s not perfect, but we are happy with the initial results.” Chief Adkins admits to initially being opposed to the conversion, but now he calls himself one of its biggest advocates. He has volunteered to talk to any city that might be considering a conversion of this type.

- Murray Hulstein (Assistant City/Utilities Manager): Mr. Hulstein believes that the public reaction was initially very negative, but that since the conversion was implemented the feedback has been mostly positive, rather than negative. The Mayor of Sioux Center agreed with this assessment. The increase in vehicle delay during peak travel periods at the signals on U.S. 75 during peak hours appears to be the most significant concern, but the most significant benefit has been the reduction in speed.

- Representative Negative Survey Responses:
  - The change has not improved anything! If anything, it has made people be more aggressive.
  - Traffic backs up pretty bad at all stoplights, can be several blocks backed up!
  - During certain times of the day you have to wait for two green lights to get through the downtown stoplight.
  - It is the semi-truck trailers that cause congestion at the traffic lights during the busiest times.
  - Highway 75 is so busy that no matter when I try to get off the side streets I always have to wait.
  - I often take 4th Avenue (a parallel local street) across town during busy times. I see others doing so also, so you might just be moving the problem to a new area.
  - I have witnessed dangerous, almost wild-eyed urgency to gain first position in the areas leading into the three-lane portions.
  - I feel with the town growing that you have not found a good solution by going four lanes to three.

- Representative Positive Survey Responses:
  - I can now stop for a pedestrian without putting them in danger of getting hit by a vehicle in another lane.
  - Even though I don't like the change it was the best alternative and I'm willing to live with it.
  - I am pleased with the results of the three-lane conversion project. I definitely feel the three-lane option was a much better option than the five-lane option.
  - Very comfortable and pleased with the three lanes. Safer, too, for elderly drivers like me.
  - So what if it does take us a bit longer to enter and exit, it definitely is safer. That's what counts.
  - We feel safer now on the main street. Thanks.
  - I was definitely against it when first proposed, but I am 100 percent for it now.
  - Safety—Yes. Convenience—No.

The preceding paragraphs represent a summary of the comments from the opinion survey, numerous public meeting discussions, and the local newspaper. A four-lane to three-lane conversion is a new idea and can only be successful or feasible if there is support in the community to experiment with it. In addition, the expected safety and traffic flow characteristics of the converted roadway must be compatible with the goals of the community. The roadway characteristics that need to be considered and evaluated to determine the feasibility of a four-lane to three-lane conversion are discussed later in these guidelines.

*Blue Grass Case Study*

In August 1999 the Iowa DOT and the City of Blue Grass converted a segment of U.S. 61 (ADT of 9,900 vpd) from a four-lane undivided roadway to a three-lane roadway. Since the conversion, Mayor Barns of Blue Grass has indicated that he has heard ". . . very few complaints about the four to three lane conversion . . . ," especially once the traffic signal timing was adjusted. He believes that the change was the correct decision and that speed has ". . . decreased substantially." Before and after speed data show a reduction in the 85th percentile speed of westbound vehicles on U.S. 61 (the primary direction of concern with respect to the conversion) between one and four miles per hour. The 85th percentile vehicle speeds along eastbound U.S. 61, on the other hand, unpredictably ranged from a decrease of one mph to an increase of two miles per hour.

The Police Department in Blue Grass (i.e., Sgt. John Jensen) acknowledged that they are still writing speeding tickets, but that the safety of the roadway appears to have improved. An analysis of the vehicle speed data at two locations in July (one month before the conversion), September (one month after the conversion), and December 1999 (four months after the conversion) indicate that the number of vehicles traveling five miles per hour faster than the speed limit initially decreased but may have rebounded. In the 45 mph posted speed limit area, the percentage of westbound (the primary direction of concern with respect to the conversion) vehicles traveling over 50 miles per hour went from 9.4 percent in July to 3.0 percent in September (a reduction of 68 percent). In December, however, the percentage over 50 miles per hour rebounded to 12.6 percent. The number of speeders in the eastbound direction stayed nearly the same (e.g., 1.8 percent in July to 1.3 percent in December). The percentage of westbound

vehicles traveling more than 40 miles per hour in the 35 mph posted speed limit area followed a similar pattern. Westbound vehicles traveling faster than 40 miles per hour represented 1.7 percent of the traffic flow in July, 0 percent in September, and 1.9 percent in December. The number of vehicles traveling east at more than 40 miles per hour, on the other hand, was reduced from 2.1 percent in July to 0.8 percent in September and 0.7 percent in December. This decrease represents a reduction in eastbound vehicles traveling over 40 miles per hour along the 35 mph posted speed limit segment of about 64 percent.

*Des Moines Case Study*

Des Moines also recently converted a portion of Beaver Avenue to a three-lane cross section, but the segment converted originally operated as several different cross sections. Some of the roadway segment converted was striped as a four-lane undivided roadway, other segments were striped with and used as a two-lane undivided cross section, and still other segments had 40 feet or more of paved surface and were marked for two lanes but used as four lanes. Unlike the other case studies, therefore, this conversion was not a “pure” four-lane undivided to three-lane roadway cross section change.

The combination of cross sections discussed in the previous paragraph and the impacts of some roadway construction that occurred on some of the Beaver Avenue cross streets appears to have produced some unusual before-and-after results. For example, it was found that the average travel speed on Beaver Avenue between Aurora Avenue and Sheridan Road actually increased from about 21 mph to about 25 mph during the peak travel periods. In addition, the average stop delay on this segment of roadway decreased for both directions of travel during the evening peak travel period, and for the northbound direction of travel during the morning peak travel period. It would appear that the initial mixture of cross sections might have produced confusion and transition conflicts, and these characteristics were removed when one three-lane cross section was installed along the entire roadway segment. The simplicity of the new cross section may have produced a smoother, although slightly faster, flow of traffic along this segment of Beaver Avenue. Overall, however, a local city councilman and Beaver Avenue merchant told the local Des Moines newspaper that they initially thought the city was crazy when they proposed the conversion, but now they both support the change.

**Summary of Findings**

Table 4 summarizes the case study analysis results and anecdotal conclusions discussed in the previous paragraphs. In general, the results of the case studies appear to support past research conclusions. The before-and-after crash results and/or LOS analysis indicate that the conversion of a four-lane undivided roadway to a three-lane cross section can improve the safety of a roadway without dramatically decreasing the LOS provided. Vehicle speeds along the roadway may/can decrease somewhat and total delay increase, but safety is usually improved (sometimes dramatically). To achieve these results, however, this type of conversion must be done at the appropriate locations. The following chapter describes the sensitivity analysis used to investigate the operational impacts of a four-lane undivided to three-lane conversion. These impacts are some of the roadway characteristics that must be considered to determine the feasibility of converting an undivided four-lane roadway to a three-lane cross section. All these factors are discussed later in this report.

**Table 4 Case Study Analysis Results (*9, 10, 11, 12, 13, 14, 15*)***

| 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<br>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<br>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<br>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.

## FOUR-LANE UNDIVIDED AND THREE-LANE ROADWAY TRAFFIC FLOW SIMULATION

The traffic flow impacts of four-lane to three-lane conversions were investigated as part this research to supplement the case study results documented in the last chapter. As previously discussed, the primary reason for most of the four-lane undivided to three-lane case study conversions was improved safety. The typical assumption, however, was that this increase in safety must be accompanied by a significant reduction in roadway mobility. This conclusion is supported, at least partially, by the case study results. The dramatic decrease in crashes that typically occurred, however, was usually only accompanied by a relatively small decrease in vehicle speed and/or increase in intersection delay. The case study conversions were also successful over a large range of traffic volumes (see Table 4).

Four-lane undivided to three-lane conversions are operationally feasible if the reduction or change in arterial LOS (i.e., the decrease in average arterial travel speed and/or increase in stop delay) that occurs with the conversion is locally acceptable. The objective of the sensitivity analysis discussed in this chapter was to determine the roadway characteristics that minimize the average arterial travel speed impacts of a four-lane undivided three-lane cross section conversion. It was concluded that this sensitivity analysis would be completed with a simulation software package, and that the average arterial travel speed and LOS would be calculated, determined, and compared for four-lane undivided and three-lane roadways with similar traffic flow and geometric characteristics.

Very little research has been done on the operational impacts of four-lane undivided to three-lane conversions. This lack of research is due to the somewhat unusual nature of the type of conversion being considered, and the general lack of TWLTL analysis and/or evaluation tools available. Recently, the interest in this type of conversion has increased, but the tools that focus on the operation of TWLTLs are still almost nonexistent. Recently proposed deterministic models (that account for some of the TWLTL weaknesses in currently available simulation packages) were also available, but were not used in this project (*5*, *6*). These models are described in the past research chapter of this document, and their application to four-lane

undivided to three-lane cross section conversion evaluation is a prime candidate for future research.

In general, this chapter describes the comparison of several simulation software packages and documents the process and results of the sensitivity analysis used to determine the roadway characteristics most compatible with four-lane to three-lane conversions. The advantages and disadvantages of each simulation software package are discussed, and one of the candidates chosen and used in the sensitivity analysis. The characteristics of the corridor evaluated in the sensitivity analysis are described, and the process used to apply the chosen simulation software package presented. Finally, the sensitivity analysis procedure, factors, and results are presented and discussed.

**Simulation Software Comparison**

Computer simulation is a powerful tool that allows the adjustment and subsequent analysis of an existing or proposed roadway corridor or system. For this project, it was concluded that a simulation approach would be used to evaluate the traffic flow impacts of converting an urban four-lane undivided roadway to a three-lane cross section. Simulation software packages quickly produce measures that represent general corridor operations and also provide a researcher with the capability to evaluate the expected performance of a particular roadway corridor with a wide range of characteristics (e.g., traffic volume, number of access points).

Very few simulation software packages have been specifically designed to model the operation of a TWLTL. The three packages reviewed and compared as part of this research included the Ohio State University arterial simulation (ARTSIM) software, the University of Nebraska TWLTL simulation (TWLTL-SIM) program, and the Federal Highway Administration corridor simulation (CORSIM) tool. Each of these software packages has been used to simulate the operation of a four-lane undivided roadway but had varying capabilities with respect to the accurate simulation and evaluation of TWLTL operation. Other simulation software packages exist and could be considered in future research in this area.

*ARTSIM*

ARTSIM was developed in 1983 at Ohio State University (*16*). This software package was specifically designed to analyze four-lane arterials with and without TWLTLs, and incorporated both free-flow and congested vehicle behavior models (*16*). Car-following routines based on stimulus-response equations are also used in ARTSIM. Unfortunately, this software cannot analyze three-lane roadways and does not appear to be available to the general public or researchers. No user manual (except Heikal's dissertation) or useable software has been developed (*16*).

*TWLTL-SIM*

TWLTL-SIM was also reviewed (*6*). This simulation package has a focus similar to ARTSIM. TWLTL-SIM was developed by Ballard and McCoy at the University of Nebraska and has five separate subprograms. Unlike ARTSIM, however, TWLTL-SIM can account for signalized intersection impacts and has the ability to evaluate various arterial configurations (i.e., different intersection spacing and access point densities). The output from TWLTL-SIM also includes average through vehicle travel time and average left-turn vehicle delay for each simulation. During its validation, the output of TWLTL-SIM was found to not be significantly different from the majority of the field site observations, and typically the results were within 10 percent of these observations (*6*).

There are some limitations to the TWLTL-SIM software. For example, if a queue of vehicles blocks the place a left-turn vehicle wants to enter the TWLTL, that vehicle will wait at the end of the queue until that particular location is no longer blocked. In reality, a vehicle turning left would typically enter the TWLTL upstream of any vehicle queue that may exist, and this would reduce the delay reported by TWLTL-SIM. A similar disadvantage relates to how lane-choice decisions are simulated. TWLTL-SIIM assumes that through vehicle drivers make lane-choice decisions based on the vehicles immediately around them. This can result in significant, but unrealistic, simulated delays if access points and/or intersections are closely spaced and traffic volumes are high enough that some lane changes require the vehicle to stop in the through lane. Realistically, drivers on roadways with high volumes and closely spaced access points and/or

intersections will make lane change decisions, and the actual lane change, upstream of where it needs to take place. Finally, TWLTL -SIM has not been updated for some time, and although the software is available, the documentation needed to adequately apply it does not exist in an adequate format.

*CORSIM*

The CORSIM software package was developed under the sponsorship of the Federal Highway Administration (*17*). It is one of the most commonly used and generally available traffic simulation tools in the United States and can be used to evaluate the traffic flow along a corridor or roadway network of freeways and surface streets. CORSIM uses widely accepted driver behavior models and produces measures of effectiveness for the evaluated transportation system that can generally be related to accepted traffic flow evaluation procedures (i.e., *Highway Capacity Manual* [*HCM*] processes). The output of CORSIM includes (but is not limited to) travel time, average vehicle delay, average stop delay, and queue length (*17*).

CORSIM was not specifically designed to evaluate the operation of TWLTLs. In the past, however, CORSIM was adapted to approximate the operation of TWLTLs. TWLTLs between two access points were represented by back-to-back left-turn lanes, and these turn lanes were designed to be as long as possible in order to serve the highest number of left-turn vehicles without an impact on the through lane(s). The weaknesses of this adaptation, especially for certain operational and physical situations, are generally recognized. For example, if the access points are close enough and the left-turn volumes high enough, left-turn vehicles can queue into the through lane(s). This situation would not occur if actual TWLTL operations could be simulated because left-turn traffic would continue to queue along the TWLTL. The impact of this approximation can be a CORSIM simulation that produces unrealistic delay results. Therefore, if CORSIM is used for the evaluation of roadways with a TWLTL, volume levels and access point and/or intersection spacing must be monitored so the simulated left-turn vehicles do not queue into the through lanes. If through lane blockages do occur and these volume and geometric design characteristics need to be evaluated, a different software package or analysis approach should be used.

*Summary of Findings*

It was concluded that a simulation software package should be used to evaluate the operation of urban four-lane undivided and three-lane roadways with similar traffic flow and geometric characteristics. Few simulation packages, however, are specifically designed analyze the operation and impacts of TWLTLs. ARTSIM and TWLTL-SIM were developed to address this deficiency, but neither of these programs is currently available for use and/or properly documented. CORSIM, on the other hand, is widely used and accepted. It is easily acquired and its use is extensively documented. Concerns exist about the ability of CORSIM to accurately simulate the operation of a TWLTL have been expressed, but it is believed that most of the impacts from these limitations can be overcome if the traffic flow and geometric design characteristics that produce unwanted results are avoided. For these reasons, CORSIM was used in this research, but all the simulations completed were visually observed to confirm that unrealistic queuing or delay results did not occur. The characteristics of the simulated case study corridor, the factors adjusted to complete the sensitivity analysis of urban four-lane undivided and three-lane operations, and the sensitivity analysis results are described in the following paragraphs.

**Case Study Corridor Characteristics**

CORSIM was used to simulate the traffic flow of a case study corridor with a four-lane undivided and a three-lane cross section. This case study corridor was defined by the authors of this report (see Figure 3) and had the following fixed characteristics for both roadway cross sections:

- The roadway segment was 1/4-mile long.
- Through traffic volumes were equally distributed in each direction along the major roadway segment (i.e., there was a 50/50 directional split).
- Pretimed two-phase signalized intersections exist at each end of the roadway segment.
- The timing of the two-phase signals was optimized using the SYNCHRO software approach (e.g., delay minimization) and assuming they comprised a two-signal system.
- No left- or right-turn lanes exist along the four-lane undivided roadway.
- No right-turn lanes exist along the three-lane roadway.

- Right- and left-turn volumes each represent 10 percent of the through volume at each signalized intersection.
- Right-turn volumes entering/exiting the number of access points used in an individual simulation represented 10 percent of the traffic flow.
- The turn volumes entering/exiting each access point and minor street are equal.
- There were no through volumes at the four-leg access points (see Figure 3), and the minor street approach volumes at the signalized intersections were assumed to be equal to 40 percent of the major roadway traffic flow at the intersection.
- A 30 mph travel speed was assumed for both cross sections.
- Only four-leg intersections occur between the major roadway and the access points and minor streets.
- All minor street and access point approaches have a single lane.

Each of the variables listed was fixed for all the four-lane undivided and three-lane CORSIM simulations completed. The traffic flow and geometric factors that were adjusted as part of the sensitivity analysis, along with the process followed in the analysis, are described in the next section.

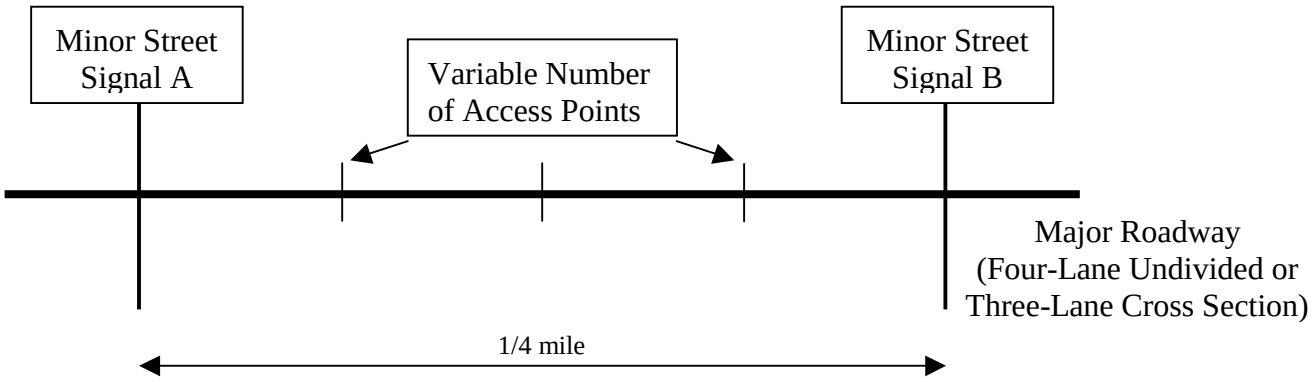


**Figure 3 Simulated Case Study Corridor**

**Sensitivity Analysis Factors**

The sensitivity analysis done as part of this research simulated the traffic flow of a case study corridor with either a four-lane undivided or three-lane cross section. Each of these cross sections was simulated with various combinations of total entering volume, access point left-turn volumes, and access point densities. The values evaluated for each of these variables are shown in Table 5, and the reasoning used to select these values is discussed in the following paragraphs.

*Total Entering Volume*

The total volume of traffic entering the simulated corridor was adjusted as part of the sensitivity analysis. As previously discussed, there have been successful case study conversions with ADT as high as 24,000 vpd. In Iowa, however, conversions have typically had an ADT between 8,400 to 14,500 vehicles. Preliminary analyses have also indicated that an unacceptable intersection LOS (i.e., LOS F) may begin to occur with daily volumes near 20,000 vpd (assuming that 10 percent of this volume occurred during the peak hour).

Based on the information discussed in the previous paragraph, daily volumes of 10,000, 15,000, 17,500, and 20,000 vpd were chosen for evaluation in the sensitivity analysis. These daily volumes were then converted into directional hourly volumes based on an assumption that 10 percent of the daily traffic would occur during the peak hour and that a 50/50 directional split would occur. These assumptions, applied to the daily volumes chosen, produced hourly directional traffic volumes of 500, 750, 875, and 1,000 vehicles per hour per direction (vphpd) (see Table 5).

*Access Point Left-Turn Volume*

The percentage of total entering vehicles that turn left at the corridor access points was also changed as part of the sensitivity analysis. In past research, Bonneson and McCoy did field studies and found that the percentage of vehicles turning left along a 1/4-mile segment (i.e., mid-block left turns) varied from 5 to 13 percent (*6*). The sensitivity analysis completed as part of this research considered left-turn percentages of 5, 10, and 15 percent (see Table 5) and assumed that these turns were equally distributed among all the access points. For example, if there were five access points per side of roadway, and it was assumed that five percent of the entering traffic

turned left, then one percent of the entering traffic would be assigned to each of the five access points.

**Table 5 Sensitivity Analysis Factors**

| Characteristic | Values Evaluated |
|---|---|
| Total Entering Volume (vehicles per hour per direction) | 500, 750, 875, and 1,000 |
| Access Point Left-Turn Volume (percent of through volume)* | 10, 20, and 30 |
| Access Point Density (points per mile per side) | 0, 10, 20, 30, 40, and 50 |

*Left-turn volumes are evenly distributed among the access points.

*Access Point Density*

In addition to the impact of total and left-turn volumes, the impact of access point density was also evaluated as part of this sensitivity analysis. Six different access point densities were simulated for each combination of entering and access point left-turn volumes considered (see Table 5). In Minnesota, it has been shown that there is an average of 8 and 28 access points per mile on roadways in rural and urban areas, respectively (*18*). In addition, Bonneson and McCoy have used data from seven case study corridors that had access point densities from 0 to 90 per mile (*6*). It was decided that this research would consider access point densities between 0 and 50 per mile per side of roadway (i.e., 0 to 100 access points per mile for both sides of the entire roadway). The six density levels considered in this sensitivity analysis included 0, 10, 20, 30, 40, and 50 access points per mile per side (ppm) of the roadway (see Table 5). These access points were evenly distributed along the 1/4-mile case study roadway segment and were positioned directly opposite each other on both sides of the roadway (see Figure 3).

**Sensitivity Analysis Process**

The values chosen for the three sensitivity analysis factors (see Table 5) result in 64 roadway corridors. All 64 of these combinations are shown in Table 6, and each of them was simulated in the following manner for both cross sections. First, Synchro, an optimization and simulation

**Table 6 Access Point Density, Access Point Left-Turn Volume, and Total Entering Volume Combinations for Sensitivity Analysis***

| Access Point Density (ppm) | Access Point Left-Turn Volume (percent) | Total Entering Volume (vphpd) |
|---|---|---|
| 0 | 0 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |
| 10 | 10 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |
| | 20 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |
| | 30 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |
| 20 | 10 | 500 |
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| | | 1000 |
| 50 | 10 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |
| | 20 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |
| | 30 | 500 |
| | | 750 |
| | | 875 |
| | | 1000 |

*ppm = access points per mile per side of roadway; percent = percent of entering volume; vphpd = vehicles per hour per direction.

software package, was used to optimize the signal timing. Then, for each combination of analysis factors, the optimized signal timings were used within CORSIM to simulate the operation of the case study corridor (see Figure 3) for each combination of analysis factors and each cross section. All 128 corridors (i.e., 64 factor combinations for two corridors) were simulated five times (for a total of 640 simulations), and the average results from these simulations are presented in the following paragraphs. Five simulations were completed (and average results calculated) to more accurately represent the expected traffic flow and to acknowledge the stochastic nature of the CORSIM simulation results.

As previously discussed, the operation of a TWLTL must be approximated in CORSIM as multiple back-to-back turn lanes. The weaknesses of this approximation were recognized, and the vehicle movements in each three-lane cross section simulation were visually observed to alleviate any concerns related to the production of unrealistic delays. Fortunately, none of the traffic flow and geometric combinations considered in this sensitivity analysis resulted in turn vehicles queuing in the through lanes of the cross section simulated. In other words, it is believed that the speed and delay results from the CORSIM simulations closely approximate the expected traffic flow.

**Sensitivity Analysis Results**

CORSIM output contains a number of measures that can be used to describe the operation of an arterial roadway. For this research, the average CORSIM output for each combination of the three factors previously described was calculated and compared for a four-lane undivided and a three-lane roadway. More specifically, the speed and delay outputs from CORSIM were used to determine, compare, and report the average arterial travel speed (for through vehicles), the arterial LOS, and the signalized intersection LOS for each roadway cross section and combination of input factors (see Table 5 and 6).

In general, the CORSIM output allowed the determination of the average arterial travel speed, arterial LOS, and intersection LOS discussed in the 1994 *Highway Capacity Manual* rather than its 1997 update (*19*). A change in 1997 from stop- to control-delay per vehicle as the LOS measure at intersections (and consequently arterial LOS) could not easily be reproduced from the

CORSIM output. For this reason, the 1994 *HCM* approach was used in this research to calculate average arterial travel speed, arterial LOS, and intersection LOS. The average arterial travel speeds, arterial LOS, and intersection LOS calculated from the simulation results revealed several trends. These trends are discussed in the following paragraphs.

*Average Arterial Travel Speed*

The average arterial travel speed for the through vehicles on the simulated roadway was calculated by dividing the length of the corridor by a summation of their roadway segment travel time (i.e., arterial running time) and signalized intersection stop delay. This measure was calculated from the CORSIM results for each simulation. The average arterial travel speed for each cross section and combination of sensitivity analysis factors are shown in Appendix B and summarized in Tables 7, 8, and 9. The difference between the average arterial travel speed for each roadway cross section (with the same volume and access density characteristics) is also shown.

**General Summary.** Overall, a comparison of the simulated four-lane undivided and three-lane average arterial travel speeds support the case study results (see Table 7). The simulation results showed that (for a given combination of volume and access density characteristics) the four-lane undivided cross section almost always resulted in a higher average arterial travel speeds than those allowed along a three-lane roadway. The largest simulated difference between four-lane undivided and three-lane average arterial travel speed was 3.9 mph for all the input factor combinations (see Table 7). This difference occurred when the simulated corridor had no access points (i.e., there were no left- or right-turn volumes). However, if the simulation results from the corridors with no access points are disregarded, the maximum difference decreased to 3.8 mph. The case study locations showed similar differences in average or 85th percentile speeds. The overall average difference in average arterial travel speeds was 1.8 mph whether the results from the corridors with no access points were accounted for or not.

The differences between the average arterial travel speeds produced from this sensitivity analysis reveal several interesting patterns (see Appendix B). For example, all the average arterial travel

## Table 7 Simulated Average Arterial Travel Speed Summary Statistics*

| Sensitivity Analysis Factor | Undivided Four-Lane Average Arterial Travel Speed (mph) | Three-Lane Average Arterial Travel Speed (mph) | Average Arterial Travel Speed Difference (mph)* | Min. Diff.* (mph) | Max. Diff.* (mph) |
|---|---|---|---|---|---|
| **Total Entering Volume (vphpd)**** | | | | | |
| 500 | 22.0 | 20.7 | 1.3 | 0.8 | 1.7 |
| 750 | 20.3 | 19.6 | 0.7 | 0.0 | 2.0 |
| 875 | 20.5 | 18.7 | 1.8 | 1.5 | 2.7 |
| 1000 | 19.4 | 16.3 | 3.1 | 1.8 | 3.8 |
| **Access Point Density (ppm)** | | | | | |
| 0 | 22.1 | 19.6 | 2.5 | 1.5 | 3.9 |
| 10 | 21.5 | 19.6 | 1.9 | 0.8 | 3.5 |
| 20 | 21.2 | 19.2 | 2.0 | 0.7 | 3.2 |
| 30 | 20.3 | 18.6 | 1.8 | 0.4 | 3.5 |
| 40 | 19.8 | 18.1 | 1.7 | 0.0 | 3.8 |
| 50 | 20.1 | 18.6 | 1.4 | 0.2 | 3.6 |
| **Access Point Left-Turn Volumes (percent of total entering volume)** | | | | | |
| 10 | 20.6 | 18.7 | 1.9 | 0.0 | 3.6 |
| 20 | 20.6 | 18.8 | 1.7 | 0.2 | 3.8 |
| 30 | 20.6 | 18.9 | 1.7 | 0.4 | 3.7 |

*Difference = Average Arterial Travel Speed with the Four-Lane Undivided Cross Section - Average Arterial Travel Speed with the Three-Lane Cross Section; vphpd = vehicles per hour per direction; ppm = access points per mile per roadway side.

**Differences for total volumes do not include those for the corridor with no access points.

## Table 8 Average Arterial Travel Speed for Various Access Point Left-Turn Volumes**

| Total Entering Volume (vphpd)* | Access Point Left-Turn Volume (percent of total entering volume) | Four-Lane Undivided Average Arterial Travel Speed (mph)* | Three-Lane Average Arterial Travel Speed (mph)* | Average Arterial Travel Speed Difference (mph)* |
|---|---|---|---|---|
| 500 | 10 | 22.1 | 20.6 | 1.5 |
| | 20 | 22.0 | 20.6 | 1.3 |
| | 30 | 21.9 | 20.8 | 1.1 |
| Avg. | — | 22.0 | 20.7 | 1.3 |
| 750 | 10 | 20.5 | 19.6 | 0.9 |
| | 20 | 20.3 | 19.7 | 0.7 |
| | 30 | 20.3 | 19.7 | 0.6 |
| Avg. | — | 20.3 | 19.6 | 0.8 |
| 875 | 10 | 20.6 | 18.6 | 2.0 |
| | 20 | 20.5 | 18.7 | 1.8 |
| | 30 | 20.5 | 18.7 | 1.8 |
| Avg. | — | 20.5 | 18.7 | 1.9 |
| 1,000 | 10 | 19.3 | 16.2 | 3.1 |
| | 20 | 19.5 | 16.3 | 3.1 |
| | 30 | 19.6 | 16.4 | 3.3 |
| Avg. | — | 19.4 | 16.3 | 3.2 |

* Difference = Average Arterial Travel Speed with the Four-Lane Undivided Cross Section - Average Arterial Travel Speed with the Three-Lane Cross Section; vphpd = vehicles per hour per direction.

**Any discrepancies in table are due to round-off error.

**Table 9 Average Arterial Travel Speed for Various Access Point Densities****

| Access Point Density (ppm)* | Left-Turn Volume (percent of total entering volume)* | Four-Lane Undivided Average Arterial Travel Speed (mph)* | Three-Lane Average Arterial Travel Speed (mph)* | Average Arterial Travel Speed Difference (mph)* |
|---|---|---|---|---|
| 0 | 0 | 22.1 | 19.6 | 2.5 |
| 10 | 10 | 21.6 | 19.6 | 2.0 |
| | 20 | 21.5 | 19.6 | 1.9 |
| | 30 | 21.3 | 19.7 | 1.6 |
| Avg. | — | 21.5 | 19.6 | 1.9 |
| 20 | 10 | 21.5 | 19.1 | 2.4 |
| | 20 | 21.1 | 19.2 | 1.9 |
| | 30 | 20.9 | 19.2 | 1.7 |
| Avg. | — | 21.2 | 19.2 | 2.0 |
| 30 | 10 | 20.3 | 18.4 | 2.0 |
| | 20 | 20.4 | 18.7 | 1.7 |
| | 30 | 20.3 | 18.7 | 1.7 |
| Avg. | — | 20.3 | 18.6 | 1.8 |
| 40 | 10 | 19.8 | 18.1 | 1.7 |
| | 20 | 19.8 | 18.1 | 1.8 |
| | 30 | 19.9 | 18.2 | 1.8 |
| Avg. | — | 19.8 | 18.1 | 1.7 |
| 50 | 10 | 19.9 | 18.6 | 1.3 |
| | 20 | 20.0 | 18.7 | 1.3 |
| | 30 | 20.3 | 18.6 | 1.7 |
| Avg. | — | 20.1 | 18.6 | 1.4 |

* Difference = Average Arterial Travel Speed with the Four-Lane Undivided Cross Section - Average Arterial Travel Speed with the Three-Lane Cross Section; vphpd = vehicles per hour per direction, ppm = access points per mile per roadway side.
**Any discrepancies in table are due to round-off error.

speed differences greater than 3 mph occurred at the highest hourly volume considered (i.e., 1000 vphpd). However, the biggest difference in average arterial travel speed for each volume level typically, but not always, occurred when the corridor was assumed to have no access points or turn vehicles. This result is not surprising; from an operational point of view there would be no reason to convert a four-lane undivided roadway with no access points to a three-lane cross section unless the signalized intersections were a concern or speed reduction was the objective.

**Total Entering Volume Summary.** Tables 7 and 8 show that the simulated average arterial travel speeds for four-lane undivided and three-lane roadways are most similar when the total entering volume was 750 vphpd. This similarity appears to become more obvious as the number of access points and the left-turn volumes increase. This trend supports the premise that four-lane undivided roadways begin to operate like "defacto" three-lane roadways as access point density and left-turn volumes increase. The average arterial travel speed difference, however, for all simulations with an entering volume of 750 vphpd was 0.7 mph, and this difference increased to 1.3, 1.8, and 3.1 mph for simulations with an entering volumes of 500, 875, and 1,000 vphpd, respectively (see Table 7). If it is assumed that these hourly volumes represent 10 percent of the daily traffic and 50 percent of the total bi-directional traffic: 500 vphpd would be equivalent to an ADT of 10,000 vpd, 750 vphpd would be equivalent to an ADT of 15,000 vpd, 875 vphpd would be equivalent to an ADT of 17,500 vpd, and 1,000 vphpd would be equivalent to an ADT of 20,000 vpd.

Not surprisingly, the impact of an increase in entering traffic on average arterial travel speed is more dramatic along a three-lane than a four-lane undivided roadway (see Table 7). The decrease in average arterial travel speed, as total entering volume increases from 500 to 1,000 vphpd, is about 2.6 mph for the four-lane undivided simulations and about 4.4 mph for the three-lane cross section. These results, along with those described in the previous paragraph, support the importance of considering the magnitude and stability of traffic volumes during the entire design period of a potential conversion. The objective of the community (e.g., a decrease in speed) must also closely match the expected results of the conversion. The simulation results show that the operational (or average arterial travel speed) impacts of four-lane undivided to three-lane conversions can be minimal for hourly volumes at or below 750 vphpd, but that these impacts should be more closely evaluated for volumes above 750 vphpd.

**Access Point Density Summary.** Tables 7 and 9 show that the difference between four-lane undivided and three-lane average arterial travel speeds change with access density. Of course, as previously discussed, the largest difference in four-lane undivided and three-lane average arterial travel speed occurs when the simulated corridor had no access points (i.e., no left- or right-turn

volumes). When access points do exist, along with left-turn volumes, the difference in average arterial travel speed is largest for the corridors simulated with an access density of 20 ppm (for the corridor characteristics considered). This difference was just 2.0 mph, but it decreased to 1.9, 1.8, and 1.7 mph for corridors with an access density of 10, 30, and 40 ppm, respectively. The range of all these average arterial travel speed differences is only 0.3 mph. The smallest difference in average arterial travel speed was simulated when the access point density was 50 ppm (the largest access point density considered). The overall average difference in average arterial travel speed was only 1.4 mph at this level of access point density. If fact, for a given total entering volume, the smallest difference in average arterial travel speed occurred when the access density was either 40 or 50 ppm.

The results discussed in the previous paragraph should not be surprising. As previously discussed, it is expected that some four-lane undivided roadways would begin to operate like a three-lane cross section as access point density and left-turn volumes increase. Table 9 shows that the overall average arterial travel speed for both roadway cross sections decrease until an access point density of 40 ppm. At an access point density of 50 ppm the average arterial travel speed of the simulated corridors actually increases for both cross sections, and the difference in average arterial travel speed continues to decrease (see the previous discussion). It is speculated that at this access point density level (for the entering and left-turn volumes considered) the traffic flow along four-lane undivided and three-lane roadways becomes more similar because of the magnitude and pattern of left-turn vehicles. For example, the inside lanes of a four-lane undivided cross section may be blocked by left-turn traffic on such a consistent basis that through vehicles primarily use the outside lane. The result is a four-lane undivided corridor that (at least partially) operates as a defacto three-lane roadway. However, even when an access density of 50 ppm was simulated, the overall average arterial travel speed for four-lane undivided roadways was still higher than a three-lane corridor with the same characteristics.

Additional analysis of the CORSIM results reveals that the average arterial travel speed trend shown in Table 7 for different total entering volumes also typically occurs for each access density that was considered. In other words, for a given access density, the average arterial travel speed for a three-lane cross section typically decreases as total entering volume increases. For a four-

lane undivided cross section, however, average arterial travel speed (for a given access density) decreases between 500 and 750 vphpd, increases at 875 vphpd, and then decreases again when the total entering volume is at 1,000 vphpd. For the entering and turn volumes, access point densities, and corridor design considered, therefore, the operation (as measured by average arterial travel speed) of the three-lane roadway decreased as volumes increased, but the operation of the four-lane undivided roadways actually improved somewhat between 750 and 875 vphpd before decreasing again between 875 and 1000 vphpd. Whatever the access density, however, the smallest difference between four-lane undivided and three-lane average arterial travel speeds still occurs when the total entering volume is 750 vphpd.

**Access Point Left-Turn Volume Summary.** In general (see Table 8), the magnitude and differences between the simulated average arterial travel speeds of the four-lane undivided and three-lane roadways decreased as access point left-turn volumes increased (for a given entering volume). As left-turn volumes increased, the average arterial travel speed of the four-lane undivided roadways usually decreased or stayed the same, but increased or stayed the same for the three-lane roadway. Not unexpectedly, left-turn vehicles become a hindrance to through vehicles along a four-lane undivided roadway but are removed as a hindrance along a three-lane roadway. It is expected that this similarity would become more obvious if larger percentages of left-turn volumes were considered.

The only instance in which the addition of left-turn vehicles did not seem to follow the pattern described in the previous paragraph was when a volume of 1,000 vphpd (the highest entering volume considered) was simulated for each cross section (see Table 8). When a volume of 1,000 vphpd was simulated, the average arterial travel speed increased with the left-turn percentage for both cross sections (rather than just for the three-lane cross section). While the simulated average arterial travel speeds along the four-lane undivided corridors are still be about three mph higher than those simulated for three-lane cross sections, the traffic flow patterns (at least with respect to the average arterial travel speed) appear to be more alike. It is speculated that the average arterial travel speed (at this high entering volume level) along a three-lane roadway increases as more vehicles are removed from the path of the through vehicles, and that four-lane undivided

roadways begin to experience a relatively stable traffic flow of mostly left-turn vehicles in the inside lanes and through vehicles in the outside lanes (i.e., a defacto three-lane operation). The fact that the difference in average arterial travel speed is still about three mph requires additional investigation. This difference may simply be due to the fact that a four-lane undivided roadway allows some lane changes (i.e., avoidance of turn vehicle conflicts) even at high volumes, but three-lane roadways do not.

Overall, for all the access point and entering volume combinations considered, the difference in simulated average arterial travel speed for four-lane undivided and three-lane roadways was between 1.7 to 1.9 mph as the left-turn volume percentage increased (see Table 7). The similarity of the speeds shown in Table 7 (for different access point left-turn volumes) is the combined result of the changes discussed in the previous paragraph (i.e., some of the differences in average arterial travel speed decrease, but others increase, as total entering volumes change). The results also show that, for the corridor design considered, specific left-turn and entering volumes are served most appropriately by a specific number of access points. It is expected that the evenly distributed left-turn percentages and access point spacing used in the case study simulation helped produce the similarity in the results for different access point left-turn volumes.

*Arterial and Intersection Level of Service*

In addition to average arterial travel speed, an arterial and intersection LOS was determined for each cross section and combination of sensitivity analysis factors. The LOS measure is a more general indicator of traffic operations and represents a range of traffic flow operations (see Table 10). The CORSIM results were used to calculate average arterial travel speed (see the previous discussion) and determine the stop delay at the signalized intersections (which, given the simulation assumptions, had equal through and turn volumes) along the case study corridor. The case study corridor simulated was defined as a minor urban arterial (or possibly a major urban collector) for both the four-lane undivided and the three-lane cross section. In the 1994 *HCM*, this type of roadway could be classified as either an Arterial Class III or IV (i.e., an intermediate or urban design category). The measures of effectiveness that define the LOS for both these arterial classes and a signalized intersection are listed in Table 10.

**Table 10 Arterial and Intersection Level of Service (LOS) Guidelines (*19*)***

| Level of Service | Arterial Class III Average Travel Speed (mph) | Arterial Class IV Average Travel Speed (mph) | Avg. Intersection Stopped Delay per Vehicle (sec) |
|---|---|---|---|
| A | ≥ 30 | ≥ 25 | ≤ 5.0 |
| B | ≥ 24 | ≥ 19 | 5.1 to 15.0 |
| C | ≥ 18 | ≥ 13 | 15.1 to 25.0 |
| D | ≥ 14 | ≥ 9 | 25.1 to 40.0 |
| E | ≥ 10 | ≥ 7 | 40.1 to 60.0 |
| F | < 10 | < 7 | > 60.0 |

*LOS and arterial classes as defined in the 1994 *HCM*, Chapters 9 and 11. Four-lane undivided to three-lane cross section conversion corridors are usually classified as Arterial Class III or IV.

As previously discussed, the difference in simulated average arterial travel speeds for the four-lane undivided and three-lane cross sections was always less than 4 mph. The range of LOS speeds for the Arterial Classes III and IV, however, are typically 2 to 6 mph (see Table 10). For this reason, the difference in the simulated average arterial travel speeds for a four-lane undivided and three-lane cross section (and a given set of sensitivity analysis factors) did not typically result in a different arterial LOS. In fact, assuming that the corridor simulated was an Arterial Class III (see Table 10), both the four-lane undivided and three-lane roadways had an arterial LOS C for all the volume and access density combinations considered except a total entering volume of 1000 vphpd. At 1000 vphpd, the four-lane undivided roadways had an arterial LOS C, and the three-lane cross section experienced an arterial LOS D. In other words, the difference between the four-lane undivided and three-lane average arterial travel speeds was large enough (although still less then 4 mph) to produce a change in LOS. LOS C is typically considered adequate for urban roadway operations, and LOS D is often considered acceptable, especially in large urban areas. The feasibility of a four-lane undivided to three-lane conversion would require an *acceptable final magnitude and change* in LOS, average arterial travel speed, and signalized intersection delay. What level of change is acceptable should be locally determined.

The arterial LOS results are somewhat different if the simulated corridor was assumed to be an Arterial Class IV roadway (see Table 10). In this case, the LOS experienced by the two cross sections (i.e., four-lane undivided and three-lane) was different for smaller values of the

sensitivity analysis factors considered. The four-lane undivided simulations, when classified as an Arterial Class IV (see Table 10), produced an arterial LOS B for all total entering volumes with access point densities less than or equal to 20 ppm. For greater access point densities, an arterial LOS B is still generally produced by the four-lane undivided simulations, except at 1,000 vphpd (which has LOS C). The simulated three-lane roadways, on the other hand, were at LOS C for total entering volumes of 875 vphpd (at access densities at or above 20 ppm) and 1000 vphpd (all access densities). In other words, the three-lane roadways had a lower simulated LOS than the four-lane undivided roadways for 1000 vphpd and access point densities less than 30 ppm, and for 875 vphpd and access densities greater than or equal to 20 ppm. For all other combinations, the LOS of both cross sections was either LOS B or LOS C. Therefore, the cross sections primarily had the same LOS, except for a small number of input variable combinations.

Average intersection stop delay was also used to determine the LOS at the signalized intersections along the simulated corridor. The relationship between the amount of measured/simulated stop delay per vehicle and the intersection LOS (as per the 1994 *HCM*) is shown in Table 10. Recall that during the sensitivity analysis the timing of both signalized intersections was optimized as part of a two-phase two-signal system. The objective of this optimization was to minimize the impact of the signals along the simulated corridor by minimizing the stop delay experienced by vehicles. Overall, it was determined that the signalized intersections in the simulations operated at LOS B for all sensitivity analysis factor combinations. This LOS is more than adequate for a signalized intersection in an urban area, and the lack of impact these signals had on the overall arterial LOS (which ranged from B to D) illustrates the importance of proper signal phasing/timing to account for the any proposed cross section change.

## FEASIBILITY DETERMINATION FACTORS

A number of factors need to be evaluated to determine the feasibility of converting an urban four-lane undivided roadway to a three-lane cross section. The feasibility of this type of conversion at a particular location should be defined by whether the three-lane cross section can be expected to maintain and/or improve traffic flow conditions and safety along the roadway corridor. If an evaluation of the factors discussed in this chapter indicates that a four-lane to three-lane conversion might be feasible, this conversion option should be included in the detailed comparison and analysis of all the feasible alternative improvements at the location of interest. The following feasibility determination factors were identified from past research, engineering judgment, case study results, and the sensitivity analysis previously discussed:

- Roadway Function and Environment
- Overall Traffic Volume and Level of Service
- Turn Volumes and Patterns
- Frequent-Stop and/or Slow-Moving Vehicles
- Weaving, Speed, and Queues
- Crash Types and Patterns
- Pedestrian and Bike Activity
- Right-of-Way Availability, Cost, and Acquisition Impacts
- General Characteristics: Parallel Roadways, Offset Minor Street Intersections, Parallel Parking, Corner Radii, and At-Grade Railroad Crossings

The design period characteristics of these factors should be investigated to determine the feasibility of a four-lane undivided to three-lane cross section conversion. The influence each factor has on the feasibility decision should be based on how well the design period characteristics of the factor match the goals and objectives of the jurisdiction for the roadway and whether the changes expected in the factor (due to the conversion) are acceptable. Undoubtedly, there will be other important factors that must be considered at a particular location. These factors should be incorporated in to the feasibility determination process.

The following paragraphs contain a discussion of the factors listed. In particular, the relevant characteristics of each factor are identified, and the changes they may experience due to a four-lane undivided to three-lane conversion described. The results of the case studies and sensitivity analysis described in the previous chapters are incorporated in to the discussion of the magnitude and characteristics of the overall traffic volume and LOS, and the turning volume and pattern factors.

**Roadway Function and Environment**

The function of a roadway is generally defined by the amount of vehicular access and mobility activity it experiences and/or provides. Arterial roadways are expected to primarily serve a mobility function, local roadways an access function, and collector roadways a mixture of the two. The conversion of an urban four-lane undivided roadway to a three-lane cross section will impact the access and mobility characteristics of that corridor. In general, it will impact the overall environment of the roadway corridor.

The *intended* function of most four-lane undivided roadways was the movement or mobility of through traffic. Traffic turning into minor roadways or driveways was typically a secondary consideration. Roadways with a three-lane cross section, on the other hand, have a TWLTL for left-turning traffic and serve less of a mobility function. Roadways with either cross section often serve a range of access and mobility, and are typically (but not always) labeled as minor arterials or major collectors. In addition, land uses along these types of roadways can vary from residential to established commercial. Concerns related to safety and traffic flow along these roadways typically occur when the *actual* function of a roadway (e.g., minor arterial or major collector) does not match its *intended* or *designed* function (e.g., major arterial). The overall environment of the roadway corridor should also match the objectives of the public that uses the area (e.g., vehicle drivers, pedestrians, bicyclists, and residents).

The objective of any design is to match the mobility and access served (i.e., the roadway environment) with the actual roadway function (i.e., the access and mobility demands). For example, an urban four-lane undivided roadway with a relatively small amount of access/turning activity may efficiently and safely serve (and many do) its major/minor arterial function. In many

cases, however, the turning volumes and/or patterns along these roadways have increased to such an extent that the four-lane undivided cross section is actually operating as a defacto three-lane roadway (i.e., most of the through flow is in the outside lane, and the inside lane is used almost exclusively by turning traffic), particularly at signalized intersections. Figure 4 is an example of a roadway segment and intersection along an urban four-lane undivided cross section operating in a three-lane mode. The expected safety and operational impacts of this type of functional mismatch are described in the following paragraphs.

The *existing and intended* function of the candidate roadway must be addressed and understood to determine the feasibility of a four-lane undivided to three-lane cross section conversion. The feasibility of this type of conversion, however, is more likely if the existing urban four-lane undivided cross section is already operating as a defacto three-lane roadway. The expected tradeoff between mobility and access must also be evaluated with respect to the intended objective for the roadway corridor.

**Figure 4 Four-lane Undivided Roadway/Intersection Operating as a "Defacto" Three-Lane Cross Section**

**Overall Traffic Volume and Level of Service**

In the past, one argument to widen a two-lane undivided roadway to a four-lane undivided roadway was that this type of cross section improvement would serve more through traffic and allow it to bypass turning traffic. Many urban four-lane undivided roadways operate both efficiently and safely in this manner. In other cases, the safety and operations of these roadways have degraded with increased through and turning volumes. The expected design period traffic flow capabilities of a four-lane undivided and a three-lane cross section need to be compared in the feasibility determination decision process. Measures for this comparison include the magnitude of existing and forecast ADT and the peak-hour volumes the cross sections appear to be capable of adequately serving.

A general knowledge of existing and expected ADT and peak-hour volumes is needed before a four-lane undivided to three-lane conversion can be recommended as a feasible improvement alternative. The ADT and peak-hour volume characteristics of the successful case study conversions described in the chapter "Four-Lane Undivided and Three-Lane Roadway Traffic Flow Simulation" provide some guidance. These urban roadway case studies had an ADT between 8,500 and 24,000 vpd (see Table 4), and according to the American Association of State Highway Transportation Officials (AASHTO) the peak-hour volumes along this type of roadway typically represent 8 to 12 percent of their ADT (*20*). For an ADT of 8,500 to 24,000 vpd these percentages represent a bi-directional peak-hour volume of 680 to 2,880 vehicles. The sensitivity analysis described in the previous chapter considered peak-hour volumes that encompass all but the smallest and largest volumes in this range.

The operational feasibility of a four-lane undivided to three-lane conversion also requires an understanding of how the peak-hour volumes of a roadway are expected to change within the design period. The sensitivity analysis results described in the previous chapter provided some guidance on this issue by comparing the average arterial travel speed, arterial LOS, and intersection LOS of similar four-lane undivided and three-lane roadways with peak-hour volumes of 500, 750, 875, and 1,000 vphpd. The analysis found that the minimum difference in average arterial travel speed for the two cross sections occurred with a peak-hour volume of 750 vphpd.

However, the simulated differences between the average arterial travel speeds were always less then four mph, and the arterial LOS was generally the same for each cross section except when 875 and/or 1,000 vphpd (depending an the arterial classification assumed) were simulated. In these cases, the arterial LOS for the three-lane cross section was often one LOS lower than that of the four-lane undivided simulations with similar input factors. The signal timing was optimized before each simulation, and when this approach was used it was found that the LOS for these intersections did not change for the input factors considered. In general, however, some reduction in average arterial travel speed should also be expected, whatever the volume, when a roadway is converted from a four-lane undivided to a three-lane cross section.

The results of past research, the cases studies, and the simulation sensitivity analysis described in the previous chapters appear to support the following conversion feasibility suggestions regarding ADT. Four-lane undivided to three-lane conversions should be expected to be more operationally feasible if the directional peak-hour volumes of the roadway remain are at or below 750 vphpd but should be considered more cautiously for volumes between 750 and 875 vphpd. Finally, this type of conversion should be expected to reduce arterial LOS when volumes are at or above 875 to 1,000 vphpd. At these volumes, at least in Iowa, the feasibility of this type of conversion should be questioned. If it is assumed that these peak-hour volumes represent 50 percent of the total bi-directional traffic and 10 percent of the daily traffic, they would be equivalent to ADT values of 15,000, 17,500, and 20,000 vpd, respectively. In addition to these recommendations, past research by Hummer and Lewis showed that they believe three-lane cross sections (for the corridors they evaluated) experience operational capacity at about 12,000 vpd (or 600 vphpd) due to vehicle platooning rather than a reduction to an arterial segment LOS E (*5*).

The details of the sensitivity analysis are described in the previous chapter, and the peak-hour/ADT recommendations above should only be used to generally identify the possible feasibility of a four-lane undivided to three-lane conversion. A more detailed operational analysis of a specific corridor would be necessary, once a four-lane undivided to three-lane cross section conversion was considered feasible, to compare its expected impacts to other potential roadway improvements. In addition, the operational success of a four-lane undivided to three-lane conversion is also usually measured by a comparison of how well the two cross sections serve the

overall actual and intended function of the roadway (see the previous discussion), and whether the safety and/or operational changes expected or experienced due to the conversion are locally acceptable. For example, a conversion could be considered successful (i.e., feasible) if the LOS or delay along a roadway was maintained or at least above an acceptable level, but its safety improved.

In some cases, because of the magnitude of the volumes, the operational feasibility of a four-lane undivided to three-lane cross section conversion may also appear to require an increase from one to two through lanes at the signalized intersections along the corridor under consideration. This increase in lanes is typically suggested for capacity reasons on roadways with significant daily volumes (e.g., 20,000 vpd or higher) and to maintain the LOS provided at the intersections. It is the author's opinion, with support from past research and the simulation sensitivity analysis, that the feasibility of a four-lane undivided to three-lane conversion should be questioned if the need for an additional through lane at one or more intersections along the corridor is required for acceptability. The lane transition areas introduced to the driver before and after each of these lane increases may produce unwanted safety and operational consequences (e.g., lane changing and/or high-speed right-lane passing within the functional area of an intersection). In these cases, a three-lane cross section may not be feasible or the most appropriate improvement alternative.

**Turn Volumes and Patterns**

The volume and pattern (i.e., how many, when, and where movements occur) of turn vehicles impact the operation and safety of all roadways. The feasibility of converting a four-lane undivided roadway to a three-lane cross section requires an estimate (e.g., simulation and LOS analysis) of how current and forecast (i.e., design period) turn volumes are served by both cross sections. It will be the expected change in LOS or operations (and safety) that determines the feasibility of a four-lane to three-lane conversion. For example, it is expected that there would be little change in the operation of a four-lane undivided roadway that operates as a defacto three-lane cross section during the peak-hour due to the magnitude and/or frequency of its left-turn volumes (see Figure 2). This type of situation, if expected during the entire design period, would be more likely to define a feasible four-lane undivided to three-lane cross section conversion location.

The sensitivity analysis discussed in the previous chapter compared (for one corridor) the average arterial travel speed and LOS for a four-lane undivided and three-lane roadway with a range of access point left-turn volumes and densities (along with a range of total entering volumes). The analysis results indicate that, given optimized signal timing, the difference between the average arterial travel speeds for the two cross sections considered decreases as access point left-turn volumes increase (from 10 to 30 percent). A similar pattern is also observed as access point density increases (from 10 to 50 ppm). The arterial levels of service for the two cross sections, on the other hand, were only found to be different at the highest access point left-turn volume and density considered in the simulation. These results are not surprising and are an indication of how the two cross sections begin to operate in a similar manner as volumes and access point density increase.

The results of the sensitivity analysis also show several patterns for the corridor geometry (e.g., non-offset intersections), volumes (e.g., total entering and access point left-turn), and access point densities (e.g., greater than zero per mile) considered. For example, the largest difference between average arterial travel speeds, for the four-lane divided and three-lane cross section roadways that were simulated, occurred when access point density was 20 ppm. However, the overall range of average arterial travel speed differences for all the access point densities considered was only 0.6 mph. This difference increased slightly between 10 and 20 ppm, and then slowly decreased from 20 to 50 ppm. In general, average arterial travel speeds also decreased as access point left-turn volumes increased along the four-lane undivided roadways, but increased along the three-lane roadways. The simulations with the largest total entering volume, however, showed a reverse in this trend for the four-lane roadways (i.e., average through vehicle arterial travel speeds actually increased with access point left-turn volume).

It is speculated that a four-lane undivided cross section begins to operate in a more stable manner (i.e., only through vehicles in the right-lane and left-turn vehicles in the left-lane) and more like a three-lane roadway with combinations of large total entering traffic, left-turn volumes, and access point densities. The three mph difference (see Table 7 and 8) that was found to remain between the four-lane undivided and three-lane cross section average arterial travel speeds simulated for

this combination of input will require additional investigation. In addition, the impact of offset access points and/or intersections on the simulation results are also of interest, and could change and/or reduce the entering traffic, left-turn access point volume, and access point density at which the operation of four-lane undivided and three-lane cross sections become more similar.

**Frequent-Stop and/or Slow-Moving Vehicles**

The amount of frequent-stop and/or slow-moving traffic (e.g., agricultural vehicles, school bus student drop-off/pick-up, mail delivery vehicles, and buggies) that occurs along a roadway being considered for a cross section conversion should also be considered. It should be expected that these types of vehicles would have a greater impact on the operation of a three-lane roadway than a roadway with a four-lane undivided cross section. The primary reason for the increased impact of frequent-stop and/or slow-moving vehicles along three-lane roadways results from the inability of passenger cars to legally pass these vehicles. This type of situation would not occur along a roadway with a four-lane undivided cross section. The feasibility of a four-lane undivided to three-lane cross section may be questionable if there are a large number of frequent-stop and/or slow-moving vehicles in the traffic stream (existing or expected) and/or these vehicles use the roadway during peak travel periods. The overall impact of these vehicles should be considered in the evaluation process of the resultant disadvantages and advantages from a four-lane undivided to three-lane conversion at a particular location. One potential mitigation measure to minimize the impact of frequent-stop vehicles is to provide a pull-out area for the vehicle(s) at specific locations along the corridor.

The number and type of frequent-stop and/or slow-moving vehicles (often heavy and long) that enter and exit the corridor should also be considered in the feasibility determination of an urban four-lane undivided to three-lane conversion. These vehicles can have a more of an impact on the traffic flow along a three-lane cross section than a four-lane undivided roadway. Some types of frequent-stop and/or slow-moving vehicles entering/exiting an access point or intersection must be properly served to have the smallest impact on traffic flow. Therefore, improvements may be necessary to corner and driveway radii and the need for these should be considered in the feasibility determination of a four-lane undivided to three-lane cross section conversion. This consideration is especially important if the frequent-stop and/or slow-moving vehicles are

expected to be significant and create traffic flow conflict and/or safety concerns. The physical ability of these vehicles (due to their length) to turn left and enter the corridor from an access point or unsignalized intersection won't typically be impacted much more than a passenger car, but this movement must be closely considered at signalized intersections. The intersection approach/departure geometry and lane marking need to provide long slow-moving vehicles the capability of turning left from a cross street to the corridor being considered for conversion.

**Weaving, Speed, and Queues**

The weaving, speed, and queuing of vehicles on a four-lane undivided roadway can be different from those on a three-lane roadway. Like some of previously discussed factors, however, the difference (especially for speed and queuing) is dependent upon the current operation of the four-lane undivided roadway. In other words, the impacts should be expected to be small if a four-lane undivided roadway is already operating as a defacto three-lane roadway.

Weaving or lane changing (other than vehicles entering the TWLTL) should not occur along a three-lane roadway. However, there is always the possibility of vehicles incorrectly using the TWLTL or bypassing right-turn vehicles on the left (completely removing the four-lane undivided markings, and properly marking the three-lane cross section is essential). Fortunately, neither of these maneuvers has been noted as a significant concern at the case study locations, but education and/or enforcement of proper TWLTL use may be necessary if this is not the case. Lane changing along four-lane undivided roadways, on the other hand, is done for lane positioning purposes and to bypass turn vehicles. The ability to make these maneuvers decreases as volumes increase, however, and it can have safety impacts (discussed later in these guidelines).

The need to "calm" or reduce vehicle speeds is often cited as a reason to convert a four-lane undivided roadway to a three-lane cross section. The case study results show that average vehicle speed and speed variability (i.e., the number of speeding vehicles) usually decrease when an urban four-lane undivided roadway is converted to a three-lane cross section. Anecdotal observations reveal that the inability to change lanes or pass along a three-lane roadway results in lower vehicle speed variability (i.e., a more "calm" or less "aggressive" traffic flow) than along a

four-lane undivided roadway. Overall, there were usually reductions of three to five mph in the 85th percentile or average speed after the conversion. The sensitivity analysis output (see the previous chapter) has supported the case study results, and showed that the vehicle speed differences they experienced (i.e., three to five mph) are possible for a large range of total entering traffic, access point left-turn volumes, and access point densities.

The conversion of a four-lane undivided roadway to a three-lane cross section includes geometric changes that can have different impacts on through vehicle delay and queues. The through vehicle delay related to left-turn traffic can be expected to decrease, but the reduction in through lanes may result in a larger increase of peak-hour segment and/or intersection through vehicle delay. The decrease in vehicle speed discussed in the previous paragraph (and in the earlier section on sensitivity analysis) is based on the difference between the overall four-lane undivided and three-lane cross section vehicle delays. This difference in delays and queues can be minimized by, among other things, optimizing and coordinating signals, adding right-turn lanes where necessary, and redesigning driveway and intersection curb radii. In fact, some or all of these improvements are almost always necessary, and the case study and sensitivity analysis observations and/or results support this conclusion. Of course, the smallest difference in delay/queues can be expected when the converted four-lane undivided roadway was already operating like a three-lane cross section (see Figure 2). Delay that results from the traffic calming impacts of this type of conversion (i.e., the fact that the slowest vehicle controls the general speed of the vehicles on a particular segment) can be simulated (see previous chapter), but not controlled. This type of delay is unavoidable in a four-lane undivided to three-lane conversion.

One concern along high-volume roadways after four-lane undivided to three-lane cross section conversions has been the delay and gap availability that may result at unsignalized intersections and access points/driveways. If a four-lane undivided roadway is not currently operating like a three-lane cross section, the minor street or private driveway traffic delay can increase due to the conversion. This increase can be the result of a potential decrease in the number of acceptable gaps within the traffic flow (due to a general reduction in through lanes). Minor street delay was not a measure of effectiveness considered in this research, but it must be considered to determine the feasibility of a four-lane undivided to three-lane cross section conversion. In most cases, the

concern about increased minor street/driveway delay has been tempered by the improved safety that results from a reduction in the complexity of unsignalized intersection turning and crossing maneuvers. Therefore, some operational efficiency may need to be traded for an expected increase in safety, but if the expected delay is considered excessive, additional traffic control may be necessary or the conversion may not be feasible.

**Crash Type and Patterns**

Based on past research and case study results, it is expected that a roadway with a three-lane cross section will have a lower crash rate than a four-lane undivided roadway. In fact, data from Minnesota indicate that three-lane roadways have a crash rate 27 percent lower than the rate for four-lane undivided roadways (*18*). The case study results also showed similar or higher crash rate decreases, and were confirmed by Hummer's research and a paper by Huang et al. (*5*, *15*). Huang et al. found that the monthly crash frequency decreased 2 to 42 percent after conversion from a four-lane undivided to three-lane cross section, and that this was significantly more than comparable sites that were not changed (*15*). Crash severity was also decreased, but the changes in crash type (between adjusted and comparable non-adjusted sites) were found to be similar (*15*). Related research has shown that that the addition of a TWLTL can be expected to decrease crash rates by 10 to 40 percent (*1*, *2*, *7*).

The expected increase in safety that results from a four-lane undivided to three-lane cross section conversion may primarily be the result of a reduction in speed and speed variability along the roadway, a decrease in the number of conflict points between vehicles, and improved sight distance for the major-street left-turn vehicles. A three-lane cross section removes left-turn vehicles from the through lane. The addition of a TWLTL, therefore, reduces the conflicts between these stopped vehicles and through traffic, and also any related lane changing conflicts that may result. The number of lanes that need to be crossed by major-street left-turn and minor street crossing vehicles is also decreased (see Figures 5 and 6). The reduction in speed variability and conflict points can decrease rear-end, sideswipe, and/or angle crashes related to left-turn and crossing vehicles on three-lane roadways. The major-street left-turn vehicle sight distance improvements that result from a four-lane undivided to three-lane cross section conversion are

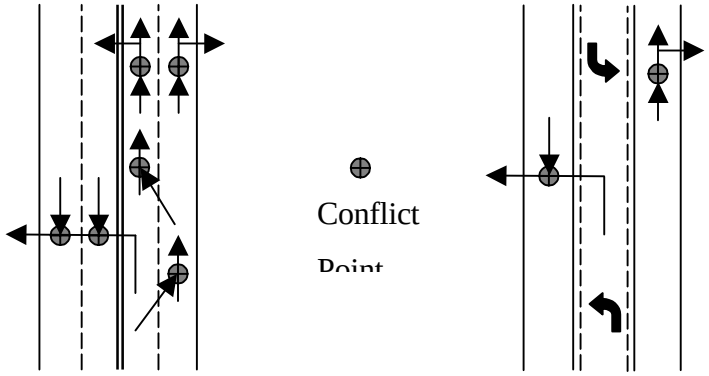


**Figure 5 Midblock Conflict Points for Urban Four-Lane Undivided Roadway and Three-Lane Cross Section (*10*)**

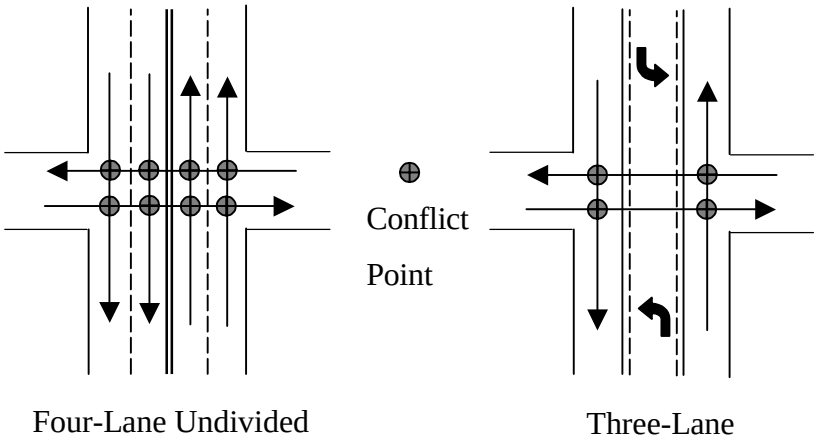


**Figure 6 Crossing and Through Traffic Conflict Points for Urban Four-Lane Undivided Roadway and Three-Lane Cross Section (*10*)**

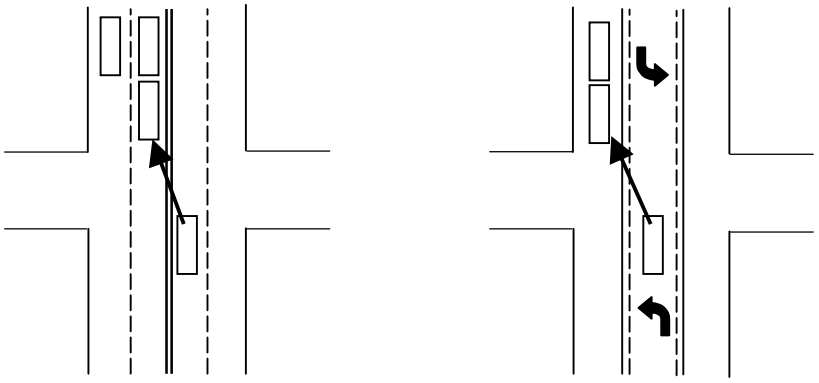


**Figure 7 Major-Street Left-Turn Sight Distance for Urban Four-Lane Undivided Roadway and Three-Lane Cross Section (*10*)**

shown in Figure 7. These improvements are also expected to improve the safety of the corridor. It is speculated that the only increase in crashes that might be experienced when an urban four-lane undivided roadway is converted to a three-lane cross section would be due to the increase in right-turn and through vehicle stop/slow conflicts, and a general increase in overall congestion (e.g., increased volumes, intersection/segment delay, and queues). In the case studies, however, it would appear that this potential increase in crashes was far outweighed by the overall reduction in crashes.

The reduction in conflict points also decreases the complexity of left-turn and crossing maneuvers. This type of operation is safer for all drivers but is especially preferable for areas with large a population of older drivers. As previously discussed, however, this decrease in complexity may be offset on high-volume roadways with an increase in delay for minor street approach and private driveway traffic (due to a decrease in acceptable major-street vehicle gaps).

**Pedestrian and Bike Activity**

The conversion of an urban four-lane undivided roadway to a three-lane cross section may have an impact on pedestrian and bike activity. These users (pedestrians and bicyclists) are not usually served well by urban four-lane undivided roadways. In fact, the case study results appear to support the conclusion that pedestrians, bicyclists, and adjacent landowners typically prefer the corridor environment of a three-lane cross section rather to a four-lane undivided roadway. The somewhat slower and more consistent speeds produced are more desirable to all three groups.

The safety of pedestrians and bicyclists is an important factor to consider. A three-lane cross section produces fewer conflict points between vehicles and crossing pedestrians. In addition, although the total roadway width does not change, the complexity of the pedestrian crossing maneuver is reduced. For example, pedestrians have two though lanes to cross rather than four, and they also sometimes use the TWLTL to cross the entire roadway width in two movements. While this two-stage pedestrian crossing movement is not recommended, it is most likely safer than a pedestrian making the same maneuver across a four-lane undivided roadway. The conversion from four to three lanes may also allow the use of wider lanes or designated bike lanes to better accommodate bicyclists. Figure 8 is a photo of a three-lane roadway with bike

lanes in Ames, Iowa. In general, the conversion of an urban four-lane undivided roadway to a three-lane cross section can be expected to benefit both pedestrians and bicyclists, and improve the overall roadway environment.

**Figure 8 Three-Lane Cross Section with Bike Lanes**

**Right-of-Way Availability, Cost, and Acquisition Impacts**

Many urban four-lane undivided roadways are located in areas that have a limited amount of additional right-of-way land available. If a roadway in this environment is widened (through the addition of a TWLTL or raised median) the cost and acquisition impacts could be significant. Typically the conversion of a four-lane undivided roadway to a three-lane cross section does not require any significant amount of additional right-of-way or the removal of trees and buildings. The existing curb-to-curb width, for example, is simply reallocated from four through lanes to two through lanes and a TWLTL. However, additional land for driveway and/or intersection radii reconstruction may be necessary to more adequately serve traffic. These improvements are normally rehabilitative in nature and only done where needed. In addition, right-turn lanes may also be necessary at some high-volume locations, but given the curb-to-curb width this addition may only require the removal of some parallel parking spaces. A three-lane cross section, therefore, is more feasible than widening along urban roadways with highly restricted right-of-way availability. Both the right-of-way impacts and costs are significantly less than widening a roadway for a TWLTL or raised median.

## General Characteristics: Parallel Roadways, Offset Minor Street Intersections, Parallel Parking, Corner Radii, and At-Grade Railroad Crossings

*Parallel Roadways*

The structure of the surrounding roadway system should also be considered to determine the feasibility of a four-lane undivided to three-lane cross section conversion. For example, the impact of a conversion on parallel roadway traffic flow must be evaluated. As previously discussed, a reduction in speed and some decrease in LOS may occur with the conversion of an urban four-lane undivided roadway to a three-lane cross section. This decrease in mobility may induce some drivers to choose a different route. Parallel roadways in close proximity to the converted corridor are candidates for this alternative route, and may experience increased traffic volumes if they offer an acceptable (in terms of travel time, etc.) alternative. Therefore, if roadways parallel to the converted corridor exist, the operational impacts or changes due to the conversion must be minimized and kept to an acceptable amount. A shift in traffic flow was not experienced by most of the case studies reviewed, but volumes along any parallel streets should be closely monitored after a conversion and the speed limits along these roadways enforced if necessary.

*Offset Minor Street Intersections*

Minor street offset intersections are considered a poor design characteristic of any roadway. The existence of “high-volume” offset minor streets or driveways must be considered to determine the feasibility of a four-lane undivided to three-lane cross section conversion. Heavily used offset minor streets or driveways can produce a situation with overlapping turn volumes within the inside through lanes and/or the TWLTL. For the three-lane cross section, this overlap can result in vehicles that slow and possibly stop within the through lanes. Therefore, it is important to understand and/or estimate the through volumes and turn volumes into the minor streets and driveways along the corridor being considered for conversion. This type of operation is difficult to simulate, but knowledge of its occurrence is especially relevant if the overlapping turn volumes are consistently large (i.e., the two turn volumes are high and occur at the same time) and are expected to impact through vehicle operation along a three-lane roadway. In most cases, the existence of a TWLTL would be expected to improve the operations and safety of a roadway

with offset minor streets or driveways, but the possibility of the issue discussed in this paragraph must be investigated.

*Parallel Parking, Corner Radii, and At-Grade Railroad Crossings*

In addition to the roadway characteristics described in the previous two paragraphs, the amount and usage of the parallel parking spaces along the corridor, the length of each corner radii, and the impact of any at-grade railroad crossings should be reviewed. Parallel parking along roadways that serve a mobility purpose are not usually recommended. Not unexpectedly, however, some cities still have parallel parking spaces along four-lane undivided roadways and would like to continue to have them with the three-lane cross section. One parallel parking striping design (used in Sioux Center, Iowa) that appears to minimize the impact of parking usage on the through lanes of a three-lane cross section includes pairs of parking spaces that are spaced to allow parking movements to occur quickly. This type of design, however, will reduce the number of parking spaces available. Caution should be also exercised if a bike lane must be included in a cross section that includes parallel parking. In this case, the bike lane is placed between the through and parking lane. This design has been used in the past, but it must take into account the conflict between parking vehicles and bicyclists that may occur.

As previously discussed, the corner radii of intersections and driveways is also an important factor to consider in the determination of a four-lane undivided to three-lane cross section conversion. Radii geometry and/or corner design impacts the ability and speed of vehicle entering/exiting the minor cross street or driveway. These types of improvements should be done on an as-needed basis. They may not be necessary along an entire corridor and/or only required at specific intersections. The existing corner radii along the four-lane undivided roadway under consideration should be evaluated for their expected traffic flow impacts along the proposed three-lane cross section. In some cases, parallel parking spaces near intersections may also need to be eliminated for the addition of a right-turn lane (if necessary).

The impact of at-grade railroad crossings should also be considered and evaluated when determining the feasibility of converting a four-lane undivided roadway to a three-lane cross section. In most cases, the queues at a railroad crossing can be expected to approximately double

when a roadway is converted to a three-lane cross section. Drivers on a four-lane undivided roadway that approach a railroad crossing occupied by a train will typically choose the lane with the shortest queue (i.e., use both lanes evenly). The three-lane cross section does not provide this option. In other words, a railroad crossing along a four-lane undivided roadway, unlike a regular signalized intersection, will almost never operate as a defacto three-lane cross section (see Figure 4). The acceptability of double the typical at-grade railroad crossing queues (along with the associated vehicle delay) must be considered closely when determining the feasibility of a four-lane undivided to three-lane cross section conversion.

**Summary of Findings**

The design period characteristics of certain feasibility determination factors (e.g., those discussed in this chapter) should be investigated before the conversion of an urban four-lane undivided roadway to a three-lane cross section. The ability to estimate the magnitudes of these factors for both cross sections (during the design period), and their expected changes, is essential to the determination of conversion feasibility and its impacts. The factors discussed in these guidelines included roadway function and environment; overall traffic volumes and level of service; turning volumes and patterns; frequent-stop and/or slow-moving vehicles; weaving, speed, and queues; crash type and patterns; pedestrian and bike activity; right-of-way availability, cost, and acquisition impacts; and some other general characteristics. The existing and forecast characteristics of all these factors should be reviewed to determine the feasibility and possible success of converting a four-lane undivided roadway to a three-lane cross section. In general, a four-lane undivided to three-lane conversion should be considered feasible if the goals and objectives for the corridor are matched by the expected three-lane cross section characteristics (i.e., the factors discussed in this chapter) in an acceptable manner. A detailed engineering study would then be necessary to quantify and compare the impacts of this alternative to the others that are feasible along the corridor of interest.

The list of factors discussed in these guidelines should not be considered exhaustive for every corridor. Other relevant factors may be identified for a particular location that is being considered for a conversion. These additional factors must be considered in conjunction with those listed

and discussed in these guidelines. These guidelines should, however, provide a good starting point for the feasibility determination of four-lane to three-lane conversions.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

The following conclusions are based on the findings past research, and the results of case study and simulation analysis investigations completed as part of this project.

- Most cross section improvement research has focused on the advantages and disadvantages of the addition of a raised median or TWLTL to a currently undivided roadway.

- The addition of a TWLTL or raised median to an undivided roadway typically reduces through-vehicle delay.

- The addition of a TWLTL or raised median to an undivided roadway typically reduces crash rates.

- In certain circumstances, the conversion of a four-lane undivided roadway to a three-lane cross section can be a feasible improvement alternative, but not necessarily the preferable alternative, at a particular location.

- Typically, a reduction of less than five mph has been observed and/or simulated in average arterial or 85th percentile speed after a four-lane undivided to three-lane cross section conversion. The magnitude of the change depends upon the current operation of the four-lane undivided roadway and a number of other factors (e.g., total volume, turn volume, access density, and signal timing changes).

- Measurements in the field show that several case study conversions resulted in a reduction of the number of drivers traveling five mph or more above the posted speed limit. These reductions can be significant (e.g., for two case studies it was measured between 60 to 70 percent). This reduction in speeders is a measure of the “traffic calming” effect produced by a four-lane undivided to three-lane cross section conversion.

- Some four-lane undivided roadways currently operate as “defacto” three-lane roadways (especially during the peak period).

- The total number of crashes is typically reduced (from 17 to 62 percent for the case studies identified) when a four-lane undivided roadway is converted to a three-lane cross section.

- Four-lane undivided roadways with an ADT between 8,400 and 24,000 vpd, and a relatively wide range of traffic flow and physical characteristics, have been successfully converted to three-lane cross sections in many areas of the United States and Iowa.

- The results of the simulation sensitivity analysis completed as part of this project support the conclusion four-lane undivided to three-lane cross section conversions, when done properly and in the correct location, can have minimal operational disadvantages.

- The simulation sensitivity analysis completed as part of this project helped identify the average arterial travel speed and LOS impacts (i.e., operational feasibility) of a four -lane undivided to three-lane conversion along a roadway with different total entering volumes, left-turn volumes, and access densities.

- The three-lane cross section can easily be incorporated as a potentially feasible alternative in to the cross section selection guidelines suggested in past research.

- The life-cycle costs and benefits, increased delay and decreased crashes, of a four-lane undivided to three-lane cross section conversion should be compared to the impacts from typical widening alternatives to determine the preferable improvement.

**Recommendations**

The following actions are recommended based on the results of this project report and the discussions in these guidelines.

- The feasibility of replacing an urban four-lane undivided roadway with a three-lane cross section should be considered on a case-by-case basis.

- At a minimum, the existing and expected characteristics of the following feasibility determination factors should be investigated when considering the design period feasibility of a four-lane undivided to three-lane cross section conversion:

    - Roadway Function and Environment
    - Overall Traffic Volume and Level of Service
    - Turn Volumes and Patterns
    - Frequent-Stop and/or Slow-Moving Vehicles
    - Weaving, Speed, and Queues
    - Crash Types and Patterns
    - Pedestrian and Bike Activity
    - Right-of-Way Availability, Cost, and Acquisition Impacts
    - General Characteristics: Parallel Roadways, Offset Minor Street Intersections, Parallel Parking, Corner Radii, and At-Grade Railroad Crossings

- The content of these guidelines, along with the summary tables in the executive summary and Appendix C should be used to assist with the investigation of the factors discussed and to determine the feasibility of a four-lane undivided to three-lane cross section conversion.

- From an operational point of view, it is suggested that four-lane undivided to three-lane cross section conversions be considered as a feasible (with respect to volume only) option when bi-directional peak-hour volumes up are less than 1,500 vph, but that more caution should be exercised when the roadway has a bi-directional peak hour volume between 1,500 vph and 1,750 vph. At and above 1,750 vph, the simulation indicated a reduction in arterial level of service. Therefore, at least in Iowa, the feasibility of a four-lane undivided to three-lane cross section conversions should be questioned and/or considered much more closely when a roadway has (or is expected to have) a peak hour volume above 1,750 vph. Assuming that these volumes represent 10 percent of the ADT along corridor, they are equivalent to 15,000 vpd and 17,500 vpd. These recommendations are based on the simulation analysis of an idealized case study corridor, and the expected operational impacts should be considered and

investigated on an individual basis if the conversion is considered feasible based on these general volume suggestions.

- A four-lane undivided roadway should not be converted to a three-lane cross section if delays and/or crash rates are expected to increase dramatically.

- A conversion of the ty pe discussed in these guidelines will be most successful if the factors that define the roadway environment remain stable during the design period (e.g., traffic volumes won't increase dramatically) and the current four-lane undivided roadway is already operating as a "defacto" three-lane roadway.

- More formal, consistent, and widespread before-and-after studies of this type of conversion should be completed and documented.

- If a three-lane cross section is determined to be feasible it should be considered, along with the other alternatives, within a detailed engineering study for comparison purposes.

- Transportation professionals should consider the three-lane cross section as just one more possible improvement alternative for urban four-lane undivided roadways.

- A simulation sensitivity analysis of a corridor with less idealized characteristics should be completed and the results compared to measurements in the field. For example, offset intersections should be considered along with less uniformly distributed left-turn volumes throughout the roadway corridor segment.

- A wider range of the parameters considered in this research should also be investigated in a simulation sensitivity analysis. The limitations of CORSIM may require the use of another software package to complete this task.

- Evaluate the use of the new software packages that claim to accurately simulate the operation of a TWLTL. Some of the new software packages may accurately represent the traffic flow that occurs after a four-lane undivided to three-lane conversion, and may be more adaptable.

- The impact of frequent-stop and/or slow-moving vehicle traffic flow on the feasibility of a four-lane undivided three-lane conversion should be more closely investigated (through simulation or other means). Some of this research is ongoing but was not complete before the publication of these guidelines.

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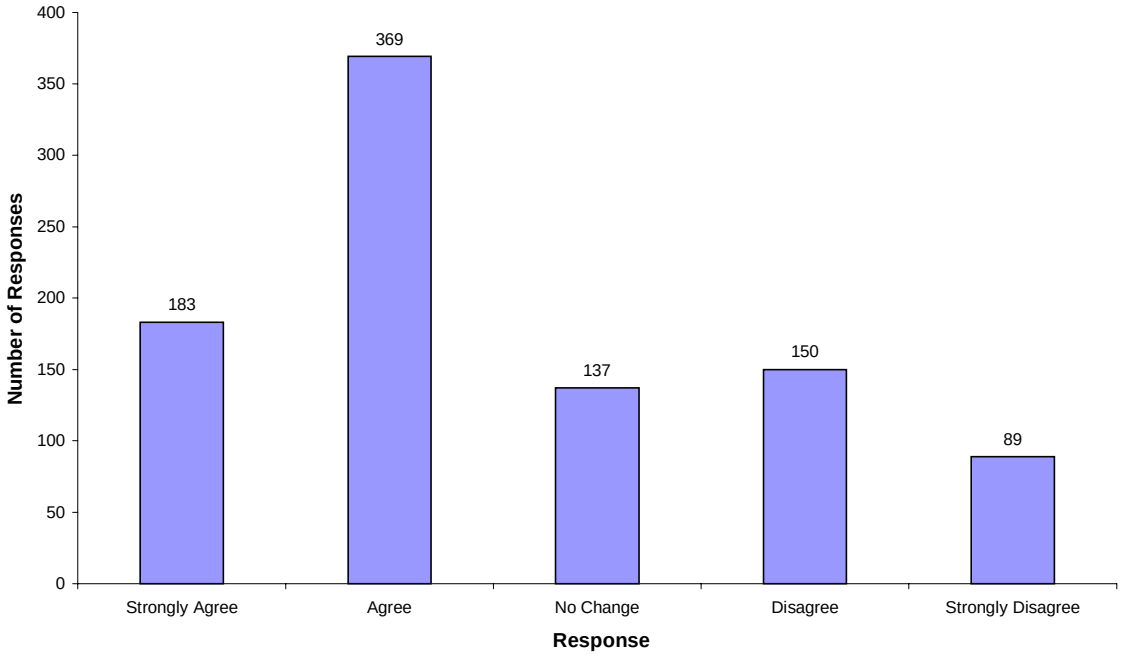
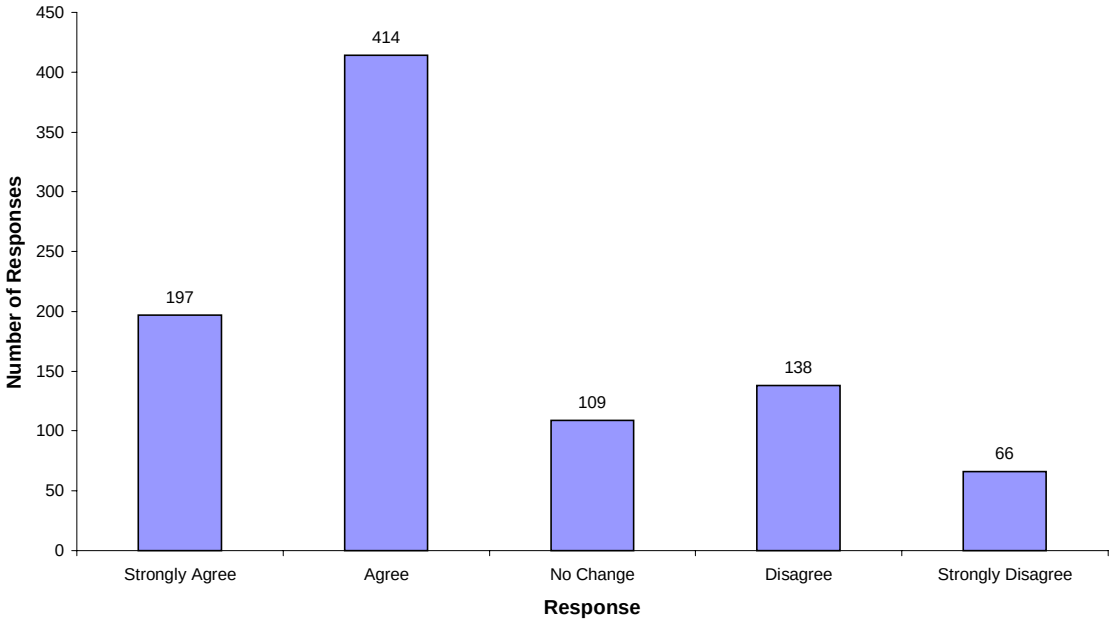
# Appendix A
# Sioux Center Resident Survey Results

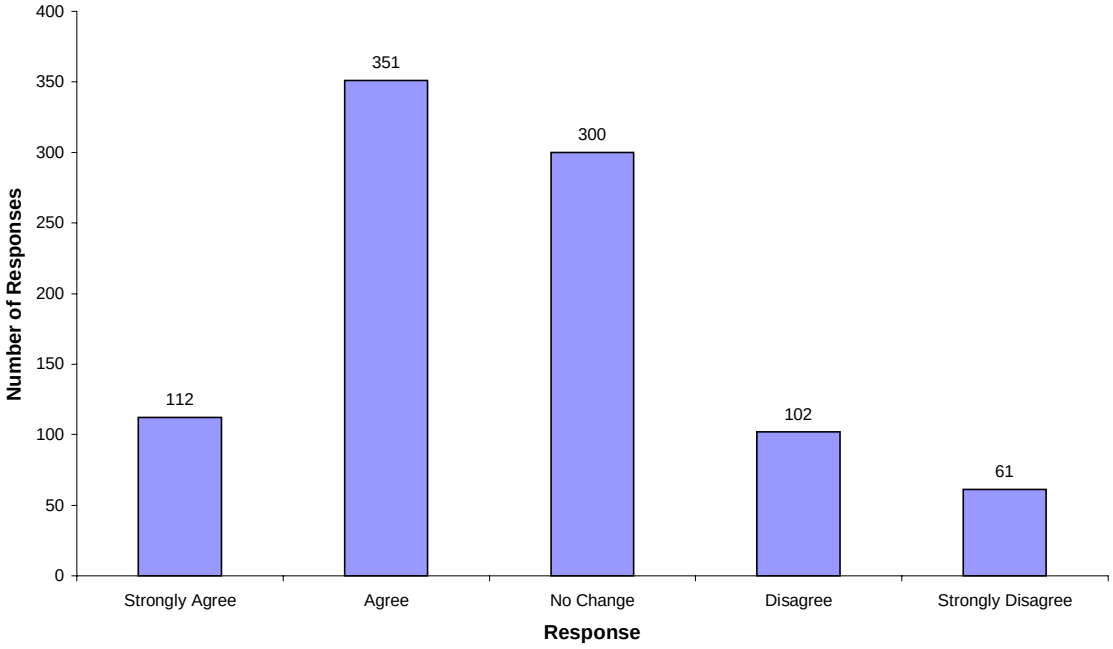
**Sioux Center, Iowa U.S. 75 Conversion Survey Results**
**Question 1: Traffic Safety Along US-75 has Been Improved.**



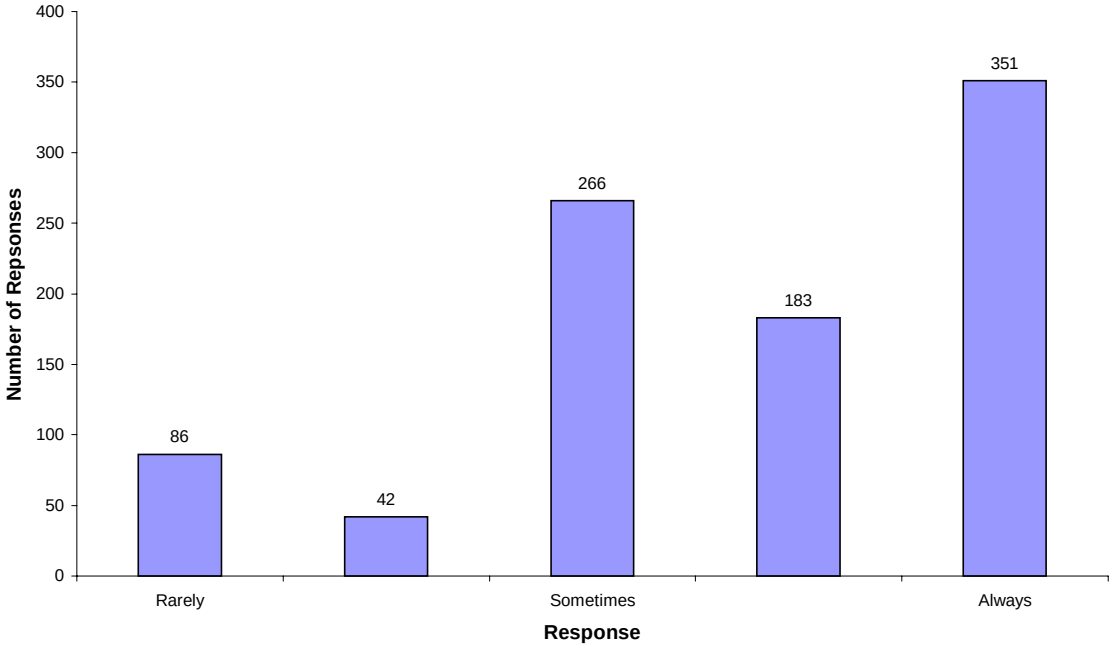

**Sioux Center, Iowa U.S. 75 Conversion Survey Results**
**Question 2: Traffic Calming Along US-75 has Occurred**
**(less speeding vehicles, less aggressive driving).**



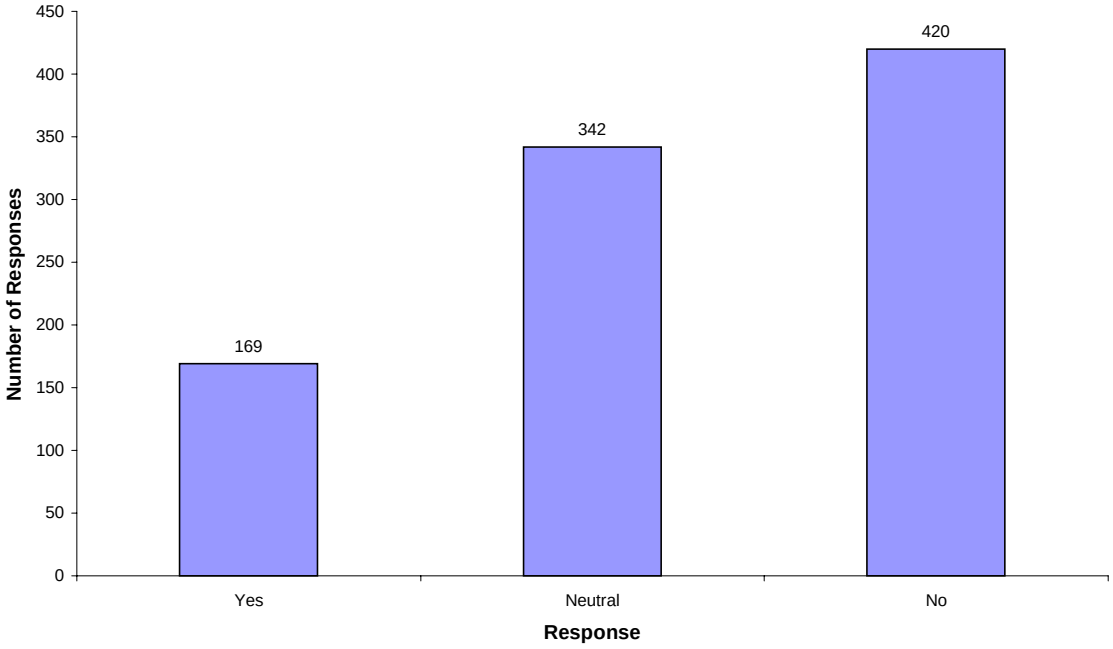
**Sioux Center, Iowa U.S.-75 Conversion Survey Results**
**Question 3: Pedestrian Crossings are Safer.**



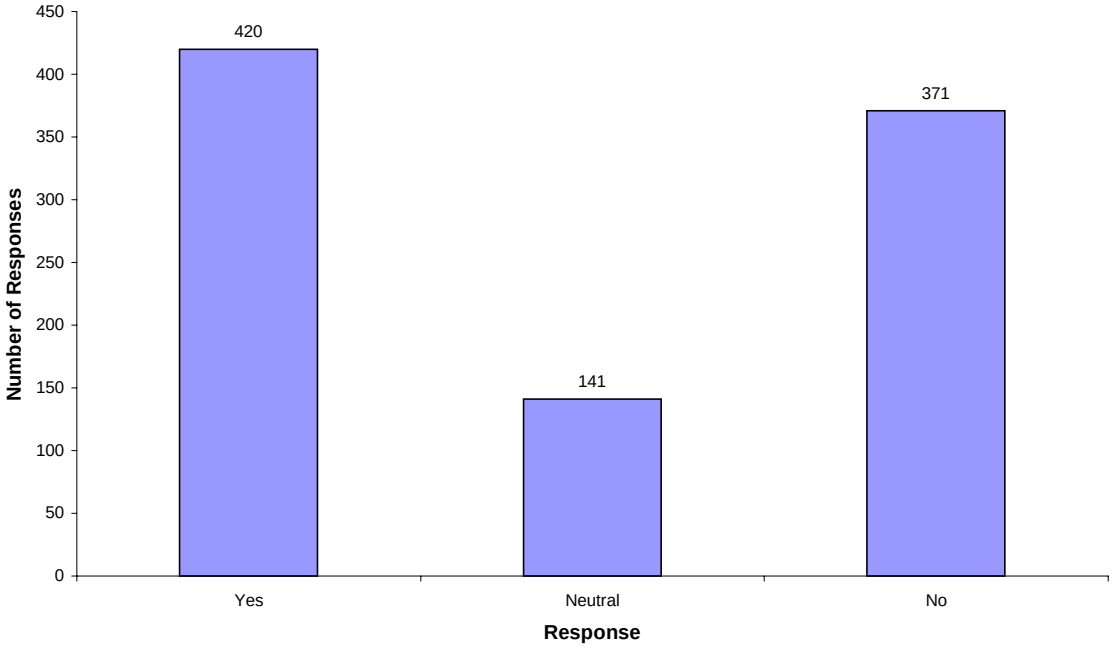

**Sioux Center, Iowa U.S.-75 Conversion Survey Results**
**Question 4: I Experience More Delay when Entering or Exiting the Side Streets.**



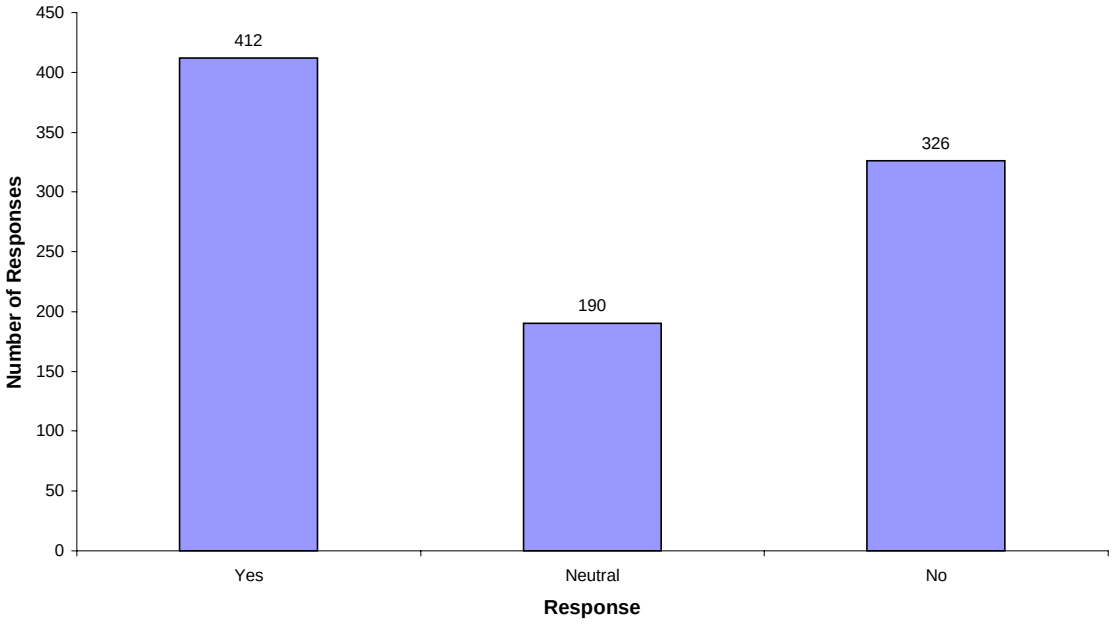
**Sioux Center, Iowa U.S.-75 Conversion Survey Results**
**Question 5: Did You Support the 4 to 3 Lane Conversion When it was First Proposed?**




**Sioux Center, Iowa U.S.-75 Conversion Survey Results**
**Question 6: Do You Support the 4 to 3 Lane Conversion Now?**



**Sioux Center, Iowa U.S.-75 Conversion Survey Results**
**Question 7: Was the Conversion in the Best Interest of a Majority of the Residents of Sioux Center?**



**Appendix B**
**Sensitivity Analysis Simulation Results**
**(Average of Five Simulation Results for Each Combination Indicated)**

**Table B.1 Average Arterial Travel Speeds for Combinations of Total Volume, Left-Turn Percentages, and Access Point Density****

| Access Point Density (per mile per side) | Left Turn Volume (total percent of directional volume) | Total Volume (vphpd) | 4-Lane Average Arterial Travel Speed (mph) | 3-Lane Average Arterial Travel Speed (mph) | Average Arterial Travel Speed Difference (mph)* |
|---|---|---|---|---|---|
| 0 | 0 | 500 | 23.2 | 21.6 | -1.5 |
| | | 750 | 21.8 | 19.5 | -2.3 |
| | | 875 | 21.9 | 19.9 | -2.1 |
| | | 1000 | 21.5 | 17.6 | -3.9 |
| 10 | 10 | 500 | 22.9 | 21.4 | -1.4 |
| | | 750 | 21.3 | 20.1 | -1.2 |
| | | 875 | 21.6 | 19.8 | -1.9 |
| | | 1000 | 20.6 | 17.1 | -3.5 |
| | 20 | 500 | 22.8 | 21.4 | -1.4 |
| | | 750 | 21.0 | 20.0 | -1.0 |
| | | 875 | 21.5 | 19.6 | -1.9 |
| | | 1000 | 20.6 | 17.3 | -3.4 |
| | 30 | 500 | 22.6 | 21.8 | -0.8 |
| | | 750 | 21.0 | 20.1 | -0.9 |
| | | 875 | 21.3 | 19.5 | -1.8 |
| | | 1000 | 20.3 | 17.3 | -3.0 |
| 20 | 10 | 500 | 22.8 | 21.2 | -1.6 |
| | | 750 | 21.7 | 19.7 | -2.0 |
| | | 875 | 21.4 | 18.7 | -2.7 |
| | | 1000 | 20.1 | 16.9 | -3.2 |
| | 20 | 500 | 22.4 | 21.1 | -1.4 |
| | | 750 | 20.8 | 19.7 | -1.0 |
| | | 875 | 21.0 | 18.8 | -2.1 |
| | | 1000 | 20.3 | 17.1 | -3.2 |
| | 30 | 500 | 22.4 | 21.2 | -1.2 |
| | | 750 | 20.6 | 19.9 | -0.7 |
| | | 875 | 20.8 | 18.7 | -2.1 |
| | | 1000 | 19.8 | 17.1 | -2.6 |
| 30 | 10 | 500 | 22.0 | 20.4 | -1.6 |
| | | 750 | 20.0 | 19.5 | -0.6 |
| | | 875 | 20.5 | 18.3 | -2.3 |
| | | 1000 | 18.8 | 15.4 | -3.5 |
| | 20 | 500 | 21.7 | 20.5 | -1.3 |
| | | 750 | 20.3 | 19.7 | -0.6 |
| | | 875 | 20.3 | 18.5 | -1.8 |
| | | 1000 | 19.2 | 16.0 | -3.1 |
| | 30 | 500 | 21.6 | 20.5 | -1.1 |
| | | 750 | 20.1 | 19.7 | -0.4 |
| | | 875 | 20.3 | 18.5 | -1.9 |
| | | 1000 | 19.3 | 15.9 | -3.4 |

**Table B.1 Continued**

| | | | | | |
|---|---|---|---|---|---|
| 40 | 10 | 500 | 21.5 | 19.8 | -1.7 |
| | | 750 | 19.3 | 19.3 | 0.0 |
| | | 875 | 19.8 | 18.3 | -1.5 |
| | | 1000 | 18.5 | 14.9 | -3.6 |
| | 20 | 500 | 21.4 | 20.0 | -1.4 |
| | | 750 | 19.7 | 19.3 | -0.5 |
| | | 875 | 19.7 | 18.2 | -1.5 |
| | | 1000 | 18.5 | 14.7 | -3.8 |
| | 30 | 500 | 21.3 | 20.0 | -1.3 |
| | | 750 | 19.7 | 19.3 | -0.4 |
| | | 875 | 19.9 | 18.3 | -1.6 |
| | | 1000 | 18.7 | 15.1 | -3.7 |
| 50 | 10 | 500 | 21.5 | 20.3 | -1.2 |
| | | 750 | 20.0 | 19.4 | -0.6 |
| | | 875 | 19.7 | 18.1 | -1.7 |
| | | 1000 | 18.2 | 16.5 | -1.8 |
| | 20 | 500 | 21.5 | 20.3 | -1.2 |
| | | 750 | 19.8 | 19.6 | -0.2 |
| | | 875 | 20.1 | 18.4 | -1.6 |
| | | 1000 | 18.7 | 16.6 | -2.1 |
| | 30 | 500 | 21.4 | 20.3 | -1.1 |
| | | 750 | 19.9 | 19.4 | -0.5 |
| | | 875 | 20.1 | 18.4 | -1.7 |
| | | 1000 | 19.9 | 16.4 | -3.6 |

*Difference = Average Simulated Through Vehicle Speed with the Four-Lane Undivided Cross Section - Average Simulated Through Vehicle Speed with the Three-Lane Undivided Cross Section.
**Any discrepancies in table are due to round-off error; mph = miles per hour; vphpd = vehicles per hour per direction.

# Appendix C
# Feasibility Determination Factor Characteristics and Sample Evaluative Questions

**Table ES.1 Feasibility Determination Factor Characteristics and Sample Evaluative Questions**

| Factor | Characteristics | Sample Evaluative Questions |
|---|---|---|
| Roadway Function and Environment | • Actual, Expected, and Desired Primary Function (Access, Mobility, or a Combination of the Two)<br>• Community Objectives/Goals for the Roadway<br>• Available Right-of-Way<br>• Current and Expected Adjacent Land Use | • What is the primary current, expected, and desired function of the roadway?<br>• Is the roadway primarily a collector or minor arterial roadway?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section?<br>• Is the goal for the roadway improvement increased safety with somewhat lower mobility?<br>• Is the right-of-way limited?<br>• Will the adjacent land use remain relatively stable throughout the design period?<br>• Will the proposed cross section match the desired function of the roadway?<br>• Will the answers to the above questions remain the same throughout the design period of the project? |
| Overall Traffic Volume and Level of Service | • Total Daily Volume<br>• Peak-Hour Volume (Morning/Noon/Evening)<br>• Directional Split<br>• Intersection and Arterial Level of Service<br>• Side Street and Driveway Vehicle Delay<br>• Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Signal Timing/Phasing<br>• Arterial Travel Speeds and Vehicle Delays<br>• Existence of Turn Lanes | • What is an acceptable increase in minor street or signal-related delay due to the conversion?<br>• Is a decrease in arterial travel speed of 5 miles per hour or less acceptable?<br>• What is an acceptable reduction in intersection level of service?<br>• What level of daily traffic volume exists (for Iowa roadways and assuming a 50/50 split and 10 percent of daily volume occurs during peak-hour):<br>≤ 15,000 vpd (feasibility probable)<br>15,000 to 17,500 vpd (exercise caution)<br>≥ 17,500 vpd (feasibility less likely)<br>• Does the signal timing/phasing need to be changed?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Turning Volumes and Patterns | • Number and Location of Turn Volumes and Access Points<br>• Peak time period of Turn Volumes<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Design of Access Points and Intersections<br>• Turn Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Minor Street and Access Point Vehicle Delay<br>• Signal Timing/Phasing | • Does the signal timing/phasing need to changes/optimized?<br>• How important is it that right-turn vehicles quickly enter/exit the roadway?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• Does the proposed marking allow the design vehicle (e.g., tractor-trailer) to turn properly?<br>• What is an acceptable increase in minor street and/or left-turn vehicle delay?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section? |
| Frequent-Stop and/or Slow-Moving Vehicles (e.g., agricultural vehicles, mail carriers, school buses, tractor-trailers, and buggies) | • Volume, Location, and Time of Frequent-Stop and/or Slow-Moving Vehicles<br>• Type, Design (Length, Width, Turning Radius, etc.) and Speed of Vehicles<br>• Arterial Travel Speeds and Vehicle Delays<br>• Level of Enforcement for Proper TWLTL Use (i.e., No Passing Allowed) | • What is acceptable delay with respect to frequent-stop or slow-moving vehicles?<br>• Can these vehicles turn properly at the access points and intersections?<br>• Can no passing of these vehicles be enforced?<br>• Are there locations for pull-outs for these vehicles?<br>• Can some or all of the stop locations for the frequent-stop vehicles be combined? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Weaving, Speed, and Queues | • Signal Timing/Phasing<br>• Number of Existing Lane Changes<br>• Turn Volume and Location<br>• Arterial Travel Speeds and Vehicle Delays<br>• Level of Enforcement for Proper TWLTL Use (i.e., No Passing Allowed)<br>• Number and Location of Turn Volumes and Access Points<br>• Peak Time Period of Turn Volumes<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Design of Access Points and Intersections<br>• Turn Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Minor Street and Access Point Vehicle Delay<br>• Queue Length<br>• Number of Speeders (i.e., greater than 5 mph over the posted speed limit) | • Does the signal timing/phasing need to changes/optimized?<br>• How important is it that right-turn vehicles quickly enter/exit the roadway?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• What is an acceptable increase in minor street and/or left-turn vehicle delay?<br>• Is a decrease in arterial travel speed of 5 miles per hour or less acceptable?<br>• What is an acceptable change in queues?<br>• Are there safety concerns related to weaving?<br>• Can no passing be enforced?<br>• Can drivers be educated about proper use of TWLTL?<br>• Is a reduction in speeders and speed variability preferred?<br>• Can all the old markings be completely removed?<br>• Does the current roadway primarily operate as a "defacto" three-lane cross section? |
| Crash Types and Patterns | • Type of Crashes<br>• Location of Crashes<br>• Number and Location of Pedestrians and Bicyclists<br>• Parallel Parking Need | • Can the crashes that are occurring be reduced with a conversion?<br>• Will a reduction in speed and speed variability increase safety?<br>• Are there safety concerns related to parallel parking maneuvers?<br>• Do pedestrians and bicyclists have safety concerns? |
| Pedestrian and Bike Activity | • Number and Location of Pedestrians<br>• Number and Location of Bicyclist Use<br>• Characteristics of Pedestrians and Bicyclists (e.g., Age)<br>• Bike and Pedestrian Friendliness of Roadway<br>• Cross Section Width<br>• Parallel Parking Need | • What is the pedestrian and bicyclist friendliness of the roadway?<br>• Do pedestrians and bicyclists have safety concerns?<br>• Will the addition of a TWLTL assist pedestrians and bicyclists?<br>• How will pedestrians and bicyclists interact with parallel parking?<br>• Can a bike lane be added after the conversion? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Right-of-Way Availability, Cost, and Acquisition Impacts | • Available Right-of-Way<br>• Cost of Right-of-Way<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Design of Access Points and Intersections<br>• Number of Properties Needed and Environmental Impacts (e.g., Tree Removal)<br>• Cross Section Width<br>• Parallel Parking Need | • Is the right-of-way limited?<br>• Will the cost of right-of-way acquisition be significant?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• What is necessary in the cross section (e.g., bike lane, parallel parking, etc.)? |
| **General Characteristics** | | |
| Parallel Roadways | • Roadway Network Layout<br>• Volume and Characteristics of Through Vehicles Diverted<br>• Impact of Diversion on Parallel Roadways | • Is a decrease in arterial travel speed of 5 miles per hour or less acceptable?<br>• Does the signal timing/phasing need to changes/optimized?<br>• Will conversion divert through vehicles to parallel roadways?<br>• Is it possible to avoid or reroute the diverted traffic?<br>• What is the impact on the parallel roadway environment? |
| Offset Minor Street Intersections | • Volume and Time of Left Turns<br>• Queue Lengths<br>• Distance between Minor Street Approaches | • Do left turns occur into both minor street/access point approaches at a similar time?<br>• Are the left-turn volumes significant?<br>• Will the left-turn volumes produce queues in the through lanes of a three-lane roadway? |
| Parallel Parking | • Parallel Parking Need<br>• Number of Parking Maneuvers<br>• Operational and Safety Impacts of Parallel Parking<br>• Design of Existing/Proposed Parallel Parking | • Does parallel parking exist?<br>• How many parking maneuvers occur during peak travel times?<br>• What are the safety and delay concerns related to parallel parking maneuvers?<br>• Is it possible to design these spaces for easy enter/exit (i.e., to minimize delay)?<br>• Will it be necessary to reduce the number of parking spaces?<br>• Does parallel parking reduce the ability of vehicles to turn in and out of minor streets and access points? |

**Table ES.1 Continued**

| | | |
|---|---|---|
| Corner Radii | • Design of Access Points and Intersections<br>• Number and Location of Turn Volumes and Access Points<br>• Peak time period of Turn Volumes<br>• Existence of Left-Turn and Right-Turn Lanes<br>• Turn Volume of Frequent-Stop and/or Slow-Moving Vehicles<br>• Minor Street and Access Point Vehicle Delay | • How important is it that right-turn vehicles quickly enter/exit the roadway?<br>• Do the access point and intersections need to be redesigned (e.g., radii, approach slopes, location)?<br>• Are right-turn lanes needed at particular locations?<br>• Does the proposed marking allow the design vehicle (e.g., tractor-trailer) to turn properly?<br>• Do parallel parking spaces need to be removed to allow proper turning? |
| At-Grade Railroad Crossing | • Volume, Location, and Time of Train Crossing<br>• Length of Crossing Train<br>• Delay Impacts of Train Crossing<br>• Queue Impacts of Train Crossing<br>• Total Daily Vehicle Volume<br>• Peak-Hour Vehicle Volume (Morning/Noon/Evening)<br>• Directional Split of Vehicles | • Do trains cross during peak travel periods? What is the typical delay from train crossing?<br>• Is double the current queue length (with four-lane undivided cross section) at a railroad at-grade crossing acceptable?<br>• Would the delay impacts of double the current queue be acceptable? |