Urban Minor Arterial Four-Lane Undivided to Three-Lane Conversion Feasibility: An Update

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ABSTRACT

At the first Urban Street Symposium in June 1999 the feasibility of converting urban four-lane undivided roadways to three-lane cross sections was introduced. Several successful examples of this type of conversion were discussed. It was found that in some cases this type of conversion might be able to improve safety with only a small reduction in operations. A significant amount of work has been done related the potential safety and operational impacts of four-lane undivided to three-lane conversions since 1999. This paper summarizes the content of some guidelines and research completed by the authors. Data from case study conversions will be presented and feasibility determination factors described. A CORridor SIMulation (CORSIM) software package sensitivity analysis approach was used in two projects to support the discussion of the factors related to the traffic flow differences of similar four-lane undivided and three-lane roadways. The variables considered in the analyses were total entering traffic volume (up to 1,150 vehicles per hour per direction), and different levels of left-turn traffic, access point densities, percent heavy vehicles, and bus stop activities (e.g., bus dwell times and headways). Investigations of the difference in signalized side-street vehicle delays and off-peak average arterial travel speed were also completed. The results of all the work recently completed in this area should help urban street designers decide whether a four-lane undivided to three-lane conversion is feasible at a particular location, and whether it will help improve their situation.

INTRODUCTION

In the last four years several projects have focused on the conversion of urban minor arterials from a four-lane undivided cross section to three lanes (See Figure 1) (*1*, *2*, *3*). This paper provides a short summary of the documentation connected to these projects. First, the content of a set of guidelines produced for the Iowa Department of Transportation is described (*1*). Case study location results, and the feasibility determination factors identified in the guidelines are briefly described. Results from projects that focused on the changes that might occur in some of the feasibility determination factors related to operations are presented when appropriate (*2*, *3*).

CONVERSION GUIDELINES

Four-lane undivided roadways are common in urban areas throughout the United States. When this type of roadway was constructed its intended function was primarily mobility. However, as access along these roadways has increased left-turn vehicles have had considerable mobility and safety impacts on through vehicles. Improvement alternatives to the cross section of an urban four-lane undivided roadway are often limited to the addition of individual or continuous left-turn lanes (See Figure 1). The safety and operational benefits of these types of improvements are generally accepted. In some cases, however, an alternative to cross section widening might be the conversion of the four-lane undivided cross section to three lanes (i.e., one lane in each direction and a two-way-left-turn-lane (TWLTL)) (See Figure 1).

In April 2001, a documented entitled “Guidelines for the Conversion of Urban Four-Lane Undivided Roadways to Three-Lane Two-Way Left-Turn Lane Facilities” was produced by two of the authors for the Iowa Department of Transportation (IaDOT) (*1*). The IaDOT was in the

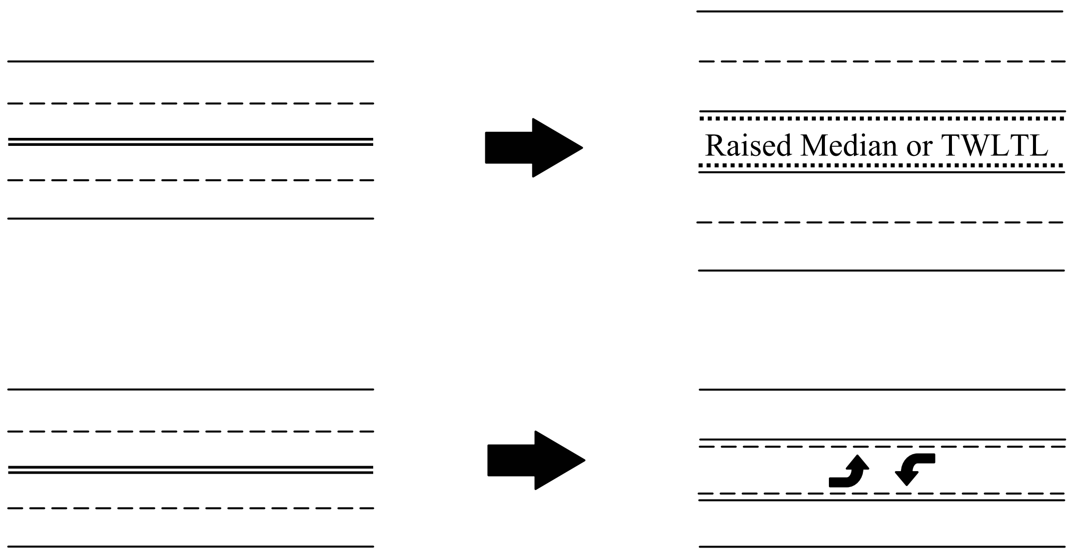

Figure 1. Two Four-Lane Undivided Roadway Conversion Options.

process of suggesting or completing several four-lane undivided to three-lane conversions and found almost no guidance about how to determine the feasibility of this alternative at a particular location. The creation of the guidelines was an attempt to at least partially fill this information gap. Other work, presented at this symposium, in the area of safety impacts, has also improved our understanding of the potential impacts of these conversions (*4*).

The IaDOT guidelines are available at www.ctre.iastate.edu/pubs/trafficsafety.htm, and includes chapters on past research, case study results, simulation of comparable four-lane undivided and three-lane operations, and feasibility determination factors (*1*). A series of sample evaluative questions for each feasibility determination factor are also provided (*1*). This paper will briefly summarize the case study results and the feasibility determination factors included in the guidelines (*1*).

Case Study Results

A series of references were used to create the list of case study locations in the IaDOT guidelines (*5*, *6*, *7*, *8*, *9*, *10*, *11*). Additional locations are also listed in the Huang, et al. paper presented at this symposium (*4*). The list of location described in the guidelines, along with their before-and-after operational and safety observations, are included in Table 1. Except for the Sioux Center, Iowa results these studies were all completed by others during different time periods. They are a collection of results intended to show past experiences with the four-lane undivided to three-lane conversion process. Statistical validity and/or data collection consistency should not be assumed. Conversions are also known to have occurred in Alaska, Colorado, Pennsylvania, Michigan, Oregon, Massachusetts, Maryland, and Texas.

The thirteen roadway conversions in Table 1 had average daily traffic (ADT) volumes of 8,400 to 14,000 vehicles per day (vpd) in Iowa and 9,200 to 24,000 vpd elsewhere. The reviewed case study

Table 1. Case Study Analysis Results (*5, 6, 7, 8, 9, 10, 11*).*

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

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

conversions appeared to result in a reduction of average or 85th percentile speeds (typically less than 5 miles per hour), and a relatively dramatic reduction in excessive speeding (a 60 to 70 percent reduction in the number of vehicles traveling 5 miles per hour faster than the posted speed limit was measured in two cases). Vehicle speeds along the converted roadway appeared to decrease somewhat and total delay slightly increased, but the total crash numbers as measured by before-and-after studies usually showed improvement. Percent reductions in total crashes ranged from 17 to 62 percent for the case studies listed. Huang, et al. have presented information at this symposium that took a more statistically valid approach to the evaluation of conversion safety and found the percent of total crashes occurring after a conversion was about 6 percent lower than that of the comparison sites (*4*). Additional analysis that controlled for factors like volume and study period showed no impact due to the difference in cross section, and no significant difference in crash severity and crash type "before" and "after" this type of conversion (*4*).

Feasibility Determination Factors

Four-lane undivided to three-lane conversions must be done at an appropriate location to achieve positive results. A number of feasibility determination factors were identified in the guidelines from a review of the past research, before-and-after case study results, and simulation sensitivity analysis (*1*). The existing and expected (i.e., design period) status of these factors should be evaluated when determining whether a four-lane undivided to three-lane conversion is a feasible alternative at a location. The factors identified and discussed in the IaDOT 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; and
- General characteristics;
  - Parallel roadways
  - Offset minor street intersections
  - Parallel parking;
  - Corner radii; and
  - At-grade railroad crossings.

Some key characteristics of these factors must be considered before a conversion. These characteristics are described in the following paragraphs. A more detailed discussion of the factors can be found in the guidelines (*1*).

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. 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.

The objective of any design change should be to match the mobility and access served (i.e., the roadway environment) with the actual roadway function (i.e., the access and mobility demands). In many cases the turning volumes and/or patterns along a roadway has 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 (See Figure 2). 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.

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, but 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. One measure of for this comparison is the magnitude of existing and forecast ADT and peak-hour volumes the cross sections appear to be capable of adequately serving. The ADT of the urban roadway case studies in Table 1 ranged from 8,500 to 24,000 vpd, 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 (*12*). For an ADT of 8,500 to 24,000 vpd these percentages represent a bidirectional peak-hour volume of 680 to 2,880 vehicles.

The sensitivity analyses completed as part of the IaDOT guidelines project encompassed all but the smallest and largest volumes of the volume range indicated above (See Table 2). The simplified corridor used in this analysis is shown in Figure 3. The initial analysis compared 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 vehicles per hour per direction (vphpd) (*1*, *2*). The analysis found a minimum difference in average arterial travel speed for the two cross sections at a peak-hour volume of 750 vphpd. However, the simulated difference between the average arterial travel speeds of similar roadways with the two cross section was always less then 4 miles per hour (mph), and differences greater than 1.9 mph were only experienced at 1,000 vphpd (*1*, *2*). The arterial LOS was generally the same for each cross section except when the 875 and/or 1000 vphpd (depending an the arterial classification assumed) were simulated. In these cases, the arterial LOS for the three-lane cross section was LOS D, and four-lane undivided roadway simulations with similar input factors had an arterial LOS C (*12*).

Additional simulations were also done on the same simplified corridor for even larger volumes (given a particular turning volume and access density) (*3*). This project attempted to evaluate the difference operations for the corridor (with a four-lane undivided and three-lane cross section) with volumes up to 1,250 vphpd (assuming 20 access points per mile per side and a total access point turning volume equal to 25 percent of the mainline traffic). The CORSIM results for

Figure 2. Four-lane Undivided Roadway/Intersection Operating as a "Defacto" Three-Lane Cross Section.

Table 2. 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.

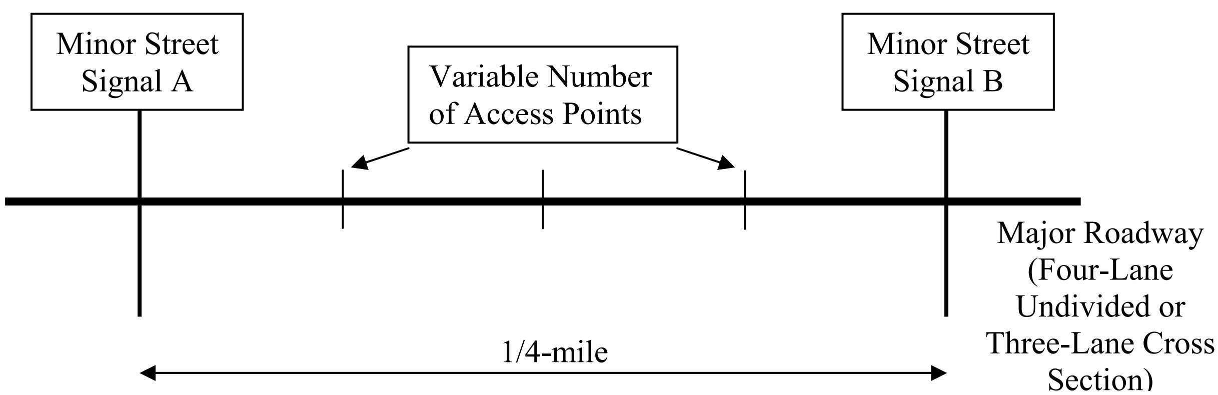

Figure 3. Simulated Case Study Corridor.

volumes above 1,150 vphpd, however, were not considered reliable, and were dropped from further consideration (*3*). At volumes of 1,000 vphpd or higher the reduction in arterial speed along the four-lane undivided roadway was larger than the three-lane roadway, but 75 percent of the three-lane arterial speed reduction occurred at between 1,000 and 1,050 vphpd (*3*). An arterial LOS D occurred along the three-lane roadway at 1,050 vphpd, and at 1,150 vphpd for the four-lane undivided roadways.

A combination of the results described above suggest that the operational impacts of a conversion may be minimal at volumes less 750 vphpd, that this impact should be more closely considered between 750 to 875 vphpd, and that volumes above 875 to 1,000 vphpd may introduce operational changes and concerns that are unacceptable to the community (*1*, *2*, *3*). Assuming a 50 percent directional split and a 10 percent peak hour factor these volumes are equivalent to 15,000 vpd, 17,500 vpd, and 20,000 vpd. Recall, however, that the success of a conversion is typically measured by the change in operations rather than the magnitude of the measures used to measure it (e.g., level of service (LOS) changed from high LOS D to a low LOS D).

It is also 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 questioned if there is a need for an additional through lane at one or more intersections along the corridor. 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. The sensitivity analyses completed as part of the guidelines project compared the simulated 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 (See Table 2 and Figure 3). 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), and as access point density increases (from 10 to 50 points per mile per side (ppm)) (*1*, *2*). Arterial LOS for the two cross sections were only different at the highest access point left-turn volume and density considered in the simulations.

The overall range of simulated average arterial travel speed differences for all the access point densities along the corridor considered was only 0.6 mph (*1*, *2*). 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. 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 (*1*, *2*).

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 four-lane undivided to three-lane cross section conversion should also be investigated. 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.

Simulations completed after the IaDOT guidelines were created did attempt to evaluate the impact of frequent-stop and slow-moving vehicles on the feasibility of four-lane undivided to three-lane conversion (*3*). Different percentages of heavy vehicles and bus activity were simulated along the corridor shown in Figure 3. More specifically, for a main roadway volume of 750 vphpd (and an access density of 20 access points per mile per side), simulations were completed for heavy vehicles percentages from 0 to 30 percent (at 5 percent increments). In addition, the impacts of 1 and 2 bus stops (with buses arriving at 5 to 60 minutes headways and 30 to 60 second dwell times) were simulated. Not surprisingly, the results showed a reduction in average arterial travel speed along the three-lane roadway that was three times more than the four-lane undivided roadway reduction (*3*). Approximately 50 percent of the speed reduction, however, occurred at and above 20 percent heavy vehicles (*3*). Not surprisingly, the impact of the bus activities on average arterial travel speed was also greater along the three-lane roadway than a similar four-lane undivided roadway (*3*). Unfortunately, the traffic volumes and corridor characteristics considered in this research did not allow more detailed conclusions, and additional analysis of the magnitude of these impacts needs to be further evaluated.

Weaving, Speed, and Queues

The weaving, speed, and queuing of vehicles on a four-lane undivided roadway are different than 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 of these factors should be small if a four-lane undivided roadway is already operating as a "defacto" three-lane roadway (See Figure 2).

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.

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 also 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, the typical reduction in 85th percentile or average speed along the case study roadway segments was 3 to 5 miles per hour. The sensitivity analysis output has supported the case study results, and showed that the vehicle speed differences they experienced (i.e., 3 to 5 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. One concern has also been the potential increase in delay for minor roadway vehicles. If a four-lane undivided roadway is not currently operating like a three-lane cross section the minor street or private driveway vehicle delay can be expected to 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 at unsignalized intersection was not a measure of effectiveness considered in this work, but it should be considered in the determination of four-lane undivided to three-lane cross section conversion feasibility. Side street vehicle delay at the signalized intersections, however, were evaluated for different volume levels and the proportion of the total delay experienced by minor street vehicles increased dramatically with main street volume (*3*). The number of signal phases was limited to two, and the cycle lengths considered were also limited. Future projects should more closely evaluate this potential conversion impact.

Cumulative off-peak impacts on travel speed are another concern when a roadway is being considered for conversion. A simulation of hourly volumes along a typical minor urban arterial revealed that the largest difference in average arterial travel speed does occur during off-peak travel times. In fact, the smallest difference in the operation of a four-lane undivided and three-lane roadway occurs during those hours with the highest traffic flow (*3*). This should not come as a surprise given the results previously described, but may imply that an evaluation of the cumulative off-peak impacts during a typical day may be necessary in the feasibility determination.

Crash Type and Patterns

Based on past data and case study results it is typically expected that a roadway with a three-lane cross section will have a lower crash frequency or rate than a similar 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 (*13*). The case study results also showed similar or higher decreases in total crashes, and these results were confirmed by Hummer (*14*). A more statistically robust analysis by Huang, et al., however, showed less of an safety improvement impact due to these conversions (*4*). These results were discussed in the case study section of this paper.

The expected increase in safety that has apparently resulted at the case study locations may be the result of the reduction in speed and speed variability observed along the roadway, a decrease in the number of conflict points between vehicles, and/or improved sight distance for the major-street left-turn vehicles. The addition of a TWLTL 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. This type of situation is safer for all drivers, but is especially preferable for areas with large a population of older drivers.

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.

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 is simply reallocated from four through lanes to two through lanes and a TWLTL. A three-lane cross section may be 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.

General Characteristics

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 because 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.

Offset Minor Street Intersections Minor street offset intersections along arterials can be a poor design characteristic. 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.

Parallel Parking, Corner Radii, and At-Grade Railroad Crossings In addition to the roadway characteristics previously described, 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, does 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.

Corner radii of intersections and driveways are 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. 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.

Finally, 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.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Four-lane undivided to three-lane cross section conversions can be a feasible, but not necessarily a preferable, cross section improvement at locations with a wide range of characteristics.

- A reduction in average arterial travel speed should be expected after a four-lane undivided to three-lane cross section conversion. However, for the corridor considered in this research average arterial travel speed reductions of only 4 mph or less were simulated. The magnitude of the change depended upon the geometric and traffic flow characteristics of the corridor (e.g., total volume, turn volume, bus activity, and access density).

- Not surprisingly, the impact of heavy vehicles and/or bus activity is different on four-lane undivided and three-lane roadways. The feasibility of a four-lane undivided to three-lane cross section conversion along a roadway with significant levels of heavy vehicles and bus activity should be closely evaluated.

- An increase in side-street delay is often raised as a concern to four-lane undivided to three-lane cross section conversions. Depending on the existing four-lane undivided traffic flow, the conversion of high volume roadways may increase the delay of vehicles attempting to enter the roadway. However, this delay increase is also combined with the simplified turning or crossing maneuver offered by a three-lane cross section. Changes in the signal timing and optimization methods must take into account expected minor street vehicle delay.

- Cumulative impacts on traffic flow and speed in off-peak vehicle travel times should also be considered. The largest differences in three-lane and four-lane undivided roadway operations (as measured by average arterial travel speed) occurs during non-peak travel times. In some cases, the cumulative influence of these off-peak impacts has resulted in concerns related to conversion feasibility.

- The results of the simulation sensitivity analyses completed as part of projects described in this paper support the conclusion that four-lane undivided to three-lane cross section conversions, when applied properly and in the correct location, can have minimal average arterial travel speed impacts.

Recommendations

- 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. An investigation of community goals for the roadway and a comparison of the expected before-and-after safety and operational impacts to what is locally acceptable must be completed for each location.

- The existing and expected (e.g., design period) characteristics of a number of factors should be investigated further in future research and when considering the design period feasibility of an urban four-lane undivided to three-lane cross section conversion. These factors include:

    - Roadway function and environment;
    - Overall traffic volume and level of service;
    - Turning 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; and

- General characteristics: parallel roadways, offset minor street intersections, parallel parking, corner radii, and at-grade railroad crossings.

- From the results of this research it is suggested that urban four-lane undivided to three-lane cross section conversions along roadways with peak-hour volumes less than 750 vphpd may experience few operational impacts, but that more caution should be exercised when the roadway has a peak-hour volume between 750 and 875 vphpd. At and above 875 vphpd, the simulations indicated a more severe reduction in average arterial travel speed and greater operational concerns. These recommendations, however, are based on the simulation analysis of an idealized case study corridor, and should only be used in a general manner. The expected before-and-after operational impacts along a particular corridor should be considered and investigated on an individual basis.

- The sensitivity of the results in this paper appear to indicate that an urban four-lane undivided to three-lane conversion 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 if the current four-lane undivided roadway is already operating as a "defacto" three-lane roadway.

- The simulation of a corridor with existing roadway characteristics should be completed and the results compared to measurements in the field. For example, offset intersections and other signal phasing could be considered along with less uniformly distributed left-turn volumes throughout the roadway corridor segment. This information could be used to check the validity and/or the accuracy of CORSIM results for the situations considered.

- It has also been observed that the general distribution and range of spot speeds are different before-and-after a four-lane undivided to three-lane conversion. The reduction in vehicles traveling 5 mph over the speed limit, for example, has been reduced dramatically in several instances. Future analysis of urban four-lane undivided to three-lane conversions should not only consider average arterial travel speed, but also the range and distribution of vehicle speeds.

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