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# Guidelines for Optimizing Roadway Cross-Section on Texas Highways

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16. Abstract
This project compiled and reviewed existing road cross-section guidance (for urban, suburban, and rural environments) from across the United States, along with research findings, to identify content that would be appropriate for inclusion in Texas-based guidelines for road cross-section optimization. A separate project task focused on considering the data needs for assessing a proposed cross-section treatment, using the results from previous efforts to determine if existing guidance and data are sufficient to develop cross-section optimization guidelines. Based on the information obtained in those tasks, this report provides recommended guidelines for selecting optimal cross-sections for highways in Texas. Those guidelines include suggested revisions to the TxDOT *Roadway Design Manual* and *Access Management Manual*.

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# GUIDELINES FOR OPTIMIZING ROADWAY CROSS-SECTION ON TEXAS HIGHWAYS

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# DISCLAIMER

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# CHAPTER 1: INTRODUCTION

## BACKGROUND

Highways and streets in Texas contain a wide variety of cross-sections, with through lanes, turning lanes, medians, shoulders, parking, and bicycle lanes as common components. Providing an appropriate cross-section is important for both operational and safety performance. It is useful to periodically evaluate whether a given cross-section is the most appropriate based on expected conditions. One alternative cross-section treatment has been called the "road diet," in which existing through lanes or shoulders may be reduced and that cross-section width reassigned for other purposes. There is currently no statewide guidance for this type of roadway optimization, and guidance for other cross-section alternatives would also benefit practitioners.

## PURPOSE OF THE PROJECT

The project team compiled and reviewed existing road cross-section guidance (for urban, suburban, and rural environments) from across the United States and internationally, along with research findings, to identify content that would be appropriate for inclusion in Texas-based guidelines for road cross-section optimization. A subsequent task focused on considering the data needs for assessing a proposed cross-section treatment, using the results from previous efforts to determine if existing guidance and data are sufficient to develop cross-section optimization guidelines. The project concluded by providing recommendations for further evaluation and adoption.

## ORGANIZATION OF THIS REPORT

This report consists of four chapters. In addition to this introductory chapter, the report contains the following material:

- Chapter 2 provides the findings from a review of literature and current practices, operational and safety benefits, and available tools and resources related to cross-section treatments.
- Chapter 3 summarizes the research team's assessment of the sufficiency of existing guidance for developing a set of guidelines for selecting a cross-section for a given roadway.
- Chapter 4 contains the recommended guidelines for cross-sections based on the information compiled for Chapters 2 and 3.

# CHAPTER 2: REVIEW OF EXISTING GUIDANCE AND RELEVANT LITERATURE

## CROSS-SECTION TREATMENTS

A variety of treatments exist for allocating cross-section on streets and highways. This chapter will describe more common treatments and examples of those treatments, as well as summarize associated research on operational effects, while subsequent sections discuss safety effects and existing guidance for choosing a particular treatment.

### Road Diet (4U-2T Conversions)

Perhaps the most familiar type of cross-section treatment is the “road diet,” which is generally described as a roadway reconfiguration that converts a four-lane, undivided (4U) road segment (primarily in an urban or suburban setting) that serves both through and turning traffic into a three-lane segment with two through lanes and a two-way left-turn lane (TWLTL) in the middle (2T). The reclaimed space can be allocated for other uses, such as bike lanes, pedestrian refuge islands, bus lanes, and parking (*1*). Variations on the road diet treatment may begin and/or end with different numbers of through lanes but typically result in fewer through lanes after the treatment is completed and may change a street’s operations from two-way to one-way.

The Every Day Counts (EDC) initiative was launched in 2009 by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) with the goal of identifying and deploying proven yet underutilized innovations. The road diet was promoted in the third round of EDC innovations to increase mobility and access and to improve safety (*1*). The road diets are used to encourage appropriate speeds and create space for dedicated turn lanes, medians, bike lanes, sidewalks, transit lanes, or other non-travel features such as planters.

One intended outcome of a 4U-2T conversion is a reduction in the speed differential between roadway users, which improves safety. The addition of turn lanes simplifies the left-turn maneuver, promoting safer turns that result in fewer vehicle-vehicle, vehicle-pedestrian, and vehicle-bicycle conflicts. The reduced number of vehicle lanes simplifies gap selection for motorists (especially older and younger drivers). Fewer travel lanes to cross also reduces pedestrian crossing distance; this combined with the opportunity to install pedestrian refuge islands means pedestrian safety can also be improved. The addition of bike lanes promotes improved bicycle safety as well (*2*).

Rosales and Sousa (*3*) described the concept of “contextually complete streets,” which contains a multimodal complete street reflecting the principles of context sensitivity and sustainability, and provided examples of these complete street solutions from the United States, Canada, and Australia. One example they provided was a 4U-2T conversion on St. George Street, a multimodal street in the downtown Toronto core through the urban St. George campus of the University of Toronto. Prior to the project, the street operated as a four-lane road during peak hours and as a two-lane road with on-street parking permitted during non-peak hours. The 4U-2T conversion treatment was implemented incrementally, the first phase of which reduced the number of lanes on St. George Street to two by permitting parking during all hours. Bicycle lanes, a narrow painted median, and turn lanes were provided at key intersections as part of the lane reduction project. The street was subsequently narrowed (i.e., the pavement width reduced from 46 ft [14 meters] to a varying width of 31 to 40 ft [9.5 to 12.2 meters]) and curbs reconstructed. The sidewalk area was also widened to increase the pedestrian zone, curb extensions were installed, and landscaping was added to provide a buffer.

The other example presented by Rosales and Sousa (*3*) was a conversion project on the Mooloolaba Esplanade, in Sunshine Coast, Australia. On the Mooloolaba Esplanade, a recreational corridor parallel to the ocean was experiencing increased traffic congestion and creating a barrier to shops and restaurants and access the ocean. It also had problems related to pedestrian and bicycle connectivity. In addition, the traffic on the corridor was creating substantial traffic noise for the street's restaurants and shops. The solution involved reducing the number of lanes. The street was converted from a two-way street to a one-way street with short-term parking, landscaping, street lighting, islands, and bulb-outs at intersections.

Road diet feasibility is generally determined using metrics such as annual average daily traffic (AADT) and peak-hour traffic volumes. Past 4U-2T conversions have been implemented on roads with AADTs from 8,500 to 24,000 vehicles per day (vpd) (*4*). Knapp et al. (*5*) summarized the guidelines related to such projects. The authors used the CORridor SIMulation (CORSIM) software package sensitivity analysis approach to compare the factors related to the traffic flow differences between four-lane undivided and three-lane roadways. The authors noted that 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. Their research results suggested that when peak-hour volumes are less than 750 vehicles per hour per direction (vphpd), urban four-lane undivided to three-lane cross-section conversions may experience few operational impacts. However, when peak-hour volume is between 750 and 875 vphpd, the roadways will start to experience reductions in operations. At and above 875 vphpd, their simulation results showed that the roadways experience a more severe reduction in average arterial travel speed and greater operational concerns.

FHWA (*6*) recommends that roadways with an AADT less than 20,000 vpd and peak-hour traffic volumes less than 750 vphpd are good candidates for a 4U-2T conversion. Based on these guidelines, potential corridors are selected for improvements and a traffic impact analysis (TIA) of proposed changes is conducted on a selected roadway before implementing changes. The measures for TIA include the analysis of traffic volumes, level of service (LOS), speeds, queue lengths, and bus operations (*4*).

Figliozzi and Glick (*7*) stated that various tools and equipment are available to effectively evaluate traffic volumes and LOS changes, but a detailed evaluation of speed and queue length distributions along a segment are significantly more cumbersome. They also noted that tools and data are not readily available for the evaluation of bus operations. The authors presented a general methodology based on the utilization of high-resolution transit datasets for the detailed evaluation of transit operations and speed and queue length distributions along roadway reallocation projects. They concluded that this methodology can be applied to future roadway reallocation projects and applicable in a wide range of traffic conditions and locations.

**Auxiliary Lanes**

The 2018 AASHTO *Green Book* (*8*) describes auxiliary lanes as cross-section elements that are generally used preceding median openings and at intersections preceding right- and left-turn movements. Auxiliary lanes can also be added to increase capacity and reduce crashes at intersections. In addition to providing for the turning movement itself, auxiliary lanes can make provision for speed-change activity (i.e., acceleration or deceleration) and lane-changing or weaving maneuvers.

The *Green Book* (*8*) further states that auxiliary lanes should have a width of at least 10 ft and desirably equal to that of the adjacent through lanes. Similarly, shoulders for auxiliary lanes should be the same as shoulders for through lanes, though reduced widths (minimum of 6 ft) are generally acceptable. Auxiliary lane shoulders may be omitted in urban areas and on turn lanes at locations where bicycle accommodation is not needed; in those cases, the auxiliary lane also serves as a usable shoulder for emergency use. Where curbing is used, an appropriate curb offset should be provided.

Auxiliary lanes are typically provided on highways having expressway characteristics and are frequently used at other intersections on primary or main highways and streets to minimize undue speed changes that may arise from conflicts between higher speeds on the through roadway and slower traffic turning to or from the through roadway. An auxiliary lane should be of sufficient width and length to enable a driver to maneuver a vehicle into it properly and, once in it, change speed from the operating speed on the originating roadway to the destination roadway. Additional description of auxiliary lanes can be found in Section 9.7 of the 2018 AASHTO *Green Book* (*8*).

**Oasis Greenway**

Bertulis (*9*) examined an approach of transforming the pavement within the right-of-way (ROW) of publicly owned streets into a new paradigm for a linear park. This park is called an "Oasis Greenway," which is a long series of interconnected low-speed, low-volume, shared-space, vegetated linear parks created from an assembly of residential streets (see Figure 1). The author stated that a few places in the United States have already implemented this approach. Notably, Seattle has used this approach because of its goal of having 0.5 acre of useable open space within 0.5 mile of every Seattle household.

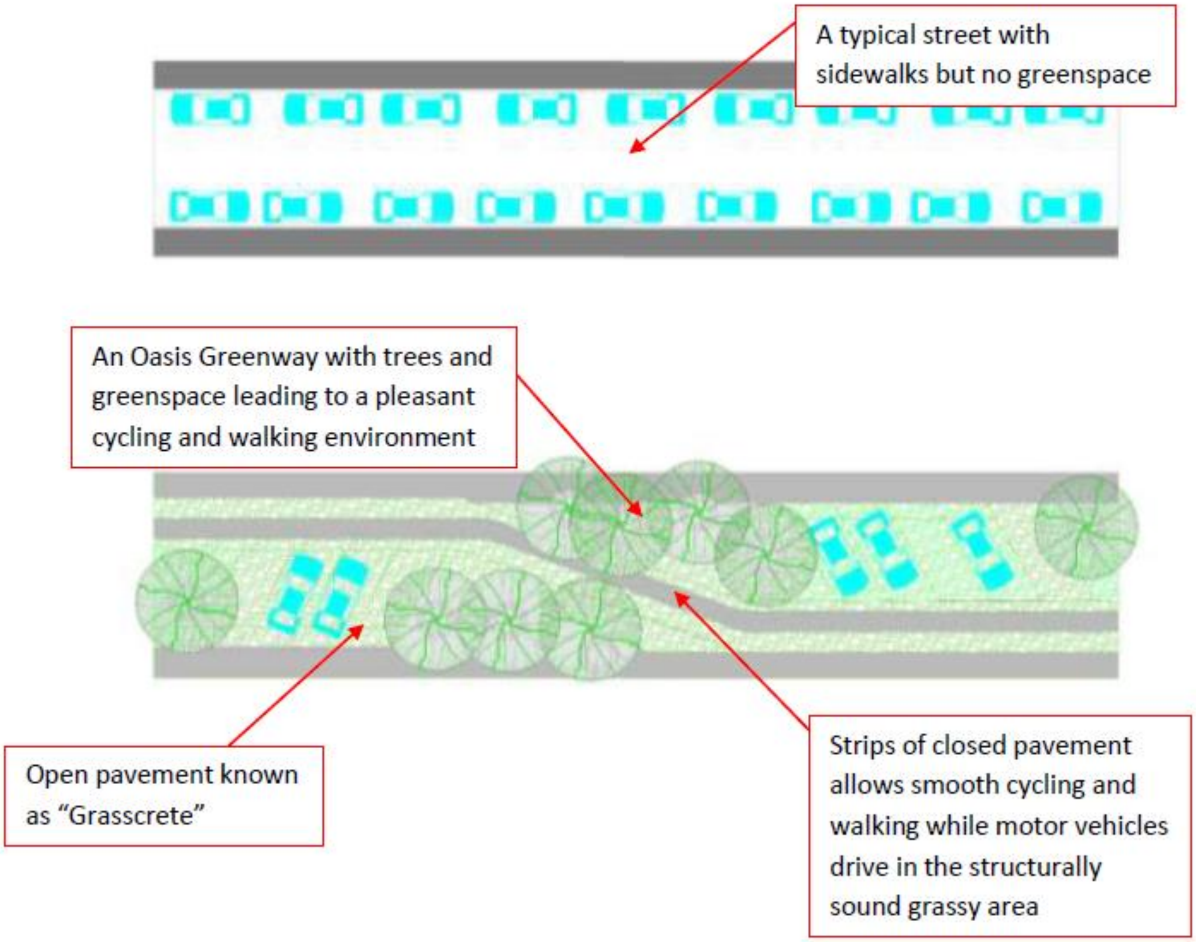
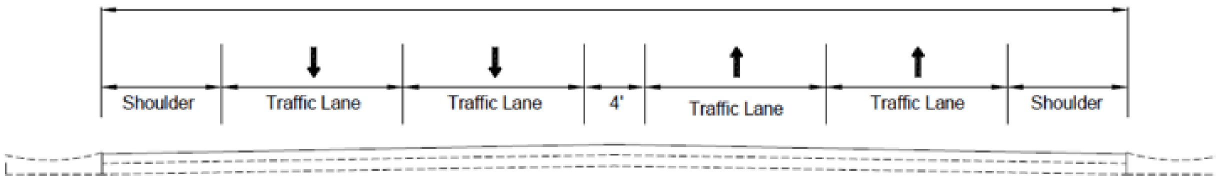


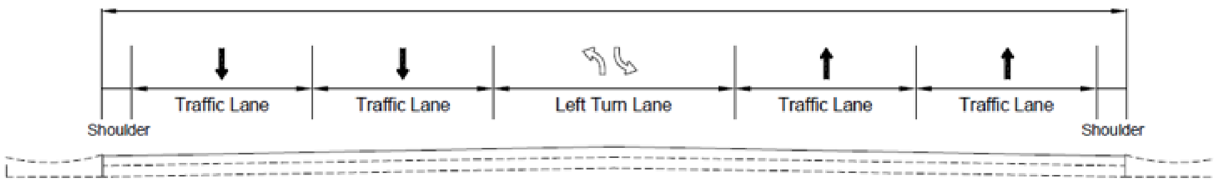

**Figure 1. An Oasis Greenway Compared to a Traditional Street (*9*)**

**Rural Cross-Section Alternatives**

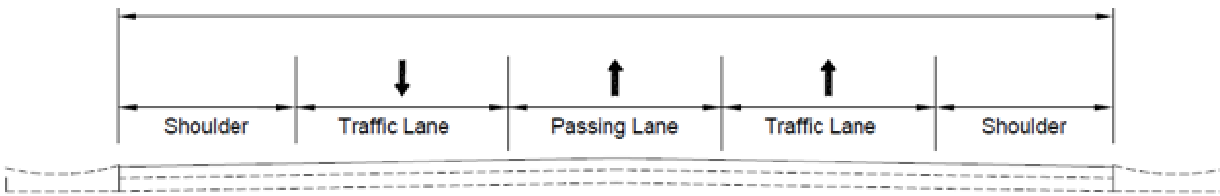
In Texas, four-lane undivided roadways constitute a significant amount of mileage in rural areas. These highways have poor safety performance compared to other cross-sections. However, there is not always sufficient space within the available ROW to accommodate a traditional four-lane divided cross-section. In a recent research project, Geedipally et al. (*10*) investigated cross-section alternatives for four-lane undivided highways that did not require changing the total roadway width. Alternative cross-sections included four-lane undivided with median buffer, four-lane with TWLTL, Super 2, and Super 2 with two-way left-turn lane. These alternative cross-sections are shown in Figure 2.




a) Four-lane with 4-ft median buffer




b) Four-lane with two-way left-turn lane

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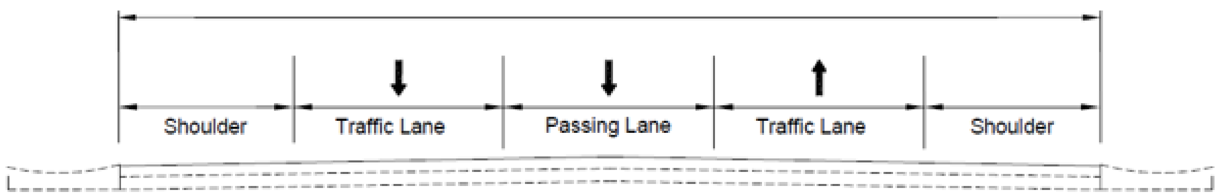
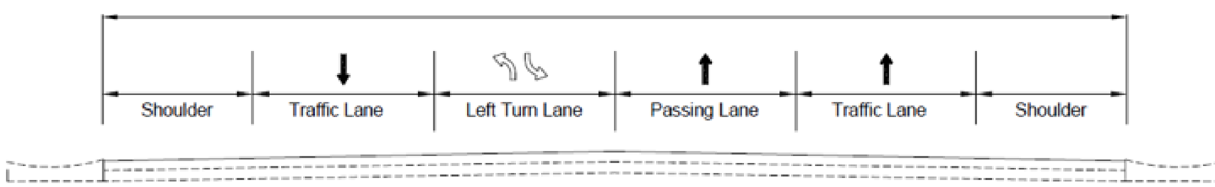



c) Super 2




d) Super 2 with TWLTL

**Figure 2. Rural Cross-Section Alternatives (*10*)**

Horizontal curve presence, driveway density, shoulder width, and operating speed have been identified as key influential variables on safety of rural highways. There is no single best cross-section for all circumstances, although the project determined that the four-lane undivided cross-section generally has the poorest safety performance of all the cross-sections considered. The Super 2 cross-section has the best safety performance in all circumstances at volumes up to 15,000 vpd. Shoulder width and driveway density have varying effects on different cross-sections. Mainly, the effect of shoulder width on the safety performance of four-lane roadways with a 4-ft median buffer is substantial, with shoulders of less than 6 ft significantly increasing crashes. These cross-sections are highly effective in reducing lane departure crashes. They produce excellent safety performance at volumes above 15,000 vpd as long as it has at least 6-ft shoulders and driveway density is low. Four-lane highways with TWLTL sections provide better safety performance when the driveway density is higher.

With respect to operations, all cross-sections experience significant delay if the total pavement width is less than 60 ft. Four-lane highway with TWLTL was the only cross-section to have much lower average delay for any heavy vehicle proportion and driveway density when the traffic volume is greater than 25,000 vpd.

The TxDOT *Roadway Design Manual* (RDM) (*11*) defines a Super 2 highway as one in which a periodic passing lane is added to a two-lane rural highway to allow for the passing of slower vehicles and the dispersal of traffic platoons. Passing lanes are provided in each direction of travel within the Super 2 corridor, allowing passing opportunities in both directions. A Super 2 project can be introduced on an existing two-lane roadway where there is substantial slow-moving traffic, where there is limited sight distance for passing, and/or where the existing traffic volume has exceeded the two-lane highway capacity, thus creating the need for vehicles to pass on a more frequent basis.

One of the benefits of the Super 2 design is that it is flexible in where and how the roadway is widened to provide the passing lanes. Figure 3 shows nine different configurations of passing lanes (*12*). Widening of the existing pavement can be symmetric about the centerline or on one side of the roadway depending on ROW availability and ease of construction. The isolated passing lane shown in Figure 3a is typically used to reduce delays occurring at a specific isolated bottleneck and is not truly a Super 2 corridor treatment. The other configurations allow some interaction between consecutive passing lanes in opposite directions, and they are used when traffic improvements are needed in both directions of travel over a corridor. The existence of multiple passing lanes along a corridor triggers the Super 2 designation.

Similarly, the distinction should be made between Super 2 passing lanes and climbing lanes. Although the purpose of each is to reduce platooning of traffic behind slower moving vehicles, the objectives are inherently different from one another. The design objectives used in the construction of a climbing lane are based on a desire to eliminate platooning due to a significant change in grade at a single location; that is, the size and length of the grade change direct the design. The design objectives for passing lanes are to disperse platoons and improve traffic operations through the provision of enhanced passing opportunities along a roadway corridor.

The alternating passing lanes shown in Figure 3f and Figure 3g can be used when sufficient width is available; Figure 3g is the typical cross-section for what is commonly described as a 2+1 road in many parts of the country and around the world. Overlapping passing lanes, shown in Figure 3h and Figure 3i, can be used when a passing lane is located on a crest or sag vertical curve, respectively. Side-by-side passing lanes, shown in Figure 3j, can be used where the location of a passing lane is constrained by nonflexible factors. Those factors include (but are not limited to) obtaining ROW, when heavy traffic is the cause of platooning rather than no-passing zones, and where the need for passing lanes exists in both directions (*12*).

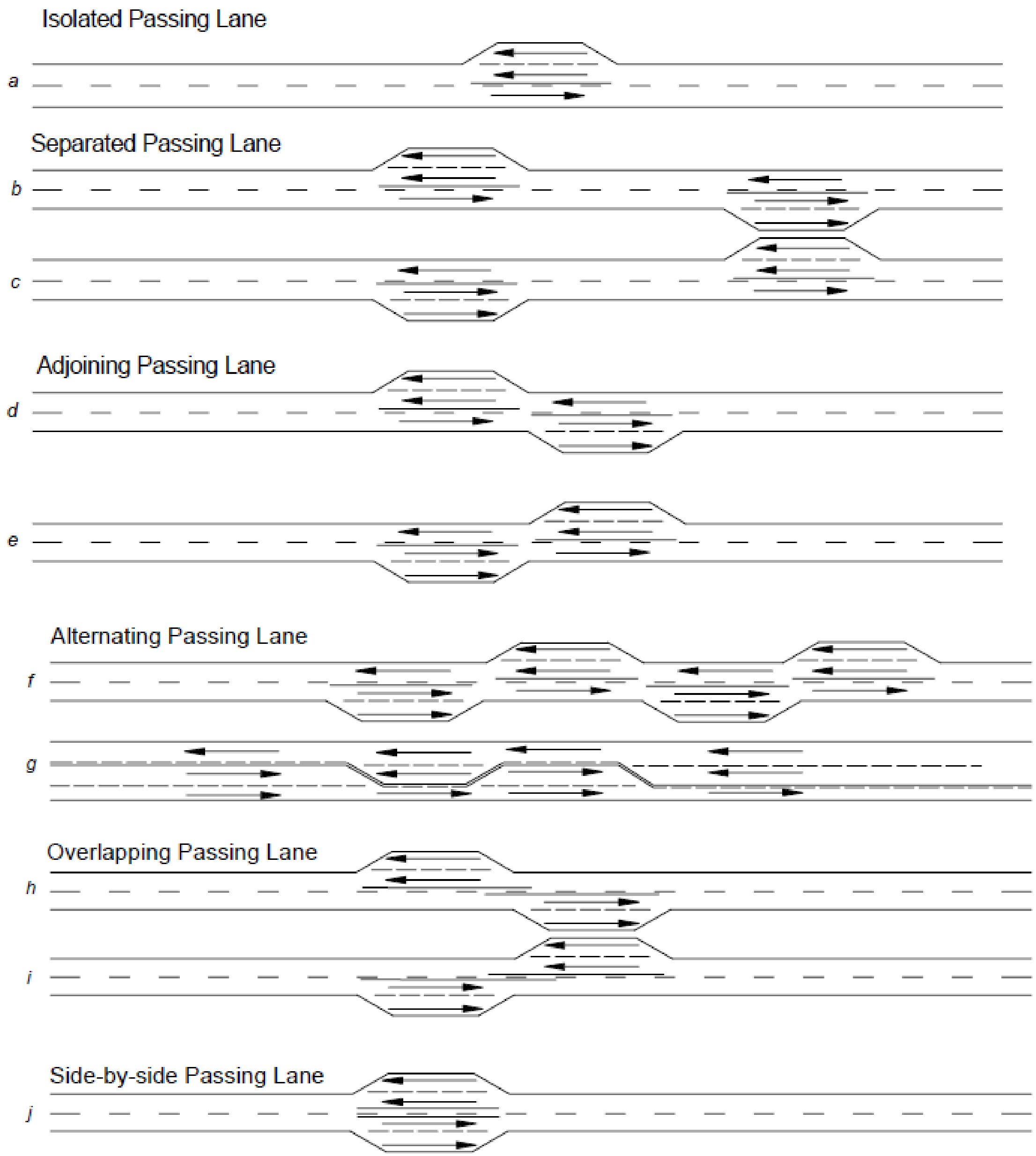



**Figure 3. Passing Lane Configurations (*12*)**

Because the Super 2 design allows such a high degree of flexibility, the practitioner has a great deal of latitude in the details of the design and implementation of a Super 2 corridor. This flexibility also means that the practitioner has a responsibility to exercise good engineering judgment in determining which details to include when designing and constructing the passing lanes and any other elements associated with a project that contains a Super 2 component. Many of the design details are consistent with the principles used for any rural highway, but the context of the passing maneuver on an otherwise two-lane highway needs to be considered. *Guidelines for Implementing Super 2 Corridors in Texas* (*13*) contains information on comparing cross-section alternatives and how to determine which of those alternatives is best to select for a given location based on operational, safety, and economic measures.

## SAFETY EFFECTS OF CROSS-SECTION TREATMENTS

### 4U-2T Conversions

Many studies have evaluated the safety effectiveness of projects and variations of 4U-2T conversions. For instance, the cross-section project deployed in Harrisburg, Pennsylvania, involved reducing travel lanes from three to two (i.e., a 2T to 2U conversion) and adding crosswalks, a bike lane, and other enhancements. This resulted in improved bicyclist and pedestrian accommodations, reduced average vehicle speeds from 40 to 35 mph, and enhanced safety and driver comfort without compromising traffic flow (*14*).

Rosales and Sousa (*3*) presented the results of a road diet treatment on St. George Street in Toronto, Ontario, that mainly involved curb extensions at specific locations in coordination with on-street parking and adding landscaping for enhanced urban environment. Their reported results are as follows (*3*):

- Crashes were reduced by 40 percent.
- Pedestrian and bicycle safety improved.
- No diversion of traffic was needed.
- Street crossing was simplified.
- Vehicular speeds were reduced.
- Pedestrian and bicyclist volumes increased.
- Landscaping provided a buffer to pedestrians and improved aesthetics.
- Over 80 percent of street users recommended similar road diet projects on city streets and university campuses when appropriate.

The Maryland State Highway Administration (SHA) funded a research study (*15*) to develop a Model of Sustainability and Integrated Corridors (MOSAIC) to help SHA estimate the sustainability impact of multimodal highway improvement options early in the transportation planning and environmental screening processes. In phase two of the project, they incorporated road diets into MOSAIC. In this study, the authors considered multiple socio-impact factors of different geometric improvement, one of which is aesthetics. They conducted an online survey and found that road diet had a minimal impact on aesthetics.

Chen et al. (*16*) developed a safety framework that considers three principal axes that affect crashes: why, who, and where. As shown in Figure 4, "why" relates to exposure, conflict, and speed, “who” considers the road users and their characteristics, and “where” considers the surrounding built environment.

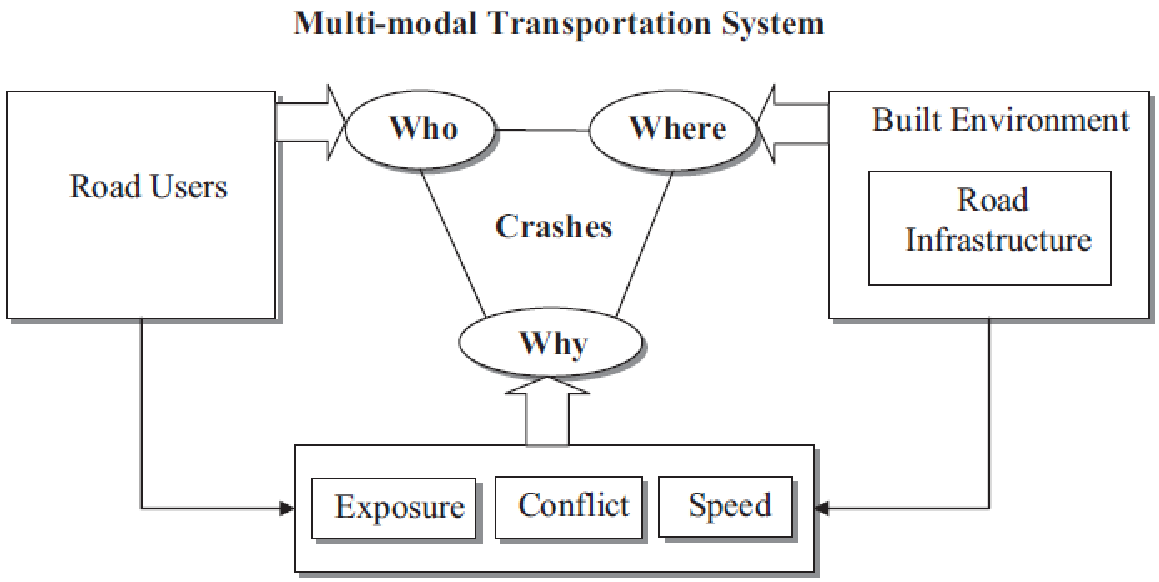



**Figure 4. Traffic Safety Framework (*16*)**

Using this framework and a before-after study with analysis of covariance (ANCOVA), these authors found that road diet projects can be highly effective. They found a reduction of segment-based total crashes by 67 percent, and injury and fatal crashes by 70 percent. They also concluded that similar reductions can be realized at intersections as well.

Persaud et al. (*17*) evaluated the effectiveness of the conversion of road segments from 4U to 2T in Iowa. They used two Bayesian approaches (empirical Bayes [EB] and full Bayes [FB]) and compared their performance. Their objective was to compare the two Bayesian methods rather than evaluating the effectiveness of the road diet itself. They found that the EB and FB results were comparable. The results showed that there was a significant reduction in left-turn, right-angle, and total crashes. The authors indicated that it may not be worth the considerable sophistication of undertaking FB studies when EB produces similar results; however, the FB is worth considering for situations where it is difficult to acquire a large enough reference group to calibrate safety performance functions required for the EB approach.

Fang et al. (*18*) presented the safety benefits of five arterial roadways in the City of Hartford in Connecticut that were placed on road diets. Every street was converted from four travel lanes (two in each direction) to two travel lanes (one in each direction) divided by an alternating left-turn lane. Parking lanes and bicycle lanes were also included on some of the post-diet streets. The authors then compared the safety performance of these streets to similar comparison roads that had not received any treatments. They used a simplified EB method to predict the “expected” crash rate of study sites during the “after” period without implementation. They found that three streets experienced large reductions and two streets had no significant change in crash rates after the road diet improvements were installed. The authors hypothesized that the large reduction in crash rates on three streets were mainly due to the decrease in speeds achieved by the road diet implementation. Speeds at the study sites were found to be reduced by up to six miles per hour, with an average reduction of three to four miles per hour. The authors also stated that the road diets prevented aggressive drivers from passing more prudent drivers, and as a consequence it eliminated one potential source of conflict.

Huang et al. (*19*) evaluated the effectiveness of road diets in cities located in California and Washington on motor vehicle crashes and injuries. The study considered 12 road diet sites and 25 comparison sites. Using a before-and-after analysis approach, the study found that the percent of crashes after conversion was 6 percent lower than that of the matched comparison sites. However, the result related to crash frequency or severity was not statistically significant. The authors found that the road diet slightly increased angle collisions but reduced rear-end collisions when compared to the comparison sites.

Noyce et al. (*20*) conducted research to determine the safety and operational characteristics of converting 4U highways to 2T. They considered nine sites in Minnesota and used a yoked/group comparison analysis for analyzing crash and operational data. The study results showed statistically significant reductions in total crashes by 37 percent, property damage-only (PDO) crashes by 46 percent, and left-turn crashes by 24 percent. The crash rates for total crashes and PDO crashes were reduced by 46 percent and 45 percent, respectively. Additionally, the change in the mean speed and 85th percentile speed was found statistically significant, but in both cases the change was less than two miles per hour. The analysis of before and after average daily traffic (ADT) data showed that the overall change in ADT was not statistically significant. The authors stated that there was no evidence to suggest that traffic diverted to other routes or that drivers changed travel behavior. The results of this research show that safety characteristics of a roadway are improved for a 4U-to-2T conversion when daily traffic volumes are less than 17,500 vpd.

### Other Cross-Section Conversions

Rahman et al. (*21*) evaluated the safety effectiveness of converting 4U highways to four-lane highways with a two-way left-turn lane (4T) in urban areas. The authors noted that while converting 4U to 2T and creating space for other uses, such as turn lanes, bus lanes, pedestrian refuge islands, sidewalks, bike lanes, transit stops, or parking, is the most prevalent road diet treatment, some agencies convert to 4T to accommodate increasing left-turn traffic towards the roadside establishments without sacrificing the capacity. The authors used the EB method to account for potential regression-to-mean bias and found that total crashes reduced by 58 percent after conversion to 4T. The authors also noted a substantial reduction of the predominant rear-end crashes on converted urban 4T highways.

Liu et al. (*22*) compared the safety performance of four-lane divided (4D) highways (i.e., four-lane highways with non-traversable median) with 4U, four-lane with 4-ft flush medians (4M), and 4T cross-sections. Since the cost of construction of 4D is typically high, the authors developed criteria to determine under what conditions each of the cross-sections yield maximum safety benefits while considering construction costs. The research team used the safety benefits and project construction costs to estimate benefit-cost ratios (BCRs) in developing the criteria. The criteria were based on AADTs, truck percentages, and access point densities.

Council and Stewart (*23*) used a cross-sectional analysis approach to evaluate the safety effects of the conversion of two- to four-lane roads and to determine whether there is any difference across multiple states. Their study results indicated that converting the "most typical" two-lane sections to the "most typical" four-lane divided sections resulted in a reduction of crashes per kilometer between 40 and 60 percent. When the best performing two-lane highways are converted to the worst performing four-lane or vice-versa, a crash reduction between 10 and 70 percent is still realized. However, when two-lane highways are converted to a four-lane undivided roadway, they found a 20-percent reduction to a slight increase in crash rate, depending on AADT.

Ahmed et al. (*24*) used data from Florida to evaluate the safety implications of upgrading two-lane roadways to four-lane divided roadways. They used various types of observational before-after (B-A) analyses such as naive, B-A with comparison group, EB, and FB methods. They noted that, with the use of FB methods, the intensive data requirements to perform the before-after with the EB method can be relaxed. The authors found that the conversion to four-lane divided highways yielded a reduction of more than 63 percent on urban roadways and a 45 percent reduction on rural roadways for fatal and injury crashes. Higher reduction was found for total and PDO crashes in urban areas than in rural areas. The authors concluded that better safety effects on total crashes were found when the AADT was greater than 10,000 vpd and 18,000 vpd for rural and urban roadway segments, respectively.

Lyon et al. (*25*) evaluated the safety effectiveness of installing TWLTLs on two-lane roads in North Carolina, Illinois, California, and Arkansas. The authors used an EB B-A approach to determine the safety effectiveness. They found a statistically significant reduction in total and rear-end crashes in each of the four states, especially those involving a lead vehicle desiring to make a turn. They noted that the treatment seems more likely to be effective in rural areas than in urban ones.

Fitzpatrick and Balke (*26*) examined differences in the operation and safety between four-lane rural highways with TWLTLs and four-lane rural highways with flush medians. The authors reviewed three years of crashes from four-lane rural highways with both types of median treatments in the Lufkin District in Texas. No statistical difference was found in crash rates and severity between highways with TWLTLs and highways with flush medians when driveway densities were low (i.e., less than 14.5 driveways per km). They also conducted field studies for evaluating the traffic operational characteristics of flush medians and TWLTLs on four-lane rural highways. They primarily evaluated how vehicles used the median area on highways with these two median treatments. Their field studies found that there was no difference in the way drivers used highways marked with TWLTLs and highways marked with flush medians. On both median types, the number of drivers observed using the flush median as a storage area and as an acceleration lane was about equal. The authors concluded that there was no difference in the way flush medians and TWLTLs function on four-lane rural highways.

Table 1 provides a summary of the preceding safety analysis sources and others. The findings are tabulated as crash modification factors (CMFs) for all crashes, fatal-and-injury (commonly referred to as KAB) crashes, or other types of crashes included in the analyses. Most of the sources focused on segment crashes, but one source also included intersection crashes. Two studies included a safety performance function (SPF) in the methodology. The sites in these analyses were urban or suburban arterials.

**Table 1. Summary of CMFs for 4U-2T Conversions**

| | | | | | CMFs for Segment-Level Crashes | | | CMFs for Intersection-Level Crashes | |
|---|---|---|---|---|---|---|---|---|---|
| **Source** | **State(s)** | **Number of Sites** | **Number of Miles** | **Methodology** | **All** | **KAB** | **Correctable** | **All** | **KAB** |
| *16* | NY | 460 | NR | B-A with ANCOVA | 0.33 | 0.30 | NR | NR | NR |
| *19* | CA, WA | 12 | NR | B-A with compare sites | 0.94 | NR | NR | NR | NR |
| *20* | MN | 9 | 10.6 | B-A with compare sites | 0.63 | NR | 0.76 | NR | NR |
| *27* | IA | 15 | 16.6 | Bayesian B-A | 0.75 | NR | NR | NR | NR |
| *28* | IA, CA, WA | 45 | 40.0 | B-A with SPF | 0.71 | NR | NR | NR | NR |
| *29* | MI | 24 | 20.0 | B-A with compare sites | 0.91 | NR | 0.59 | NR | NR |
| *30* | VA | 15 | 10.4 | B-A with SPF | 0.62 | 0.36 | NR | 0.65 | 0.54 |
| *31* | RI | 11 | 6.6 | B-A with reference sites | 0.71 | 0.63 | NR | NR | NR |

Note: NR = Not reported.

Lyles et al. (*29*) provided CMFs for all crashes and for crashes that are “correctable” by implementing a 4U-2T conversion. They listed rear-end crashes involving left-turning vehicles in the left lane as an example of correctable crashes. Noyce et al. (*20*) focused on left-turn-related crashes as a correctable crash type. Stamatiadis et al. (*32*) provided a list of correctable crash types that is repeated in Table 2.

**Table 2. Correctable Crash Types for 4U-2T Conversions (Adapted from *32*)**

| Correctable Crash Type | Rationale |
|---|---|
| Rear-end involving left-turning vehicles | Remove stopped left-turning vehicles from the inside through lanes. |
| Sideswipe | Eliminate the need to change lanes to avoid delay behind a stopped left-turning vehicle in the inside through lanes. |
| Left-turn-related due to offset left turns | Eliminate the negative offset between opposing left-turning vehicles and increase sight distance for left-turning drivers. |
| Bicycle-related | Provide space to separate bicycles from vehicles. |
| Pedestrian-related | Decrease crossing distance and possibly add refuge space. |

The crash types listed in Table 2 are shown as some of the conflict types visible in Figure 5. Table 3 provides an expanded list of crash types based on the illustrated conflict types and the list assembled by Stamatiadis et al. Most of the illustrated crash types are (at least partially) correctable with a 4U-2T conversion.

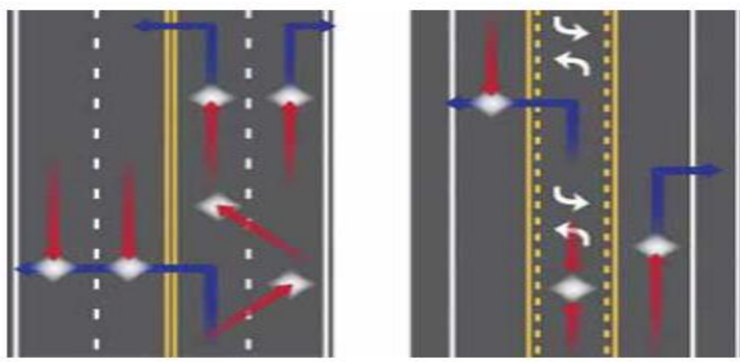
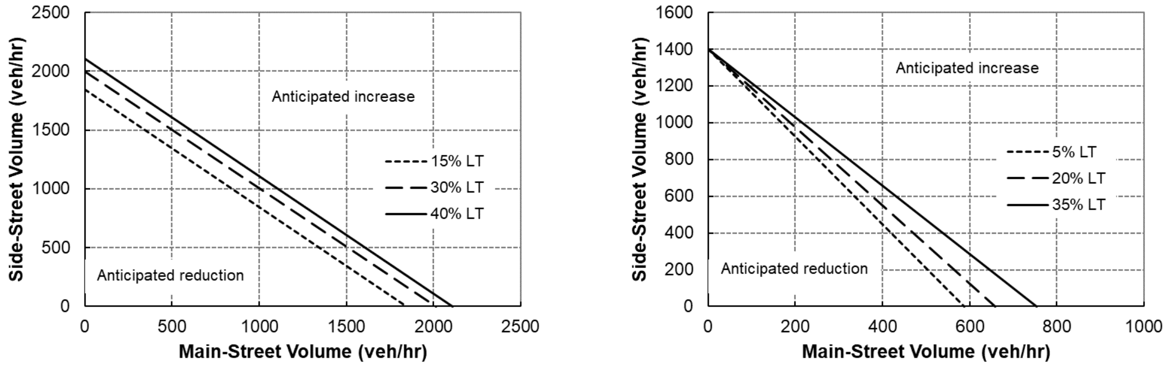


**Figure 5. Conflict Types (*33*)**

**Table 3. Expanded List of Crash Types for 4U-2T Conversions (*32*)**

| Category | Crash Type | Notes |
|---|---|---|
| Correctable | Rear-end involving left-turning vehicles | Provide median space for left-turning vehicles to use. |
| | Rear-end involving right-turning vehicles | Provide shoulder space that could be used by right-turning vehicles (depends on whether the shoulder space is marked for other uses, such as parking or bicycle lanes). |
| | Sideswipe | Eliminate the need to change lanes to avoid delay behind a stopped left-turning vehicle in the inside through lanes. |
| | Left-turn-related due to offset left turns | Eliminate the negative offset between opposing left-turning vehicles and increase sight distance for left-turning drivers. |
| | Bicycle-related | Provide space to separate bicycles from vehicles. |
| | Pedestrian-related | Decrease crossing distance and possibly add refuge space. |
| Partially correctable | Left-turn opposed and right-angle | Provide only one lane for opposing through vehicles. Eliminate the double-threat scenario where one opposing through driver stops to allow the left-turning driver to proceed while an opposing through driver in the other lane does not stop. |
| New to 2U configuration | Head-on in two-way left-turn lane | Opposing left-turning vehicles may encounter each other in the two-way left-turn lane. |

Figure 6 shows conflict guidelines developed by Stamatiadis et al. The regions on the graph represent combinations of hourly main-street volume and side-street volume where a 4U-2T conversion would likely increase or decrease conflicts, with sensitivity to left-turn percentage in addition to volumes. Similar to the trend shown in Figure 7, conflicts are expected to decrease with lower volume combinations but increase with higher volume combinations.




**a. Sideswipe Conflicts** **b. Rear-End Conflicts**

**Figure 6. Conflict Guidelines for 4U-2T Conversion (Adapted from *32*)**

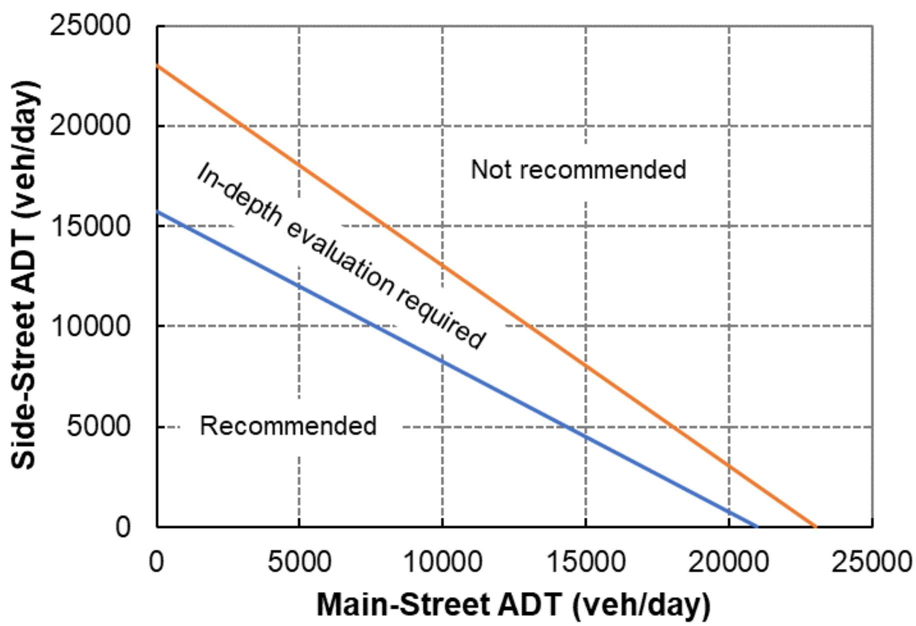



**Figure 7. Operational Performance Guideline for 4U-2T Conversion (Adapted from *32*)**

**Passing Lanes**

For passing opportunities in rural areas, passing relief lanes are provided on two-lane rural roads where there are extensive no-passing zones, high opposing traffic volumes, or both. Cafiso et al. (*34*) assessed the safety impact of the passing lanes using rear-end and lane-changing conflict analysis. The main objective of the study was to evaluate the application of the minimum passing lane lengths in terms of road safety. The author used microsimulation models and Surrogate Safety Assessment Model (SSAM) software for estimating the traffic conflicts. In this study, empirical data with varying minimum lengths were used for calibrating and validating the simulated model in terms of platoon sharing and overtaking maneuvers. The study found that passing lanes shorter than 2600 ft (800 m) worsen traffic safety and the number of conflicts increase exponentially with the traffic volume. For highways with peak hour volume greater than 800 vphpd, the study recommended passing lanes longer than 3280 ft (1000 m).

Gattis et al. (*35*) examined the effects of passing lane length on platooning, passing, speed, and passing lane crash rates. With the presence of passing lanes, the authors found a short-term increase in speed and amount of passing. However, they found that the more prevalent outcome of passing lanes is in the form of decreased platooning and increased safety. They noted that greater benefits were observed in the first 0.9 mi (1.5 km) and less pronounced benefits between 0.9 and 1.9 mi (1.5 and 3.0 km). The authors concluded that passing lanes may yield smaller benefits when the daily volumes are low.

In Sweden, passing lanes have been in use since the 1990s on rural 42-ft (13-m) two-lane roads. They use a median barrier to separate opposing flows, as shown in Figure 8.

**Figure 8. Passing Lane with a Median Barrier in Sweden (*36*)**

In 2009, Sweden also started using passing lanes on rural roads with a road width of about 30 to 33 ft (9 to 10 m). For these narrow roads, the share of passing lanes varies between 15 and 30 percent compared to about 40 percent for the 42-ft (13-m) roads. Vadeby (*36*) evaluated the safety effects of the narrow roads by conducting a B-A study with a control group. The study also used a limited EB approach to adjust for regression to the mean. The results showed that the total number of fatalities and seriously injured decreased by 50 percent and the total number of personal injury crashes decreased by 21 percent. The number of segment-only fatalities and seriously injured decreased by 63 percent and the personal injury crashes by 28 percent. Though the safety benefits were similar between wider and narrower roads, another research study found that the capacity for narrow roads is 15 percent less than for wider roads (*37*).

Because many studies, such as those previously mentioned here, provided a single-valued CMF for installing a passing lane, Persuad et al. (*38*) developed crash modification functions (CMFunctions) for evaluating the safety effectiveness of installing a passing lane or lengthening an existing one. The authors applied full Bayes Markov Chain Monte Carlo estimation techniques for developing the CMFunctions. Their study was built on an earlier one that developed and recommended single-valued CMFs for various crash types based on a cross-sectional analysis of Michigan two-lane rural roads with and without passing lanes. Persuad et al. (*38*) expanded Michigan data by including sites from Ontario, Canada.

While the fundamental benefits of a Super 2 emphasize operational measures of effectiveness, safety benefits exist as well because drivers are less likely to execute a passing maneuver in a two-lane section of the corridor. Depending on the traffic characteristics of the site in question, a Super 2 can also provide safety benefits that should be considered when determining what specific design alternative to select in an improvement project. Previous research in Texas by Brewer et al. (*45*) showed that that the installation of passing lanes on the corridors that were studied led to a statistically significant crash reduction of 35 percent for KABC segment-only crashes and 42 percent for KABC segment and intersection crashes. This finding is consistent with previous safety-related studies of Super 2 corridors, which show improvements in safety from the installation of passing lanes, even at traffic volumes higher than those considered under previous guidance in Texas.

A combination of data from studies in other states (*39*, *40*) produced a CMF for a conventional passing or climbing lane added in one direction of travel on a two-lane highway of 0.75 (i.e., a 25 percent reduction) for total crashes in both directions of travel over the length of the passing lane from the upstream end of the lane addition taper to the downstream end of the lane drop taper. This CMF assumed that the passing lane is operationally warranted and that the length of the passing lane is appropriate for the operational conditions on the roadway.

In addition to the crash reductions documented in the Texas research (*45*), the CMF Clearinghouse (*41*) provides results from other studies with similar reductions in crashes. A search on “passing lane” in the CMF Clearinghouse produces results ranging from 7 to 42 percent reductions in crashes, depending on the type of crash (e.g., roadway departure, head-on, etc.) or location (e.g., at intersection, not at intersection, etc.) being studied. Crash reduction benefits on a specific corridor will vary, but a practitioner installing new Super 2 passing lanes on a rural two-lane highway should expect some crash reduction along the improved corridor.

Thus, while a Super 2 is primarily an operational treatment, the treatment typically comes with safety benefits as well.

**Comparison of Cross-Section Treatments**

The research team used crash rates to compare the safety effectiveness of different existing cross-section alternatives. The analysis was conducted separately for total, KAB, and non-intersection crashes. The number of crashes on any given segment are due to multiple factors, but the length of the segment and traffic volume (which combined are known as "exposure") have a great influence. The cross-sectional alternatives considered for analysis are of differing lengths and traffic volumes. Therefore, it is desirable to know the crash rate to better understand the safety performance of each cross-section and to make comparisons between alternatives.

The crash rate takes exposure data of a cross-section into account when evaluating the safety performance compared to other alternatives. For exposure data, vehicle miles traveled (VMT) is typically used. The crash rate is calculated by dividing the total number of crashes on a given cross-section by the VMT, which is the product of length and traffic volume. Because the number of crashes relative to the number of vehicle miles is very small, the rates are expressed per million vehicle miles because the resulting values are more convenient to express and understand. The following formula is typically used to calculate the crash rate:

$$R_i = \frac{C_i \times 10^6}{N \times 365 \times VMT_i} \tag{1}$$

where $R_i$ is the crash rate for cross-section type $i$ (in million vehicle miles), $C_i$ is crash frequency at all segments of cross-section $i$, $N$ is the number of years of crash data considered, and $VMT_i$ is the total vehicle-miles traveled (product of traffic volume and the total mileage) on cross-section $i$.

Crash rates may be interpreted as the probability of being involved in a crash per instance of the exposure measure. In this task, first, the crash rates on different two-lane rural cross-section configurations were compared, as shown in Table 4. The table shows that the crash rate on Super 2 (2S) highways is always significantly lower than the crash rate on two-lane (2U) highways. The crash rate on Super 2 with TWLTL (2ST) is higher than that of 2S for all crash types but lower than 2U for total and non-intersection crashes. The 2ST configurations are present when there is a large number of driveways. It has been proven that the driveway presence increases the crash risk. The smaller sample size of 2ST may also have affected the results. Only two highways (i.e., US-79 and SH 36) were considered in this analysis. As such, the comparison could not be made for different ADT ranges.

**Table 4. Crash Rate Comparison between Two-Lane Configurations**

| ADT | Total Crashes | | | KAB Crashes | | | Non-Intersection Crashes | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2S** | **2U** | **2ST** | **2S** | **2U** | **2ST** | **2S** | **2U** | **2ST** |
| ≤ 2000 | 4.15 | 11.38 | NR | 0.98 | 4.27 | NR | 4.15 | 6.59 | NR |
| 2000–3000 | 5.36 | 9.87 | NR | 1.81 | 3.65 | NR | 4.45 | 6.13 | NR |
| 3000–4000 | 6.75 | 8.63 | NR | 2.70 | 3.13 | NR | 5.74 | 5.41 | NR |
| 4000–5000 | 5.76 | 8.62 | NR | 2.29 | 3.21 | NR | 4.96 | 4.97 | NR |
| 5000–10000 | 4.68 | 9.37 | 9.22 | 1.94 | 3.37 | 4.40 | 3.83 | 5.27 | 4.83 |
| > 10000 | 5.28 | 9.79 | NR | 2.15 | 3.77 | NR | 3.46 | 5.01 | NR |

Note: NR = Not reported.

Second, the crash rates on different four-lane rural cross-section configurations were compared, as shown in Table 5. The table shows that the crash rate on 4D highways is always significantly lower than the crash rate on 4T highways and 4U highways. The crash rate on 4T is higher for half of the situations, and 4U has higher crash rates for the other half of the situations. It should be noted that 4T configurations are present when there is a large number of driveways, and consequently the crash risk is increased due to presence of driveways.

**Table 5. Crash Rate Comparison between Four-Lane Configurations**

| ADT | Total Crashes | | | KAB Crashes | | | Non-Intersection Crashes | | |
|---|---|---|---|---|---|---|---|---|---|
| | **4D** | **4T** | **4U** | **4D** | **4T** | **4U** | **4D** | **4T** | **4U** |
| ≤ 5000 | 6.37 | 12.90 | 9.64 | 2.32 | 3.04 | 3.61 | 4.42 | 6.83 | 4.74 |
| 5000–10000 | 5.70 | 13.11 | 9.80 | 2.11 | 5.76 | 3.62 | 4.22 | 5.09 | 4.98 |
| 10000–15000 | 5.39 | 12.06 | 9.85 | 1.90 | 4.34 | 3.21 | 4.27 | 5.32 | 4.61 |
| 15000–20000 | 5.68 | 10.84 | 9.03 | 1.95 | 4.66 | 3.08 | 4.00 | 4.66 | 4.10 |
| 20000–25000 | 3.99 | 7.14 | 16.62 | 1.31 | 2.52 | 4.28 | 3.18 | 5.15 | 8.26 |
| 25000–30000 | 7.16 | 7.35 | 5.08 | 2.51 | 2.42 | 1.86 | 5.80 | 4.96 | 4.25 |
| > 30000 | 7.66 | 9.03 | 26.94 | 2.66 | 2.75 | 6.60 | 5.04 | 4.01 | 6.23 |

## Safety Performance Functions

In TxDOT research project 0-7035, the SPFs were developed for 2S, 4U, 4T, and 4M configurations (*10*). In this task, the SPFs were developed for 2U and 4D configurations and compared with other configurations, as shown in Figure 9. The SPFs for 4D and 2U highways do not include all the variables that influence the safety, and, as a result, a direct comparison should not be made with other cross-sectional configurations. Figure 9 is shown for informational purposes only.

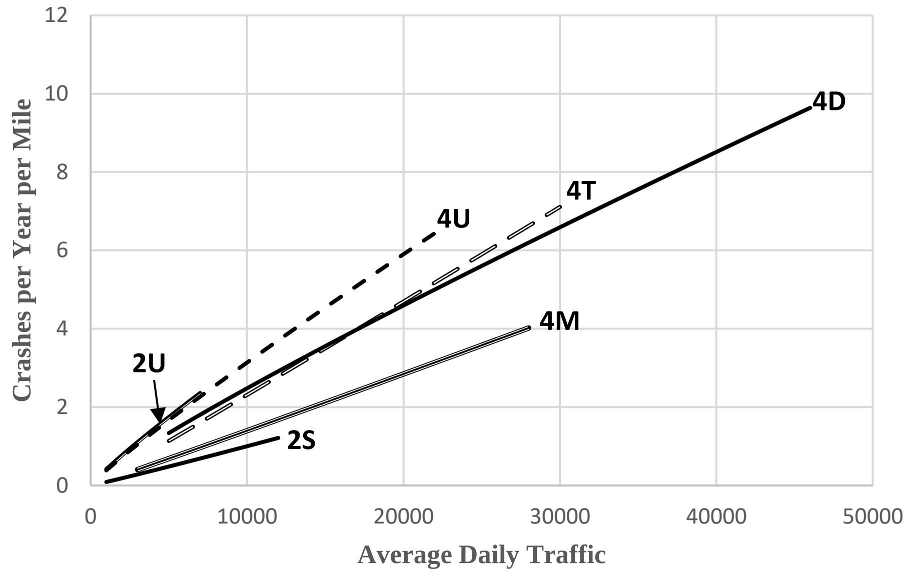



**Figure 9. Graphical Form of the SPF for Total Crashes**

## Safety Evaluation of Cross-Section Conversion

In 2019, a portion of the US-79 highway corridor in the Atlanta District was converted from a 4U cross-section to a 2ST cross-section. The research team evaluated the safety effectiveness of this conversion by considering the crashes in the before and after periods. Table 6 shows this conversion with the construction limits, construction dates, and before-after periods considered in this analysis.

**Table 6. Conversion from 4U to 2ST Cross-Sections**

| Limits | Construction Period | Before Period | Before ADT | After Period* | After ADT |
|---|---|---|---|---|---|
| Louisiana State Line to FM 31 | 08/20/2019 to 06/29/2020 | 08/20/2016 to 08/19/2019 (36 months) | 7149 | 06/30/2020 to 12/31/2022 (30 months) | 7596 |

* 12/31/2022 is the last date for which complete crash data were available.

Table 7 and Figure 10 show the change in crashes after the conversion. Although there is a slight increase in total crashes, fatal (K), incapacitating injury (A), and non-incapacitating injury (B) crashes decreased after the conversion to 2ST. There is an increase in intersection-related and angle crashes. It is unknown why these types of crashes increased, and thus further investigation is needed to determine the cause(s) of this increase and any potential related treatments. Also, there will be a change in driving patterns and safety over time that is due to factors other than just the exposure.

Table 7. Change in Crashes after Conversion from 4U to 2ST

| Crash Measure | Before Period Crashes | Before Period Crash rate | After Period Crashes | After Period Crash rate | Change in Crash rate | % Change in Crash rate |
|---|---|---|---|---|---|---|
| Total crashes | 67 | 1.22 | 63 | 1.29 | 0.08 | 6% |
| KAB crashes | 22 | 0.40 | 15 | 0.31 | −0.09 | −23% |
| KA crashes | 9 | 0.16 | 7 | 0.14 | −0.02 | −12% |
| B crashes | 13 | 0.24 | 8 | 0.16 | −0.07 | −30% |
| Int-related crashes | 17 | 0.31 | 26 | 0.53 | 0.22 | 73% |
| OD crashes | 6 | 0.11 | 5 | 0.10 | −0.01 | −6% |
| ROR crashes | 20 | 0.36 | 21 | 0.43 | 0.07 | 19% |
| SD crashes | 19 | 0.35 | 12 | 0.25 | −0.10 | −29% |
| Angle crashes | 12 | 0.22 | 19 | 0.39 | 0.17 | 79% |

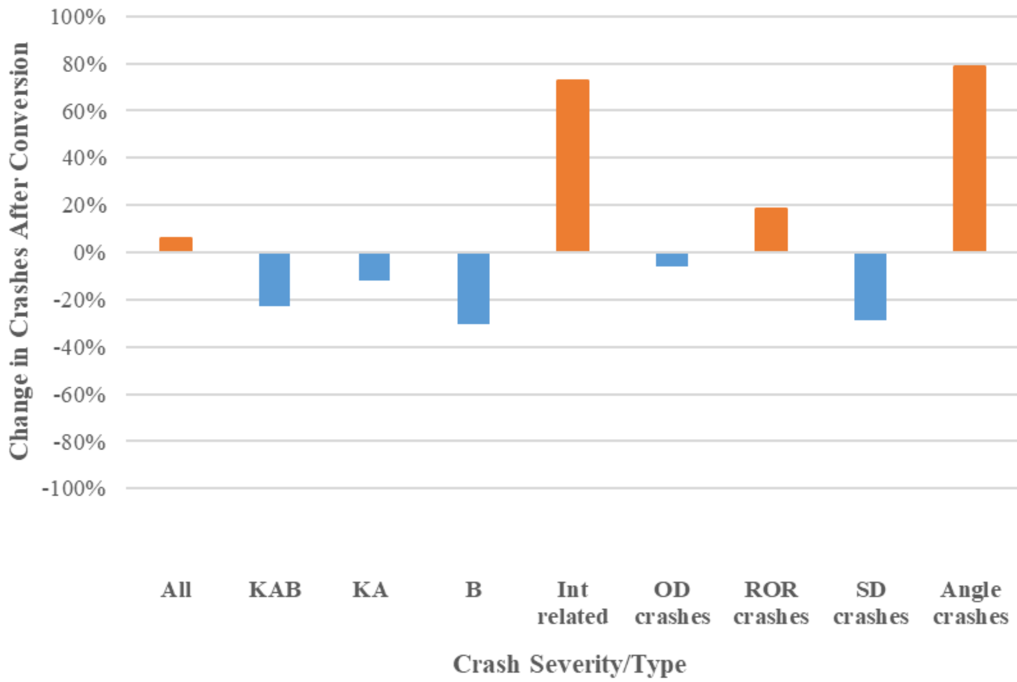



**Figure 10. Graphical Representation of Change in Crashes after Conversion from 4U to 2ST**

## OPERATIONAL EFFECTS OF CROSS-SECTION TREATMENTS

While there are multiple considerations for implementing a cross-section treatment, the effects on operations are forefront in evaluating potential alternatives. Operational effects of selected treatments are discussed in this section.

## Operational Effects of 4U-2T Conversions

Conversions from 4U to 2T configurations are commonly considered as treatments in lower-speed environments in urbanized and suburban areas. The reduced number of travel lanes in 4U-2T conversions typically facilitate the inclusion of accommodation for non-motorized road users, such as bicycle lanes and/or shorter crossing distances for pedestrians. Accommodation of transit and freight are also important considerations in determining suitable road diet treatments.

FHWA's *Road Diet Informational Guide* (*4*) lists the following benefits for 4U-2T conversions:

- Easier side-street traffic crossing—drivers crossing the main street can more easily make the crossing movement because they are crossing fewer lanes. This may reduce delays for the side streets if through volumes are low enough that sufficient gaps for crossing movements can be identified.
- Better accommodation of left turns into and out of side streets and driveways—if the volumes for these movements are high, a four-lane undivided cross-section will often function as a de facto three-lane cross-section because drivers must stop in a travel lane to wait for a safe gap to turn.
- Reclamation of cross-sectional space for bicycle lanes, on-street parking, or even sidewalks. Bicycle lanes or on-street parking can also serve as buffer space between pedestrians and through traffic.
- Availability of median space for pedestrian refuge islands.

The *Road Diet Informational Guide* additionally notes the following tradeoffs with a 4U-2T conversion:

- Increased congestion as vehicles queue behind stopped buses or mail trucks. Some drivers have been observed making illegal passing maneuvers in the TWLTL attempting to avoid this delay. This issue can be addressed with dedicated pull-outs or shoulders if adequate space is available.
- Pedestrian usage of the two-way left-turn lane as a refuge, possibly exposing them to moving vehicles in the lane. This issue can be addressed by installing a pedestrian refuge island if the location is known to have high pedestrian crossing volume.
- Narrowed through lanes on the main street.
- Concentration of through traffic into one lane, making it more difficult to find adequate gaps for crossing movements if through traffic volumes are sufficiently high.

Various case studies and simulation analyses have been conducted to examine the operational effects of 4U-2T conversions, accounting for these issues. These sources have generally found that 4U-2T conversion is feasible only on roads with volumes up to about 23,000 veh/day.

Stamatiadis et al. (*32*) developed guidance for 4U-2T conversions for the state of Kentucky that accounted for the tradeoff between safety and operational effects of the conversion. They provided a nomograph to show the expected benefit for a candidate conversion site based on the main-street and side-street traffic volumes at major intersections within the site. Figure 7 shows this nomograph. The guidance suggests that a roadway would be a good candidate for conversion if it has a main-street volume up to about 21,000 veh/day, and a possible candidate for conversion if it has a volume up to about 23,000 veh/day, depending on side-street volumes.

Gudz et al. (*42*) conducted a case study of a 4U-2T conversion in Davis, California, consisting of a 0.8-mile segment with a traffic volume of about 15,000 veh/day. Bicycle lanes were added as part of the conversion project, and the regulatory speed limit was lowered from 30 mph to 25 mph. The authors conducted a B-A study of travel times and bicyclist and pedestrian volumes in October 2014 and May 2015. The authors observed the following changes following the conversion:

- Mean travel time decreased from 210.1 s to 197.1 s (not statistically significant) in morning test runs.
- Mean travel time decreased from 228.2 s to 206.5 s (statistically significant) in evening test runs.
- The count of bicyclists traveling on the converted road increased by an average of 243 percent at intersections.
- The count of bicyclists crossing the converted road did not notably change.
- The count of pedestrians at intersections on the converted road decreased slightly, but the change was not statistically significant and may have reflected changes in events in the area.

Nixon et al. (*43*) conducted a case study of a 4U-2T conversion in San Jose, California, consisting of a 0.7-mile segment with a traffic volume of about 14,000 veh/day. Bicycle lanes were added as part of the conversion project. The site had a 25-mph regulatory speed limit and space for parallel on-street parking both before and after the conversion. The authors conducted a B-A study of vehicle counts and speeds on the treated road and adjacent roads in February 2015 and February 2016. They included adjacent roads to determine how much traffic volume, if any, diverted from the treated road as a result of the treatment; however, they noted that their analysis did not include control or comparison sites, so they could not be certain if observed changes were caused by the treatment or other area-wide trends. They also did not conduct statistical testing due to limited sample size. They observed the following trends in descriptive statistics:

- Daily traffic volumes decreased on the treated road, both on the segment that was converted and on an unchanged segment south of the conversion. The magnitudes of these decreases were 6 percent and 2 percent, respectively.

- Peak-hour traffic volumes decreased on the treated and untreated segments by magnitudes ranging from 10 percent to 23 percent.
- Volume changes on adjacent major streets and neighborhood streets were negligible.
- The proportion of drivers exceeding the regulatory speed limit by 5+ mph or 10+ mph decreased notably on the converted segment, but increased notably on the unconverted segment, adjacent major streets, and adjacent neighborhood streets. Table 8 provides a portion of the data that Nixon et al. reported for changes in speeding behavior.

**Table 8. Changes in Speeding Vehicles at and near a 4U-2T Conversion (Adapted from *43*)**

| Amount Over Limit | Time Period | Converted Segment | | Unconverted Segment | | Adjacent Major Streets | | Adjacent Neighborhood Streets | |
|---|---|---|---|---|---|---|---|---|---|
| | | Count | % | Count | % | Count | % | Count | % |
| 5+ mph | All day | −1625 | −44 | 365 | 24 | 375 | 24 | 75 | 16 |
| | AM peak | −231 | −55 | 25 | 21 | 40 | 34 | 15 | 34 |
| | PM peak | −168 | −63 | 37 | 26 | 40 | 31 | 6 | 12 |
| 10+ mph | All day | −525 | −60 | 101 | 38 | 111 | 43 | 31 | 36 |
| | AM peak | −68 | −70 | 10 | 63 | 10 | 59 | 4 | 53 |
| | PM peak | −42 | −82 | 10 | 42 | 9 | 53 | 2 | 28 |

Nixon et al. explained that an examination of average speeds before and after the conversion can reveal whether the conversion unreasonably decreased speeds on the converted segment, but an examination of the number of speeders above a specified threshold is more important because it allows the analyst to determine if the conversion succeeded in reducing the number of vehicles traveling at dangerous speeds. They also explained that percentage changes may be more informative on arterials that have higher volumes, but absolute changes may be more informative on neighborhood streets where volumes are low and an absolute increase of just a few speeding vehicles may pose a notable threat to pedestrians and bicyclists, particularly children who may be playing in these streets.

### Operational Benefits of Super 2 Highways

Because the Super 2 is primarily an operational treatment, current Super 2 guidelines emphasize consideration of operational effects. Previous research in Texas (*44*) demonstrated that periodic passing lanes can improve operations on two-lane highway corridors with low to moderate volumes (e.g., ADT at or below 5,000 vpd), but more recent research (*45*, *46*) indicates that Super 2 corridors can provide operational benefits for volumes as high as 19,000 vpd. Results from Brewer et al. (*45*) shown in Figure 11 indicate that a roadway with nearly 15,000 ADT sees a decline in both delay and the percent time spent following as the number and length of passing lanes increase, in both rolling and level terrain, even as the truck percentage increases.

Research also indicates that providing passing lanes on two-lane rural highways provides a benefit in reduced delay and time spent following, which improves operations and reduces the need for drivers to pass on two-lane sections. A single passing lane has a carryover benefit into the downstream two-lane section because previous platoons are partially or completely dispersed and traffic flow is improved. This carryover benefit of a single passing lane exists for high-volume locations, but it is even greater for low-volume sites where a single slower vehicle can delay a higher proportion of trailing vehicles.

A similar look at average speeds across a variety of cross-sections in Figure 12 shows that Super 2 corridors perform better than two-lane undivided roadways at every volume level. The Super 2 cross-sections also perform as well as or better than most other options across the ADT spectrum. Table 9 shows a description of the abbreviations for each cross-section in the legend in Figure 12.

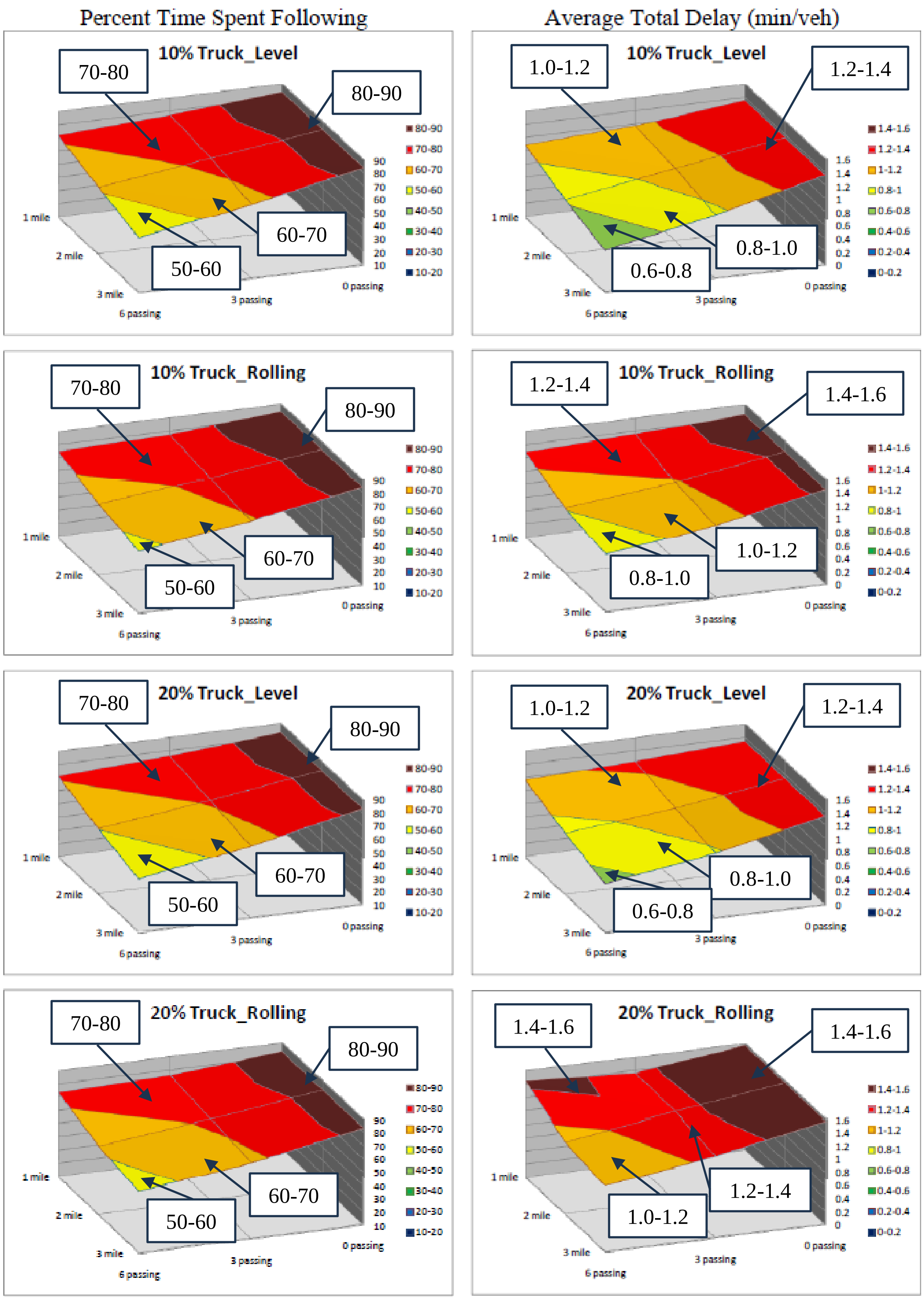



**Figure 11. Performance Measures for Different Passing Lane Configurations—14,667 ADT Scenarios (*45*)**

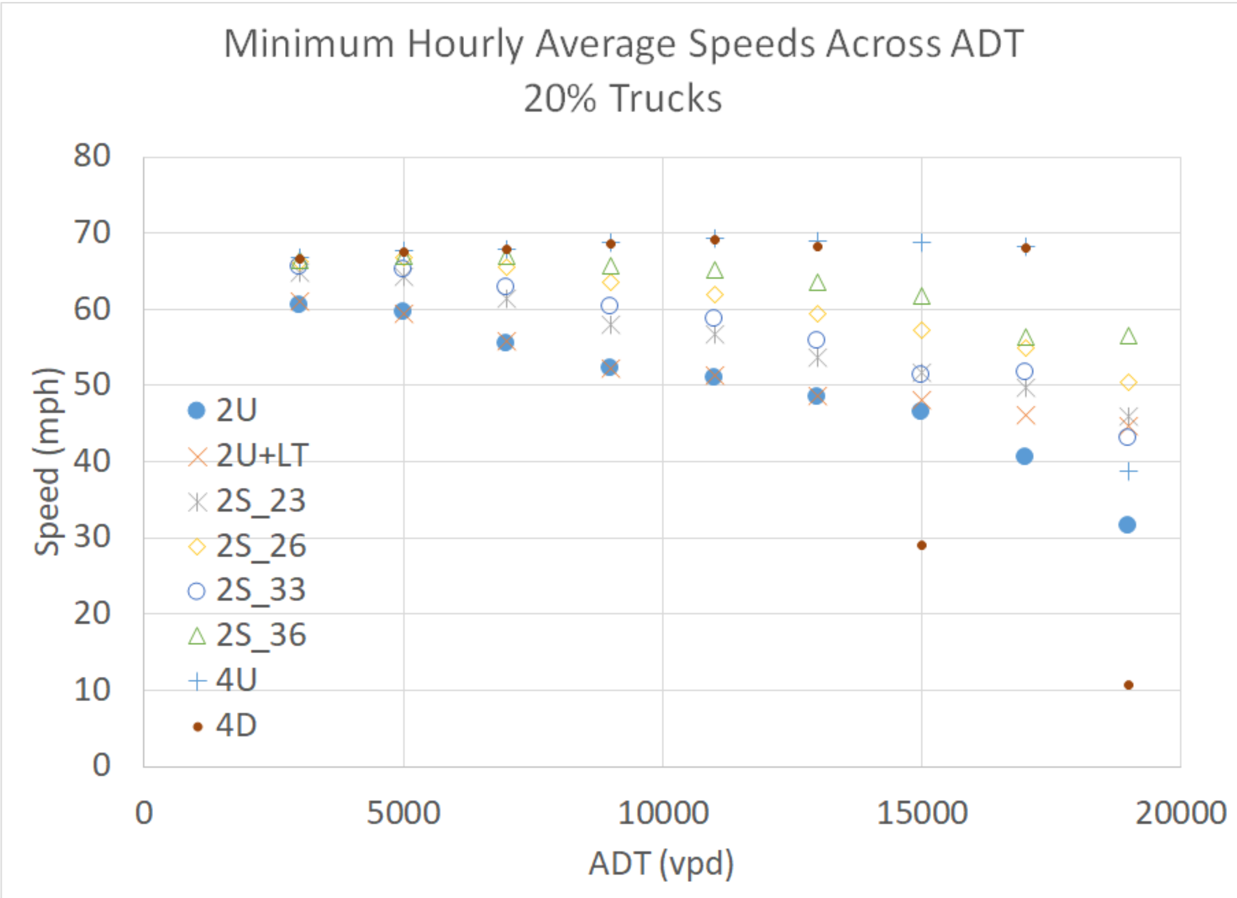



**Figure 12. Minimum Hourly Average Speeds across ADT—20 Percent Trucks (*46*)**

**Table 9. Description of Cross-Section Abbreviations (*46*)**

| Abbreviation | Cross-Section | Passing Lane Length | Number of Passing Lanes in Each Direction |
|---|---|---|---|
| 2U | 2-lane undivided | None | None |
| 2U+LT | 2-lane undivided with left-turn lanes at highway intersections | None | None |
| 4U | 4-lane undivided | None | None |
| 4D | 4-lane divided | None | None |
| 2S-23 | Super 2 | 2 miles | 3 passing lanes |
| 2S-33 | Super 2 | 3 miles | 3 passing lanes |
| 2S-26 | Super 2 | 2 miles | 6 passing lanes |
| 2S-36 | Super 2 | 3 miles | 6 passing lanes |

As a result, there is not an upper limit of ADT for the installation of passing lanes. There is a theoretical capacity of a two-lane highway above which a four-lane cross-section will perform better, but adding passing lanes can substantially extend this theoretical capacity.

While ADT need not be a limiting factor in installation, it can be used to prioritize candidate sites for passing lanes, particularly when considering truck volumes. A traffic analysis of candidate sites will help the designer determine which locations may receive greater benefit from lengthening existing passing lanes or installing new passing lane sections.

Super 2 corridors can accommodate heavy vehicles as well. Relative to ADT, truck percentage tends to have very limited impact on many performance measures, particularly the influence by truck percentage on percent time spent following. That said, an increase in trucks does affect the operational performance of a highway, and, in comparison to a traditional two-lane highway, the addition of passing lanes can provide benefits in average delay and the number of passing maneuvers completed.

An important consideration in evaluating the expected performance of an improved two-lane highway corridor is the amount of traffic that travels the entire length of the corridor compared to vehicles that turn into and/or out of access points within the corridor. A Super 2 corridor is most effective for through traffic because it provides passing opportunities for vehicles that are traveling long distances. A corridor that has frequent driveways or intersections (particularly locations that are substantial traffic generators) may see greater benefit from turning treatments (e.g., left-turn lanes, wider shoulders, acceleration/deceleration lanes for right turns, etc.) than from additional opportunities for high-speed passing. Turning and passing treatments are not exclusive—both can be installed on the same corridor—but on corridors where a high level of turning traffic creates interrupted flow, passing lanes may not be as effective as on corridors that primarily or exclusively serve through traffic.

As budget, terrain, and other factors allow, passing lanes may be added or lengthened to provide additional passing opportunities regardless of volume. There is, of course, the proviso that as passing lanes are added and lengthened, the highway more closely resembles a four-lane undivided alignment, and the incremental cost and operational benefits of each added lane can diminish. (*13*)

## EXISTING PRACTICES

The TxDOT RDM (*11*) contains descriptions of cross-sectional elements based on the classification of the roadway (e.g., rural or urban freeway, rural highway, urban or suburban street). Regarding medians, the RDM says that they are provided primarily to separate opposing traffic streams. The general range of median width is from 4 ft to 76 ft, with design width dependent on the type and location of the highway or street facility and the need to accommodate U-turn movements. Medians in rural areas are often wider than in urban areas, with a recommendation of 76 ft to provide complete shelter for trucks at median openings and crossovers. For low-speed urban arterial streets, flush or curbed medians are used, where a width of 16 ft will effectively accommodate left-turning traffic for either raised (turn lane plus raised median) or flush medians; however, where pedestrian refuge is a consideration for raised medians, the RDM states that a 6-ft width raised median, measured from the back of curb, is preferred. The RDM provides guidance for lane and shoulder widths as well, but it does not specify how many lanes should be provided for a given roadway classification; rather, guidance is provided for urban streets, suburban roadways, and two- and four-lane rural highways as well as freeways.

In Chapter 3 on new location and reconstruction (4R) design criteria for urban streets, the RDM discusses raised, flush, and TWLTL medians:

- A raised median is used on urban streets where it is desirable to control or restrict mid-block left-turns and crossing maneuvers. A raised median design should be considered where:
  - ADT exceeds 20,000 vpd;
  - New development is occurring, and volumes are anticipated to exceed 20,000 vpd; or
  - There are operational concerns for mid-block turns.
- Flush medians are medians that can be traversed. Although a flush median does not permit left-turn and cross maneuvers, it cannot physically prevent these maneuvers because the median can be easily crossed. Therefore, for urban arterials where access control is desirable, flush medians should not be used.
- Two-way left-turn lanes are flush medians that may be used for left turns by traffic from either direction on the street. The TWLTL is appropriate where there are operational concerns for mid-block turns, such as areas with (or expected to experience) moderate or intense strip development. Used appropriately, the TWLTL design can improve the safety and operational characteristics of streets as demonstrated through reduced travel times and crash rates. A site can be considered suitable for the use of a TWLTL when an urban street meets the following criteria:
  - Future ADT volume of greater than 3,000 vpd for an existing two-lane urban street, 6,000 vpd for an existing four-lane urban street, or 10,000 vpd for an existing six-lane urban street; and
  - Side roads plus driveway density of 20 or more entrances per mile.

Guidance for medians on suburban roadways is similar to that of urban streets, with discussion of raised medians and TWLTLs.

Medians are not discussed for two-lane rural highways in the 4R chapter of the RDM, but there is guidance for medians on multi-lane rural highways. In areas that are likely to become suburban or urban in nature, medians wider than 60 ft should be avoided at intersections except where necessary to accommodate turning and crossing maneuvers by larger vehicles. Wide medians may be a disadvantage when signalization is required at future intersections. The increased time for vehicles to cross the median can lead to inefficient signal operation. Conversion of a two-lane highway to a four-lane highway facility should include a median when possible. If an existing two-lane highway has rolling terrain or restricted ROW conditions, conversion to a four-lane undivided highway may be considered to improve passing opportunities and traffic operations. In cases where a median is being proposed and the existing roadbed will remain in place, Non-Freeway Rehabilitation (3R) alignment criteria may be applied to the existing roadbed, as described in Chapter 4; however, 4R criteria must be applied to the new roadbed. The 3R criteria do not contain specific directions on medians, but they do indicate lane widths of at least 11 ft for most conditions, with an encouragement to consider 12-ft lanes in conjunction with rehabilitation projects where the highway is a high-volume route utilized extensively by large trucks. The 4R criteria indicate a minimum of 11 ft for lane widths on urban and suburban streets (with a preferred width of 12 ft), 12 ft on multilane rural highways, and 10 to 12 ft on two-lane rural highways depending on volumes.

**Existing Practices for Cross-Sections**

The AASHTO *Green Book* (*8*) discusses number of lanes in its guidance on the cross-sections of different street and roadway categories. In Section 7.2.3.2, it says that the number of traffic lanes on a rural arterial should be determined based on consideration of volume, LOS, context category, and capacity conditions. For urban arterials, in Section 7.3.3.4, it says that the number of lanes varies depending on traffic demand, presence and needs of other users, and availability of ROW; a capacity analysis for all users should be performed to determine the proper number of lanes in consideration of the space needed to accommodate all users of the right of way.

The AASHTO *Green Book* refers to the *Highway Capacity Manual* (HCM) (*47*) for more guidance on capacity and LOS. The HCM states that, in general, uninterrupted flow can exist when there is no traffic signal or other traffic control device to interrupt traffic for at least 2 miles and no platoons are formed by upstream signals. Under those conditions, Chapter 15 of the HCM considers the capacity of a two-lane highway to be 1,700 passenger cars/hour (pc/h) in one direction or 3,200 pc/h in both directions, under base conditions. For a multilane highway, described in HCM Chapter 14, capacity is 2,200 pc/h/lane for a free-flow speed of 60 mph; with each 5-mph decrease in free-flow speed to 45 mph, capacity decreases by 100 pc/h/lane. Similarly, Chapter 11 of the HCM states that the capacity of a basic freeway segment under base conditions is 2,400 pc/h/lane at a free-flow speed of 70 or 75 mph; the capacity decreases by 50 pc/h/lane for every decrease of 5 mph in free-flow speed to 55 mph. Thus, the HCM capacity could be used as a threshold for the volume at which to consider widening a roadway and adding lanes to a highway with uninterrupted flow.

Several states have policies on 4U-2T conversion. The following resources are examples of stand-alone policies and guidance documents published by state and local agencies. Most of these policy documents are checklists or forms that are intended for use in the development of a 4U-2T conversion project, focusing on administrative issues or general principles rather than quantitative thresholds for assessing the feasibility of the project.

- Florida Department of Transportation's (FDOT's) *Statewide Lane Elimination Guidance* (*48*, *49*) provides 4U-2T conversion and space reallocation guidance (referred to as lane elimination). These documents include examples and impacts of 4U-2T conversions in Florida, guidance for development of a 4U-2T conversion review process, and discussion of issues associated with the conversion. These documents are intended to assist FDOT district staff in developing processes for reviewing requests for lane elimination on state highways.
- FDOT's *Lane Repurposing Guidebook* (*50*) contains guidance for various types of lane-repurposing concepts, including the 4U-2T conversion. This document acknowledges the need to evaluate lane-repurposing projects based on their impacts on all travel modes, not just the LOS for automobiles. The document also states that when a project like a 4U-2T conversion is implemented, it may have impacts on adjacent roadways, which will often be controlled by other jurisdictions, and that these impacts must also be measured and considered. In the case of a 4U-2T conversion, for example, reducing travel lanes on a roadway will cause some through traffic to divert to parallel routes.
- Maine Department of Transportation's (MaineDOT's) *Guidelines to Implement a Road Diet or Other Features Involving Traffic Calming* (*51*) provides 4U-2T conversion guidance for Maine municipalities. The document includes a brief overview of the treatment, Maine-specific implementation guidance, an overview of the countermeasure's limitations, and a list of minimum study requirements. This document specifies conditions where a 4U-2T conversion may not be appropriate, including sites where traffic volumes exceed 20,000–25,000 vpd, LOS or travel time is significantly affected, or unsignalized intersections or driveways have overlapping left-turn paths. This document also acknowledges that if a 4U-2T conversion is considered for a roadway that abuts adjacent municipalities, all affected municipalities should be involved in the request for the project.
- Michigan Department of Transportation's (MDOT's) *Road Diet Checklist* (*52*) is a step-by-step list used by agency personnel when considering the applicability of a 4U-2T conversion in a given situation. It includes consideration of general items such as local municipality approval and funding sources, complete streets items such as accommodation for transit riders and non-motorized road users, operational and safety items such as delay analysis and road safety audit review, and environmental items. Department staff should use the completed checklist along with engineering judgment to determine if a road diet should be implemented.
- St. Louis County's (Missouri) *Road Diet Policy* (*53*) provides factors to consider when determining if a 4U-2T conversion is feasible for a location, including average weekly traffic (AWT) volumes, directional peak hour volumes, left turns, intersection impacts, alternate bypass routes, bus transit, bicyclists, and pedestrians. The AWT is considered to be the first indicator as to whether a road diet will be successful; roadways with less than 15,000 AWT are deemed to have good feasibility, while roadways with more than

20,000 AWT are not considered for conversion. The policy also discusses the benefits of temporary field tests for striping and parking, the importance of which increases with traffic volume.
- California's Institute for Local Government (*54*) documents the polices related to 4U-2T conversions in California, as well as examples of implementation.

The research team further investigated existing practices in other states by reviewing a selection of state design manuals and related guidance. Of the 16 states in which an online search was conducted, 12 states had online manuals and/or guides available for review. In general, those states relied on the HCM to determine the appropriate (theoretical) capacity for two-lane and four-lane roads; the implied or stated practice is that when a street or highway approaches or exceeds the capacity for two lanes, then a four-lane facility is appropriate. Those capacities are often expressed in state manuals in terms of design hourly volume (DHV). Lane widths were also commonly either specified as 12 ft (except for intersection approaches where ROW is restricted and/or low-volume, low-speed roadways) or the state guidance referred to the AASHTO *Green Book* for widths. Some states provided additional guidance on selecting the number or type of lanes.

Arizona's *Roadway Design Guidelines* (*55*) describes a selection of predefined cross-sections and provides additional guidance:

- Section 301.3: "The pavement width shall provide for the number of traffic lanes required by the projected traffic volumes plus the appropriate minimum paved shoulder widths given in Table 302.4."
- Section 306.2: "Areas where rural cross sections should be used are characterized by open public lands or private lands with very sparse development; very limited and generally minor side access requirements; away from populated areas; and, reasonably not subject to development. Highways in these areas will have higher operating, posted, and design speeds. The highways will be uncurbed except as required for drainage and embankment erosion control."
    - Rural Section A (RA) "is required where the design year DHV exceeds 800 vph and should be considered where the DHV is above 500 vph. The section is applicable to both controlled and non-controlled-access highways." Rural Section B (RB) "should be used when the design year DHV is between 200 vph and 800 vph." Rural Section C (RC) "may be used on State routes and miscellaneous roads when the design year DHV is less than 200 vph." Examples of these cross-sections are shown in Figure 13.
- Section 306.3: Fringe-urban cross sections "are applicable to highways in those areas which do not meet the definitions of urban or rural area. Generally, the fringe-urban areas could be classified as suburban or emerging areas. In such areas, there is a reasonable expectation that the area would undergo some level of urbanization within the 20-year

design projection period of highway projects. These areas have light to moderate general development with sparse commercial or other major traffic generating development, and they are generally proximate to a city or town." These highways "have higher operating and posted speeds than in an urban area, but there is an expectation that both will decline during the 20-year design period of the highway. Generally, there is no curb with initial construction; however, curbs may be needed in the future." Selection of a cross-section for a fringe-urban area should recognize the probable length of time between initial construction and the need for conversion to an urban section; short-term conversions are typically anticipated within 5-10 years of construction, while more than 10 years is considered long-term.

  - Short-term conversion Section IS1 (shown in Figure 14) is the preferred section for fringe-urban areas where the design speed is 45 mph or less. The divided roadway section with a curbed median can be readily converted to an urban section by saw-cutting the excess width paving and constructing a curb and gutter at the outer edge of the roadway.
  - Short-term conversion Section IS2 with a flush median may be used only where a divided roadway is not practical and feasible, or where the current level of strip development has progressed to the point where a divided roadway could not be readily implemented. A median barrier is not required; the paved median may be used as a left-turn lane.
  - Short-term conversion Section IS3 is a divided roadway section with an uncurbed, unpaved median; it should be used where a divided roadway is practical and feasible, and where the design speed is normally 50 mph or greater. The median width for Section IS3 is 46 ft. The initial design for the four-lane section shall include a concept, including normal and superelevated typical sections, for a future widening. The future widening could provide a two- or three-lane section with a raised median.

- Section 306.4: Urban cross-sections should be used in areas "characterized by reasonably continuous current development, or expectations of such within five years, and a high density of side access points. The urban sections normally are used within a city or town." (See Figure 15 and Figure 16 for examples.)
  - Urban Section UA "should be used on highways for the initial construction to four lanes. This section is normally used as the urban extension of a divided rural or fringe-urban highway. Use of this section should be based, in part, on a consideration of the access requirements of adjacent properties. The section may not be appropriate for areas of heavy strip development. A 17-ft outside lane, inclusive of curb and gutter, is to further accommodate bicycle usage."
  - Urban Section UB "should be used where an existing four-lane undivided highway is being widened or where existing strip development requires the continuous two-way left-turn lane. A 17-ft outside lane, inclusive of curb and gutter, is to further accommodate bicycle usage."

- Urban Section UC "has limited usage and is applicable only in small urban areas with low traffic volumes. This section would be the final upgrading where volumes do not warrant four lanes."
- Urban Section UD "is to be used for the urban portions of controlled-access highways." The ultimate facility has four lanes in each direction and the interim facility has three lanes in each direction. Normal crown sections are shown in each of the figures.
- Non-standard sections can be used on a limited, restricted basis, subject to prior approval. "Use of a three-lane section is restricted to local traffic or non-through routes (i.e., routes with little or no external through traffic, which have very restrictive existing right-of-way). Further, the section is limited to application in small urban areas, and where implementation will constitute final, ultimate construction. The roadway will be 44 ft wide with two 12-ft through lanes, a 12-ft turn lane, and 4-ft non-curbed shoulders on each side. With curb and gutter, use a 17-ft wide outside lane inclusive of curb and gutter to further accommodate bicycle traffic."

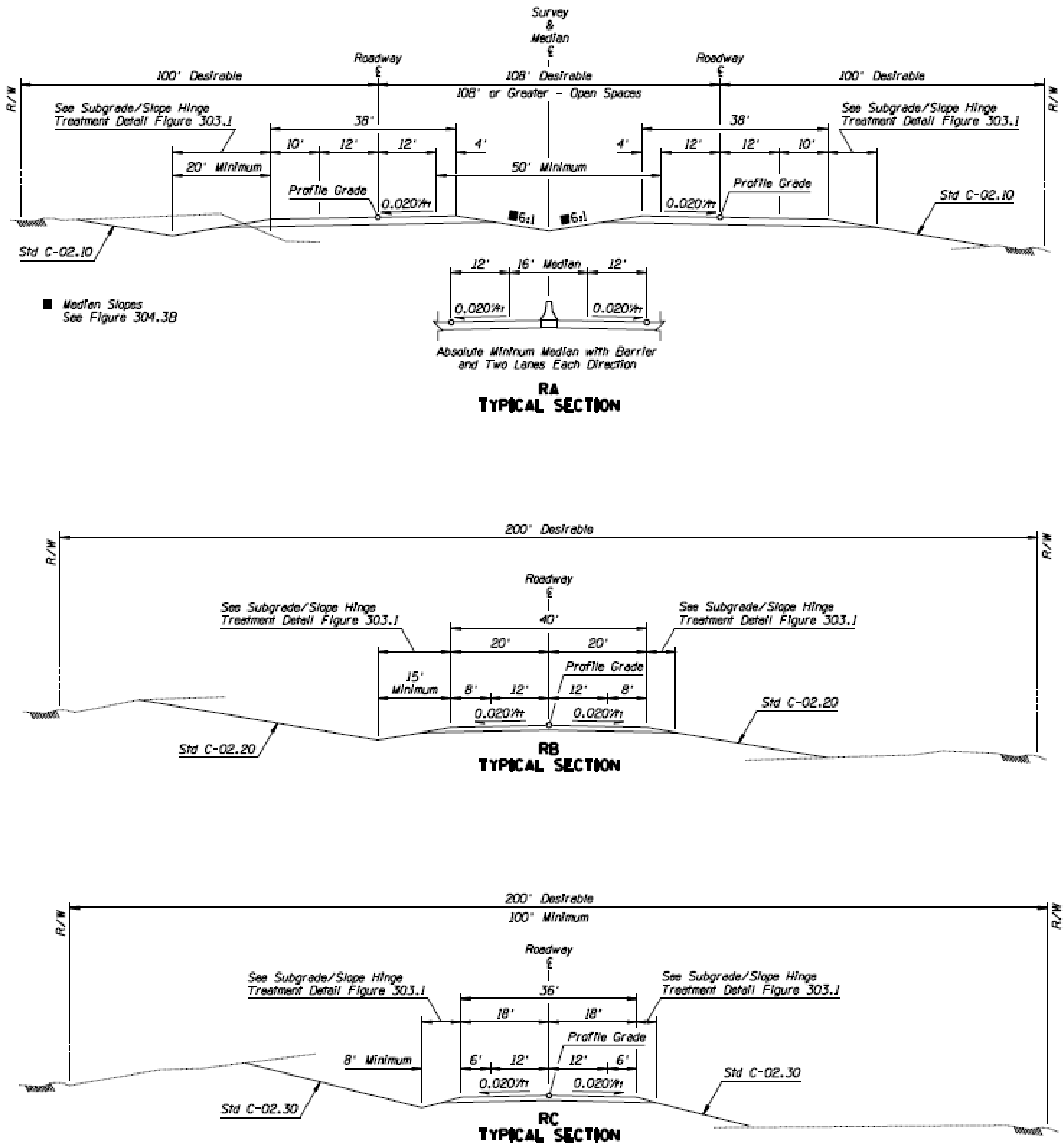



**Figure 13. Arizona Rural Highway Typical Sections (Figure 306.2 in *55*)**

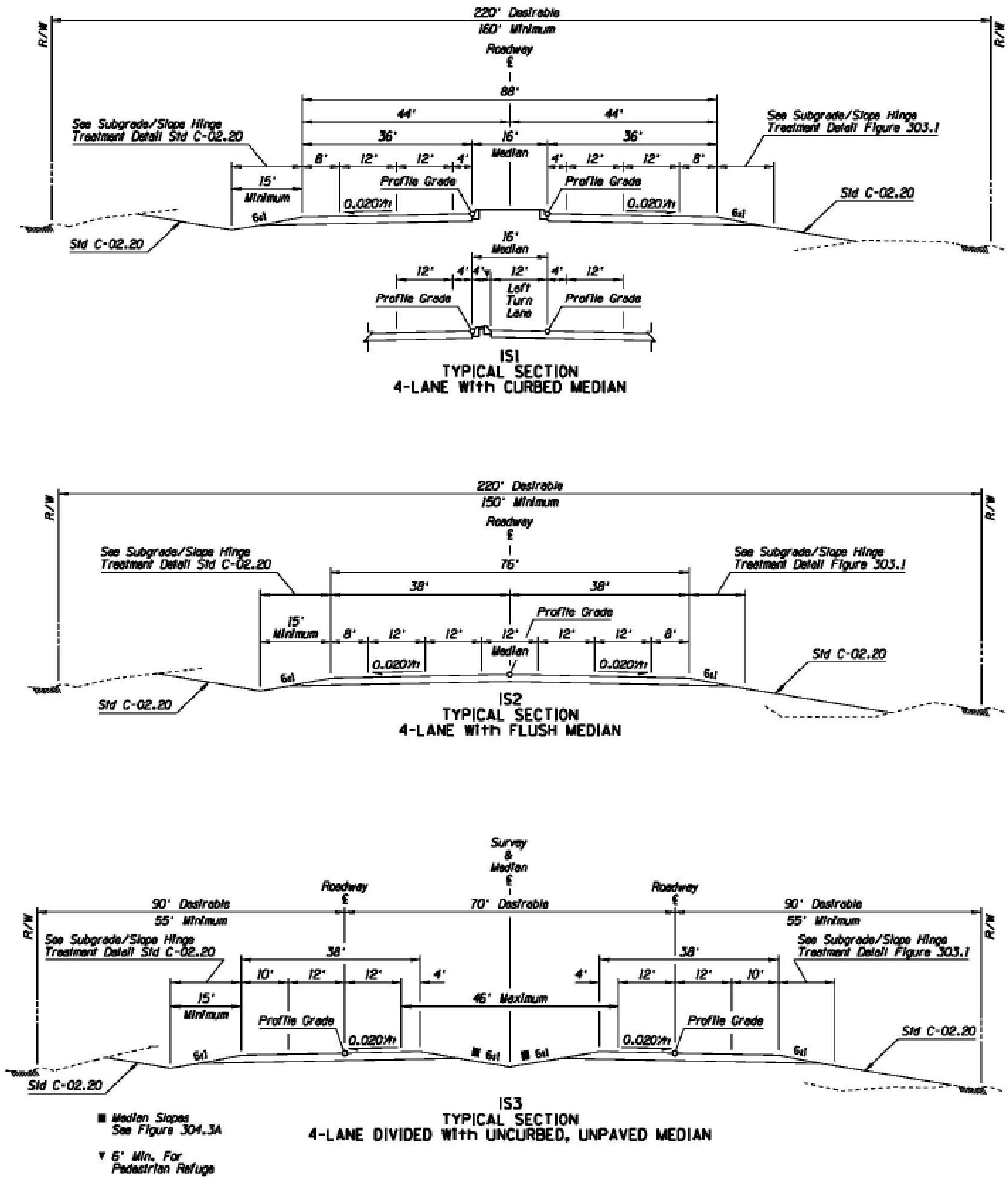



**Figure 14. Arizona Fringe-Urban Highway Typical Sections (Figure 306.3 in *55*)**

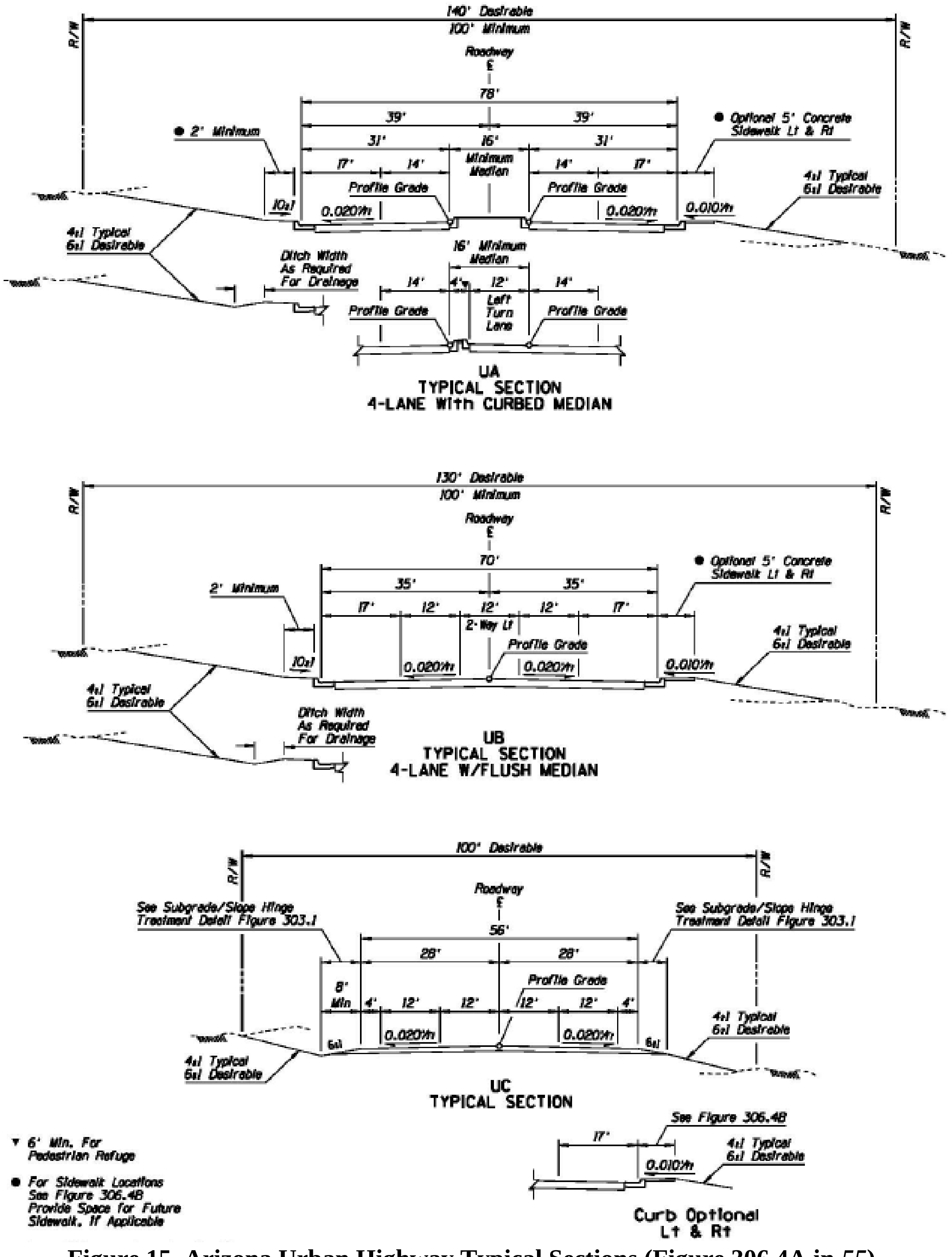



**Figure 15. Arizona Urban Highway Typical Sections (Figure 306.4A in *55*)**

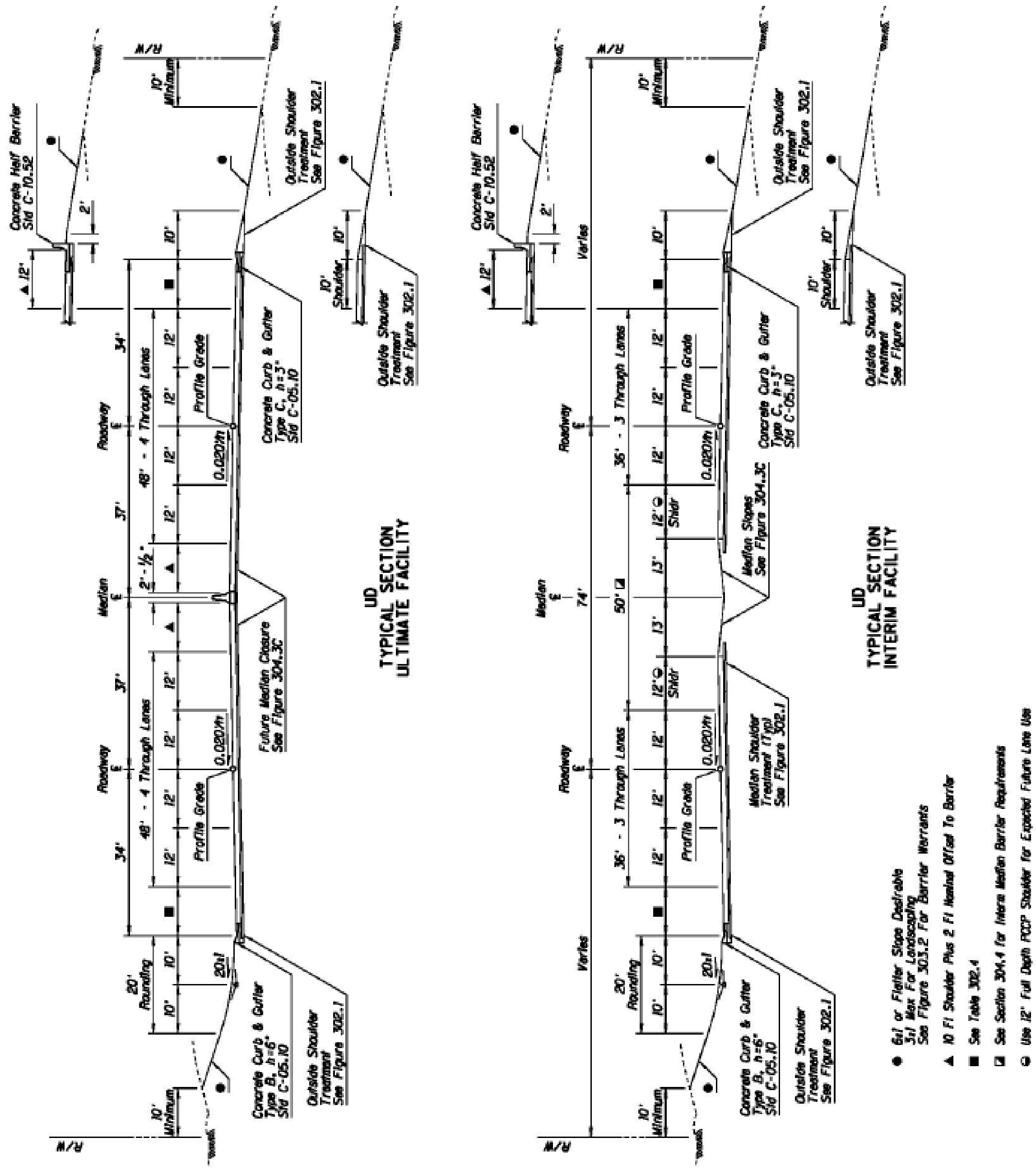



**Figure 16. Arizona Controlled-Access Urban Highway Typical Sections (Figure 306.4B in *55*)**

Colorado also has prescribed choices for cross-sections in their guidance. Colorado Department of Transportation (CDOT) provides a table in its *Roadway Design Guide* (*56*) that summarizes minimum and desirable cross-section dimensions; information from that table is reproduced here as Table 10. In that table and associated guidance, Type AA roadways have six travel lanes, Type A roadways are four-lane freeways, and Types B, C, and D are two-lane roadways.

**Table 10. Colorado Geometric Design Standards for Cross-Sections (from Table 4-1 in *56*)**

| Design Type [1] | Number of Lanes | Lane Width (ft) | Min. Outside Shoulder Width (ft) [2] | Min. Inside Shoulder Width (ft) [2] | Desir. ROW Width (ft) | Min. ROW Width (ft) with Frontage Road | Min. ROW Width (ft) without Frontage Road | Desir. Access Control |
|---|---|---|---|---|---|---|---|---|
| Type AA Freeways | 6 [3] | 12 | 10 [4] | 10 [4] | 300 | 275 | 175 | Full |
| Type AA Arterials | 6 [3] | 12 | 10 | 8 [4] | 300 | 275 | 175 | Full |
| Type A | 4 [3] | 12 | 10 | 4 | 300 | 250 | 150 | Full [7] |
| Type B | 2 [3,8] | 12 | 8 or 10 [9] | N/A | 250 | 250 | 150 | Varies [7] |
| Type C | 2 | 11 or 12 | 6 [10] | N/A | 120 | N/A | 60 | Varies [7] |
| Type D | 2 | 10 or 11 | 4 | N/A | 100 | N/A | 60 | Varies [7] |

Notes: ROW = Right of way, Min. = Minimum, Desir. = Desirable, N/A = Not applicable.
1. "Types" refers to details shown on Figures 4-1 through 4-5 in the CDOT Roadway Design Guide.
2. Shoulder widths may not apply when roadway has curb and gutter, speed-change lanes, etc.
3. See Highway Capacity Manual.
4. Where the DDHV for truck traffic exceeds 250 veh/h, a paved shoulder width of 12 ft should be considered.
5. Alternate loadings for two 24,000-pound axles shall be used where applicable on the Interstate.
6. Bridge widths will be determined in accordance with requirements set forth in the latest revision of the AASHTO Green Book, AASHTO Standard Specifications for Highway Bridges and CDOT Standard Plans - M & S Standards. Special cases will be subject to consideration by the CDOT Staff Bridge Engineer.
7. To be decided on an individual project basis. Interstate requires full access control.
8. Climbing lanes should be provided in accordance with Section 3.4.5 of this Guide.
9. Minimum 10' shoulder should be used when DHV exceeds 400, except in mountainous terrain where the 8' minimum shoulder will remain standard for DHV over 400.
10. Minimum 3' paved shoulder with 3' gravel shoulder.

California Department of Transportation's (Caltrans') *Highway Design Manual* (*57*) states that the cross-section of a highway on the state highway system is based on the number of vehicles (including trucks, buses, bicycles), safety, terrain, transit needs, and pedestrians. Other factors such as sidewalks, bike paths, and transit facilities, both existing and future, should also be considered. The roadbed width for multilane facilities should be adequate to provide capacity for the DHV. A two-lane, two-way roadbed consists of a 24-ft wide traveled way plus paved shoulders. To provide structural support, the minimum paved width of each shoulder should be 2 ft, but the specified shoulder width for new construction is 4 ft for a two-way design year ADT of less than 400 vpd and 8 ft for a two-way design year ADT over 400 vpd.

Caltrans specifies that shoulders less than 4 ft are not adequate for bicycles. Bicycles are not prohibited on conventional highways; therefore, where the shoulder width is 4 ft, the gutter pan width should be reduced to 1 ft, so a 3-ft width is provided between the traffic lane and the longitudinal joint at the gutter pan. Where 4-ft shoulders are not possible, consideration should be given to providing turnouts for bicycles.

A recent National Cooperative Highway Research Program (NCHRP) report provides a guide for reallocation of cross-section on streets in urbanized areas. The pre-publication draft of NCHRP Report 1036 (*58*) provides opinions, research findings, and case studies on allocating roadway space for multiple road users with an implied outcome to "ensure safety" on the treated streets.

The document contains a broad framework for a decision-making process and discusses a spreadsheet tool developed by the authors on the corresponding NCHRP Project 15-78; however, the information contained in the report is written from a perspective of minimizing the amount of cross-section allocated to motor vehicles, and the safety benefits described in the report are often described only in general terms and not always fully documented. Consequently, while the objective of the guide may be well-intentioned, the information contained in this pre-publication version of the report is of limited use in rural and suburban areas, and even in urban areas it may minimize operational benefits to emphasize actual or perceived improvements for other metrics.

### Existing Practices for Auxiliary Lanes

When 2U highway segments are converted to wider configurations such as 2S or 2ST, decisions must be made at intersections or busy driveways regarding the addition of speed-change lanes for turning vehicles. The *Urban Intersection Design Guide* (*59*) contains discussion of several types of accommodations for right-turning vehicles. Figure 4-7 of the *Urban Intersection Design Guide* is repeated here as Figure 17. Speed-change lanes are visible in the southwest and southeast quadrants of the example intersection.

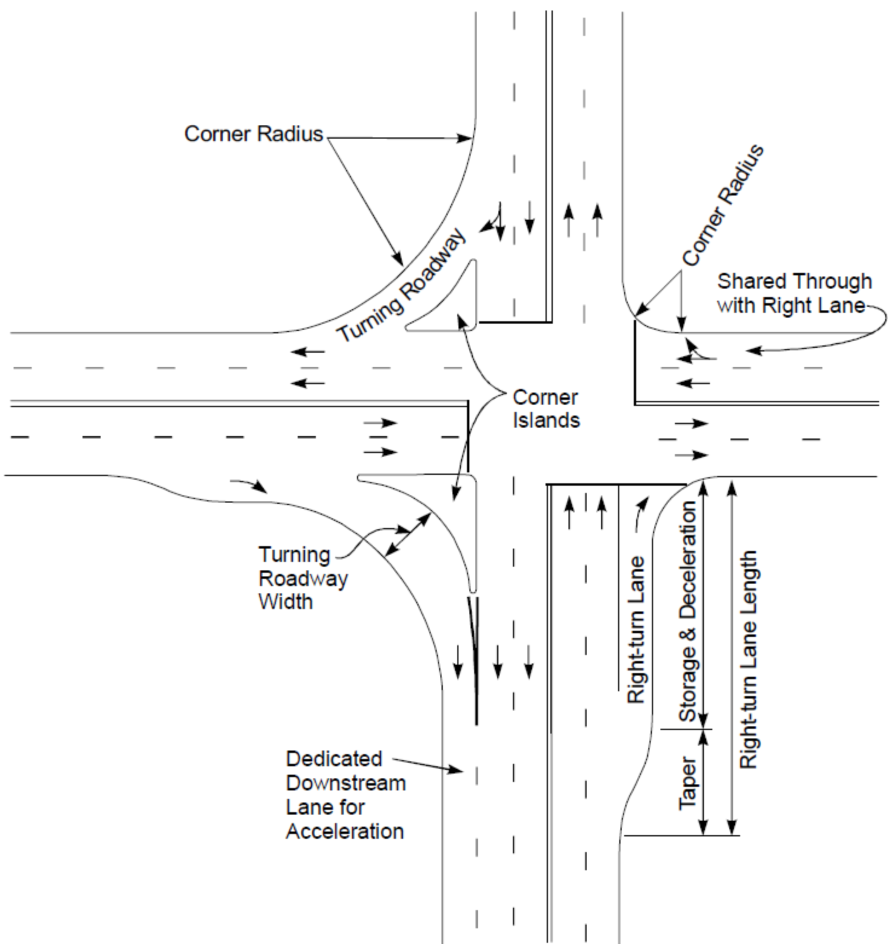



**Figure 17. Right-Turn Lane Examples (*59*)**

As explained in the *Urban Intersection Design Guide*, the benefits of speed-change lanes include provision of deceleration and storage space for right-turning vehicles. These benefits affect operational efficiency (reduce impedance of through vehicles by right-turning vehicles) and safety (reduce the probability of rear-end crashes involving through vehicles and slowing right-turning vehicles). However, the provision of speed-change lanes can result in safety tradeoffs for pedestrians at intersections, including increasing the crossing distance and exposing pedestrians to faster-moving right-turning vehicles.

NCHRP Project 3-91 (NCHRP Report 745, *60*) and Project 3-102 (NCHRP Report 780, *61*) present information and guidance on intersection auxiliary lanes, specifically left-turn lanes, right-turn lanes, and through bypass lanes, along with details on deceleration lanes and double left-turn lanes. The research included recommended warrants, which were adopted in the 2018 AASHTO *Green Book* (*8*), for installing left-turn lanes and bypass lanes for various conditions, as well as recommended dimensions for lane-change, deceleration, and storage lengths. Those dimensions are illustrated in Figure 18, and left-turn lane warrants are reproduced here in Table 11 through Table 13 and Figure 19 through Figure 21. The low volumes in the tables indicate that left-turn lanes are justified at almost all locations. The warrants were developed based on the costs of crashes and turn-lane installation projects. Similar warrants are not available for right-turn lanes, but the volume thresholds would likely be higher due to the differences in severity distribution between left turns (which require crossing paths with opposing through vehicles and can involve left-turn-opposed crashes that are often as severe as right-angle crashes) and right turns (which do not require crossing paths with opposing through vehicles).

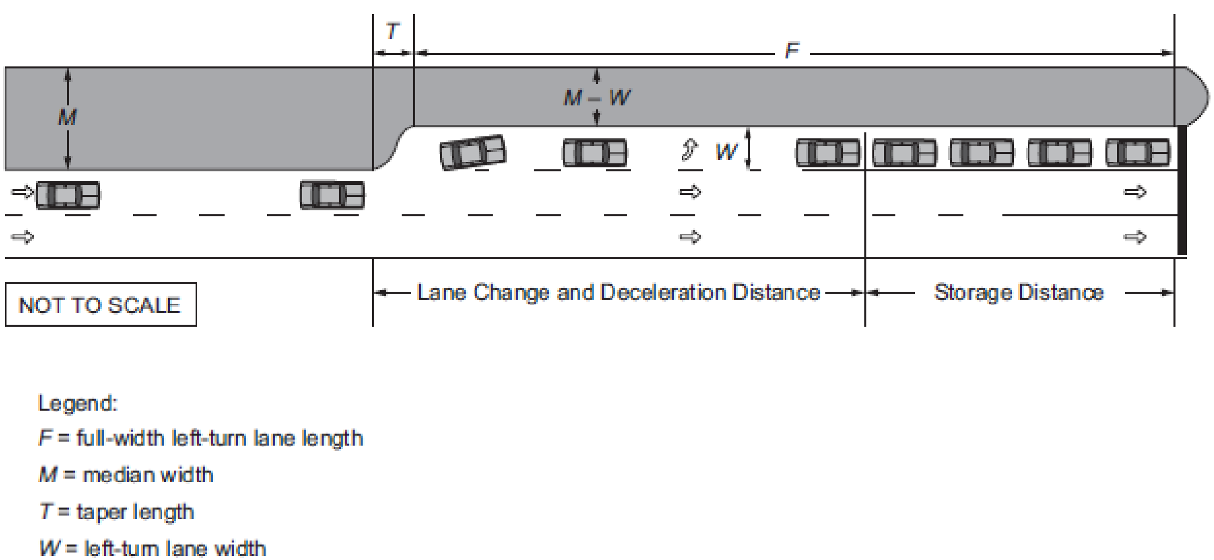
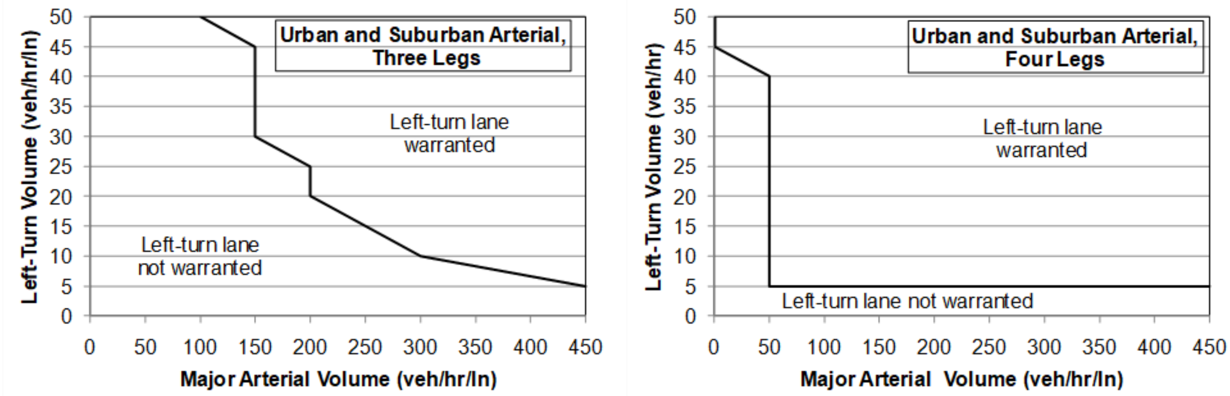



**Figure 18. Key Dimensions for Maneuvers and Physical Boundaries at Left-Turn Auxiliary Lanes (*8*)**

**Table 11. Suggested Left-Turn Lane Warrants Based on Results from Benefit-Cost Evaluations for Urban and Suburban Arterials (*61*)**

| Left-Turn Lane Peak-Hour Volume (veh/hr) | Three-Leg Intersection, Major Urban and Suburban Arterial Volume (veh/hr/ln) That Warrants a Left-Turn Lane | Four-Leg Intersection, Major Urban and Suburban Arterial Volume (veh/hr/ln) That Warrants a Left-Turn Lane |
|---|---|---|
| 5 | 450 | 50 |
| 10 | 300 | 50 |
| 15 | 250 | 50 |
| 20 | 200 | 50 |
| 25 | 200 | 50 |
| 30 | 150 | 50 |
| 35 | 150 | 50 |
| 40 | 150 | 50 |
| 45 | 150 | < 50 |
| 50 or More | 100 | < 50 |

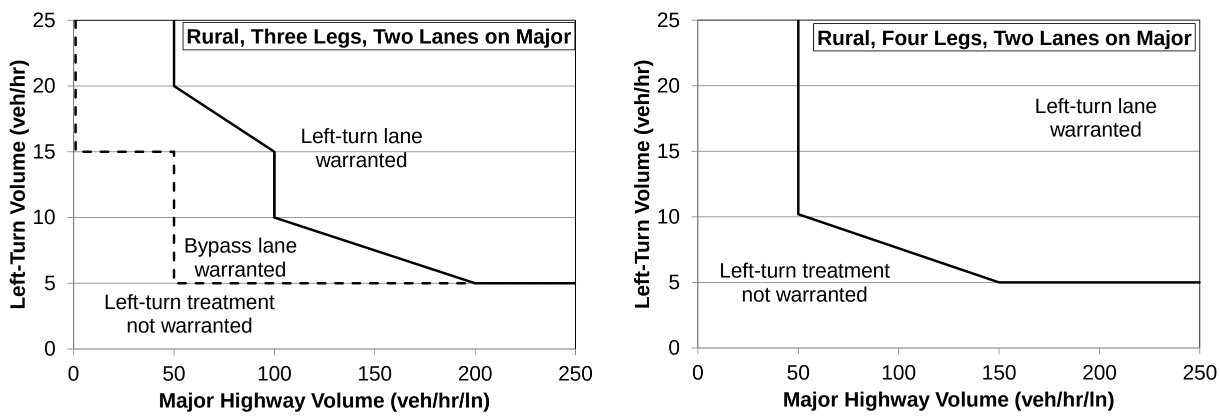



**(a) Three Legs** **(b) Four Legs**

**Figure 19. Suggested Left-Turn Lane Warrants Based on Results from Benefit-Cost Evaluations for Intersections on Urban and Suburban Arterials (*61*)**

**Table 12. Suggested Left-Turn Treatment Warrants Based on Results from Benefit-Cost Evaluations for Rural Two-Lane Highways (*61*)**

| Left-Turn Lane Peak-Hour Volume (veh/hr) | Three-Leg Intersection, Major Two-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Bypass Lane | Three-Leg Intersection, Major Two-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Left-Turn Lane | Four-Leg Intersection, Major Two-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Left-Turn Lane |
|---|---|---|---|
| 5 | 50 | 200 | 150 |
| 10 | 50 | 100 | 50 |
| 15 | < 50 | 100 | 50 |
| 20 | < 50 | 50 | < 50 |
| 25 | < 50 | 50 | < 50 |
| 30 | < 50 | 50 | < 50 |
| 35 | < 50 | 50 | < 50 |
| 40 | < 50 | 50 | < 50 |
| 45 | < 50 | 50 | < 50 |
| 50 or More | < 50 | 50 | < 50 |

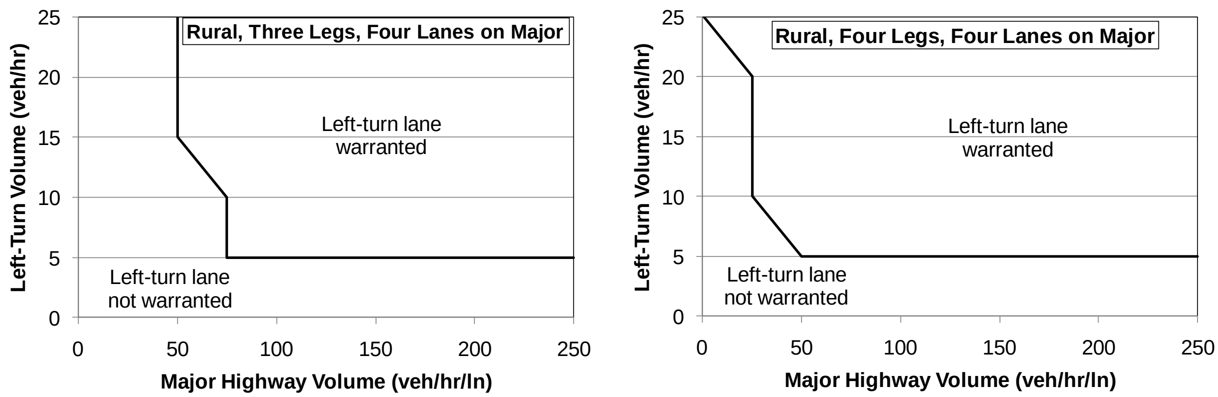



**(a) Three Legs** **(b) Four Legs**

**Figure 20. Suggested Left-Turn Treatment Warrants Based on Results from Benefit-Cost Evaluations for Intersections on Rural Two-Lane Highways (*61*)**

**Table 13. Suggested Left-Turn Lane Warrants Based on Results from Benefit-Cost Evaluations for Rural Four-Lane Highways (*61*)**

| Left-Turn Lane Peak-Hour Volume (veh/hr) | Three-Leg Intersection, Major Four-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Left-Turn Lane | Four-Leg Intersection, Major Four-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Left-Turn Lane |
|---|---|---|
| 5 | 75 | 50 |
| 10 | 75 | 25 |
| 15 | 50 | 25 |
| 20 | 50 | 25 |
| 25 | 50 | < 25 |
| 30 | 50 | < 25 |
| 35 | 50 | < 25 |
| 40 | 50 | < 25 |
| 45 | 50 | < 25 |
| 50 or More | 50 | < 25 |




**(a) Three Legs** **(b) Four Legs**

**Figure 21. Suggested Left-Turn Lane Warrants Based on Results from Benefit-Cost Evaluations for Intersections on Rural Four-Lane Highways (*61*)**

These NCHRP research projects provide guidance on the length of taper (i.e., lane-change), deceleration, and storage for left-turn lanes as well. These recommended guidelines have also been integrated into the AASHTO *Green Book*. NCHRP Report 745 contains discussion of several left-turn treatments, including a "passing blister" that functions as a bypass lane that allows through vehicles to separate from slowing left-turning vehicles. Figure 22 shows this treatment for the southbound approach of a three-leg unsignalized intersection.

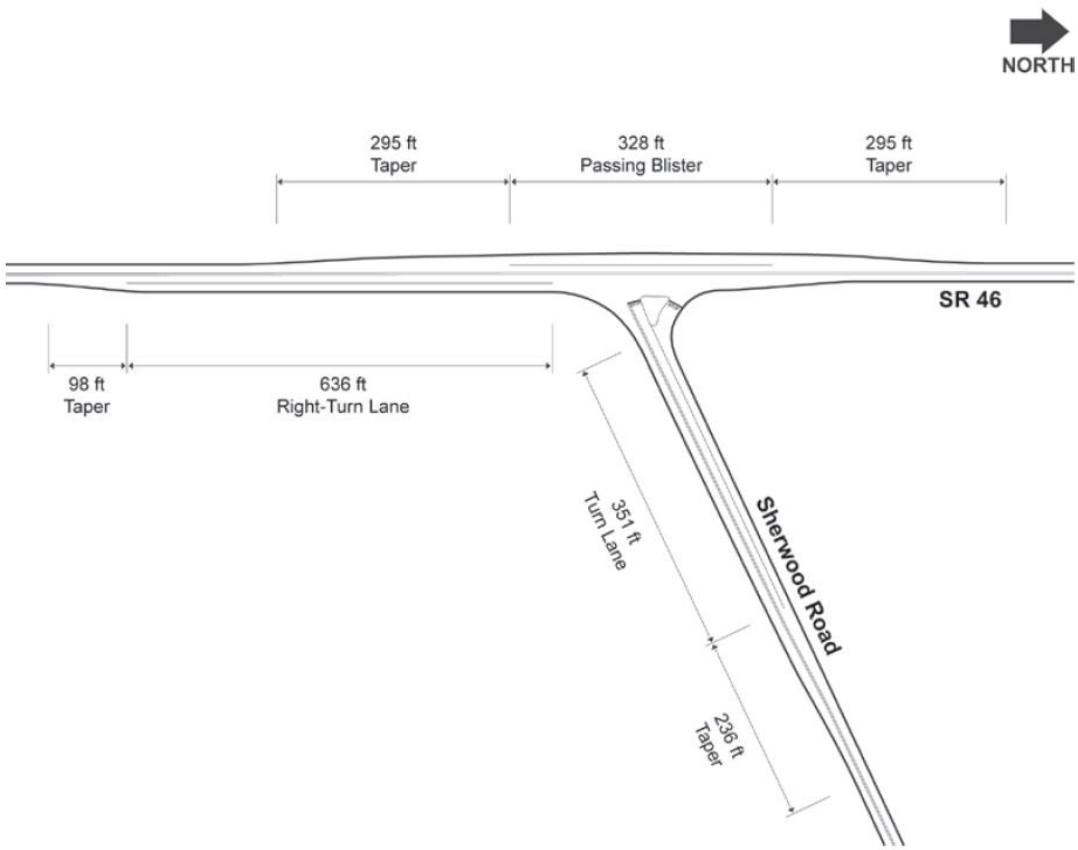
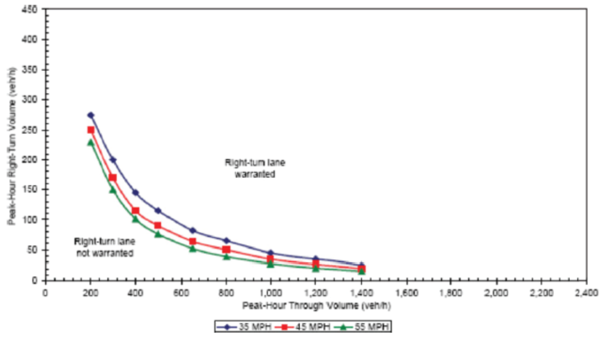



**Figure 22. Left-Turn Lane "Passing Blister" Treatment (*60*)**

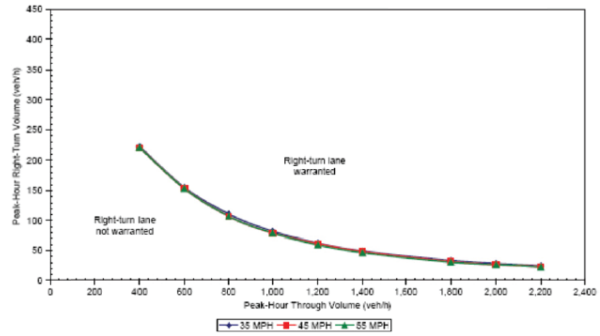
Table 2-2 in NCHRP Report 780 contains a summary of state design practices for warranting right-turn lanes on rural highways; this summary is repeated in this document as Table 14. The summary was carried forward from NCHRP Report 279, which was published in 1985. NCHRP Report 780 also cited Potts et al. (*62*), who developed economic warrants for right-turn lanes on urban and suburban arterials. Figure 23 shows these warrants.

**Table 14. Summary of State Design Practice in Providing Right-Turn Lanes on Rural Highways (*61*)**

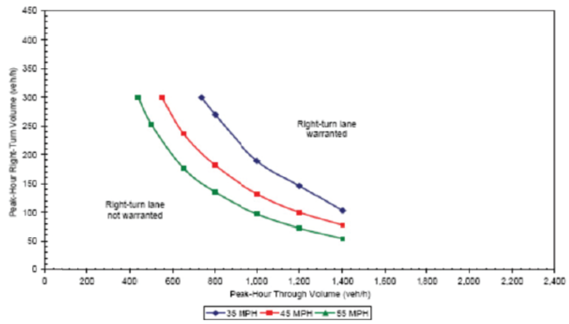
| State | Condition Warranting Right-Turn Lane off Major (Through) Highway | | |
|---|---|---|---|
| | **Through Volume** | **Right-Turn Volume** | **Highway Conditions** |
| Alaska | Not applicable | DHV = 25 veh/hr | Not provided |
| Idaho | DHV = 200 veh/hr | DHV = 5 veh/hr | 2 lane |
| Michigan | Not applicable | ADT = 600 veh/day | 2 lane |
| Minnesota | ADT = 1500 veh/day | All | Design speed > 45 mph |
| Utah | DHV = 300 veh/hr | ADT = 100 veh/day | 2 lane |
| Virginia | DHV = 500 veh/hr | DHV = 40 veh/hr | 2 lane |
| | All | DHV = 120 veh/hr | Design speed > 45 mph |
| | DHV = 1200 veh/hr | DHV = 40 veh/hr | 4 lane |
| | All | DHV = 90 veh/hr | 4 lane |
| West Virginia | DHV = 500 veh/hr | DHV = 250 veh/hr | Divided highway |
| Wisconsin | ADT = 2500 veh/day | Crossroad ADT = 1000 veh/day | 2 lane |



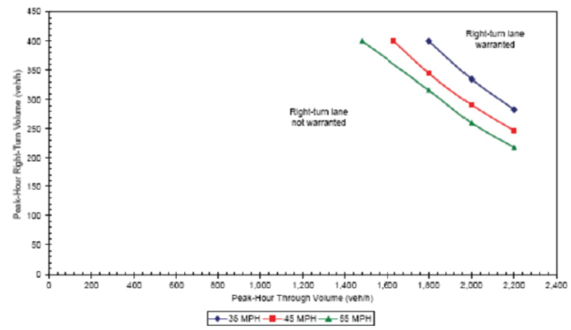

Economic warrant for right-turn lane (B/C=1) for four-leg unsignalized driveway or intersection on two-lane major street




Economic warrant for right-turn lane (B/C=1) for four-leg unsignalized driveway or intersection on four-lane major street




Economic warrant for right-turn lane (B/C=1) for three-leg driveway or intersection on two-lane major street




Economic warrant for right-turn lane (B/C=1) for three-leg driveway or intersection on four-lane major street

**Figure 23. Economic Warrants for Right-Turn Lanes (*62*)**

The TxDOT *Access Management Manual* (*63*) provides thresholds for installing right-turn lanes, in Table 2-3, as follows:

- Roads > 45 mph where right turn volume is > 50 vph.
- Roads where right turn volume is > 60 vph.

Conditions for providing an exclusive right-turn lane when the right-turn traffic volume projections are less than indicated in Table 2-3 include:

- High crash experience.
- Heavier than normal peak flow movements on the main roadway.
- Large volume of truck traffic.
- Highways where sight distance is limited.

Conditions for not requiring a right-turn lane where right-turn volumes are more than indicated in Table 2-3 include:

- Dense or built-out corridor where space is limited.
- Where queues of stopped vehicles would block the access to the right turn lane.
- Where sufficient length of property width is not available for the appropriate design.

Several states have current warrants for right-turn lanes. For example, Section 245 of Arizona Department of Transportation's (ADOT's) *Traffic Guidelines and Processes* (*64*) provides minimum peak-hour right-turn volumes to warrant installation of right-turn lanes for several combinations of peak-hour approach volume, through lane count, and posted speed limit. Table 15 shows the right-turn volumes used in these guidelines. Additionally, ADOT guidance suggests considering shoulder width, truck percentage, sight distance, grade, horizontal and vertical curvature, and crash history when performing a turn lane warrant study.

**Table 15. Arizona Right-Turn Lane Warrants Based on Peak Hour (*64*)**

| Peak-Hour Traffic Volume on the Highway in Advancing Direction | Minimum Peak-Hour Right-Turn Traffic Volume | | | | |
|---|---|---|---|---|---|
| | 1 through lane per direction, < 45 mph posted speed | 1 through lane per direction, ≥ 45 mph posted speed | 2 through lanes per direction, < 45 mph posted speed | 2 through lanes per direction, ≥ 45 mph posted speed | 3 lanes per direction, all posted speeds |
| ≤ 200 | None specified | None specified | None specified | None specified | None specified |
| 201–300 | None specified | 30 | None specified | None specified | None specified |
| 301–400 | None specified | 19 | None specified | 55 | None specified |
| 401–500 | 85 | 14 | None specified | 30 | None specified |
| 501–600 | 58 | 12 | 140 | 25 | None specified |
| 601–700 | 27 | 9 | 80 | 18 | None specified |
| 701–800 | 20 | 8 | 53 | 15 | None specified |
| 801–900 | 12 | 7 | 40 | 12 | None specified |
| 901–1000 | 9 | 6 | 30 | 11 | None specified |
| 1001–1100 | 8 | 5 | 23 | 9 | 18 |
| 1101–1200 | 7 | 5 | 18 | 8 | 16 |
| 1201–1300 | 6 | 4 | 14 | 8 | 15 |
| 1301–1400 | 6 | 4 | 11 | 6 | 12 |
| ≥ 1400 | 5 | 3 | 8 | 6 | 10 |

Missouri Department of Transportation's (MoDOT's) *Engineering Policy Guide* includes a section addressing auxiliary acceleration and turning lanes (*65*). Figure 24 and Figure 25 show nomographs from MoDOT's guidance, which require knowledge of major-road approach volume, right-turn volume, and operating speed. The analyst applies the guidance by plotting the combination of volumes on the appropriate nomograph and determining if the point is located above the curve that corresponds to the roadway's operating speed.

Finally, research sponsored by the Minnesota Department of Transportation (*66*) produced a set of 20 nomographs for right-turn lanes at unsignalized intersections or driveways for two different fuel costs ($3/gallon or $4/gallon) and five different installation costs ($20,000–$60,000 in $10,000 increments). This guidance was developed by analyzing crash data, traffic operations simulation, and field data that were used to determine conflict rates and vehicle speeds. Figure 26 and Table 16 provide an example of a right-turn lane warrant nomograph and supporting data table.

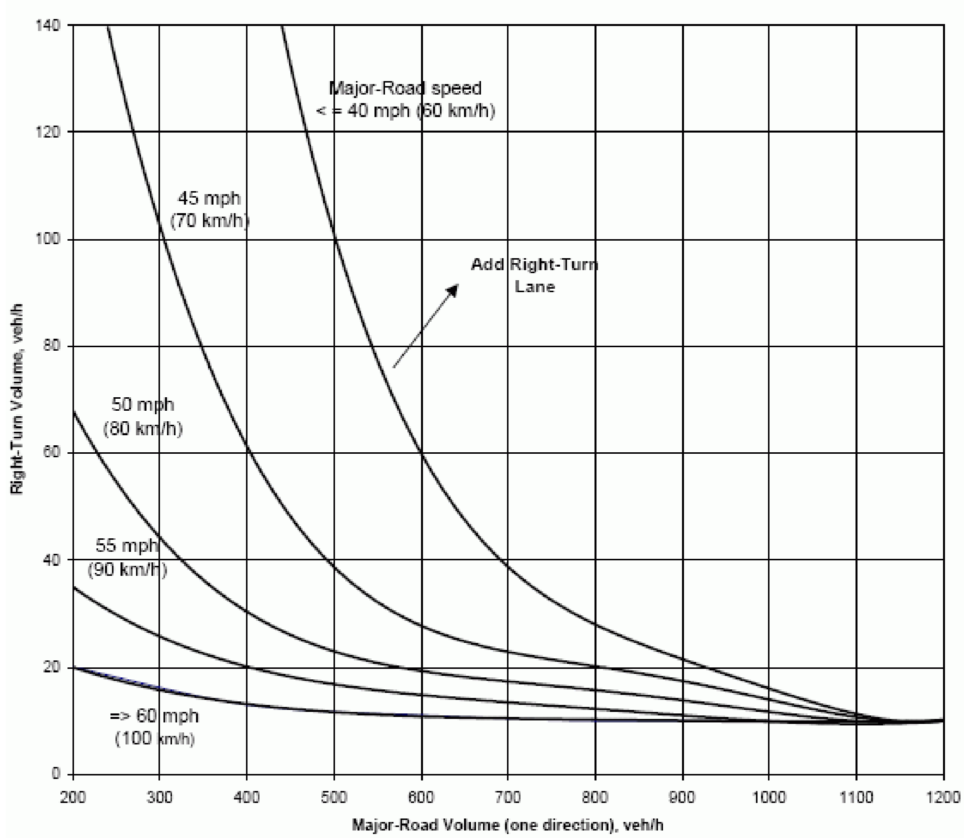



**Figure 24. Missouri Right-Turn Lane Guidelines for Two-Lane Roadways (*65*)**

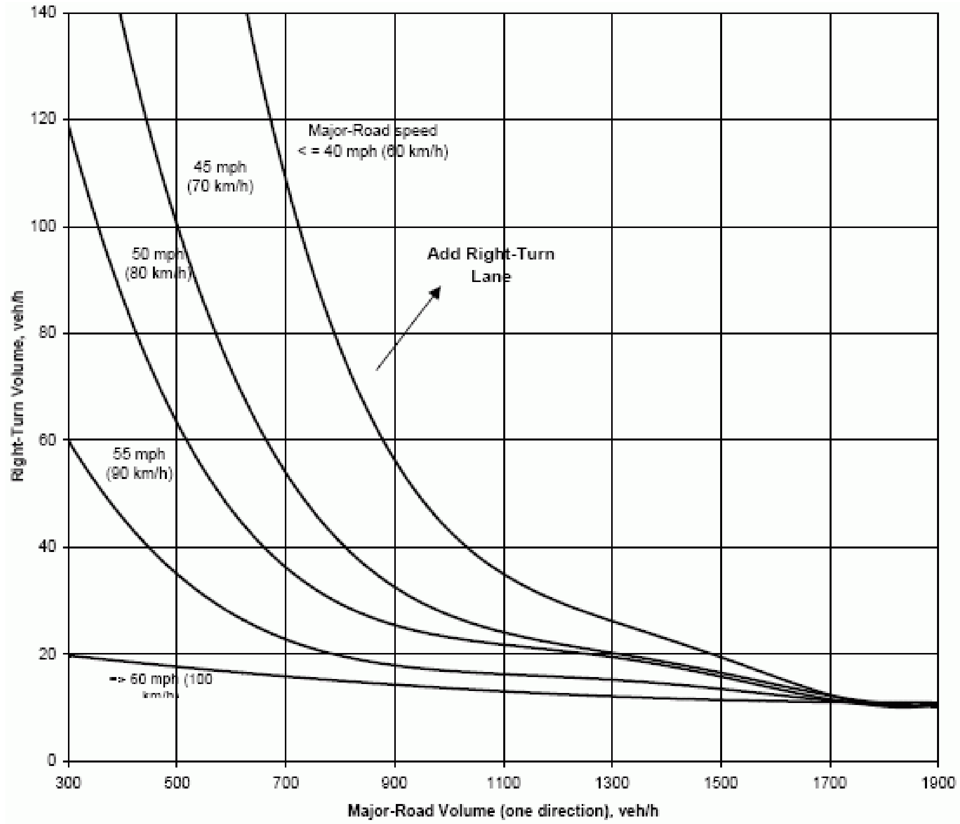



**Figure 25. Missouri Right-Turn Lane Guidelines for Four-Lane Roadways (*65*)**

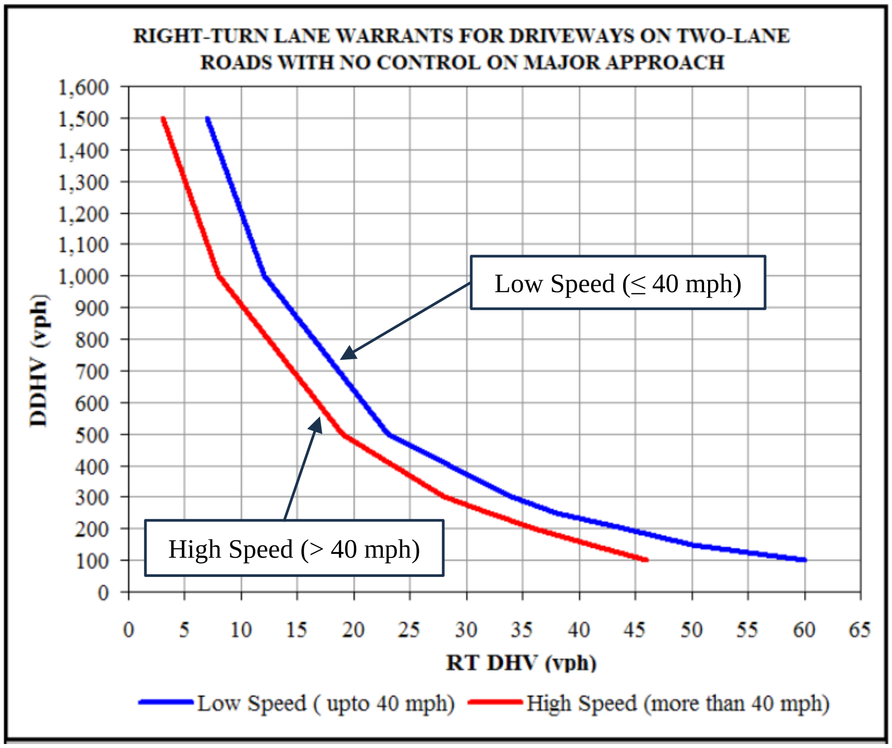



**Figure 26. Example Minnesota Right-Turn Lane Warrant (*66*)**

**Table 16. Data Table for Example Minnesota Right-Turn Lane Warrant (*66*)**

| Speed (mph) | DDHV (vph) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 100 | 150 | 200 | 250 | 300 | 500 | 1,000 | 1,500 |
| ≤ 40 | 60 | 50 | 44 | 38 | 34 | 23 | 12 | 7 |
| > 40 | 46 | 41 | 36 | 32 | 28 | 19 | 8 | 3 |

Note: Minimum right-turn DHV (vph) required to warrant a right-turn lane, based on a right-turn lane cost of $20,000, delay cost of $13.00 per hour, and a fuel cost of $3.00 per gallon.

Right-turn lanes serve a similar purpose as speed-change lanes at intersections. Hence, the preceding warrants address the issue of speed-change lanes by providing guidance to weigh the costs and operational and safety benefits of adding right-turn lanes.

## EXISTING GUIDANCE

Recently, Geedipally et al. (*10*) developed a framework to assist practitioners in making decisions on cross-sections for new and resurfaced roadway segments. They recommended using the framework to convert the existing four-lane undivided sections that experience significant safety issues into other cross-section types. In Texas, 4U roadways constitute a significant amount of mileage in rural areas, and they have poor safety performance compared to other cross-sections. Their guidelines account for traffic exposure, cross-sectional width, and access point density, which are the three key variables for selecting a cross-section type.

Table 17 provides a comparison of criteria developed by Liu et al. (*22*) and Geedipally et al. (*10*). Geedipally et al. (*10*) also included Super 2 and 2ST highways but not 4D in their study. Also, this study provided guidelines for narrow, intermediate, and wide cross-sectional widths separately, and the below comparisons are based on wide cross-sectional widths. In addition, they did not consider highways with AADT greater than 25,000 vpd.

**Table 17. Comparison of Guidelines Developed in Georgia and Texas**

| AADT | Access Points / Mile | ≤ 5% Trucks | | 5–10% Trucks | | 10–15% Trucks | | 15–20% Trucks | | > 20% Trucks | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GA | TX | GA | TX | GA | TX | GA | TX | GA | TX |
| ≤ 5000 | ≤ 10 | 4U | 4M | 4U/4M | 4M | 4U/4M | 4M | 4U/4M | 4M | 4M | 4M |
| | 10–20 | 4U | 4M | 4U/4M | 4M | 4U/4M | 4M | 4U/4M | 4M | 4M | 4M |
| | 20–30 | 4U | 4M | 4U/4M | 4M | 4U/4M | 4M | 4U/4M | 4M | 4M | 4M |
| | >30 | 4U | 2ST | 4U/4M | 2ST | 4U/4M | 2ST | 4U/4M | 2ST | 4M | 2ST |
| 5000–10000 | ≤ 10 | 4M | 4M | 4M | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M |
| | 10–20 | 4M | 4M | 4M | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M |
| | 20–30 | 4M | 4M | 4M | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M |
| | > 30 | 4M | 2ST | 4M | 2ST | 4M/4T | 2ST | 4M/4T | 2ST | 4M/4T | 2ST |
| 10000–15000 | ≤ 10 | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M |
| | 10–20 | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T/4D | 4M |
| | 20–30 | 4M/4T | 4M | 4M/4T | 4M | 4M/4T | 4M | 4M/4T/4D | 4M | 4M/4T/4D | 4M |
| | >30 | 4M/4T | 2ST | 4M/4T | 2ST | 4M/4T | 2ST | 4M/4T/4D | 2ST | 4M/4T/4D | 2ST |
| 15000–20000 | ≤ 10 | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4T |
| | 10–20 | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4T |
| | 20–30 | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4T |
| | > 30 | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4M | 4T/4D | 4T | 4T/4D | 4T |
| 20000–25000 | ≤ 10 | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T |
| | 10–20 | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T |
| | 20–30 | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T |
| | > 30 | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T | 4D | 4T |

Note: GA – Georgia study by Liu et al. (*22*); TX – Texas study by Geedipally et al. (*10*).

In TxDOT project 0-7035, the researchers provided guidance (*10*) for selecting different alternatives in rural areas based on the existing cross-sectional widths. The crash rate comparisons in Table 4 show that 2S highways always provide superior safety performance than 2U highways. In addition, guidance from TxDOT project 0-6997 (*46*) shows that a BCR around 2.0–2.5 can be achieved for the 2S at 3,000 vpd, and that ratio increases substantially with volume and truck percentage. Thus, the research team recommends selecting 2S cross-section for highways greater than 3000 vpd.

In Georgia, Liu et al. (*22*) recommended the 4D cross-section for all highways greater than 20,000 vpd. However, TxDOT project 0-7035 (*10*) recommended the 4T cross-section for highways between 20,000 and 25,000 vpd (4D highways were not considered in their study). The crash rate comparisons in Table 5 show that 4D always provides superior safety performance than the 4T, but it is not always a cost-effective alternative due to significant higher costs of construction. As such, the research team recommends doing a benefit-cost analysis (BCA) before selecting 4D over 4T. Table 18 provides a framework for selecting a cross-section in rural areas based on a given traffic volume, number of driveways, and truck percentage.

**Table 18. Potential Guidelines for Selecting Rural Cross-Sections**

| AADT | Driveway Activity Index[a] per Mile | Truck Percentage | Preferred Cross-Section |
|---|---|---|---|
| ≤ 3000 | Any | Any | Two-Lane Undivided/ Two Lanes with TWLTL |
| 3000–15,000 | ≤ 30 | Any | Super 2 |
| | > 30 | ≤ 15% | Super 2 with TWLTL |
| | | 15–25% | Super 2 with TWLTL |
| | | > 25% | Four Lanes with TWLTL |
| 15,000–20,000 | ≤ 30 | ≤ 15% | Four Lanes with 4-ft Median Buffer[b] |
| | | 15–25% | Four Lanes with 4-ft Median Buffer[b] |
| | | > 25% | Four Lanes with TWLTL |
| | > 30 | ≤ 15% | Four Lanes with 4-ft Median Buffer[b] |
| | | 15–25% | Four Lanes with TWLTL |
| | | > 25% | Four Lanes with TWLTL |
| > 20,000 | Any | Any | Four Lanes with TWLTL/ Four-Lane Divided |

Note:
[a] Driveway activity index is the number of residential driveways. The index is equal to three times the number of industrial driveways, or 12 times the number of commercial driveways (measured per mile).
[b] 6-ft minimum shoulder width. Greater widths are desirable.

A recent document by Brewer (*13*) summarizes TxDOT-sponsored research on Super 2 corridors and provides guidelines for selecting and implementing Super 2 treatments. Key operational measures to consider in selecting a Super 2 treatment include overall traffic volume, truck percentage, the demand for turning vehicles compared to through vehicles, and the terrain or vertical alignment. Highways with high volumes of through vehicles, particularly with many trucks, and rolling terrain are generally better candidates for Super 2 treatments. When implemented under these conditions, operational benefits are typically accompanied by reductions in number and/or severity of crashes, which are associated with economic benefits as the construction costs are outweighed by the declines in delay and crashes.

The cost of a construction project in comparison to its expected economic benefit should not be ignored when considering the installation of a Super 2 corridor. An economic analysis model was developed to calculate the benefits and costs for Super 2 projects in Texas (*46*). That BCA model also has the ability to consider four-lane divided and four-lane undivided cross-sections, all compared to a baseline scenario of a traditional two-lane highway. The model exists in a spreadsheet tool (distributed with this guidelines document) that enables practitioners to calculate the benefits and costs of their own construction projects in order to decide which cross-section may be best suited for a particular location.

The spreadsheet tool provides prompts for a selected number of inputs from the user to the model and then provides results based on those user inputs. Table 19 depicts the model inputs for a sample 2S-26 project (i.e., Super 2 with 2-mile passing lanes and six passing lanes in each direction of travel), as entered into the BCA spreadsheet model. The top three factors highlighted in yellow allow the user to select from a pull-down menu, while the Project Cost Override factor, located at the bottom, allows the user to override the default project cost calculated by the model if more accurate project cost information is available. The remaining default factors highlighted in gray depict the values used for this analysis that can be altered if other data are available.

**Table 19. BCA Model Inputs (*46*)**

| **Inputs** | |
|---|---|
| **Please Select from Pull-Down Menu** | |
| Project Type | 2S-26 |
| ADT | 11,000 |
| Percent Trucks | 40% |
| Traffic Growth Rate | 2% |
| Construction Start Year | 2021 |
| Operation Start Year | 2023 |
| Constant Dollar Year | 2020 |
| Project Length (Miles) | 40.0 |
| Estimated Project Cost | $40,545,609 |
| Known Project Cost Override | |

Table 20 shows the outputs of the BCA model for the sample project. The total benefits over the 20-year period of operation are presented at the top (discounted at 3 percent), followed by the discounted project cost. The model also presents the BCR and the net present value (NPV) of the sample project. The BCA calculations include consideration of previously discussed operational benefits, which are components of the operational cost benefits, time cost benefits, and environmental benefits that result from reduced delay and increased capacity.

**Table 20. BCA Model Outputs (*46*)**

| Outputs | |
|---|---|
| **Benefits and Costs** | **Present Value (M 2018$)** |
| Vehicle Operating Cost Savings | $149.5 |
| Business and Personal Time Cost Savings | $176.4 |
| Safety Benefits | $230.0 |
| Environmental Benefits | $1.3 |
| **Total Benefits** | **$557** |
| Capital Costs | $38.8 |
| **Total Costs** | **$39** |
| **Benefit-Cost Ratio** | **14.4** |
| **Net Present Value** | **$518** |
| *3% Discount Rate* | |

The results shown in Table 20 indicate that this sample 2S-26 corridor has a robust BCR of 14.4:1 and an NPV of $518 million (in 2018 dollars) when compared to a traditional two-lane highway. Table 21 and Table 22 summarize the results of other sample scenarios that were considered in the development of the model (*46*). Values shown in red represent BCRs less than 1.0 and negative NPVs. Values in Table 22 are in millions of 2018 dollars. Abbreviations for the project type in Table 21 and Table 22 are shown in Table 9.

**Table 21. Benefit-Cost Ratios (Discounted at 3 Percent) (*46*)**

| Project Type | 3,000 ADT | | 19,000 ADT | |
|---|---|---|---|---|
| | 20% Trucks | 40% Trucks | 20% Trucks | 40% Trucks |
| 2S-23 | 2.1 | 2.2 | 26.2 | 70.6 |
| 2S-33 | 2.2 | 2.3 | 28.6 | 73.8 |
| 2S-26 | 2.3 | 2.5 | 33.9 | 80.6 |
| 2S-36 | 2.4 | 2.5 | 40.1 | 87.7 |
| 4U | 0.2 | 0.2 | 6.2 | 13.4 |
| 4D | 1.0 | 1.0 | 5.9 | 26.2 |

**Table 22. Net Present Values (M 2018$, Discounted at 3 Percent) (*46*)**

| Project Type | 3,000 ADT | | 19,000 ADT | |
|---|---|---|---|---|
| | 20% Trucks | 40% Trucks | 20% Trucks | 40% Trucks |
| 2S-23 | $42 | $46 | $977 | $2,700 |
| 2S-33 | $45 | $49 | $1,072 | $2,825 |
| 2S-26 | $52 | $56 | $1,277 | $3,090 |
| 2S-36 | $55 | $59 | $1,517 | $2,264 |
| 4U | ($191) | ($185) | $1,271 | $3,062 |
| 4D | ($7) | ($1) | $829 | $4,236 |

Practitioners should use the BCA tool with the specific details of their projects to determine the applicable benefit-cost values for those projects. Results will vary with each project; however, the results in Table 21 and Table 22 show that Super 2 corridors consistently outperform the baseline two-lane scenario, and they also generally outperform the 4U and 4D at lower volumes and can do so at higher volumes as well. The four-lane cross-sections in Table 21 and Table 22 have negative NPVs and marginal BCRs at the lower ADT because the project costs are higher, and the lower volumes produce smaller operational and safety benefits than those benefits attributed to the Super 2 scenarios. These comparative results are intuitive based on the normal assumption that a four-lane widening project typically is not necessary for volumes that low. Results in Table 21 and Table 22 also show that the 2S-26 scenario showed better results than the 2S-33; this discovery is consistent with findings from previous research (*45*, *46*) indicating that adding shorter passing lanes to a Super 2 corridor is often more beneficial than providing fewer but longer passing lanes.

The BCA tool provides calculations for both BCR and NPV. When comparing two specific scenarios, one scenario may have a better BCR, while the other may have a better NPV. In general, this possibility underscores that, when evaluating BCA results, BCR and NPV should be mutually considered in decisions regarding benefits or ranking of one project type over another. It also underscores the fact that the BCA tool is a single component in the decision-making process and should not be used as the only source of information when evaluating alternatives; although the BCA tool does contain considerations for operational and safety benefits, those benefits should also be considered in detail in conjunction with the BCA tool to produce a more comprehensive evaluation of alternatives when making a final decision.

A subsequent BCA of turning lanes and passing lanes (*67*) reinforced the findings from previous research. Testbeds used in the analysis had varying configurations in terms of presence of left-turn lane, presence of passing lane, and distance from the intersection to the beginning or end of the passing lane. To investigate the influence of passing lane beginning and ending locations in the above scenarios, a total of 21 testbeds were designed. Table 23 provides the geometric details for these testbeds. The testbeds had the major approaches oriented north-south and a length of

10.5 mi, while the minor approach was included as a south leg with a 700-ft length. One-mile segments at each entry point of vehicles for eastbound and westbound directions were reserved for simulation loading so platoons could form from the randomly generated traffic.

**Table 23. Geometric Variables of Interest for Simulation Analysis (*67*)**

| Testbed | LTL | PL at Intersections | Downstream Start Next PL | Downstream PL Length | Upstream PL Length | Upstream End Previous PL |
|---|---|---|---|---|---|---|
| 1.1 | No | No | 2 mi | NA | NA | 2 mi |
| 2.1 | Yes | No | NA | NA | NA | NA |
| 3.1 | No | Yes, SD | NA | 2 mi | 2 mi | NA |
| 3.2 | No | Yes, SD | NA | 2 mi | 750 ft | NA |
| 3.3 | No | Yes, SD | NA | 2 mi | 2150 ft | NA |
| 3.4 | No | Yes, SD | NA | 750 ft | 2 mi | NA |
| 3.5 | No | Yes, SD | NA | 1500 ft | 2 mi | NA |
| 3.6 | No | Yes, SD | NA | 2640 ft | 2 mi | NA |
| 4.1 | Yes | Yes, SD | NA | 2 mi | 2 mi | NA |
| 4.2 | Yes | Yes, SD | NA | 2 mi | 750 ft | NA |
| 4.3 | Yes | Yes, SD | NA | 2 mi | 2150 ft | NA |
| 4.4 | Yes | Yes, SD | NA | 750 ft | 2 mi | NA |
| 4.5 | Yes | Yes, SD | NA | 1500 ft | 2 mi | NA |
| 4.6 | Yes | Yes, SD | NA | 2640 ft | 2 mi | NA |
| 5.1 | No | No | 2 mi | NA | NA | 2 mi |
| 5.2 | No | No | 2 mi | NA | NA | 500 ft |
| 5.3 | No | No | 2 mi | NA | NA | 1000 ft |
| 5.4 | No | No | 500 ft | NA | NA | 2 mi |
| 5.5 | No | No | 1000 ft | NA | NA | 2 mi |
| 5.6 | No | No | 2640 ft | NA | NA | 2 mi |
| 5.7 | No | No | 1 mi | NA | NA | 2 mi |

Note: NA = not applicable; PL = passing lane; LTL = left-turn lane; SD = same direction. Gray shading provides separation between groups of Testbeds.

For the range of ADTs considered (10,000 to 20,000 vpd), the addition of a left-turn lane or passing lanes almost always resulted in a positive BCR. The few comparisons with a negative BCR were when the corridor was congested and only occurred when the assumed major-road ADT was 20,000 vpd and the percent of trucks was 22 or 35 percent. In all other comparisons, the BCR was much greater than 1.

Table 24 provides a sample of the BCA results. The sample includes both 10,000 and 15,000 major-road ADT, and 5 and 10 percent left-turn vehicles and 10 and 22 percent trucks. When adding a left-turn lane to the rural intersection (i.e., Testbed 2.1 compared to Testbed 1.1) with 10,000 major-road ADT and 1000 on the minor road with 5 percent left turns and 10 percent trucks, the treatment results in a BCR of 21.2, meaning that the benefit of the treatment is 21.2 times the cost of the treatment. Table 25 provides a description of the parameters for each of the scenarios in Table 24.

**Table 24. Sample of BCA Results (*67*)**

| Testbed Comparison | Benefit-Cost Ratio, 3% Discount | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Scen. 1** | **Scen. 2** | **Scen. 3** | **Scen. 4** | **Scen. 5** | **Scen. 6** | **Scen. 7** | **Scen. 8** |
| 1.1 to 2.1 | 21.2 | 21.8 | 22.3 | 24.4 | 32.2 | 37.9 | 39.7 | 38.1 |
| 1.1 to 3.1 | 59.8 | 60.2 | 59.9 | 60.8 | 90.5 | 93.1 | 92.2 | 91.9 |
| 1.1 to 3.2 | 59.2 | 59.5 | 59.3 | 60.0 | 88.5 | 90.5 | 90.3 | 88.6 |
| 1.1 to 3.3 | 59.6 | 60.0 | 59.7 | 60.4 | 89.8 | 91.9 | 91.1 | 89.8 |
| 1.1 to 3.4 | 59.9 | 60.3 | 60.1 | 61.0 | 91.1 | 93.2 | 92.4 | 91.5 |
| 1.1 to 3.5 | 60.0 | 60.4 | 60.1 | 61.0 | 91.1 | 93.2 | 92.5 | 91.3 |
| 1.1 to 3.6 | 59.9 | 60.3 | 60.1 | 60.9 | 91.0 | 93.2 | 92.4 | 91.3 |
| 1.1 to 4.1 | 50.3 | 50.6 | 50.5 | 51.1 | 75.8 | 77.8 | 77.4 | 77.4 |
| 1.1 to 4.2 | 49.8 | 50.0 | 50.1 | 50.6 | 74.7 | 76.3 | 76.4 | 76.0 |
| 1.1 to 4.3 | 50.2 | 50.4 | 50.3 | 50.9 | 75.5 | 77.4 | 77.2 | 77.0 |
| 1.1 to 4.4 | 50.4 | 50.6 | 50.7 | 51.4 | 76.2 | 78.0 | 77.8 | 77.7 |
| 1.1 to 4.5 | 50.5 | 50.7 | 50.7 | 51.3 | 76.3 | 78.3 | 78.0 | 78.0 |
| 1.1 to 4.6 | 50.5 | 50.8 | 50.6 | 51.4 | 76.2 | 78.2 | 77.8 | 77.8 |
| 1.1 to 5.1 | 38.8 | 38.7 | 38.8 | 38.9 | 58.1 | 58.5 | 57.8 | 58.5 |
| 1.1 to 5.2 | 38.6 | 38.3 | 38.6 | 38.4 | 56.2 | 51.2 | 55.8 | 51.2 |
| 1.1 to 5.3 | 38.6 | 38.3 | 38.6 | 38.4 | 56.0 | 52.3 | 56.3 | 52.3 |
| 1.1 to 5.4 | 38.7 | 38.6 | 38.7 | 38.6 | 57.5 | 57.1 | 56.5 | 57.1 |
| 1.1 to 5.5 | 38.7 | 38.6 | 38.6 | 38.5 | 57.4 | 57.5 | 57.1 | 57.5 |
| 1.1 to 5.6 | 21.2 | 21.6 | 21.3 | 22.0 | 58.0 | 57.3 | 57.3 | 52.8 |
| 1.1 to 5.7 | 32.3 | 32.8 | 32.5 | 33.2 | 58.2 | 57.5 | 57.6 | 54.1 |

Note: Scen. = Scenario.

**Table 25. Scenarios for BCA Results (*67*)**

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Major-Road ADT | 10,000 | 10,000 | 10,000 | 10,000 | 15,000 | 15,000 | 15,000 | 15,000 |
| Minor-Road ADT | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| Left Turn % | 5% | 5% | 10% | 10% | 5% | 5% | 10% | 10% |
| Truck % | 10% | 22% | 10% | 22% | 10% | 22% | 10% | 22% |

Substantial changes in traffic patterns on Energy Highways led the Odessa District to conduct a review of practices and policies to improve operational and safety performance. A review of access management practices resulted in a revised access management policy (*68*) that included consideration of cross-sections. While this policy was drafted for use on Energy Highways in the Odessa District, principles from it can be used statewide. Table 26 defines the design requirements for the successful implementation of access management in the Odessa District.

**Table 26. Access Management Design Requirements (*68*)**

| Classification[4] | Passing Lanes | Turn Lanes | Access Point Spacing (Passenger Cars) | Access Point Spacing (increased for Heavy Trucks) | Minimum Offset Between Access on Opposite Sides of Road | Hybrid Driveway Design |
|---|---|---|---|---|---|---|
| Energy Highway—Primary Route | YES | YES | Minimum 1/2 Mile | Minimum 1 Mile | 1/4 mile | YES |
| Energy Highway—Secondary Route | OK | YES | Minimum 1/3 Mile | Minimum 3/4 Mile | 1/8 mile | YES |
| Energy Highway—Minor Route | NO | OK | Table 2-2 | Table 2-2 | Minimize where possible | Preferred |

Specific implementation guidance from the Odessa District includes:

- Passing Lanes: Include in design of roadway widening/repaving projects.
- Left-Turn Lanes: Include key left-turn locations in design (e.g., high volume, restricted sight); partner with applicant for locations not under design.
- Right-Turn Lanes: Add shoulders to roadways identified for turn lanes; applicants to add shoulders for acceleration and deceleration purposes at driveways if not present.
- Access Point Spacing: The separation of the driveways or access points will be governed by the highest demand. Two locations with primarily passenger car traffic (e.g., man-camps) would need to be separated by the passenger car distance. A location with primarily passenger car traffic adjacent to a location with primarily truck traffic would be governed by the truck traffic.
- Driveway Consolidation: Adding new driveways may require consolidating locations to minimize the number of access points.
- Driveway Signing: New driveways shall be marked with a D3-1 Sign (green background, white 8-inch letters) mounted on a 7-ft pole near the edge of ROW. The text of the street sign shall be the milepost marking to the first decimal place as defined by the district staff.
- Driveway Design: Hybrid configuration allows for the cab to track for the smaller radius and the trailer tires to off-track on the apron, preventing damage to fences, pavement edge, etc. (See Figure 27). Designs submitted in the hybrid driveway configuration are presumed to meet all engineering requirements. Alternative configurations in accordance with the TxDOT *Roadway Design Manual* will also be considered with substantiating traffic data.

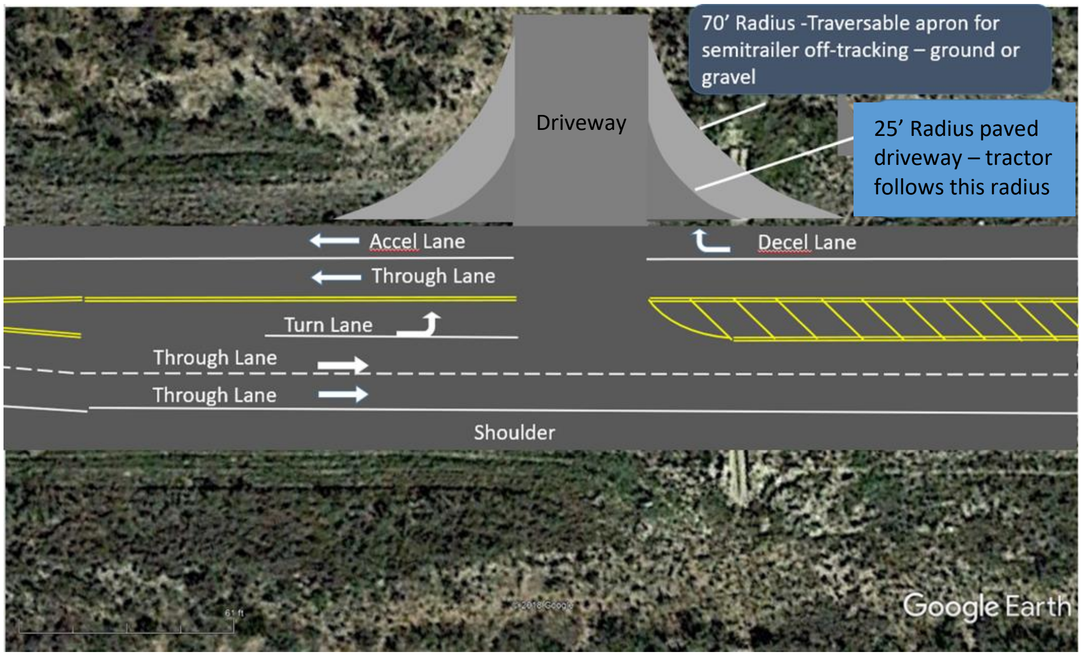



**Figure 27. Hybrid Driveway Design (*68*)**

The policy applies to rural sections of state highways impacted by the development of energy and natural resources as generally defined on the "Odessa District Energy Highway Designation Map" (latest revision) and the judgment of the district engineer (or designee). Applicability includes new driveways, existing permitted driveways where uses have changed, unpermitted driveways, and county/local road intersections.

Exceptions include driveways exclusively for the purpose of residential access (three or fewer dwellings), agricultural field access, and driveways where municipalities have been granted permitting authority. In addition, developed areas designated on the map are also excluded.

Locations on state highways not designated as Energy Highways or in designated developed areas will continue to be reviewed in accordance with the applicable policies and procedures and appropriate engineering judgement. This policy does not modify the formal driveway application process. Applicants are encouraged to discuss planned driveways prior to submission to streamline the review process and speed approval.

This policy does not modify the formal appeal process. Applicants meeting the above criteria are presumed to meet all requirements for engineering study in the application process. Applicants not meeting the above requirements may be required to submit an engineering analysis as required by the district engineer (or designee). While all appeals processes remain in place, applicants are encouraged to contact the district staff to coordinate designs and to address location-specific issues.

## EXISTING DATABASES

The project work plan and subsequent discussions with the Project Monitoring Committee described an evaluation of existing databases for suitability in making decisions on cross-sections. The findings for those evaluations are provided here.

### TMAS

The Traveling Analysis Monitoring System (TMAS) database is an archived traffic volume database maintained by FHWA and available for download from the U.S. Department of Transportation Bureau of Transportation Statistics. This database consists of several data tables, including the volume table (*69*) that contains archived volumes and the stations table (*70*) that contains information to describe the locations and types of continuous traffic count stations on the national highway system. The volume table contains one record per day from each continuous traffic count station, and each record contains an hourly vehicle count for each of the 24 hours in the day. The volume table can be merged with the stations table to determine the locations of the archived traffic counts. The formats and coding values for the variables in TMAS are described in the *Traffic Monitoring Guide* (*71*).

#### *Temporal Coverage*

The research team obtained a query of the TMAS volume table for the state of Texas for calendar year 2021. This query contained 206,468 volume records. Table 27 shows the distribution of the volume records across the months in 2021. Other than February, the distribution is mostly uniform. The smaller number of volume records for February may be attributable to the severe winter storm and resulting power failures that occurred in that month.

**Table 27. Temporal Distribution of Volume Records**

| Month | Number of Records | Percent of Sample |
|---|---|---|
| January | 17,298 | 8.38 |
| February | 14,844 | 7.19 |
| March | 17,458 | 8.46 |
| April | 17,436 | 8.44 |
| May | 16,842 | 8.16 |
| June | 17,540 | 8.50 |
| July | 17,792 | 8.70 |
| August | 18,061 | 8.75 |
| September | 17,534 | 8.49 |
| October | 17,066 | 8.27 |
| November | 16,575 | 8.03 |
| December | 17,842 | 8.64 |

*Spatial Coverage*

Figure 28 shows the locations of the TMAS data stations in Texas. There is a notable concentration of data stations in the urbanized areas, but fewer data stations in the rural areas.

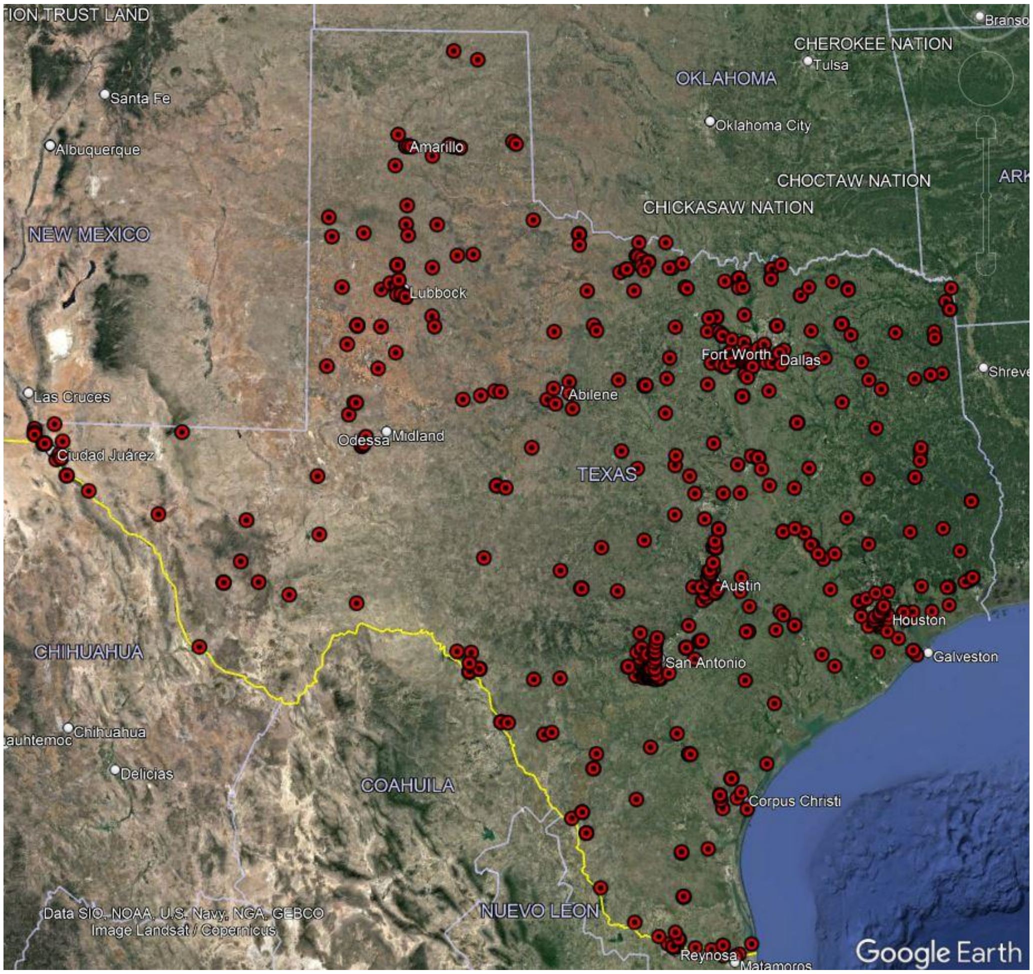



**Figure 28. TMAS Data Station Locations**

The research team obtained the stations table and merged it with the volume table query for Texas to obtain information about the locations where the volume records were collected. Table 28 provides the distribution of the 206,468 volume records by signed route type and area type. The categories for signed route type are defined in the *Traffic Monitoring Guide*. The research team manually examined data from Farm to Market (FM) and Ranch to Market (RM) roads to determine that these roads fall within the category of "parkway or forest route marker." As shown, about two-thirds of the volume records come from rural count locations, with the bulk of the rural volume records coming from interstates, U.S. highways, or state highways.

Table 29 shows the distribution of the volume records by lane count. About half of the records come from sensors that monitored two lanes, and almost 92 percent come from sensors that monitored at most three lanes. The research team manually examined station locations on rural divided highways and determined that the sensors are typically arranged to monitor the two roadbeds separately. Additionally, it appeared that frontage roads on rural interstates are typically not provided with sensors. An additional variable in the stations table showed that Texas TMAS volume records always contain total volumes for all monitored lanes combined.

**Table 28. Distribution of Volume Records by Signed Route Type and Area Type**

| Signed Route Type | Sample Percentage by Area Type | | |
|---|---|---|---|
| | Rural | Urban | All |
| Interstate | 13.27 | 14.72 | 27.99 |
| U.S. highway | 28.33 | 5.44 | 33.77 |
| State highway | 17.44 | 9.21 | 26.65 |
| Off-interstate business marker | 0.00 | 1.00 | 1.00 |
| Parkway or forest route marker (includes FM and RM roads) | 7.66 | 1.89 | 9.54 |
| Other | 1.05 | 0.00 | 1.05 |
| All | 67.74 | 32.26 | 100.00 |

**Table 29. Distribution of Volume Records by Lane Count**

| Number of Lanes | Number of Records | Percent of Sample |
|---|---|---|
| 1 | 68,306 | 33.08 |
| 2 | 103,138 | 49.95 |
| 3 | 17,955 | 8.70 |
| 4 | 7377 | 3.57 |
| 5 | 7499 | 3.63 |
| 6 | 1384 | 0.67 |
| 7 | 572 | 0.28 |
| 8 | 237 | 0.11 |

*Possible Applications*

Given the sparse distribution of the data stations in rural areas, the TMAS database will not often be useful to obtain an hourly distribution directly from a rural highway site of interest. However, the database can still be used to obtain default hourly distributions for a site of interest based on stations near the site. For example, default hourly distributions could be computed and aggregated by TxDOT district, functional classification, and/or signed route type.

## RHiNO

The research team obtained the TxDOT's Road–Highway Inventory Network Offload (RHiNo) database for the year 2021 (the most recent full year for which the data are available). TxDOT publishes this data annually and submits to FHWA every year as part of the Highway Performance Monitoring System Program. These data include all roadway inventory attributes and as well nine years of historical traffic volumes for each roadway segment in the state. All the data are available in geospatial format. The variables from RHiNo that can assist in making the decision about a cross-sectional alternative are:

- Posted speed limit (SPD_MAX): This variable is not always updated when there is a change in posted speed limit so should be used with caution.
- Number of lanes (NUM_LANES): This variable is generally well populated but may not always reflect what is in the field (especially when there are passing and turning lanes). Additional sources such as aerial photography can be used to verify the value in RHiNo.
- Surface width (SUR_WID): This variable is generally well populated but additional sources such as aerial photography can be used to verify the value in RHiNo.
- Median type (MED_TYPE): This variable is generally well populated but may not always reflect what is in the field. Additional sources such as aerial photography can be used to verify the value in RHiNo.
- Median width (MED_WID): Similar to the median type; additional sources such as aerial photography can be used to verify the value in RHiNo. Another median width variable (HP_MED_W) includes both inside shoulders as well.
- Shoulder widths (S_WID_I and S_WID_O): This variable can include the width of a paved or unpaved shoulder, so it must be used in conjunction with shoulder type (S_TYPE_I and S_TYPE_O) variables.
- Climbing and passing lanes (CLMB_PS_LA): This variable includes information about continuous two-way left turn, Super 2, and climbing/passing lanes. However, the research team's investigation in the TxDOT 0-7035 project showed that this variable often includes inaccurate information.
- Acceleration/deceleration lanes (ACCEL_DECEL_LANE): This variable includes information about the presence of acceleration and deceleration lanes. However, the research team's investigation in the TxDOT 0-7035 project showed that this variable often includes inaccurate information.
- Curb type (CURB_L and CURB_R): This variable includes information about the curb type on the left and right side. The research team did not use this variable in their previous studies so they cannot comment on its accuracy.
- ADT (ADT_CUR): This variable provides the traffic volumes on each roadway segment for the most current year. The RHiNo database also includes nine years of historical volumes.
- Truck ADT (AADT_TRUCK): This variable provides the truck volumes on the roadway segment. This is estimated based on the truck percentage in the mix.
- Horizontal curve (CURV_CLASS_*x*): These variables provide information about the length of curves for six different ranges of degree of curve ($x$ = A, B, C, D, E, or F). However, these variables are seldom populated.
- Vertical grade (VERT_GRADE_CLASS_*x*): These variables provide length of segment with different ranges of grade levels ($x$ = A, B, C, D, E, or F). However, these variables are seldom populated.

**CRIS**

TxDOT is responsible for assembling and maintaining the crashes reported by the law enforcement in a database known as the Crash Records Information System (CRIS). CRIS contains multiple tables that are linked by a common crash identification number. These tables summarize information related to the crash (e.g., day, time, weather, crash severity, and surface condition), each unit (e.g., contributing factors, vehicle body style, and vehicle model year), and each person involved in the crash (both drivers and passengers). For this analysis, researchers retrieved crash data for the years 2017–2022 from the CRIS database.

# CHAPTER 3: DETERMINE SUFFICIENCY OF EXISTING GUIDANCE

The research team compiled information on practices, findings, and existing guidance for selecting cross-sections for various conditions. Based on a review of that information, the research team provided the following conclusions regarding the sufficiency of existing guidance for developing guidelines for use in future decision-making.

## TWO-LANE HIGHWAYS

A great deal of research has been conducted in Texas on improving safety and operations of two-lane highways through the addition of passing lanes and turning lanes. Research in Texas can be supplemented by research elsewhere, but Texas has more published research findings and more published guidance on the use of passing and turning lanes than elsewhere, and the foundation for future guidance can be largely provided by what already exists in Texas. Examples of key principles for future guidance include the following:

- Two-lane undivided highways are generally sufficient for ADT less than 3,000 vpd, though site-specific treatments could be considered (e.g., turning lanes at intersections, passing or climbing lanes for locations with recurring platoons, etc.).
- Between 3,000 and 15,000 vpd, it is appropriate to consider some combination of passing lanes and turning lanes to improve safety and operational performance. The optimum combination (e.g., Super 2, two-lane with TWLTL, or Super 2 with TWLTL) is related to the overall volume, the truck volume, and the driveway and intersection activity along the corridor. Details on those combinations have been developed on previous projects and can be refined for use in specific guidance to be used in future decision-making.
- Between 15,000 and 20,000 vpd, widening to a four-lane cross-section (with a TWLTL [4T] or a median buffer [4M]) becomes more effective than an improved two-lane cross-section in terms of cost, safety, and operations.
- Above 20,000 vpd, highways should be widened to four lanes with a full-width TWLTL (4T) or median (4D), using the widths provided in the *Roadway Design Manual*.

## FOUR-LANE HIGHWAYS

Similar to the principles described above for two-lane highways, some principles can be described for four-lane highways:

- Four-lane undivided highways should be avoided for reasons of safety and operational performance.
  - New projects to install four-lane rural highways should include a TWLTL (4T) or a median treatment (4D or 4M) consistent with the principles described above and in the findings from TxDOT Project 0-7035 (*10*).

  - Existing four-lane undivided rural highways should be considered for improvement based on the guidance from Project 0-7035 for various roadway width categories. Highways with volumes lower than 15,000 vpd can be considered for conversion to two-lane highways with additional treatments (e.g., Super 2, TWLTL, intersection auxiliary lanes, or median buffer treatments) without changing the paved surface width or narrowing shoulders. Highways with higher volumes may need to be widened to accommodate median or intersection treatments while maintaining appropriate shoulder width.
  - Four-lane undivided roadways in urban or suburban areas with low to moderate volumes (e.g., 20,000 vpd or less) may be candidates for conversion to two-lane with TWLTL cross-sections to improve safety while maintaining operational performance.
- Above 20,000 vpd, four-lane highways with a median buffer (4M) should be widened to include a full-width TWLTL (4T) or full-width median (4D), depending on access needs.
- For 4T or 4D roadways experiencing higher volumes, the guidance provided in the *Highway Capacity Manual* describes when it may be appropriate to widen the road and add another travel lane in either direction. In addition to volume and capacity, the operational and safety performance of the corridor should be considered to determine whether access management treatments or full access control (e.g., conversion to expressway or freeway) is appropriate to reduce the likelihood of crashes and improve operational performance along the corridor.

## ADDITIONAL CONSIDERATIONS FOR LANE TREATMENTS

In addition to the principles above, considerations for lane treatments that are not through lanes (e.g., passing lanes, turning lanes, etc.) include the following:

- Appropriate lane addition and reduction tapers as described in the *Roadway Design Manual* must be used when providing passing lanes, TWLTLs, and intersection auxiliary lanes. Similarly, the RDM provides guidance for transitions from two-lane undivided to four-lane cross-sections.
- Where passing lanes are provided in the vicinity of intersections, appropriate separation between passing lanes and turning lanes should be provided based on the guidance from TxDOT Project 0-7044 (*67*). This guidance also includes the consideration of appropriate sight distance at the intersection.
- Left-turn lanes for intersections should be considered for locations that meet the warrants described in NCHRP Report 780 (*61*) and the AASHTO *Green Book* (*8*). Designs for such left-turn lanes should consider the recommended dimensions for lane-changing, deceleration length, and storage length provided with the warrants.
- Right-turn lanes for intersections should be considered for locations that meet the warrants described in Potts, et al. (*62*). Where right-turn lanes are provided, they should accommodate existing bicycle treatments or allow for the inclusion of future bicycle

treatments as applicable. Dimensions for lane-changing, deceleration, and storage should also be considered similar to left-turn lanes.

## FORMAT OF GUIDELINES

TxDOT Project 0-7035 (*10*) has provided a useful framework for describing a variety of conditions and their recommended treatments. This framework can be used and expanded to include additional details as described above, and accompanying text and guidance can be developed with the expanded framework to be included in the TxDOT *Roadway Design Manual* and *Guidelines for Implementing Super 2 Corridors in Texas*.

The expanded guidelines can be developed based on the material reviewed in Tasks 2 and 3, which largely pertain to operational and safety performance. Some information exists on economic performance (i.e., benefit-cost analysis) that can also be included in the guidelines; however, to develop the economic analysis at that level of detail for other scenarios would require a separate effort, either in extending the current project or initiating a new project. Another topic that could be explored in a separate effort is producing more detail on when a 2T is beneficial from a safety and operations standpoint compared to 2U and intersection auxiliary lanes at lower volumes; the 2T has been studied along with 2S and 2ST in Project 0-7035 for moderate volumes, but it could be useful to have more information on the 2T at lower volume to compare to existing left-turn lane warrants. A benefit of having a separate effort on the above topics is that TxDOT can define specific scenarios about which more information is desired or required and the analysis can focus on those scenarios.

## SUMMARY

In summary, the research team concluded that there is sufficient existing guidance and information to develop a robust set of guidelines for making decisions on appropriate cross-sections for many scenarios. Other scenarios and additional supporting information can be added to these guidelines through additional efforts that could be accomplished by adding tasks to this project or initiating new research projects to develop those details.

# CHAPTER 4: RECOMMENDED GUIDANCE ON CROSS-SECTION

The research team's review and evaluation of existing guidance and research, combined with feedback from the Project Monitoring Committee, led to the development of recommendations for updated guidance for optimized cross-sections, including recommended updates to the TxDOT *Roadway Design Manual*. That recommended guidance is provided in this chapter.

## GUIDELINES FOR SELECTING RURAL CROSS-SECTIONS

The information compiled in this project, using findings and recommendations from previous projects in Texas and elsewhere, provide support for the following guidelines for selecting the optimum cross-section for rural highways:

- Super 2 highways always provide superior safety performance compared to 2U highways for any traffic volume that a 2U highway can accommodate; however, they are not always a cost-effective alternative due to significantly higher costs of construction. The 2U highways are generally sufficient for ADT less than 3,000 vpd, though site-specific treatments could be considered (e.g., turning lanes at intersections, passing or climbing lanes for locations with recurring platoons, etc.).
- Two-lane with TWLTL (2T) cross-section is recommended for rural highways where the ADT is less than 3,000 vpd but the highway contains a large number of driveways.
- Between 3,000 and 15,000 vpd, it is appropriate to consider some combination of passing lanes and turning lanes to improve safety and operational performance. The optimum combination (e.g., Super 2 [2S], or Super 2 with TWLTL [2ST]) is related to the overall volume, the truck volume, and the driveway and intersection activity along the corridor; details of these combinations are provided in Table 18.
- Between 15,000 and 20,000 vpd, widening to a four-lane cross-section (with a TWLTL [4T] or a median buffer [4M]) becomes more effective than an improved two-lane cross-section in terms of cost, safety, and operations.
- Above 20,000 vpd, highways should be widened to four lanes with a full-width TWLTL (4T) or median (4D), using the widths provided in the *Roadway Design Manual*. The 4D always provides superior safety performance to the 4T, but it is not always a cost-effective alternative due to significantly higher costs of construction. As such, a BCA is recommended before selecting a specific cross-section.
- Four-lane undivided (4U) cross-sections have poor safety performance and mediocre operational performance compared to other alternatives and should be avoided. For existing 4U roadways:
    - Four-lane undivided sections with 15,000 vpd or less should be reviewed for conversion to a Super 2 section, per the guidelines provided here and in Project 0-7035 (*10*). These sections can be restriped as Super 2 roadways to significantly reduce traffic crashes without creating any operational issues. It may be necessary to include turn lanes in the conversion (i.e., a 2ST cross-section) for highways with higher levels of driveway activity.
    - Four-lane undivided sections with volumes above 15,000 ADT should be reviewed for adding a 4-ft striped median buffer (i.e., 4M cross-section). Adding a

buffer to a four-lane undivided roadway results in significant safety improvement if shoulders of 6 ft or more are provided and foreslopes are not reduced. If driveway activity is high, a center turn lane (i.e., a 4T cross-section) may be necessary.
    - Above 20,000 vpd, 4U and 4M highways should be widened to include a full-width TWLTL or full-width median, depending on access needs.
- For all roadways, traffic volume, shoulder width, truck percentage, and driveway activity all have significant effects on safety and operational performance. When considering the potential widening of a two-lane undivided roadway or changing the cross-section of any other rural highway, these effects should be considered. Based on these effects, as identified, preferred cross-sections for various combinations of rural highways are summarized in Table 18.
- Appropriate lane addition and reduction tapers as described in the *Roadway Design Manual* must be used when providing passing lanes (Chapter 4, Section 6) or turning lanes (i.e., TWLTLs and intersection auxiliary lanes/speed change lanes) (Chapter 3, Sections 2 and 5). Similarly, the RDM (Chapter 3, Section 5) provides guidance for transitions from two-lane undivided to four-lane cross-sections.
- Where passing lanes are provided in the vicinity of intersections, the beginning and ending of passing lanes and turning lanes should be appropriately separated based on the guidance from TxDOT Project 0-7044 (*67*). This guidance also includes the consideration of appropriate sight distance at the intersection.
- Left-turn lanes for intersections should be considered for locations that meet the warrants described in NCHRP Report 780 (*61*) and the AASHTO *Green Book* (*8*). Designs for such left-turn lanes should consider the recommended dimensions for lane-changing, deceleration length, and storage length provided with the warrants.
- Right-turn lanes for intersections should be considered for locations that meet the warrants described in Potts et al. (*62*) or the conditions described in the TxDOT *Access Management Manual*. Where right-turn lanes are provided, they should accommodate existing bicycle treatments or allow for the inclusion of future bicycle treatments as applicable. Dimensions for lane-changing, deceleration, and storage should also be considered similar to left-turn lanes.

**Table 30. Potential Guidelines for Selecting Rural Cross-Sections.**

| AADT | Driveway Activity Index[a] per Mile | Truck Percentage | Preferred Cross-Section |
|---|---|---|---|
| ≤ 3000 | Any | Any | Two-Lane Undivided/ Two Lanes with TWLTL |
| 3000–15,000 | ≤ 30 | Any | Super 2 |
| | > 30 | ≤ 15% | Super 2 with TWLTL |
| | | 15–25% | Super 2 with TWLTL |
| | | > 25% | Four Lanes with TWLTL |
| 15,000–20,000 | ≤ 30 | ≤ 15% | Four Lanes with 4-ft Median Buffer[b] |
| | | 15–25% | Four Lanes with 4-ft Median Buffer[b] |
| | | > 25% | Four Lanes with TWLTL |
| | > 30 | ≤ 15% | Four Lanes with 4-ft Median Buffer[b] |
| | | 15–25% | Four Lanes with TWLTL |
| | | > 25% | Four Lanes with TWLTL |
| > 20,000 | Any | Any | Four Lanes with TWLTL/ Four-Lane Divided |

Note:
[a] Driveway activity index is the number of residential driveways. The index is equal to three times the number of industrial driveways, or 12 times the number of commercial driveways (measured per mile).
[b] 6-ft minimum shoulder width. Greater widths are desirable.

## GUIDELINES FOR SELECTING URBAN CROSS-SECTIONS

Similar to the guidelines for rural cross-sections, the research team has compiled recommendations for guidelines on selecting urban cross-sections. Some principles are similar for both rural and urban, while others differ because the typical speeds found in the urban environment are lower than the rural environment. The following guidelines are recommended for selecting cross-sections for urban roadways:

- For roads with higher speeds (e.g., 50 mph and higher), the recommendations in Table 18 for rural cross-sections can be applied to urban and suburban cross-sections.
    - For additional support, guidance in the *Highway Capacity Manual* on uninterrupted flow can apply to these roadways. The HCM states that, in general, uninterrupted flow can exist when there is no traffic signal or other traffic control device to interrupt traffic for at least 2 miles and no platoons are formed by upstream signals. Under those conditions, the HCM considers the capacity of a two-lane highway to be 1,700 passenger cars/hour (pc/h) in one direction, or 3,200 pc/h in both directions, under base conditions. For a multilane highway,

capacity is 2,200 pc/h/lane for a free-flow speed of 60 mph; with each 5-mph decrease in free-flow speed to 45 mph, capacity decreases by 100 pc/h/lane.

- For roads with lower speeds (e.g., 45 mph and lower), the practitioner should consult the guidance in the *Highway Capacity Manual* on capacity and LOS for interrupted flow conditions. The HCM describes methodology and applications for level-of-service criteria and capacity for automobiles, as well as methodologies for pedestrians, bicycles, and transit, for urban street facilities (defined as having a length of 1 mi or more in downtown areas and 2 mi or more in other areas). It also provides similar guidance for urban street segments, which are shorter than urban street facilities and allow analysis of more specific locations as needed. The theoretical automobile capacity of a through lane on an urban street facility or segment is 1,800 vph; adjustment factors reduce this capacity to account for the effects of certain roadway characteristics. Practitioners should use the HCM methodology to determine the recommended number of through lanes needed for given conditions on a specific facility or segment.
- Appropriate lane addition and reduction tapers as described in the *Roadway Design Manual* must be used when providing TWLTLs and intersection auxiliary lanes. Similarly, the RDM provides guidance for transitions from two-lane undivided to four-lane cross-sections.
- Left-turn lanes for intersections should be considered for locations that meet the warrants described in NCHRP Report 780 (*61*) and the AASHTO *Green Book* (*8*). Designs for such left-turn lanes should consider the recommended dimensions for lane-changing, deceleration length, and storage length provided with the warrants.
- Right-turn lanes for intersections should be considered for locations that meet the warrants described in Potts et al. (*62*) or the conditions described in the TxDOT *Access Management Manual*. Where right-turn lanes are provided, they should accommodate existing bicycle treatments or allow for the inclusion of future bicycle treatments as applicable. Dimensions for lane-changing, deceleration, and storage should also be considered similar to left-turn lanes.

## RECOMMENDED UPDATES TO THE ROADWAY DESIGN MANUAL

To provide the best opportunity for implementing these guidelines, the research team recommends, with the concurrence of the Project Monitoring Committee, that the guidance be included in the *Roadway Design Manual*. The following provides recommendations on specific updates to include in relevant sections of the RDM to incorporate this guidance, with underlines to indicate additions to the existing content and ~~strikethroughs~~ to indicate removal of existing content. The recommended updates are based on the content in the December 2022 edition of the RDM publicly available through the TxDOT Online Manual System and may not reflect internal drafts being considered through other updating efforts ongoing at the time of this report.

### Chapter 3—New Location and Reconstruction (4R) Design Criteria

*Section 2—Urban Streets*

**Level of Service**

Urban streets and their auxiliary facilities should be designed for Level of Service (LOS) B as defined in the *Highway Capacity Manual*. Densely developed urban areas may necessitate the use of LOS D. The *Highway Capacity Manual* describes methodology and applications for level-of-service criteria and capacity for automobiles, as well as methodologies for pedestrians, bicycles, and transit, for urban street facilities (defined as having a length of 1 mi or more in downtown areas and 2 mi or more in other areas). It also provides similar guidance for urban street segments, which are shorter than urban street facilities and allow analysis of more specific locations as needed. The theoretical automobile capacity of a through lane on an urban street facility or segment is 1,800 vph; adjustment factors reduce this capacity to account for the effects of certain roadway characteristics. The HCM methodology should be used to determine the recommended number of through lanes needed for given conditions on a specific facility or segment. The functional class of urban facility according to the Statewide Planning Map should be used to determine the appropriate LOS. For more information regarding LOS as it relates to facility design, see Service Flow Rate under subheading Traffic Volume in Chapter 2, Section 3.

**Medians**

*Two-Way Left-Turn Lanes*. Two-way left-turn lanes (TWLTL) are flush medians that may be used for left turns by traffic from either direction on the street. The TWLTL is appropriate where there are operational concerns for mid-block turns, such as areas with (or expected to experience) moderate or intense strip development. Used appropriately, the TWLTL design can improve the safety and operational characteristics of streets as demonstrated through reduced travel times and crash rates.

Recommended median lane widths for the TWLTL design are as shown in Table 3-2. When applying these criteria to new location projects or on reconstruction projects where widening necessitates the removal of exterior curbs, the median lane width should not be less than 12-ft, and preferably the corresponding desirable value shown in Table 3-2. Minimum values shown in Table 3-2 are appropriate for restrictive right-of-way projects and improvement projects where attaining the desirable width would necessitate removal and replacement of exterior curbing to gain a small amount of roadway width.

(*Existing Table 3-2: Median Lane Widths for Two-Way Left-Turn Lanes*)

A site can be considered suitable for the use of a TWLTL when an urban street meets the following criteria:

- Future ADT volume of greater than 3,000 vehicles per day for an existing two-lane urban street, 6,000 vehicles per day for an existing four-lane urban street, or 10,000 vehicles per day for an existing six-lane urban street; and
- Side roads plus driveway density of 20 or more entrances per mile.

When the above two conditions are met, the site should be considered suitable for the use of a TWLTL.

In addition to the above conditions, four-lane undivided roadways in urban or suburban areas with low to moderate volumes, as shown in Figure 3-X1, may be candidates for conversion to two-lane with TWLTL (2T) cross-sections to improve safety while maintaining operational performance.

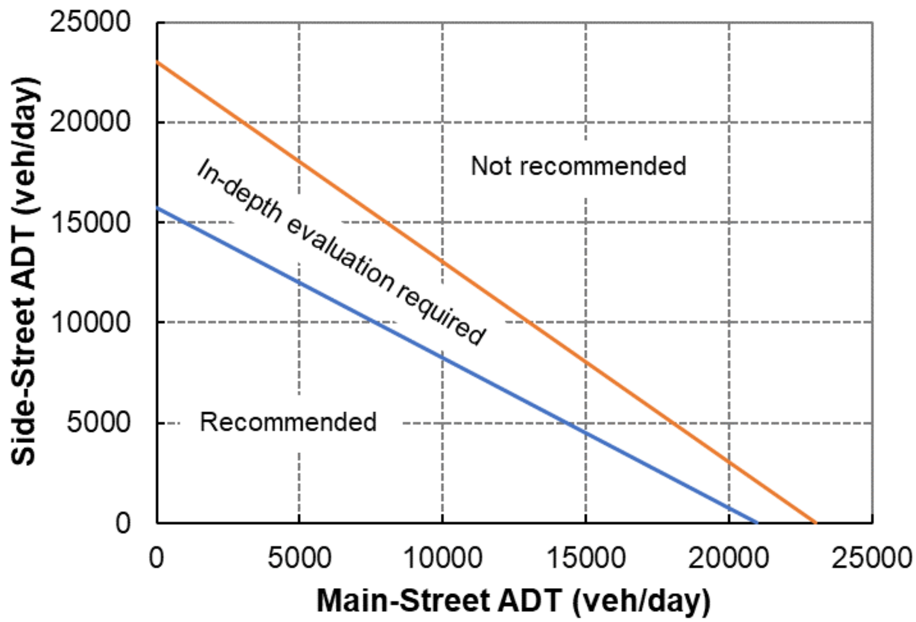



Figure 3-X1. Operational Performance Guideline for Conversion from 4-Lane Undivided to 2-Lane with TWLTL.

Source: Stamatiadis et al. (2011)

All cross-sections should be evaluated for pedestrian crossing capabilities. See Chapter 7, Pedestrian Facilities for additional guidance.

**Speed Change Lanes**

Speed Change Lanes are defined as acceleration or deceleration lanes for left or right turns, exit or entrance acceleration or deceleration lanes, or climbing lanes. A design waiver is required for speed change lanes that do not meet minimum length and width criteria.

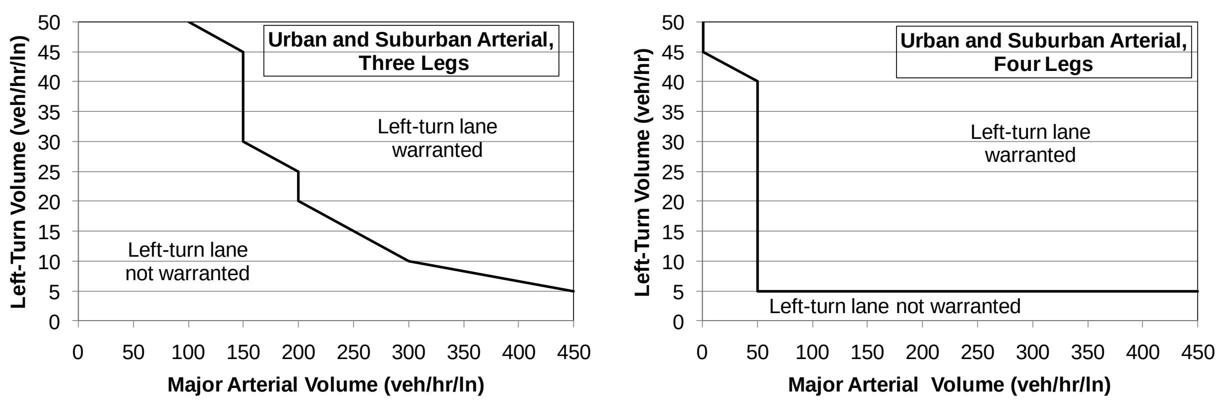
On urban streets, speed change lanes generally provide space for the deceleration and optional storage of turning vehicles. The length of speed change lanes for turning vehicles consists of the following two components:

- Deceleration length; and
- Storage length.

*Left-Turn Deceleration Lanes*. Suggested guidelines and warrants for the installation of left-turn lanes in urban and suburban areas based on turning and through volumes are provided in Table 3-X1 and Figure 3-X2. These volume-based guidelines indicate situations where a left-turn lane may be desirable, not necessarily situations where a left-turn lane is required. Further discussion and examples of left-turn lane guidance can be found in AASHTO's *Policy on Geometric Design of Highways and Streets*.

**Table 3-X1. Guide for Left-Turn Lane Warrants for Urban and Suburban Arterials. Source: AASHTO's *A Policy on Geometric Design of Highways and Streets***

| Left-Turn Lane Peak-Hour Volume (veh/hr) | Three-Leg Intersection, Major Urban and Suburban Arterial Volume (veh/hr/ln) That Warrants a Left-Turn Lane | Four-Leg Intersection, Major Urban and Suburban Arterial Volume (veh/hr/ln) That Warrants a Left-Turn Lane |
|---|---|---|
| 5 | 450 | 50 |
| 10 | 300 | 50 |
| 15 | 250 | 50 |
| 20 | 200 | 50 |
| 25 | 200 | 50 |
| 30 | 150 | 50 |
| 35 | 150 | 50 |
| 40 | 150 | 50 |
| 45 | 150 | < 50 |
| 50 or More | 100 | < 50 |




**(a) Three Legs** **(b) Four Legs**

Figure 3-X2. Suggested Left-Turn Lane Warrants Based on Results from Benefit-Cost Evaluations for Intersections on Urban and Suburban Arterials.
Source: AASHTO's *A Policy on Geometric Design of Highways and Streets*

Figure 3-4 illustrates the use of left-turn lanes on urban streets.

(*Remainder of Section 2 remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

*Section 3 – Suburban Roadways*

**Basic Design Features**

This subsection includes information on the following basic design features for suburban roadways:

- Geometric Design Criteria for Suburban Roadways;
- Access Control;
- Medians;
- Median Openings;
- Clear Zone;
- Borders;
- Grade Separations and Interchanges;
- Right of Way Width;
- Intersections;
- Speed Change Lanes; and
- Parking.

For suburban roadways with more urban characteristics, the Level of Service subsection in Chapter 3, Section 2 provides guidance on selecting the number of through lanes based on volume and refers to the *Highway Capacity Manual* for more details. For suburban roadways with more rural characteristics, Table 3-X2 in Chapter 3, Section 4 lists the preferred cross-section for various combinations of volume, driveway activity, and truck percentage.

Table 3-5 shows tabulated basic geometric design criteria for suburban roadways. The basic design criteria shown in this table reflect minimum and desired values that are applicable to new location, reconstruction, or major improvement projects.

See Chapter 2 for additional guidance on choosing an appropriate design speed.

(*Existing Table 3-5: Geometric Design Criteria for Suburban Roadways*)

**Medians**

*Two-Way Left-Turn Lanes*. Two-way left-turn lanes (TWLTL) are applicable on suburban roadways with moderate traffic volumes and low to moderate demands for left turns. For suburban roadways, TWLTL facilities should be between 14-ft and 16-ft wide.

The desired value of 16-ft width should be used on new location projects or on reconstruction projects where widening necessitates the removal of exterior curbs. The minimum width of 14-ft is appropriate for restrictive right-of-way projects and improvement projects where attaining desirable median width would necessitate removing and replacing exterior curbing to gain only a small amount of roadway width.

A site can be considered suitable for the use of a TWLTL when a suburban roadway meets the following criteria:

- Future ADT volume of greater than 3,000 vehicles per day for an existing two-lane suburban roadway, 6,000 vehicles per day for an existing four-lane suburban roadway, or 10,000 vehicles per day for an existing six-lane suburban roadway; and
- Side roads plus driveway density of 10 or more entrances per mile.

When the above two conditions are met, the site should be considered suitable for the use of a TWLTL.

In addition to the above conditions, four-lane undivided roadways in urban or suburban areas with low to moderate volumes, as shown in Figure 3-X1, may be candidates for conversion to two-lane with TWLTL cross-sections to improve safety while maintaining operational performance.

All cross-sections should be evaluated for pedestrian crossing capabilities. See Chapter 7, Pedestrian Facilities for additional guidance.

**Speed Change Lanes**

Speed Change Lanes are defined as acceleration or deceleration lanes for left or right turns, exit or entrance acceleration or deceleration lanes, or climbing lanes. A design waiver is required for speed change lanes that do not meet minimum criteria.

Speed change lanes may be provided as space for deceleration/acceleration to/from intersecting side streets with significant volumes and high operating speeds. For information regarding the installation and design of left-turn (median) speed change lanes and right-turn speed change lanes, see Chapter 3, Section 2, Urban Streets, Speed Change Lanes. (See Table 3-3 for lengths of single left-turn lanes; Table 3-4 for lengths of dual left-turn lanes, Figure 3-5 for length of right-turn lanes.)

*Section 4 – Two-Lane Rural Highways*

**Basic Design Features**

This subsection includes information on the following basic design features for two-lane rural highways:

- Geometric Design Criteria for Two-Lane Rural Highways;
- Access Control;
- Transitions to Four-Lane Divided Highways;
- Passing Sight Distances;
- Speed Change Lanes; and
- Intersections.

Additional information on structure widths may be obtained in TxDOT's *Bridge Design - LRFD* and the *Bridge Project Development Manual*.

Selection of the appropriate cross-section is important for optimal safety and operational performance. Table 3-X2 provides guidelines for selecting cross-sections for rural highways. While this section provides guidance on designing two-lane rural highways, additional design guidance for Super 2 highways is provided in Chapter 4, Section 6. For cross-sections with more than one lane of traffic in each direction, further guidance for the design of multilane rural highways can be found in Chapter 3, Section 5.

**Table 3-X2. Potential Guidelines for Selecting Rural Cross-Sections.**

| **AADT** | **Driveway Activity Index[a] per Mile** | **Truck Percentage** | **Preferred Cross-Section** |
|---|---|---|---|
| ≤ 3000 | Any | Any | Two-Lane Undivided/ Two Lanes with TWLTL |
| 3000–15,000 | ≤ 30 | Any | Super 2 |
| | > 30 | ≤ 15% | Super 2 with TWLTL |
| | | 15–25% | Super 2 with TWLTL |
| | | > 25% | Four Lanes with TWLTL |
| 15,000–20,000 | ≤ 30 | ≤ 15% | Four Lanes with 4-ft Median Buffer[b] |
| | | 15–25% | Four Lanes with 4-ft Median Buffer[b] |
| | | > 25% | Four Lanes with TWLTL |
| | > 30 | ≤ 15% | Four Lanes with 4-ft Median Buffer[b] |
| | | 15–25% | Four Lanes with TWLTL |
| | | > 25% | Four Lanes with TWLTL |
| > 20,000 | Any | Any | Four Lanes with TWLTL/ Four-Lane Divided |

NOTE:
a Driveway activity index is the number of residential driveways. The index is equal to three times the number of industrial driveways, or 12 times the number of commercial driveways (measured per mile).
b 6-ft minimum shoulder width. Greater widths are desirable.

(*Remainder of Basic Design Features subsection remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

**Transitions to Other Cross-Sections ~~Four-Lane Divided Highways~~**

Typical transitions from two-lane to four-lane divided highways are discussed in Transitions to Four-Lane Divided Highways, Multi-Lane Rural Highways, and illustrated in Figure 3-16.

Typical transitions for opening and closing passing lanes for Super 2 highways are discussed in Chapter 4, Section 6. Transitions for speed change lanes are discussed in the Speed Change Lanes subsection later in this section.

## Speed Change Lanes

*Right-Turn Deceleration Lanes.* Shoulders 10-ft wide alongside the traffic lanes generally provide sufficient area for acceleration or deceleration of right-turning vehicles. Where the right turn deceleration or acceleration lane is being constructed adjacent to the through lanes, the minimum lane width is 10-ft with a 2-ft surfaced shoulder. Speed change lanes should be symmetrical along both sides of the highway to provide drivers with a balanced section. Refer to the TxDOT *Access Management Manual* for guidelines as to when to consider a right-turn deceleration lane.

A deceleration-acceleration lane on one side of a two-lane highway, such as at a "tee" intersection, results in the appearance of a three-lane highway and may result in driver confusion. Therefore, right-turn speed change lanes are generally inappropriate for "tee" intersection design except where a four-lane section is provided. An example of this configuration is two through lanes (i.e., one through lane in each direction of traffic), one median left turn lane, and one right acceleration/deceleration lane.

Figure 3-5 shows an example of right-turn deceleration lanes.

The length of a right-turn deceleration lane is the same as that for a left-turn lane (see Table 3-12). On some low-volume rural highways, it may be acceptable to provide right turn lanes shorter than the lengths given in Table 3-12.

*Right-Turn Acceleration Lanes.* Right-turn acceleration lanes may be appropriate on some two-lane rural highways such as high-volume highways where significant truck percentages are encountered. See Table 3-13 for acceleration distances and taper lengths.

## Intersections

The provision of adequate sight distance is of utmost importance in the design of intersections along two-lane rural highways. At intersections, consideration should be given to avoid steep profile grades and limited horizontal or vertical sight distance. An intersection should not be situated just beyond a short crest vertical curve or a sharp horizontal curve. Where necessary, backslopes should be flattened and horizontal and vertical curves lengthened to provide additional sight distance. For more information on intersection sight distance, see Intersection Sight Distance in Chapter 2.

Where passing lanes are provided in the vicinity of intersections, appropriate separation between the extents of passing lanes and turning lanes should be provided based on the guidance from TxDOT Project 0-7044. The beginning or end of a passing lane should be at least 1000 ft upstream of an intersection and at least 1500 ft downstream of an intersection to avoid introducing intersection delay associated with the interactions of the minor-road vehicles turning on the major road and those vehicles merging at the end of the passing lane. Guidance from TxDOT Project 0-7044 also includes the consideration of appropriate sight distance at the intersection, as described by AASHTO's *A Policy on Geometric Design of Highways and Streets*.

The roadways should intersect at approximately right angles and should not intersect less than 75 degrees. Where crossroad skew is less than 75 degrees to the highway, the crossroad should be realigned to provide for a near perpendicular crossing. As a general rule, the higher the functional classification, the closer the crossroad intersection should be to 90 degrees.

Chapter 7 provides additional information regarding the accommodation of various types of truck class vehicles in intersection design in the section on Minimum Designs for Truck and Bus Turns. Further information on intersection design may also be found in AASHTO's *A Policy on Geometric Design of Highways and Streets*.

*Section 5 – Multi-Lane Rural Highways*

(*Section 5 contains different presentations of the phrase used as the title for the section. While the section is titled "Multi-Lane Rural Highways" other uses of the phrase in Section 5 are shown as "multilane rural" or "rural multilane". It is recommended that Section 5, and any other instances of the phrase throughout the RDM, use a consistent word order and formatting. It is further recommended that "rural multilane highways" be the selected word order, because it better reflects the common usage elsewhere, which describes the area first, followed by the cross-section, and omits the hyphen in "multilane". To promote consistency, this would also facilitate a change in Section 4 and elsewhere to use the term "rural two-lane highways"*.)

**Basic Design Features**

(*Section 5 has two subsections labeled "Basic Design Features". If this is not already being considered in an update of the manual, it is recommended that the second of these two subsections be merged into the first. The recommended updates shown below are based on this merging of the two subsections*.)

This subsection includes information on the following basic design features for multi-lane rural highways:

- Access Control;
- Medians;
- Turn Lanes;
- Travel Lanes and Shoulders;
- Intersections;
- Transitions to Four-Lane Divided Highways; and
- Grade Separations and Interchanges.

This subsection includes guidelines on geometric features for multilane rural highways. Selection of the appropriate cross-section is important for optimal safety and operational performance; guidance for selecting cross-sections for rural highways is provided in Table 3-X2 in Chapter 3, Section 4. The guidelines are outlined in Table 3-11, Figure 3-10, and Figure 3-11. These guidelines apply for all functional classes of roadways.

(*Remainder of Basic Design Features subsection remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

**Level of Service**

Rural arterials and their auxiliary facilities should be desirably designed for Level of Service B in the design year as defined in the *Highway Capacity Manual*.

Generally, undivided four-lane roadways have been associated with higher crash rates than divided roadways. This higher crash rate has frequently been attributed to the lack of protection for left-turning vehicles. ~~Therefore, if an undivided facility is selected for a location, the impact of left-turning vehicles should be examined~~ The guidance for selecting cross-sections for rural highways in Table 3-X2 in Chapter 3, Section 4 provides a TWLTL or striped median buffer for many four-lane cross-sections that are not divided with a median barrier.

For more information regarding level of service as it relates to facility design, see Service Flow Rate in the sub section titled Traffic Volume of Chapter 2, Section 3.

**Medians**

The width of the median in a multi-lane rural highway is the distance between the inside edges of the opposing travel lanes. If practical, wide medians (approximately 76-ft) should be used to provide sufficient storage space for tractor-trailer combination vehicles at median openings, reduce headlight glare, provide a pleasing appearance, reduce the chances of head-on collisions, and provide a sheltered storage area for crossing vehicles, including tractor-trailer combinations. Wide medians should generally be used whenever feasible but median widths greater than 60-ft have been found to be undesirable for intersections that are signalized or may be signalized in the design life of the project.

In areas that are likely to become suburban or urban in nature, medians wider than 60-ft should be avoided at intersections except where necessary to accommodate turning and crossing maneuvers by larger vehicles. Wide medians may be a disadvantage when signalization is required at future intersections. The increased time for vehicles to cross the median can lead to inefficient signal operation.

*Four-Lane Undivided Highways.* Four-lane undivided cross-sections have poor safety performance and mediocre operational performance compared to other alternatives and should be avoided. Table 3-X2 in Chapter 3, Section 4 lists preferred cross-sections for various combinations of volume, driveway activity, and truck percentage. Conversion of a two-lane highway to a four-lane highway facility should include a median when possible. If an existing two-lane highway has rolling terrain or restricted right-of-way conditions that affect the feasibility of widening to a four-lane divided highway, conversion to a ~~four-lane undivided highway~~ Super 2 highway, a two-lane highway with TWLTL, or a Super 2 with TWLTL may be considered to improve passing opportunities and traffic operations. Table 3-11 and Figure 3-10 include the general geometric features for existing four-lane undivided highways. In cases where a median is being proposed and the existing roadbed will remain in place, Non-Freeway

Rehabilitation (3R) alignment criteria may be applied to the existing roadbed as described in Chapter 4. However, 4R criteria must be applied to the new roadbed.

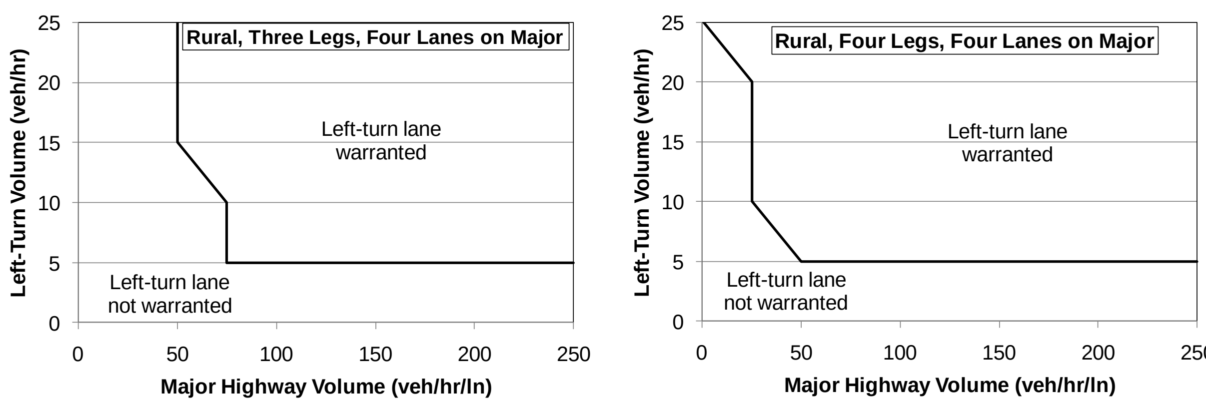
(*Remainder of Medians subsection remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

**Turn Lanes**

Turn lanes, or speed change lanes, should generally be provided wherever vehicles must slow to leave a facility or accelerate to merge onto a facility. Suggested guidelines and warrants for the installation of left-turn lanes on four-lane rural highways based on turning and through volumes are provided in Table 3-X3 and Figure 3-X3. These volume-based guidelines indicate situations where a left-turn lane may be desirable, not necessarily situations where a left-turn lane is required. Further discussion and examples of left-turn lane guidance can be found in AASHTO's *Policy on Geometric Design of Highways and Streets*.

**Table 3-X3. Guide for Left-Turn Lane Warrants for Rural Four-Lane Highways.**
**Source: AASHTO's *A Policy on Geometric Design of Highways and Streets***

| Left-Turn Lane Peak-Hour Volume (veh/hr) | Three-Leg Intersection, Major Four-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Left-Turn Lane | Four-Leg Intersection, Major Four-Lane Highway Peak-Hour Volume (veh/hr/ln) That Warrants a Left-Turn Lane |
|---|---|---|
| 5 | 75 | 50 |
| 10 | 75 | 25 |
| 15 | 50 | 25 |
| 20 | 50 | 25 |
| 25 | 50 | < 25 |
| 30 | 50 | < 25 |
| 35 | 50 | < 25 |
| 40 | 50 | < 25 |
| 45 | 50 | < 25 |
| 50 or More | 50 | < 25 |




**(a) Three Legs** **(b) Four Legs**

Figure 3-X3. Suggested Left-Turn Lane Warrants Based on Results from Benefit-Cost Evaluations for Rural Four-Lane Highways.

Source: AASHTO's *A Policy on Geometric Design of Highways and Streets*

(*Median Turn Lane (Left-Turn Lane) subsection and Storage Length Calculations subsection remain unchanged from existing, other than renumbering existing tables and figures as needed*.)

*Right-Turn Lane.* Right-turn lanes (12-ft lane with 4-ft adjacent shoulders) provide deceleration or acceleration areas for right-turning vehicles. The deceleration length and taper lengths for right-turn lanes are the same as for Median Turn lanes (see Table 3-12). Adjustment factors for grade effects are shown in Table 3-14. Refer to the TxDOT *Access Management Manual* for guidelines as to when to consider a right-turn deceleration lane.

(*Remainder of Turn Lanes subsection remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

*Section 7 – Freeway Corridor Enhancements*

*(While not directly related to the current project, this review of the RDM identified that references in this section are somewhat dated. The inclusion of NCHRP 835 below provides a more recent (and comprehensive) reference to add to the guidance.*

**Freeways with High Occupancy Vehicle Treatments**

High Occupancy Vehicles (HOV) lanes are a commonly used approach in urban freeway environments to reduce congestion and travel times.

Guidelines for the planning and designs of HOV facilities are given in NCHRP Report 835, *Guidelines for Implementing Managed Lanes*, AASHTO's *Guide for the Design of High Occupancy Vehicle Facilities* and in the *Guidance for Future Design of Freeways with High Occupancy Vehicle (HOV) Lanes Based on an Analysis of Crash Data from Dallas, Texas*, by the Texas Transportation Institute (TTI), 2004. Note that a Design Exception would be required if the desirable lane and shoulder widths shown in the AASHTO Guide for the Design of HOV Facilities are not met.

**Chapter 4—Non-Freeway Rehabilitation (3R) Design Criteria**

*Section 1—Purpose*

**Overview**

Rehabilitation (3R) projects consist of non-freeway transportation projects that extend the service life and enhance the safety of a roadway. In addition to resurfacing and restoration, the activities may include upgrading the geometric design and safety of the facility. Work on 3R projects does not include the addition of through travel lanes (i.e., no added capacity). 3R projects may include upgrading geometric features such as roadway widening, minor horizontal realignment, and bridge improvements to meet current standards for structural loading and accommodate the approach roadway width. Guidance for selecting cross-sections for rural highways is provided in Table 3-X2 in Chapter 3, Section 4; in many cases, use of those preferred cross-sections in a 3R project can minimize the need for roadway widening by reallocating existing pavement width and restriping. See alignment discussion in Chapter 4 Section 2, Design Characteristics for additional clarification on horizontal and vertical alignment.

*Section 2 – Design Characteristics*

**Geometric Design**

Geometric design guidelines are provided for the following roadways in the tables indicated.

- Rural multilane highways, Table 4-1;
- Rural two-lane highways, Table 4-2;
- Urban streets, Table 4-3;
- Rural frontage roads, Table 4-4; and
- Urban frontage roads, Table 4-5.

Guidance for selecting cross-sections for rural highways is provided in Table 3-X2 in Chapter 3, Section 4; in many cases, use of those preferred cross-sections in a 3R project can minimize the need for roadway widening by reallocating existing pavement width and restriping.

To measure bridge width on bridges without curbs, measure to the nominal face of rail. Reference TxDOT's Bridge Railing Manual and Bridge Railing Standards for the nominal widths of specific rail types and additional guidance. To measure bridge width on bridges with curbs, measure to the face of curb.

(*Remainder of Geometric Design subsection remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

*Section 6 – Super 2 Highways*

**Overview**

A Super 2 highway is ~~where a~~ one in which periodic passing lanes are ~~is~~ added to a two-lane rural highway to allow slower vehicles to pass and traffic platoons to disperse. ~~The passing lane will alternate from one direction of travel to the other within a section of roadway~~ Passing lanes are provided periodically in each direction of travel along the Super 2 corridor, allowing passing opportunities in both directions. A Super 2 project can be introduced on an existing two-lane roadway where there is a significant amount of slow-moving traffic, limited sight distance for passing, prevalence of head-on crashes, and/or the existing traffic volume has exceeded the two-lane highway capacity (creating the need for vehicles to pass on a more frequent basis).

Widening of the existing pavement can be symmetric about the centerline or on one side of the roadway depending on right-of-way availability and ease of construction. Figure 3-X4 shows nine different configurations of passing lanes. The isolated passing lane shown in Figure 3a is typically used to reduce delays occurring at a specific isolated bottleneck and is not truly a Super 2 corridor treatment. The other configurations allow some interaction between consecutive passing lanes in opposite directions, and they are used when traffic improvements are needed in both directions of travel over a corridor.

The alternating passing lanes shown in Figure 3-X4f and Figure 3-X4g can be used when sufficient width is available; Figure 3-X4g is the typical cross-section for what is commonly described as a 2+1 road. Overlapping passing lanes, shown in Figure 3-X4h and Figure 3-X4i, can be used when a passing lane is located on a crest or sag vertical curve, respectively. Side-by-side passing lanes, shown in Figure 3-X4j, can be used where the location of a passing lane is constrained by nonflexible factors. Those factors include (but are not limited to) obtaining ROW, when heavy traffic is the cause of platooning rather than no-passing zones, and where the need for passing lanes exists in both directions.

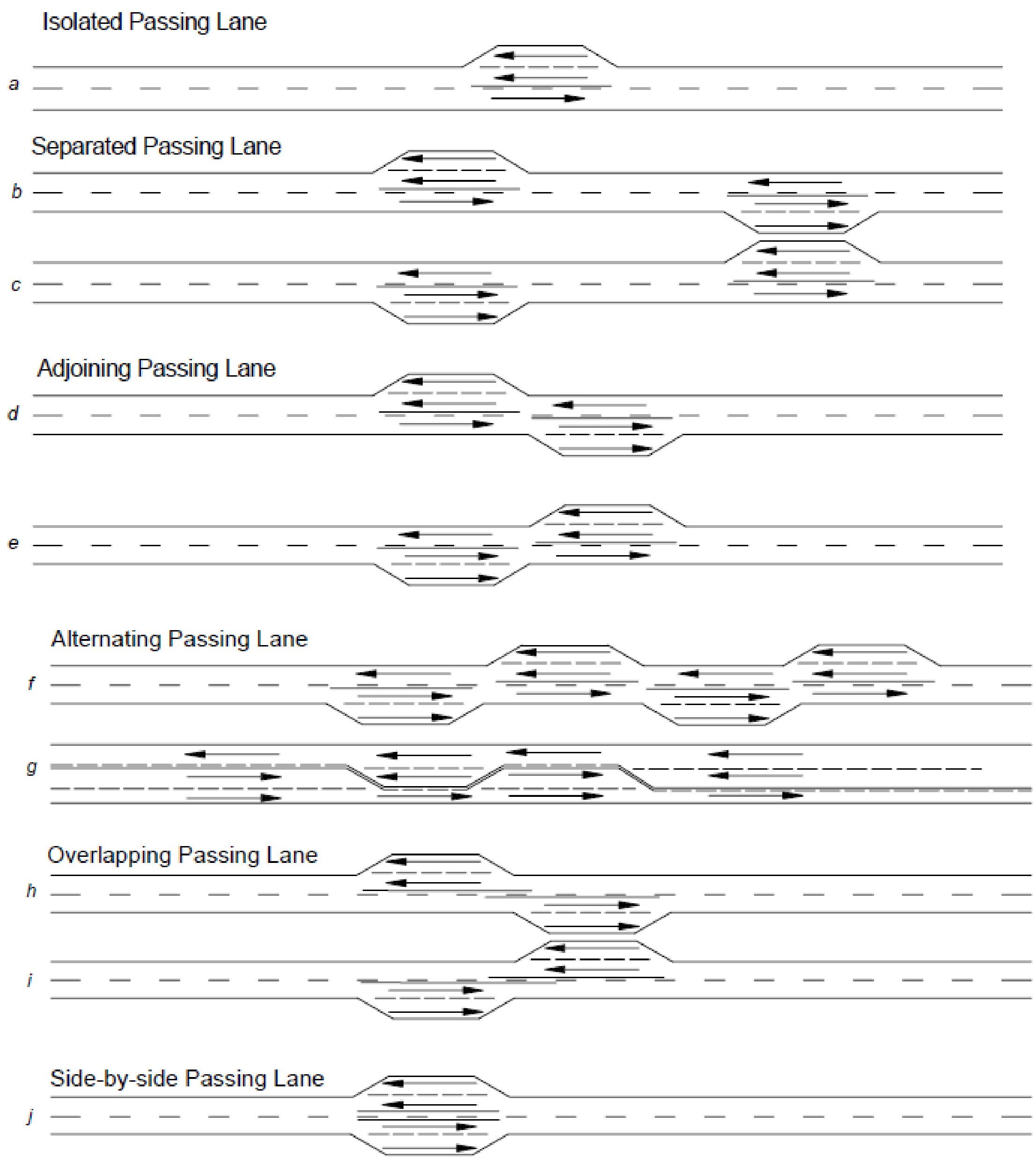



*Figure 4-X1. Passing Lane Configurations.*
*Source: Mutabazi et al. (1999)*

Because the Super 2 design allows such a high degree of flexibility, the practitioner has a great deal of latitude in the details of the design and implementation of a Super 2 corridor. This flexibility also means that the practitioner has a responsibility to exercise good engineering judgment in determining which details to include when designing and constructing the passing lanes and any other elements associated with a project that contains a Super 2 component. Many of the design details are consistent with the principles used for any rural highway, but the context of the passing maneuver on an otherwise two-lane highway needs to be considered. *Guidelines for Implementing Super 2 Corridors in Texas* contains information on comparing cross-section alternatives and how to determine which of those alternatives to select for a given location based on operational, safety, and economic measures.

Some issues to consider when designing a Super 2 project:

- Analyze existing right-of-way width considerations to determine feasibility of upgrading to a Super 2;
- Consider providing a left turn or right turn lane if a significant traffic generator falls within the limits of a Super 2;
- Consider providing wider shoulders (8-ft to 10-ft) in areas with high driveway density;
- Evaluate the location and associated treatment to achieve clear zone values at large drainage structures and bridges when considering the placement of passing lanes;
- Evaluate traffic operations including truck volumes if consideration is given to terminating passing lanes on significant uphill grades. Coordinate passing lanes with climbing lane needs to improve operating characteristics;
- Avoid terminating a passing lane over a hill or around a horizontal curve where the pavement surface at the end of the taper isn't visible from the beginning of the taper;
- ~~Consider traffic operations, unexpected lane changes, and intersection geometrics when evaluating the termination of a passing lane at an intersection. If termination of the passing lane at the intersection would result in significant operational lane weaving, then consider extending the passing lane beyond the intersection;~~
- Provide adequate sight distance (stopping sight distance desirable) between the end of a lane termination taper and a constraint such as metal beam guard fence, a narrow structure, or major traffic generator; and
- Consider providing the passing lane in the direction leaving an incorporated area for potential platoons generated in the urban area.

Where passing lanes are provided in the vicinity of intersections, appropriate separation between the extents of passing lanes and turning lanes should be provided based on the guidance from TxDOT Project 0-7044. The beginning or end of a passing lane should be at least 1000 ft upstream of an intersection and at least 1500 ft downstream of an intersection to avoid introducing intersection delay associated with the interactions of the minor-road vehicles turning on the major road and those vehicles merging at the end of the passing lane. Guidance from TxDOT Project 0-7044 also includes the consideration of appropriate sight distance at the intersection, as described by AASHTO's *A Policy on Geometric Design of Highways and Streets.*

(*Remainder of Section 6 remains unchanged from existing, other than renumbering existing tables and figures as needed*.)

## RECOMMENDED UPDATES TO THE ACCESS MANAGEMENT MANUAL

To further promote implementation of the guidelines and to promote consistency of guidance between TxDOT manuals, the research team recommends a selection of updates to the *Access Management Manual* (AMM). The following provides recommendations on specific updates to include in a relevant section of the AMM to incorporate this guidance, with underlines to indicate additions to the existing content and ~~strikethroughs~~ to indicate removal of existing content. The recommended updates are based on the content in the July 2011 edition of the AMM publicly available through the TxDOT Online Manual System and may not reflect internal drafts being considered through other updating efforts ongoing at the time of this report.

## Chapter 2—Access Management Standards

*Section 3—Number, Location, and Spacing of Access Connections*

### Auxiliary Lanes

This subsection describes the basic use and functional criteria associated with auxiliary lanes. Auxiliary lanes consist of left-turn and right-turn movements, deceleration, acceleration, and their associated transitions and storage requirements. Left-turn movements may pose challenges at driveways and street intersections. They may increase conflicts, delays, and crashes and often complicate traffic signal timing. These problems are especially acute at major highway intersections where heavy left-turn movements take place, but also occur where left-turn movements enter or leave driveways serving adjacent land development. As with left-turn movements, right-turn movements pose problems at both driveways and street intersections. Right-turn movements increase conflicts, delays, and crashes, particularly where a speed differential of 10 mph or more exists between the speed of through traffic and the vehicles that are turning right.

Table 2-3 ~~presents~~ and Figure 2X-1 present thresholds for auxiliary lanes. These thresholds represent examples of where left-turn and right-turn lanes should be considered. Refer to the TxDOT *Roadway Design Manual*, Chapter 3, for proper acceleration and deceleration lengths.

**Table 2-3: Auxiliary Lane Thresholds**

| Median Type | Left Turn to or from Property | | Right Turn to or from Property (5) | |
|---|---|---|---|---|
| | Acceleration | Deceleration | Acceleration | Deceleration |
| Non-Traversable (Raised Median) | (2) | All | Right turn egress > 200 vph (4) | • > 45 mph where right turn volume is > 50 vph (3)<br>• where right turn volume is > 60 vph (3) |
| Traversable (Undivided Road) | (2) | (1) | Same as above | Same as above |
| (1) Refer to ~~Table 3-11, TxDOT *Roadway Design Manual*, for alternative left-turn-bay operational considerations~~ Chapter 3 of the TxDOT *Roadway Design Manual* and AASHTO's *A Policy on Geometric Design of Highways and Streets* for guidelines on when to install left-turn deceleration lanes. | | | | |

(2) A left-turn acceleration lane may be required if it would provide a benefit to the safety and operation of the roadway. A left-turn acceleration lane would interfere with the left-turn ingress movements to any other access connection.

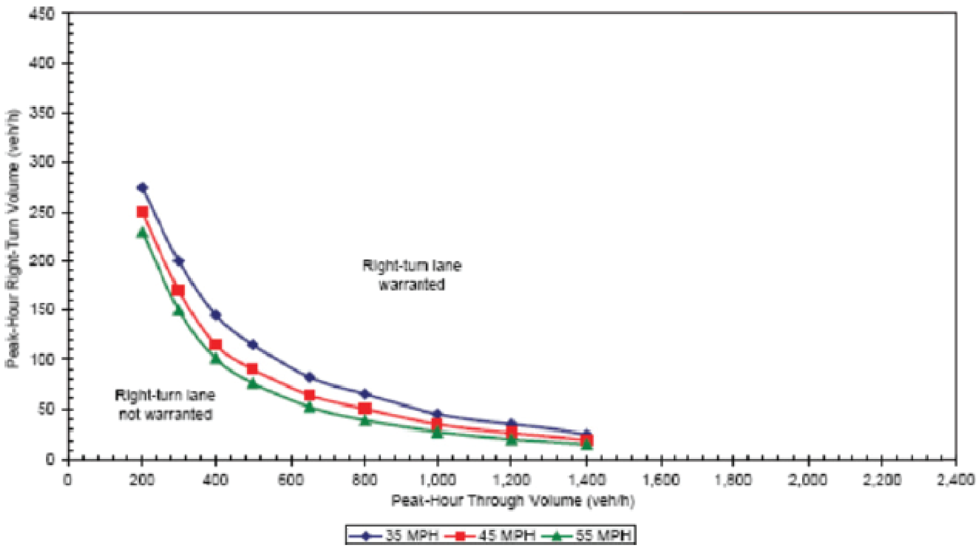
(3) Additional right-turn considerations:

- Conditions for providing an exclusive right-turn lane when the right-turn traffic volume projections are less than indicated in Table 2-3:
    - High crash experience
    - Heavier than normal peak flow movements on the main roadway
    - Large volume of truck traffic
    - Highways where sight distance is limited
- Conditions for NOT requiring a right-turn lane where right-turn volumes are more than indicated in Table 2-3:
    - Dense or built-out corridor where space is limited
    - Where queues of stopped vehicles would block the access to the right turn lane
    - Where sufficient length of property width is not available for the appropriate design

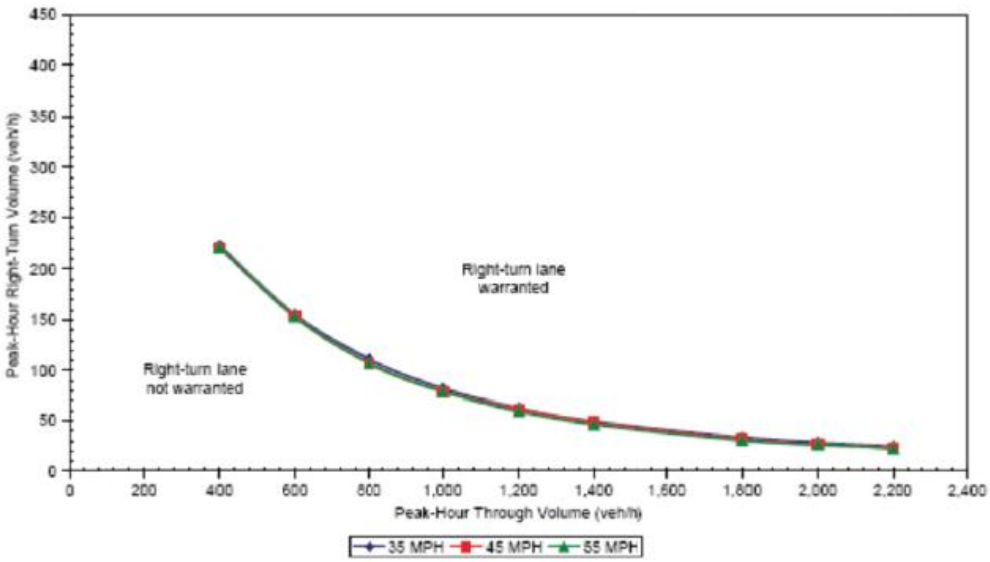
(4) The acceleration lane should not interfere with any downstream access connection.

- The distance from the end of the acceleration lane taper to the next unsignalized downstream access connection should be equal to or greater than the distances found in Table 2-2.
- Additionally, if the next access connection is signalized, the distance from the end of the acceleration lane taper to the back of the 90th percentile queue should be greater than or equal to the distances found Table 2-2.

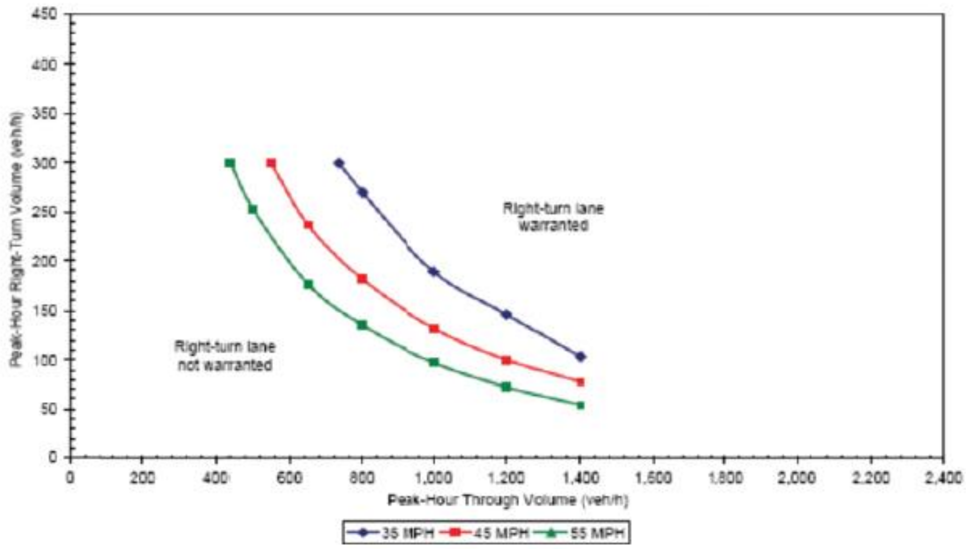
(5) Continuous right-turn lanes can provide mobility benefits both for through movements and for the turning vehicles.[1] Access connections within a continuous right turn lane should meet the spacing requirements found in Table 2-2. However, when combined with crossing left in movements, a continuous right-turn lane can introduce additional operational conflicts.



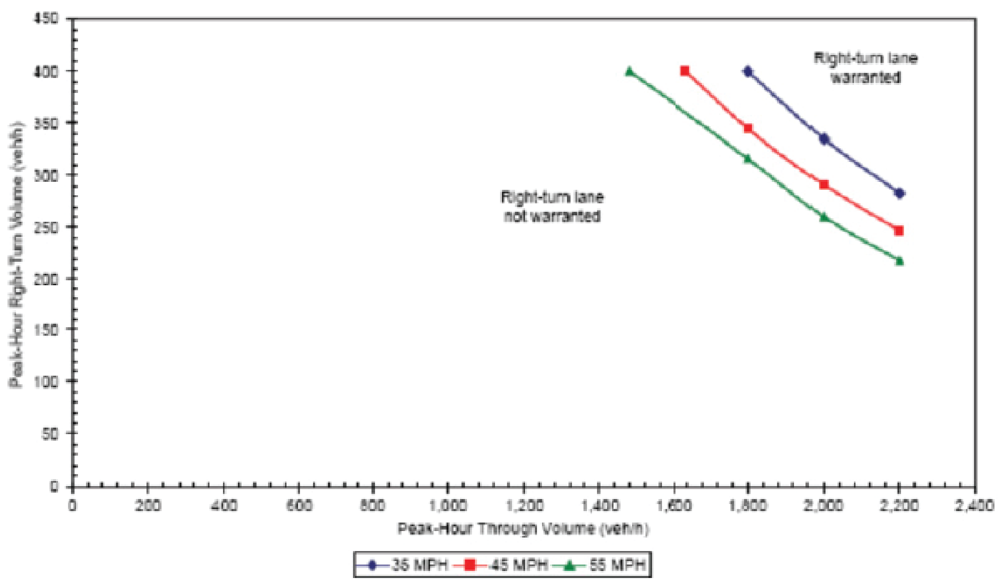

Economic warrant for right-turn lane (B/C=1) for four-leg unsignalized driveway or intersection on two-lane major street




Economic warrant for right-turn lane (B/C=1) for four-leg unsignalized driveway or intersection on four-lane major street




Economic warrant for right-turn lane (B/C=1) for three-leg driveway or intersection on two-lane major street




Economic warrant for right-turn lane (B/C=1) for three-leg driveway or intersection on four-lane major street

Figure 2-X1. Economic Warrants for Right-Turn Lanes
Source: Potts et al. (2007)

## RECOMMENDED UPDATES TO GUIDELINES FOR IMPLEMENTING SUPER 2 CORRIDORS IN TEXAS

Since the completion of *Guidelines for Implementing Super 2 Corridors in Texas* (*13*) in 2020, additional research has been completed that supplements the information found in the Guidelines. To further promote implementation of the guidelines and to promote consistency of guidance between TxDOT manuals, the research team recommends a selection of updates to the *Guidelines for Implementing Super 2 Corridors in Texas*. The following provides recommendations on specific updates to include in a relevant section of the *Guidelines* to incorporate this guidance, with underlines to indicate additions to the existing content. In addition to this recommended update, the information in the Guidelines that refers to Chapter 4, Section 6 of the RDM also needs to be updated when updates to the that section of the RDM are completed.

### Chapter 3—Design Considerations

*Cross-Section Configurations*

#### Auxiliary Lanes

As discussed in Chapter 1, configuration of the passing lanes in the cross-section of a Super 2 corridor can take many forms. Figure 3 illustrates nine general options, under which there are numerous variations. The RDM, as discussed in the previous section, provides guidance on beginning and ending passing lanes in each of the configurations found in Figure 1, so the designer has a great deal of latitude to produce a design that is tailored to meet the needs of a particular corridor. The benefit of having that flexibility in Super 2 design is that the designer can choose to place passing lanes where they will serve the greatest need while still accounting for budgetary constraints, ROW boundaries, and other corridor-specific limitations. The resulting cross-section can therefore look like any one of the nine configurations found in Figure 1, or it can change to resemble different configurations at different locations throughout the corridor. Some considerations for where a designer should locate passing lanes and choose the resulting cross-section configuration are as follows:

- Consider existing ROW width, terrain, and structures to evaluate the feasibility of a Super 2 corridor and determine the best locations to install passing lanes with a minimum of ROW acquisition, earthwork, and structure widening.
- The location of major traffic generators, such as intersections with other state highways or driveways to large developments, should be identified when the proposed alignment is planned. It is preferable to avoid locating high-traffic intersections and driveways within the boundaries of a passing lane. When such generators are unavoidable, it is preferable that they be located near the midpoint of the passing lane to provide as much separation as possible from the opening and closing tapers. The designer should also consider providing auxiliary lanes for turning vehicles to decelerate, queue, and/or accelerate at access points that are major generators to reduce the likelihood of conflicts between low-

speed turning vehicles and high-speed through (and passing) vehicles. Where passing lanes are provided in the vicinity of intersections, appropriate separation between the extents of passing lanes and turning lanes should be provided based on the guidance from TxDOT Project 0-7044. The beginning or end of a passing lane should be at least 1000 ft upstream of an intersection and at least 1500 ft downstream of an intersection to avoid introducing intersection delay associated with the interactions of the minor-road vehicles turning on the major road and those vehicles merging at the end of the passing lane. Guidance from TxDOT Project 0-7044 also includes the consideration of appropriate sight distance at the intersection, as described by AASHTO's *A Policy on Geometric Design of Highways and Streets.*

- Avoid locating passing lanes at locations with restrictive geometry (e.g., sharp horizontal curves) or other impediments to traffic flow (e.g., approaches to urbanized areas). However, providing passing lanes downstream of these features is beneficial for dispersing platoons.
- Where passing lanes are terminated, sufficient sight distance must be provided to avoid conflicts with oncoming traffic or constraints such as guard rails, guard fences, or narrow bridges. The minimum distances are provided in the RDM, as described in Figure 4 through Figure 8, but SSD is recommended. Avoid terminating passing lanes on substantial uphill grades.

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