APPENDIX B: Complete Literature Review

This appendix provides a literature review of safety improvements that may be applied at intersections of rural multi-lane divided highways. Although most of the information presented is derived from literature in the public domain, in some cases the experience of state transportation agencies is discussed to augment what is available in the literature.

This appendix begins by reviewing the safety performance of conventional intersections as background information. This background will assist the reader in understanding why some treatments do or do not address safety problems at median crossover intersections. The remainder of the appendix covers safety treatments that have been applied or could be applied to intersections of rural multi-lane divided highways.

Conventional Intersections

Conventional intersections between two-lane roadways and rural median-divided highways involve stop control on the minor roadway, with vehicles on both roadways able to make right, left, and through movements right at the intersection or through the median crossover (1, p. 9). A conventional four-legged intersection is shown in Figure 2-1. Figure 2-1 includes a left turn lane, but a conventional median crossover intersection may not include turning lanes and may include a right turn lane, depending on local practice, turning volumes, and crash history. However, the primary feature of a conventional intersection is that all movements are permitted through the intersection. The subject of this research project is this type of intersection on rural median-divided highways and potential modifications to this design and markings to improve safety while maintaining or improving operational performance.

To demonstrate the safety performance of conventional rural median crossover intersections, the next few sections present descriptive statistics and statistical analysis of crashes with respect to traffic volume and geometric characteristics. Understanding the safety performance of a conventional intersection facilitates an understanding of the benefits of the treatments described in the remainder of this appendix.

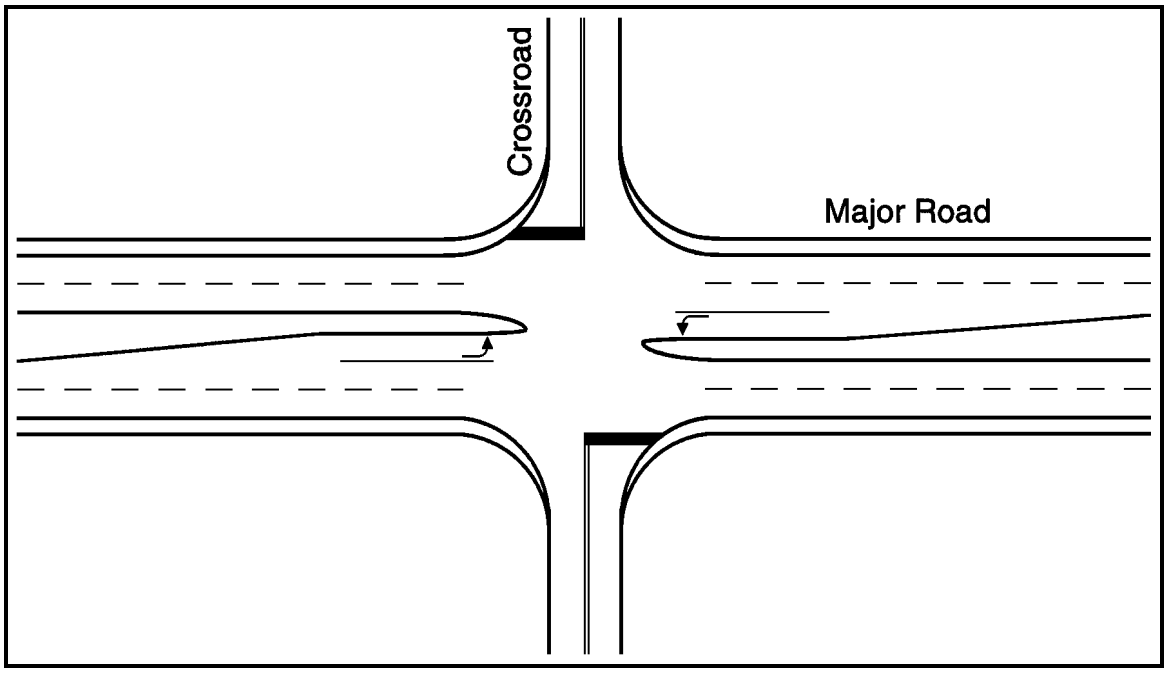


Figure 2-1. Conventional median crossover intersection

Descriptive analysis

In a 2004 study by Maze, Hawkins, and Burchett, the authors identified 644 intersections on rural median-divided roadways in Iowa (2). Using the Iowa Department of Transportation's (Iowa DOT) crash database, roadway inventory information (traffic and limited geometry information), video logs, and aerial imagery, data elements were assembled from each of these databases to create an intersection database of 644 two-way stop-controlled intersections on median-divided highways that have speed limits of 50 miles per hour or higher and are outside of any incorporated city limits. The database included a limited amount of intersection feature information, including presence, length, and type of auxiliary lanes and median width, as well as the average daily traffic (ADT) count/estimate during the study period (1996–2000) for each of the four approaches. All data were verified through inspection of the Iowa DOT video log and through aerial imagery. Five years of intersection crash data (1996–2000) were included in the database. Intersection crashes were identified as those within a 150-foot buffer around the intersection, and then each crash record was examined to ensure that the crash had been properly located and that any crashes that were incorrectly located were removed.

To obtain a measure of relative crash severity, the researchers used a simple ranking of 1 for property-damage-only crashes, 2 for possible or unknown injury, 3 for minor injury, 4 for major injury, and 5 for a fatal crash. Figure 2-2 shows a bar chart of the crash rate in crashes per million entering vehicles (MEV), the severity rate index in MEV, and fatal crash rate in hundred million entering vehicles per mile (HMEV). The severity rate index took the severity rank (1–5) for each crash, summed the rank, and then divided by MEV over five years. The bars are divided by increasing minor roadway volume, and the graph clearly shows that all rates increase with increasing minor roadway volume. This not only means that the crashes per entering vehicle are increasing, but also that the crashes that

occur are becoming more severe. Similar results were also found by Maze et al. when a similar analysis was done using data from Minnesota intersections (3).

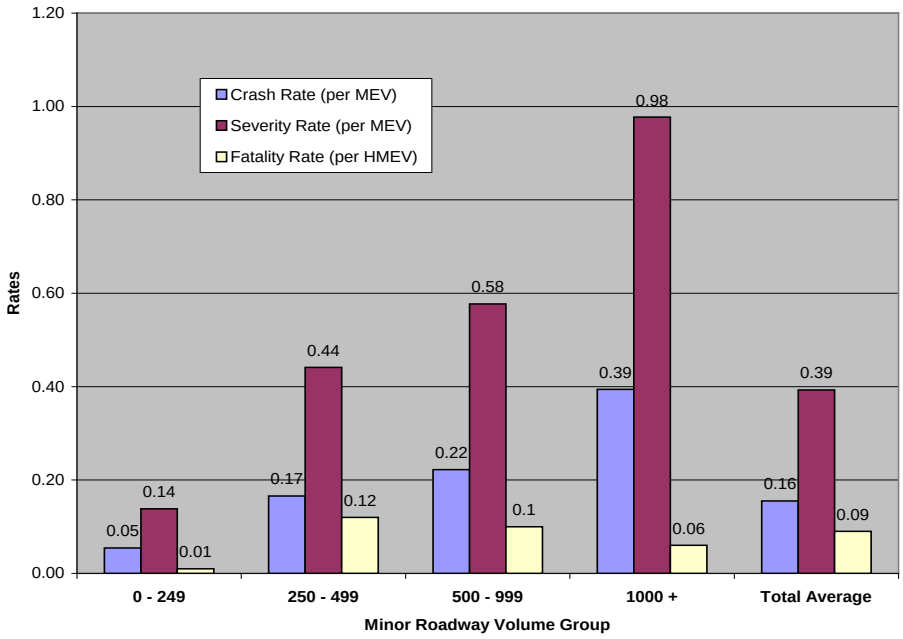


Figure 2-3. Crash severity and fatality rate versus minor road volume

In the same Iowa study, when crashes were categorized by crash type, it was found that as minor road volume increased, the incidence of right-angle crashes increased. After subtracting out the property-damage-only crashes, Figure 2-3 shows the percentage of total crashes divided into five categories, head-on crash, right-angle crashes, rear-end crashes, sideswipe crashes, and other, by increasing minor roadway volume. Clearly, right-angle crashes increase as a percentage of total crashes with increasing minor roadway volume. Right-angle crashes at high-speed, two-way stop-controlled intersections are generally more severe than other types of crashes, further illustrating that crash severity increases with increased minor roadway volume. The higher percentage of right-angle crashes also means that when minor roadway volumes increase, drivers on the minor road are having more difficulty selecting a safe gap.

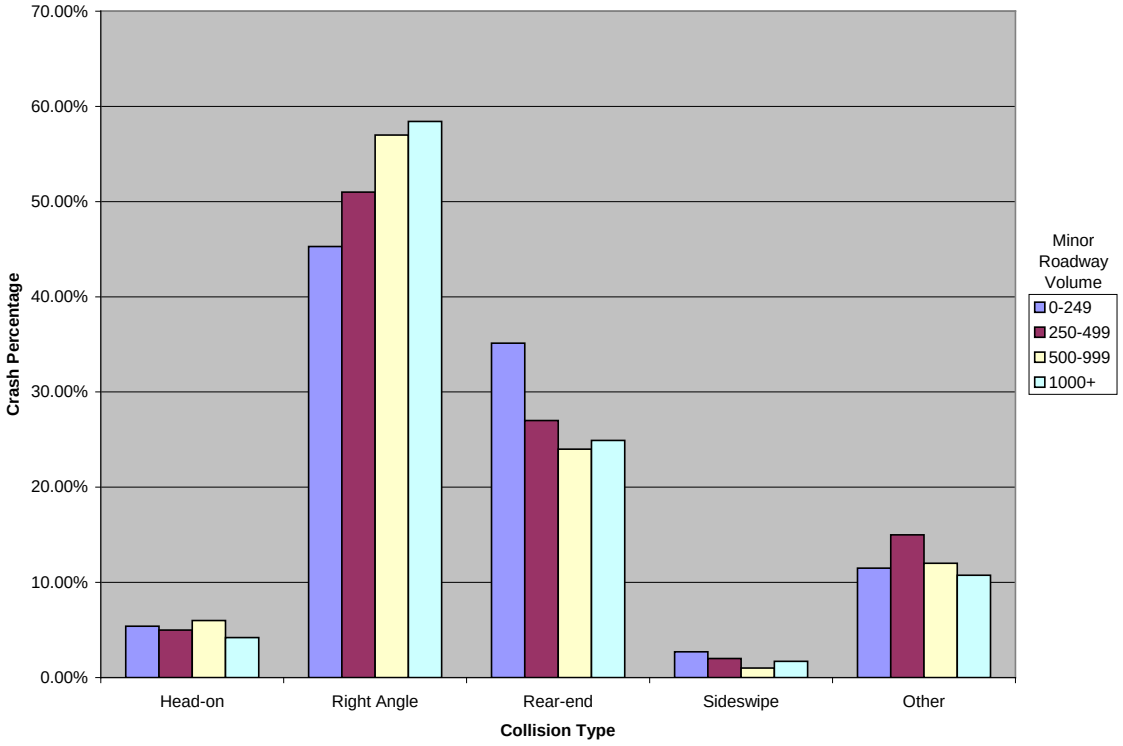


Figure 2-4. Crash type distribution (without property damage-only) by minor road volume

The increase in right-angle crashes at median crossover intersections was also found in Minnesota and Utah data by Harwood et al. in NCHRP report 375 (4). In an analysis conducted by the Nebraska Department of Roads, the agency compared the crash rates for 111 miles of roadways that had been converted to median-divided four-lane roadways to 324 miles of two-lane highways that were planned for conversion to median-divided four-lane roadways (5). The portion of the Nebraska roadways that had already been converted had a right-angle crash rate of 0.149 crashes per million vehicle miles while the yet-to-be-converted two-lane highways had a right-angle crash rate of 0.087, which represents a 71% increase in right-angle crash rates. Although the Nebraska cross-sectional comparison is unsophisticated and neglects the other co-variants that would explain some of the increase in right-angle crash rates (for example, higher volumes on the converted roadways), the large increase in right-angle crashes after conversion does indicate that four-lane roadways with median crossover intersections are more prone to right-angle crashes.

Statistical analysis

Safety performance functions (SPF) are generally used to represent the relationship between crash frequency and variables and explain changes in crash frequency (crashes per unit of distance or per intersection). Hauer introduced the concept of safety performance functions to generalize the representation of exposure as a non-linear function of the traffic volume (6). Crash rates, which are commonly used to make comparisons between the crash risks of intersections and roadways, are normalized by

traffic exposure (ADT or daily entering vehicles) and are, therefore, insensitive to changes that occur in crash intensity as a result of volume. As can be seen in Figure 2-2, crash rates at median crossover intersections clearly depend on volume and, therefore, crash rate is an inappropriate measure for the analysis of changes in safety performance. An SPF involves the estimate of crash intensity using volume as an explanatory variable, potentially with other characteristics that may explain variations in crash intensity.

It has long been recognized that traffic volume is an important explanatory factor for intersection crashes (7). Studies have concluded that traffic volume is the most significant single factor contributing to crash frequency at rural crossover intersections (2,7,8). Several alternative statistical models have been used to incorporate traffic volumes and other variable into estimates of crash frequency (SPFs). In general, it has been found that considering major and minor roadway traffic volumes as separate independent variables leads to better results. This was shown as early as 1953 by McDonald, who estimated the model shown in Equation 1 using Ordinary Least Squares (9). The crash data used to fit Equation 1 are from 150 three- and four-legged intersections on rural multi-lane highways in California. In 1993, Bonneson and McCoy (Equation 2) provided an example of the use of negative binomial regression to estimate a traffic safety performance function for rural two-way stop-controlled intersections using data from 125 rural Minnesota intersections (10). Seventeen of the intersections in the database are intersections with multi-lane median-divided highways. Equation 3 was estimated using negative binomial regression and reported by Maze et al. in 2004 (2). The model by Maze et al. used 644 two-way stop-controlled crossover intersections in Iowa.

Mc Donald	$N = 0.000783(V_{Maj})^{0.455}(V_{Min})^{0.633}$	(1)
Bonneson and McCoy	$N = 0.00379(V_{Maj})^{0.256}(V_{Min})^{0.831}$	(2)
Maze et al.	$N = e^{(0.02278 + 0.00005(Vmaj) + 0.00042(Vmin))}$	(3)

In each model, crash frequency is more sensitive to the minor roadway volume than the major roadway volume. In Equation 3, the parameter for the minor roadway volume is 8.4 times the parameter for the major roadway volume. At a typical rural intersection where the major road has a average daily volume of 12,000 vehicles per day (VPD) and the minor road has an average daily volume of 500 VPD, an additional 100 VDP on the minor roadway increases the expected crash frequency by 4.3% while an additional 100 vehicles on the major roadway increases the expected crash frequency by 0.5%.

Using the same Iowa data (with 644 median crossover intersections), Burchett and Maze again created a SPF, where the dependent variable was the crash severity rate for the intersection, using the index created for this research (1 for property damage-only, 2 for possible/unknown injury, 3 for minor injury, 4 for major injury, and 5 for fatal) (11). In addition, the authors added variables to take into account intersections on major roadway horizontal curves (more than 1.5° of curvature per 100 feet) and vertical curves (intersections located on grades greater than or equal to 4%), intersections skewed more than 15°, and land use surrounding the intersection (agricultural, residential, or commercial). When dummy variables (a variable that is zero or one) are used where the

dummy's value represents the presence (=1) or non-presence (=0) of each land use type in the surrounding square mile, the major road volume dropped out of the equation due to lack of statistical significance, but minor roadway volume continued to be an important explanatory variable. Clearly, land use intensity is collinear with major road volume, but this finding further reinforces the fact that crash frequency and crash severity are a function of the intensity of activity (both land use and traffic volumes) adjacent to the intersection, and not necessarily the volume on the median-divided highway. This further justifies such strategies as applying full access control as rural median-divided highways approach suburbs in metropolitan areas and as rural median-divided highways bypass rural cities and villages.

The authors took the 100 intersections with the worst safety performance (as measured by crash severity rate) and investigated the distribution of crash types at locations where skew, horizontal curvature, or vertical curvature exist (geometric features of interest). There are 34 intersections on vertical curves, 21 on horizontal curves, 40 skewed intersections, and 34 on tangent sections (no curves or skew). The intersections totaled more than 100 because some intersections have more than one type of geometric feature of interest. Figure 2-5 shows the distribution of crash type by geometric feature of interest and clearly shows that right-angle crashes become a much greater proportion of the total crashes when one or more geometric features of interest are present. This finding indicates that each of these features results in the driver having more difficulty selecting gaps in traffic, resulting in a much higher occurrence of right-angle crashes.

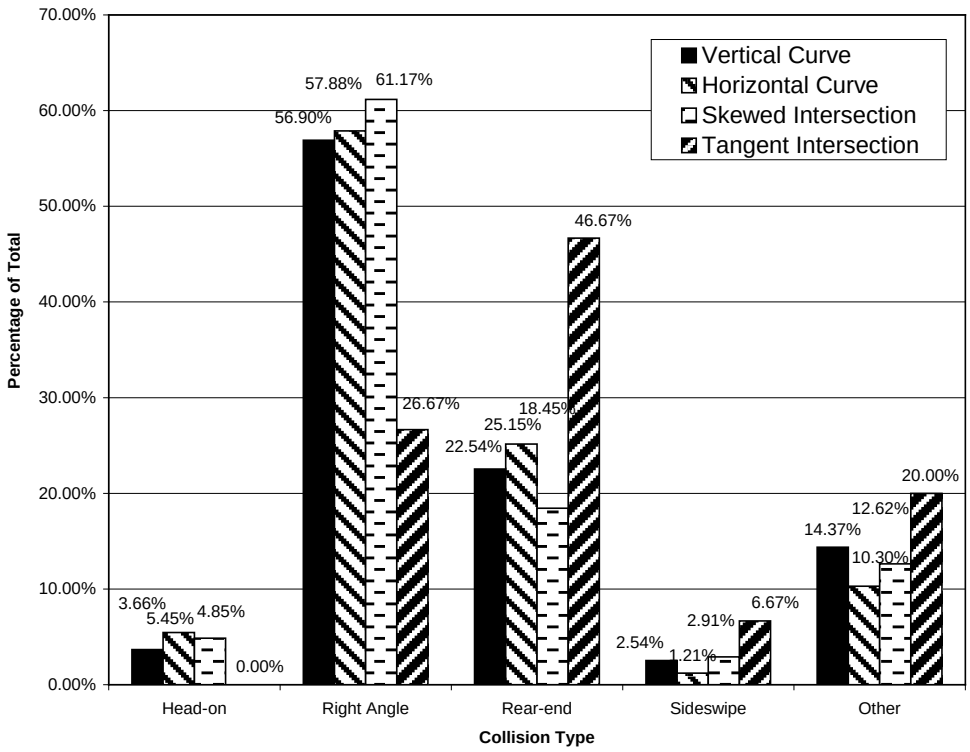


Figure 2-5 Crash type by geometric feature of interest

Burchett and Maze went on to explore a subset of intersections in greater detail and selected the 30 intersections with the poorest safety performance as measured by the greatest severity index rate. Collision diagrams were created for all 30, and sight visits were made to each intersection. For each median crossover intersection, there are two decision points for left turning and through maneuvers; the first is before the vehicle crosses the near set of lanes, and the second is following the median crossover and before crossing the far-side lanes. Once the run-off-the-road (fixed object) crashes and rear-end crashes were removed from the data set, 62% of the crashes take place in the far-side lanes while 38% take place in the near lanes. The authors found that crashes were less likely to occur on the far side when an intersection is located on a horizontal curve, but the sample size was very small, making it difficult to determine the relationship between near-side and far-side crashes and horizontal curves. In other words, horizontal curves on the mainline intersection approach made it more likely that the driver would make a poor gap decision on the near-side decision point than at other median crossover intersections, but more data needs to be collected before this relationship can be identified with certainty. Preston et al. also observed that right-angle crashes occur more commonly on the far side when the authors reviewed crossover intersection crash data in Minnesota and Wisconsin (12).

Description of Crash Trends

The descriptive statistical analysis clearly points out that crashes at median crossover intersections are most sensitive to minor roadway volumes. As minor roadway volumes become greater, the proportion of right-angle crashes becomes greater, which leads to more severe crashes. The land use surrounding a multi-lane highway has a strong relationship with crash frequency, a stronger statistical relationship than the relationship between crash frequency and major roadway volumes. Crash frequency tends to increase with the intensity of land use. Finally the analysis shows that intersections with vertical and horizontal curves on the major road and skewed intersections tend to have a higher proportion of right-angle crashes than intersections without these features.

Intersection Treatment Experiences

Intersection treatments in this case are considered to be any strategy used to improve a median crossover intersection beyond the minimum guidance in AASHTO's "A Policy on Geometric Design of Highways and Streets" (the Green Book) and the Manual on Uniform Traffic Control Devices (MUTCD) (13,14). In this discussion, we have divided treatments into the following categories:

1. Minor and major roadway intersection recognition treatments. These treatments warn the drivers on one or more approach that they are approaching an intersection and need to exert care.
2. Median control and delineation. These treatments provide guidance to drivers on the appropriate lane position and traffic control through the median.
3. Speed-change lanes. These strategies involve auxiliary lanes to reduce conflicts between through and turning vehicles.
4. Treatments that replace a high-risk movement with a lower risk movement. These treatments involve removing one or more of the permissible movements through a

traditional intersection and replacing it with a movement that results in a lower crash risk.

5. Gap acceptance guidance. Since right-angle crashes represent the greatest risk to drivers traveling through the median crossover, and since right-angle crashes generally result from drivers misjudging the gap between vehicles in the traffic stream, treatments have or are being developed to assist drivers in making gap acceptance decisions.
6. Physical separation of conflicting movements. These treatments involve partial- or full-grade separations of the intersection.
7. Policy and planning treatments. These strategies seek avoid or reduce high-risk locations.

Intersection Recognition Treatments

Intersection recognition treatments involve warning signs, lighting, and perceptual treatments to help the driver recognize that there is a intersection ahead, indicate to drivers that they must pay increased attention, or provide a perceptual queue resulting in slowing and/or becoming more attentive.

Minor Roadway Treatments

Commonly applied treatments when right-angle crashes occur attempt to make the intersection more apparent to the minor roadway driver and thereby increase the probability that the minor roadway driver will observe the stop control and proceed through the intersection when there is an appropriate gap in traffic. Providing greater intersection recognition reduces the likelihood that the minor roadway driver will fail to observe the stop-control and fail to yield to traffic on the major road. However, while minor road intersection recognition can provide beneficial results when drivers fail to observe the approaching intersection, studies of rural two-way stop-controlled intersections have shown that failure to observe the stop control is typically not the problem that leads to right-angle crashes. For example, a study of five years of crash data (1998–2002) in Kentucky found that only about 0.70% of all crashes and only 1.46% of the fatal crashes on public highways in the state involved a driver disregarding a stop sign. The percentage of crashes caused by disregarding a stop sign were even lower when crashes for only state highways were examined (15).

Two studies completed in Kansas and Minnesota of two-way stop-controlled rural intersections (not necessarily median crossover intersections) had similar objectives and resulted in very similar findings. The objective of both studies was to identify the causes of crashes when drivers on the minor roadway of a two-way stop-controlled intersection either fail to stop and collide with a vehicle on the major roadway or stop but fail to yield the right-of-way to a conflicting vehicle, resulting in a crash. The study in Kansas was conducted by a group of researchers at Kansas State University (Stokes et al.) and the Minnesota study was conducted by Preston and Storm (16,17).

Both studies began by analyzing the statewide database of crash records and identifying locations where several right-angle crashes had occurred at two-way stop-controlled

intersections. In both cases, the police records provided information about the contributing cause of the crash. Having conducted a statistical investigation of the crashes using the crash database, the researchers in each study selected a group of intersections to conduct field investigations of typical two-way stop-controlled intersections to identify intersection attributes that might lead to right-angle crashes. In both studies, the researchers came to the same conclusion. The major contributing cause was found to be a failure to select gaps adequately after stopping and then crossing or turning into the major roadway.

Both studies look at conventional countermeasures for reducing the number of stop sign violations, for example, application of larger signs, more widespread use of “STOP AHEAD” signs, or use of “CROSS TRAFFIC DOES NOT STOP” signs. Both sets of researchers came to the same conclusion: although conventional countermeasures may help reduce crashes marginally, they do not address the predominate cause of right-angle crashes. Therefore, all intersection recognition strategies marginally improve safety, but they do not address the dominant safety issue.

In-Lane Rumble Strips

Rumble strips are intended to provide drivers with a tactile sensation and an audible warning that they need to be alert to the driving task. Rumble strips generally involve grooved or raised patterns on the roadway surface. Shoulder rumble strips (along the edge line) and center-line rumble strips are intended to alert drivers that they have departed the lane and should take corrective actions to steer back into the lane. Transverse, in-lane rumble strips are intended to warn drivers that they are approaching a decision point (e.g., an intersection) and are generally thought to be effective in reducing speed and increasing stop compliance (18).

In-lane rumble strips can generally be of two types: those that cross the entire width of the approach lane, and those that only cross the two wheel paths, shown in Figure 2-6 (19, p. 4). According to a 1993 synthesis by Harwood, 89% of all state transportation agencies have installed rumble strips at locations to alert drivers of approaching changes in the roadway, including work zones, horizontal curves, and intersections (20). While reviewing state practices of safety treatments at rural median crossover intersections, Maze et al. conducted a survey of that included 28 states. When asked about special safety treatments at these intersections, 13 states reported using approach, in-lane rumble strips (2).

Figure 2-6. Transverse rumble strips in the wheel path

Although rumble strips are commonly used at intersections to alert drivers to approaching decision points, there currently exists little rigorous statistical analysis to support the belief that rumble strips actually improve safety performance of intersections, and most studies of in-lane rumble strip safety performance are inconclusive. For example, Fitzpatrick et al. studied 14 approaches to rural intersections before and after the installation of rumble strips and found that speed averages and 85th percentile speeds on the approach dropped by a statistically significant but very small amount (about one to two miles per hour) (21). Despite the lack of conclusive findings regarding in-lane rumble strips, Harwood recommends that rumble strips can be effective and should be considered at locations where rear-end crashes and ran-stop sign crashes occur (19). In AASHTO's "Strategic Highway Safety Plan, Volume 5: Guide for Addressing Unsignalized Intersection Collisions," AASHTO identifies in-lane rumble strips as a tried but not yet proven safety improvement approach. Similarly, the guide recommends in-lane rumble strips where crashes have occurred that were correctable with better driver awareness of the intersection (22).

Traffic Control Devices to Improve Intersection Recognition

A variety of signage and marking strategies seek to improve intersection recognition at median crossover intersections. These have included larger stop signs, supplemental "STOP AHEAD" and "CROSS TRAFFIC DOES NOT STOP" signs, wider stop bars, flashers, and supplemental stop signs over the roadway. All of these strategies are listed as tried but yet proven strategies in AASHTO's "Strategic Highway Safety Plan, Volume 5: Guide for Addressing Unsignalized Intersection Collisions" (22). All help to provide better recognition of intersections and are generally believed to reduce rear-end and ran-stop sign accidents. On the other hand, there is little or no evidence to suggest that any of these strategies assist in reducing gap selection related right-angle crashes and little conclusive evidence showing that they improvement intersection safety performance (16). Gattis even found that the "CROSS TRAFFIC DOES NOT STOP" supplemental sign is of limited effectiveness because of inconsistent application, and some drivers are confused and do not understand the concept of cross traffic (23).

Perception of Intersection Approach Lane Width Reduction

Splitter islands on the minor approach coupled with an edge-line strip that narrows the perception of the lane width in the throat of the intersection (see Figure 2-7) represent

one strategy that has been used to channelize traffic and reduce approach speeds. The splitter island provides an identifiable feature for the approaching intersection, and the restricted lane width alerts drivers to a decision point. Reducing the intersection throat width may also be accomplished through center-line and shoulder rumble strips.

Figure 2-7. Intersection with splitter island and reduce throat lane width

Splitter islands are also recommended in AASHTO's "Strategic Highway Safety Plan, Volume 5: Guide for Addressing Unsignalized Intersection Collisions" at locations where intersection recognition presents a safety issue. However, the guide splitter islands are identified as a tried but still unproven strategy (22).

Intersection Lighting

There is ample evidence that supports the safety benefits of lighting rural intersections. Preston and Schoenecker studied 12 rural intersections before and after lighting in Minnesota and found that nighttime crashes were reduced by 25% to 40% (24). Isenbrands et al. conducted another study of rural street lighting in Minnesota with 34 intersections and found that the nighttime crash rate after installation decreased by about 35% even though the daytime crash rate at the same intersections increases by 30% (25). What is not clear from the literature is how the quality of lighting and the location of the lights impacts safety at rural intersections. Furthermore, no studies that we were aware of have specifically dealt with intersection lighting on rural median-divided highways. Given the apparent difficulty with gap selection in median crossover intersections, it is reasonable to believe that lighting, lighting coverage, and location of lighting upstream at

a distance equal to a safe gap in traffic may impact intersection safety, but no known research has been done on this issue.

Median crossover design, control, and delineation

Median crossover design, traffic control at the far-side intersection after traveling through the median, and delineation of the median lanes can impact the safety of the intersection. Harwood et al. found that the design of the median crossover (median width and opening) can impact the number of errant maneuvers by drivers within the median (4). Some state transportation agencies have experimented with the following median treatments:

- Traffic control and markings at the far-side intersection
- Stripping to better delineate lanes
- Wider medians to improve storage within the median
- Narrow median openings to channel vehicles and reduce errant maneuvers within the median
- Acceleration lanes along the far-side of the median to improve storage for vehicles turning left from the minor roadway and provide a speed change lane for better merging with through traffic in the far lanes

Median width

Intersection median width at crossover intersections is generally governed by the width of medians along the entire roadway cross section. AASHTO's "A Policy on Geometric Design of Highways and Streets" (the Green Book) recommends that medians at unsignalized rural intersections should generally be "as wide as practical" (13, p. 341). In urban and suburban areas, the reverse is recommended: medians should only be wide enough to allow selected design vehicles to maneuver safely through the intersection. Through field observations, Harwood et al. found that wider medians in urban and suburban areas only allowed drivers to make undesirable maneuvers, with drivers queuing side-by-side in the median, drivers driving on the inside lane (left lane) when making a left turn through the intersection, or queuing inline in the median with the last vehicle in line encroaching into the travel lanes (4). We suspect what Harwood et al. are actually observing is the impact of higher volumes and peaked volumes that result in more opportunity for conflicts when drivers make undesirable maneuvers (aggressive driving).

Harwood et al. used a data set consisting of three years of crash data at 2,140 California median-divided intersections. There were 153 rural four-leg intersections. When the authors estimated a safety performance function for the rural intersections using Poisson regression, they found an average 4% reduction in crashes per year with every meter increase in the width of the intersection median (4, p. 32). Similarly, Maze et al. used their Iowa rural median intersection data to estimate a safety performance function and found that each foot of median width decreased crash frequency by 0.74%, or roughly 2.5% per meter (2). The Green Book recommends that rural intersection medians should be wide enough to shelter the design vehicle (13). Many state agencies have design

policies based on a large school bus as their design vehicle; medians must be capable of sheltering a large school bus.

Median opening width

The Green Book recommends that it is best to keep median opening widths at unsignalized intersection as narrow as possible and, if possible, the same width as the crossing roadway. Harwood et al. found that at unsignalized intersections wide openings give drivers the opportunity to perform undesirable maneuvers such as queuing up in the crossover side-by-side (4). The Green Book also recommends that openings be sized to meet only the turn radius of the design vehicle (13).

Median acceleration lanes (MALS)

A median acceleration lane is shown in Figure 2-8 (26). The median acceleration lane predominately provides three safety benefits. The first is an opportunity for left turning traffic from the minor roadway to accelerate and merge into traffic, thereby making it less difficult for drivers to find a suitable gap in high-speed and high-volume traffic. The second benefit is more storage in the median crossover and storage for a large vehicle at locations where the median is too narrow to provide refuge for an entire truck. The third benefit is the improvement of sight distance at intersections where sight distance is inadequate. Allowing vehicles to accelerate and then merge with traffic requires less sight distance.

A 1986 Institute of Transportation Engineers (ITE) survey of 53 transportation agencies found that 13 of the respondents had used median acceleration lanes (27). Respondents were split in their opinion regarding the desirability of median acceleration lanes. The ITE concluded that the lanes appear to reduce crashes, promote efficiency in left-turn movements, and reduce conflicts, but insufficient data were available to quantify their safety and operational benefits.

Harwood et al. recommend that highway agencies consider left-turn acceleration lanes at locations where the available median width is adequate to pave an acceleration lane without compromising the median, and when the following attributes are true (4):

1. Limited gaps are available in the major-road traffic stream.
2. Turning traffic must merge with high-speed through traffic.
3. There is a significant history of rear-end or sideswipe accidents.
4. Intersection sight distance is inadequate.
5. There are high volumes of trucks entering the divided highway.

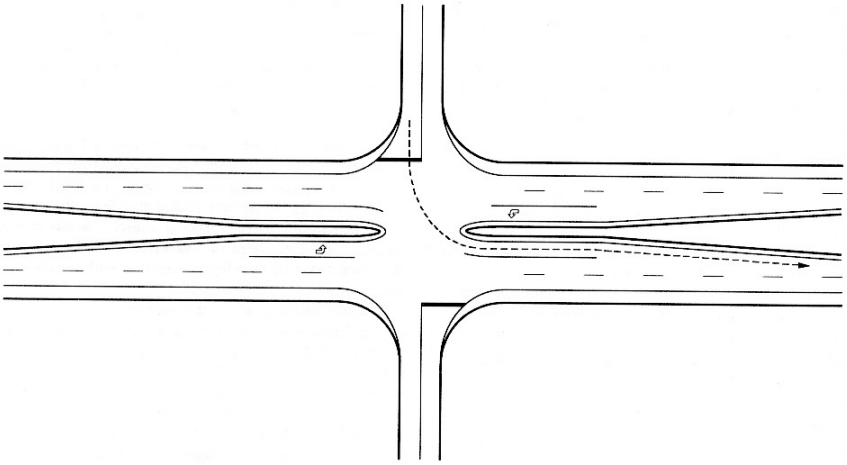


Figure 2-8. Left-turn median acceleration lanes

As of 2002, the Minnesota Department of Transportation (Mn/DOT) had constructed 10 expressway intersections with median acceleration lanes (28). In 2002, Mn/DOT evaluated nine of these intersections. Their evaluation measures included operational performance measured by delay, safety measured by crash rates, and the public's perception measured through a mail-out opinion survey.

When there is no median acceleration lane, automobile drivers on the minor roadway approach will generally make a through or left-turn movement in two steps. After crossing the lanes on the near side of the expressway, drivers have the opportunity to stop in the median and wait for a gap in the traffic in the far lanes. The Mn/DOT study considered the waiting time in the median to be a delay, and this type of delay is reduced by the presence of a median acceleration lane. The Minnesota study found that the percentage of vehicles that stopped in the median decreased from 74% to 4%. The percentage of vehicles that waited in the median for more than 10 seconds was reduced from 17% to 1%.

In a before and after comparison, the rear-end crash rate declined by 40% when the median acceleration lane was constructed. Additionally, in a comparison to similar intersections without median acceleration lanes, the rear-end crash rate at median acceleration lane intersections was 75% lower. Sideswipe crashes where both cars are traveling in the same direction also declined.

The Minnesota study also conducted a survey of intersection users through a questionnaire. Two hundred surveys were distributed, and 119 were completed. Ninety-five percent of the respondents said they usually or always use the acceleration lane, 70% thought the acceleration lane helped their merge "very much," and another 20% thought that the lanes were of "much" help in merging.

The Minnesota study also recommends acceleration lane lengths. For multi-lane roads operating at 55 miles per hour or higher, the study recommends acceleration lanes of at least 1,000 feet in length, with longer acceleration lanes required on roadways with

higher traffic volumes. The standard acceleration lane recommended by the study is 1,500 feet.

The Tennessee Department of Transportation (DOT) uses median acceleration lanes to increase storage at median crossovers, as opposed to improving merging maneuvers and facilitating speed changes. For example, in Tennessee DOT Region 1 (the region surrounding Knoxville in eastern Tennessee), roughly 15 to 20 median acceleration lanes have been added to median crossovers throughout the region, largely to increase the amount of storage at the intersection after a safety or operational problem has been observed (29). All of the median acceleration lanes have been added using maintenance funds to pave an additional lane in the grass median. Since the purpose of the median acceleration lane is to provide storage and not to facilitate mergers into the mainline, typically these lanes are only built 200 to 300 feet long.

Median Traffic Control and Delineation

There are really two issues being addressed by intersection delineation and traffic control. The first issue is to keep median traffic within its travel lane across the median. This has the benefit of clearly identifying the travel path through the median crossover, thereby reducing conflicts in the median and reducing incidents of drivers turning left through the median who cut diagonally across the median. The second issue is providing drivers with cues that advise them to treat the crossing of the second set of lanes (after the median crossover) as a second intersection.

Figure 2-8 shows a median crossover with a double yellow centerline. The purpose of the double yellow line is to delineate the path drivers should take through the median. At rural, low-volume intersections, the Iowa DOT has conducted limited sample studies of crashes before and after the double yellow line is in place and has found that crash frequency declines with the double yellow line and that crash frequencies increase as the double yellow line ages and fades. One of the issues that the implementing agency has to take into account when using this strategy is the opportunity for left turning traffic in both directions from the mainline to interlock simultaneously. What is meant by interlocking left turning patterns is illustrated in Figure 2-9. This situation occurs when two vehicles turn behind one another instead of in front of one another. The behind maneuver would be reinforced by the double yellow line. The probability of interlocking vehicles becoming an operational and a safety issue increases with increasing left turning volume. Further, as Harwood et al. note, there is a greater propensity for drivers to turn in front of one another when the median is narrow, and drivers are more likely to turn behind one another when the median becomes wider (4). Harwood et al. speculated that turning in front is more common at medians less than 50 feet wide, while turning behind becomes most common at medians greater than 50 feet wide (8, p. 45).

Figure 2-8. Rural median with double yellow and stop bar in the median crossover (source: Iowa DOT)

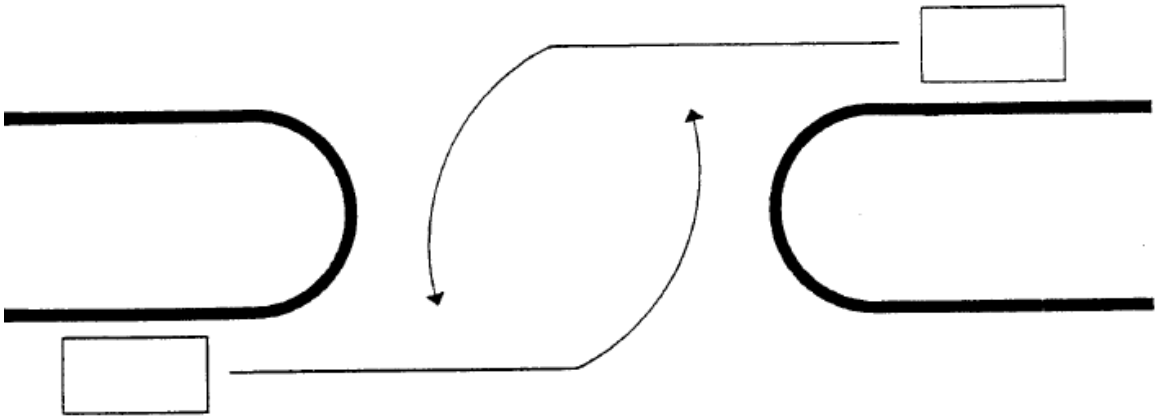


Figure 2-9. Vehicles turning behind one another through the median opening

Another delineation strategy recommended in AASHTO's "Strategic Highway Safety Plan, Volume 5: Guide for Addressing Unsignalized Intersection Collisions" is to provide dashed markings. This extends the left edge line to create major-road continuity across the median opening. Figure 2-10 shows a median crossover with a skip line across its mouth. The dashed lines physically help to delineate the median crossover and can help distinguish the crossover from the through roadway, thus making the approaching drivers more aware of the presence of the intersection. The AASHTO guide identifies this as a tested (but not proven) technique.

Figure 2-10. Edge line extended across median crossover (U.S. 31 in Alabama)

The MUTCD provides an example of a stop control in a median crossover, with a stop bar painted across the lane in the far side of the median for medians of 30 feet or wider. In general, however, stop control in the median is discouraged unless the median can provide refuge for the entire design vehicle (usually a large bus), while yield signs can be used in medians with a width smaller than that of the design vehicle. The yield sign in the median encourages drivers to treat the far side as a second intersection and promotes crossing the intersection in two steps. Again, a small-scale crash analysis by the Iowa DOT has shown that this strategy reduces crashes. The stop bar at an intersection can be seen clearly in the crossover in depicted in Figure 2-8.

Far-Side Intersection Designation Markings and Signage for Narrow Medians

In narrow medians (less than 30 feet), the MUTCD does not recommend the use of stop control to control traffic crossing the far-side lanes. However, yield signs may be used to help designate the approach to a second intersection. Figure 2-11 shows a median crossover where a yield sign is used in the median, and instead of a stop bar, tiger teeth markings are used to designate the point where drivers should yield to cross traffic. Another approach used in some states is to place signs in the median warning drivers to look to the right. Figure 2-12 shows a roadway with narrow median. A supplemental “LOOK” sign is attached below the yield sign, and “LOOK RIGHT’ is painted on the roadway where the crossing vehicle should yield. A variety of non-standard sign have been placed in medians, fundamentally to warn drivers that they should look to the right again at the median crossover. Two non-standard signs that have been used for this

purpose are shown in Figure 2-13. Although no known scientific evaluation has been conducted to determine whether these treatments successfully reduce crashes at narrow medians and far-side intersections, several states are known to use them and believe they help reduce right-angle crashes.

Figure 2-11. Narrow median with yield sign and tiger teeth markings (Wisconsin)

Figure 2-12. Narrow median with look warning and look right markings (North Carolina)

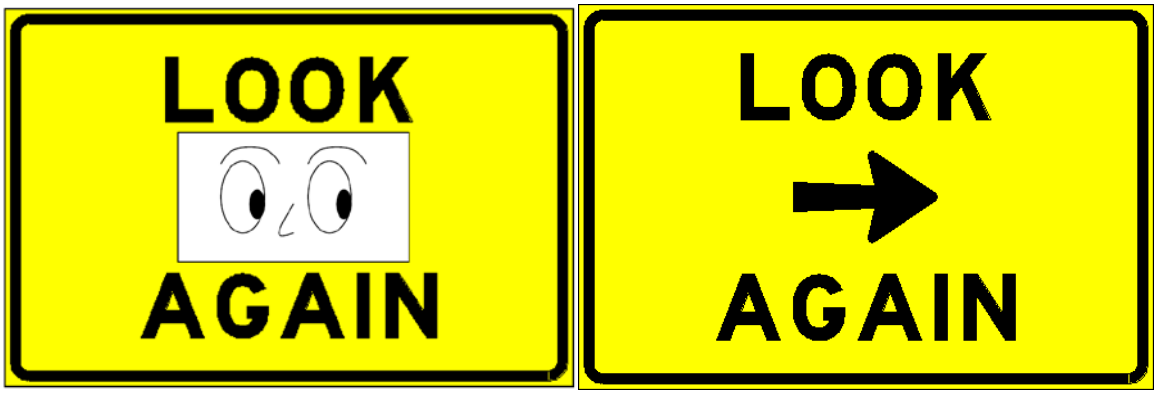


Figure 2-13. Signs used to encourage motorists look right at the far side of the median crossover

Speed-change lanes

Acceleration and deceleration lanes are intended to reduce the speed differentials between through and turning vehicles. These lanes decrease the turbulence in the traffic flow and reduce the incidence of rear-end crashes resulting from vehicles traveling in the same direction at different speeds. Deceleration lanes are used in advance of intersections for vehicles departing the highway. Left-turn deceleration lanes, and sometimes right-turn lanes, are used for vehicle storage and as speed-change lanes. Acceleration lanes are used for vehicles entering the roadway through an intersection and are typically on the right side of the roadway. However, the discussion of median treatments above pointed out that median acceleration lanes are acceleration lanes on the left side of the median crossover and are left of the left-most through lane.

Deceleration lanes

Deceleration lanes are generally optional auxiliary lanes. Several state transportation agencies have policies or warrants that dictate when deceleration lanes are required. Harwood et al. also notes that some agencies have policies requiring deceleration lanes at all median openings, except in cases such as median openings for T-intersection, where either a right or left turn is impossible (4). Most state guidelines for including a deceleration lane are based on either volume, particularly left turning volumes, or an examination of crashes that could have been avoided or made less severe if a deceleration lane were present (30).

In general, deceleration lanes have four parts: (1) the segment of the through lane at which drivers begin to slow in reaction to the approaching deceleration lane, (2) the deceleration lane taper, (3) the portion of the lane used solely for deceleration, and (4) the segment of the lane used for storage of vehicles waiting to turn. These four parts are shown in Figure 2-14 (31, p. 11). Guidance on the deceleration lane length generally considers that some deceleration takes place in through lane before the taper, as well as in the taper.

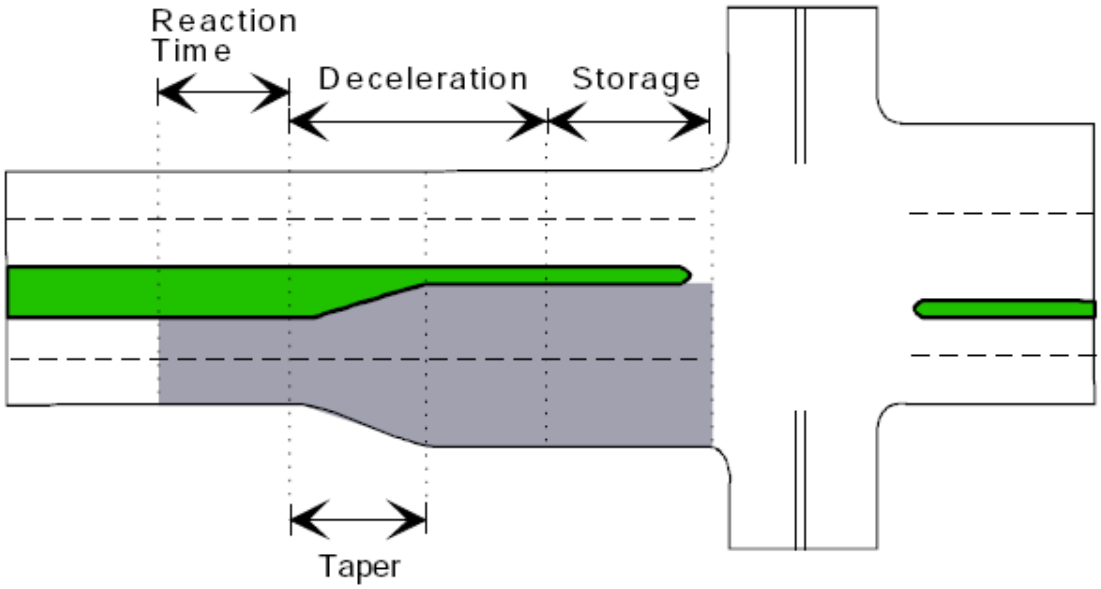


Figure 2-14. Components of a deceleration lane

Presence of Left Turn Lanes

Guidance for left-turn lane placement and the length of left turns lanes in AASHTO's Green Book and in many state design guidelines is based on work published in 1967 by Harmelink (32). Harmelink provided graphs that are based on the probably of a left turning vehicle blocking through traffic while the vehicle waits for a gap in opposing traffic. For four-lane divided highways, the probability at any given time of having a vehicle located in the median crossover and blocking additional traffic from entering the median crossover is limited to a probability of 0.005%. Therefore, the guidance for conditions above this threshold is to build a left-turn lane, and guidance is provide in the form of a nomograph for determining the amount of storage that should be provided by the deceleration lanes.

The Green Book and other design guidance recommend the use of left-turn deceleration lanes, except in very low volume conditions (13). Several crash studies conducted in the past have all found safety benefits through the provision of left-turn lanes (most of these studies address intersections in general and not just intersections on rural median-divided highways). McCoy and Malone found that installation of left-turn lanes on urban four-lane roadways reduces rear-end, sideswipe, and left-turn crashes (33). Foody and Richardson found that crash rates decreased by 38% with the addition of a left-turn lane at signalized intersections and 76% at unsignalized intersections (34). Gluck et al. reported crash rate reductions ranging from 18% to 77% due to the installation of left-run lanes, based on a the review of work by several sources that include the New Jersey Department Transportation, Griewe, Agent, Ben-Yokov and Craus, Craus and Mahalel, Tamburri and Hammer, and Wilson et al. (35,36,37,38,39,40,41,42). More recently, in a Federal Highway Administration Pooled Fund study involving ten state transportation agencies and the District of Columbia, Harwood et al. found through using crash data

from all the involved agencies and three different methods to measure the impact of the construction of left-turn lanes that installing a single left-turn lane on the major roadway of an unsignalized rural intersection should reduce crash frequency by 28% at four-legged intersections and 44% at three-legged intersections (43). Installation of left-turn lanes on both major road approaches to a four-leg intersection would be expected to increase, but not quite double, the resulting reduction in the total intersection crash frequency.

There is some concern that the length of the deceleration lane recommended by the Green Book may be inadequate when taking into account the performance of heavy commercial vehicles. The length of deceleration lanes in the Green Book is based on stopping sight distance (SSD). SSD is the distance traveled while reacting (assumed to be 2.5 seconds) and then breaking to a stop at a deceleration rate of 11.2 ft/sec^2. This braking rate is considered a comfortable rate of deceleration on wet pavement. A wet pavement coefficient of friction is used to represent conditions that are not ideal. Semi-tractor-trailer combination trucks equipped with antilock braking systems (ABS) can achieve deceleration rates in controlled braking nearly equal to the rate the Green Book uses for passenger cars (44, p. 57). The 2002 Vehicle Inventory and Use Survey (VIUS) found that almost 60% of the truck fleet is equipped with ABS, compared with 21% in the 1997 VIUS (45). At the same time, a truck operator's eye height is assumed to be 8 feet above the pavement, while the driver of a passenger car is assumed to have an eye height of 3.5 feet. Being able to see from a higher vantage point provides truck operators with the ability to better anticipate the need to brake and partially compensates for the poorer stopping performance.

The SSD at 50 mph and 55 mph is 425 feet and 490 feet, respectively (13, p. 117). A minimum additional 100 feet is recommended for storage, and the Green Book recommends a total 550 to 680 feet for design speeds of 50 mph and 55 mph, respectively (13, p. 718), In addition to deceleration, additional length may be added for the taper. Although there is no known study of the safety of making longer deceleration lanes, it is expected that because of the poorer stopping performance of heavy commercial vehicles on median-divided highways where there is a high percentage of left turning trucks, lanes longer than those recommended by the Green Book will improve safety performance. Longer lanes could be particularly useful for improving safety in locations that might be adversely impacted by poorer stopping conditions due to weather conditions (e.g., snow and ice or heavy rains).

Left-Turn Lane Type

Figure 2-15 illustrates a conventional median crossover intersection with left-turn lanes in both directions along the major roadway (46). The figure also illustrates how opposing left turning traffic can obstruct the driver's line of sight from approaching vehicles in the through lanes. To alleviate the problem of blocking the sight of drivers in opposing left-turn lanes, offset left-turn lanes move the throat of the left turn to the left of the throat of the opposing lane.

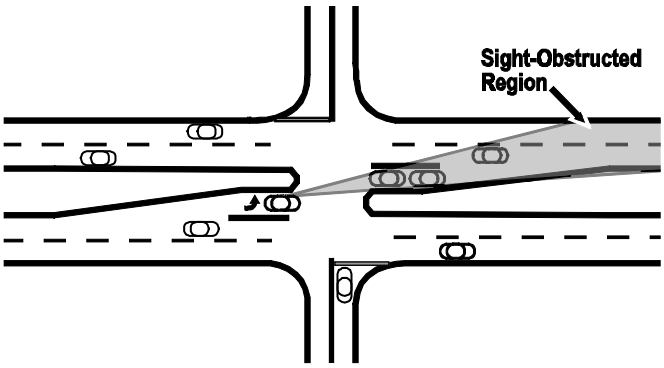


Figure 2-15. Obstructed sight in conventional left-turn lanes

Two examples of off-set left-turn designs are shown in Figure 2-16. The upper intersection drawing is a tapered offset, and the bottom drawing shows a parallel offset. There is no evidence that one design is superior to the other. Although offsetting left-turn lanes is widely believed to improve safety at median crossover intersections and Harwood et al. found no operational problems though the field observation of offset lefts at signalized intersections, there is no known rigorous safety analysis of offset left turns (4). Both McCoy et al. and Joshua and Saka developed procedures for determining the amount of offset required for clear sight lines (47).

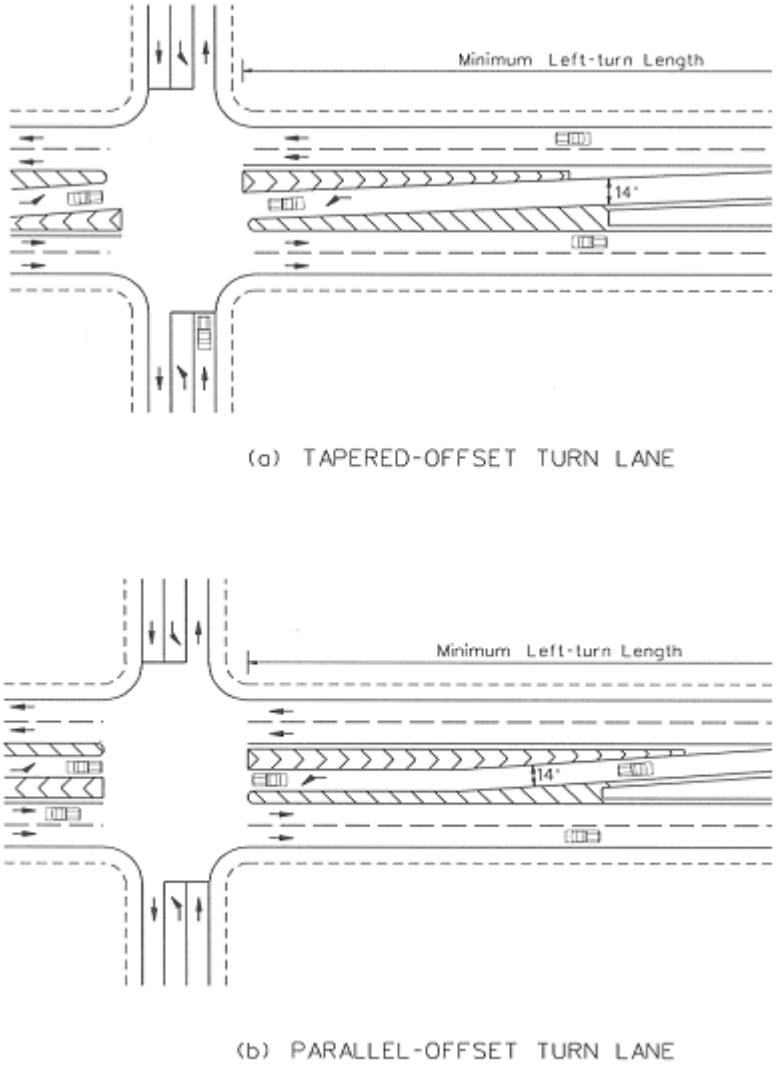


Figure 2-16. Offset left-turn lanes (South Carolina DOT Design Manual)

Right-Turn Lane Presence

Similarly to left-turn lanes, right-turn lanes are intended to allow vehicles to change speed and, to a lesser extent, provide storage for vehicles waiting to turn. It is generally thought that the presence of right-turn lanes reduce the potential for rear-end collisions, particularly at high-speed intersections. Much less research has been conducted on right-turn lanes than was conducted on the safety improvements of left-turn lanes. Harwood et al. found that the installation of right-turn lanes at rural unsignalized intersections could reduce the total intersection crashes by 27% (44).

The limited research assessing the safety effects of providing right-turn lanes at rural divided highway intersections revealed that conventional right-turn lanes might actually increase crashes. A crash model developed by Van Maren in 1980 for 39 randomly

selected, multi-lane divided highway intersections in rural Indiana showed that intersection crash rates increased with the presence of a right-turn deceleration lane on divided highways (48). Although not statistically significant, the inclusion by Maze et al. of the presence of a right-turn lane in their rural expressway intersection safety performance model revealed a negative relationship between right-turn lanes and intersection safety (2). The authors did not attempt to advance this finding because the direction of specific effects in predictive models often represent surrogate effects of other variables rather than the true effect of interest. Therefore, Maze et al. speculated that what was being observed was that the state transportation agency was constructing right-turn lanes at intersections with poor safety performance as a countermeasure to the crashes already observed. The authors believed that what was being seen was the causation created by the agency between poor safety performance and the presence of a right-turn lane, rather than impact of right-turn lanes on crashes. However, these counterintuitive findings might also be explained by the fact that vehicles using a conventional right-turn lane to exit the divided highway can obstruct a minor road driver's view of oncoming expressway traffic approaching the intersection from the left, as shown in Figure 2-17. This situation creating a more dangerous environment. Therefore, the effect that expressway right-turn lanes have on the available intersection sight distance for vehicles entering or crossing the expressway from a minor road approach should be considered in the intersection design process.

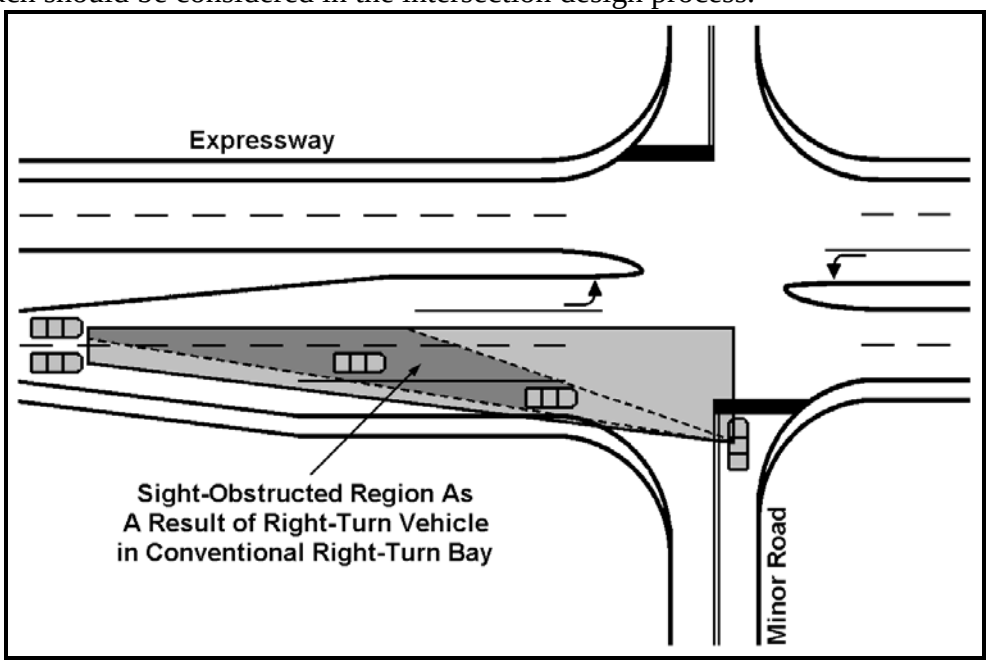


Figure 2-16. Obstructed sight in conventional right-turn lanes

Similar to guidance for left-turn decelerations lanes, guidance for right-turn length for deceleration is probably insufficient to support the deceleration length requirements of heavy commercial vehicles without ABS. However, there is no known research on the safety impacts of lane length.

Right-Turn Lane Types

Two alternative right-turn lane design options are available to help alleviate sight obstructions inherent in conventional right-turn lanes. One design is an offset right turn lane, shown in Figure 2-17, and the other is a free right-turn lane, shown in Figure 2-18.

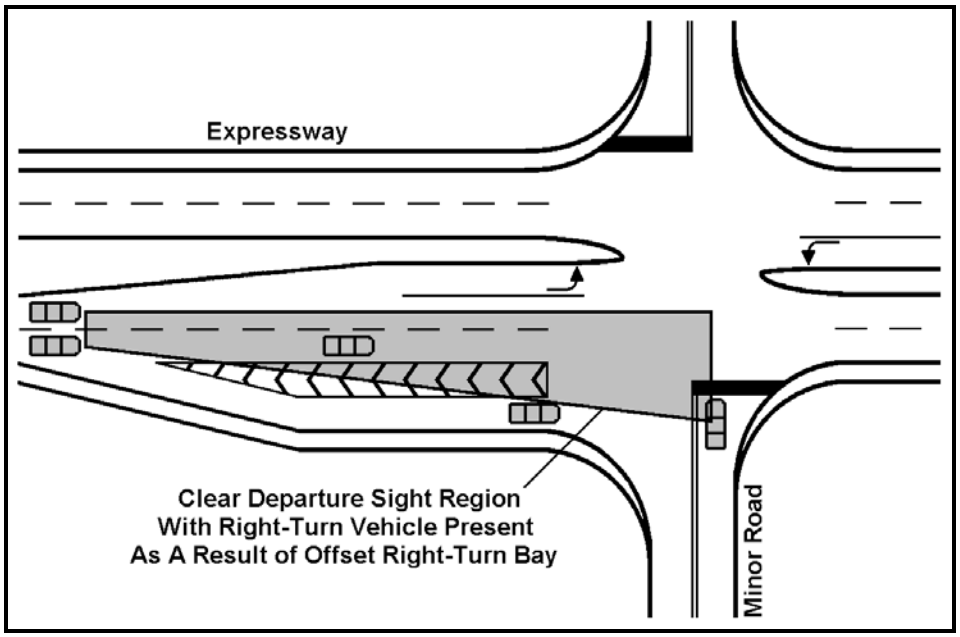


Figure 2-17. Offset right-turn lane

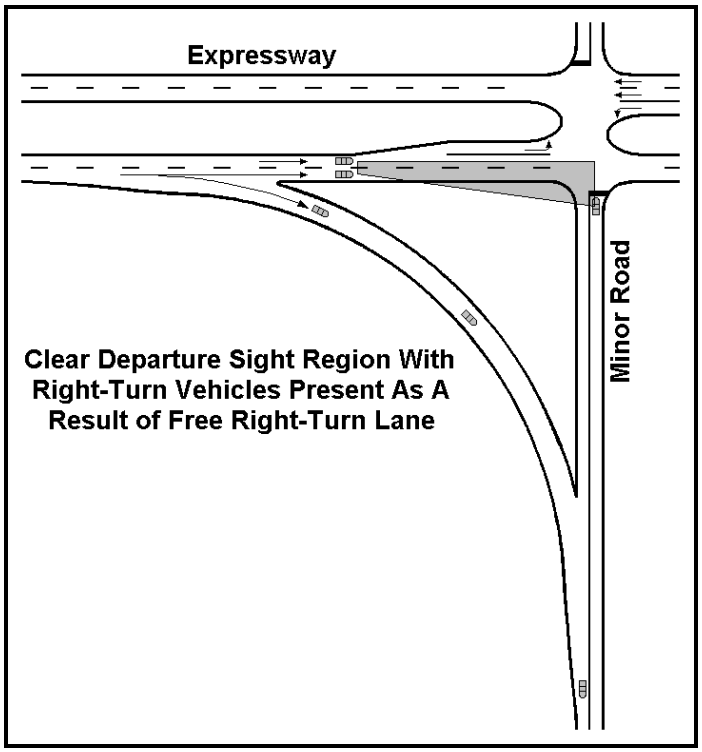


Figure 2-18. Free right turn

Right-turn lanes can be offset by moving them laterally to the right as far as necessary to give drivers positioned at the stop bar on the minor road approach an unobstructed view of oncoming expressway traffic. Unfortunately, no guidance on the use or design of offset right-turn lanes is provided in the AASHTO Green Book (13). As such, offset right-turn lanes do not appear to be used as frequently by state transportation agencies as offset left-turn lanes. A recent survey of state transportation agencies conducted by Maze et al. revealed that only 5 of the 28 responding agencies have used offset right-turn lanes as a corrective measure at rural expressway intersections (2). Offset right-turn lanes should improve intersection safety by increasing sight distance and making it easier for minor roadway drivers to select safe gaps in the expressway traffic stream. However, no research was found addressing the safety effects of providing offset right-turn lanes at divided highway intersections.

At some locations, it may be desirable to create a separate right-turn roadway by using a channelizing island on the expressway intersection approach. The right-turn roadway may be controlled by a yield sign where it joins the minor road, or it may operate as a free-flow roadway if an acceleration lane is provided to merge with traffic on the minor road (22). Either way, these right-turn roadways are usually referred to as free right-turn lanes (FRTLs). By providing an increased right-turn radius, FRTLs facilitate high-speed right-turn movements, which can improve the efficiency of traffic operations and offer a high level of service to right turning vehicles (49). FRTLs can also remove the sight distance obstruction created by the presence of right turning vehicles without introducing a large, unused pavement area, as seen in Figure 2-17, when an offset right-turn lane is implemented.

No research was found regarding the safety effects of providing FRTLs at median crossover intersections. However, the results of a 1996 analysis by McCoy and Bonneson indicate that the presence of FRTLs do not significantly influence the frequency, severity, or types of crashes that occurred on high-speed, two-lane highway intersection approaches in rural Nebraska (50).

The design of free-flow right-turn roadways at intersections is covered in the AASHTO Green Book, although warrants for their use are not provided (13). The volume warranting FRTLs at unsignalized intersections on rural two-lane highways developed by McCoy and Bonneson provides guidance regarding whether a FRTL is justified (50). Since the authors found no different in safety performance between intersections with and without FRTLs, most of the benefits were associate with the reduced operating cost of not having to slow down as much when using a FRTL as opposed to a conventional intersection. The benefits of a FRTL increase with the percentage of trucks in the traffic stream and with the number of right turning vehicles. Furthermore, there is nothing to suggest that the operational benefits of FRTLs on a two-lane roadway would be different for a right turn from a median-divided highway, since on a multi-lane roadway all right turns are going to be made from the right lane. Therefore, the warrants for FRTLs between a two-lane and a two-lane roadway should be the same as the warrants for a four-lane to a two-lane roadway. With no trucks, a FRTL is warranted at roughly a right-

turn volume of 825 right turning vehicles per day, and when trucks are 25% of the traffic stream, a FRTL is justified at a right-turn volume of 545 vehicle per day.

Right-Turn Acceleration Lanes

There is little design guidance for right-turn acceleration lanes. The Green Book states that "acceleration lanes are not always desirable at stop-controlled intersections where entering drivers can wait for an opportunity to merge without disrupting traffic" (13, p. 689). The Green Book goes on to state that acceleration lanes are desirable where stop control is not used (e.g., yield control) or where traffic is of a sufficient volume that sufficient gaps are infrequent. One problem observed at rural intersections is the provision of yield control for right turns without the provision of an acceleration lane of sufficient length to allow vehicles to accelerate to the speed of the major highway. Figure 2-19 shows a right turn channelization island with insufficient acceleration lane length. The picture on the left is taken from the minor leg approach while the picture on the right is taken while standing on the channelization island.

Figure 2-19. Channelization of right turn without sufficient acceleration lane length

AASHTO's Strategic Highway Safety Plan guidance recommends right-turn acceleration lanes where there is high right turning volume or where rear-end or sideswipe crashes have indicated that right-turn maneuvers have created a crash problem (22). There is no design guidance regarding the length of right-turn lane acceleration lanes in the Green Book, but the Green Book instead provides guidance on the length of acceleration lanes for entrance ramps to freeways. However, even the recommended lengths of freeway acceleration lanes are too short, given the performance of the truck fleet.

The length of the acceleration lanes necessary for trucks to accelerate to the operating speed of the highway is typically related to the truck weight-to-horsepower ratio. NCHRP project 15-21 collected weight-to-power ratio information from trucks at weigh stations in three states (51). The weight-to-horsepower measured ranged from 60 to 400 lbs/hp. The 85th percentile weight-to-horse power ratio for trucks on the freeway was found to be in the range of 170 to 210 lbs/hp. In other words, only 15% of the fleet has a higher weight-to-power ratio. The same project estimated that to accelerate within the lane lengths specified by the Green Book, trucks would have to have a weight-to-horsepower ratio ranging from 110 to 140 pounds/hp. Furthermore, the authors estimate that the lane

lengths need to be increased by 1.8 times over the Green Book recommendation to be able to accommodate the 85th percentile trucks.

Replacing a High-Risk Turning Movement with a Low-Risk Movement

One of the methods for improving the safety of median-divided highway intersections is through the use of features that replace a high-risk movement with a low-risk movement. Conflict points include any point where the paths of two through or turning vehicles diverge, merge, or cross (52). For example, a conventional median crossover intersection has 42 conflict points, as shown in Figure 2-20 (53). Because the conventional design allows every combination of movements through the intersection, a conventional intersection will have the largest number of conflict points. For example, an offset T-intersection involves realigning the minor roadway and moving the mouths of the minor roadway apart (offsetting). As shown in Figure 2-21, a T-intersection has only 11 conflict points. If a conventional intersection can be replaced by two T-intersections as show in Figure 2-22 (an off-set T intersection) the number of conflict points is 22 for the two intersections plus four merge and diverge conflict points for the minor road through movements. Therefore, replacing a four-legged intersection with an offset T-intersection reduces the number of conflict points from 42 to 26 or a reduction of 38 percent.[1] Similar reductions in conflicts can be achieved by replacing a conventional intersection with an intersection that has indirect left turns and direction medians.

[1] The counting of conflict points is somewhat subjective. When Bared and Kaisar considered an offset T-intersection, they arrived at 30 conflict points (53).

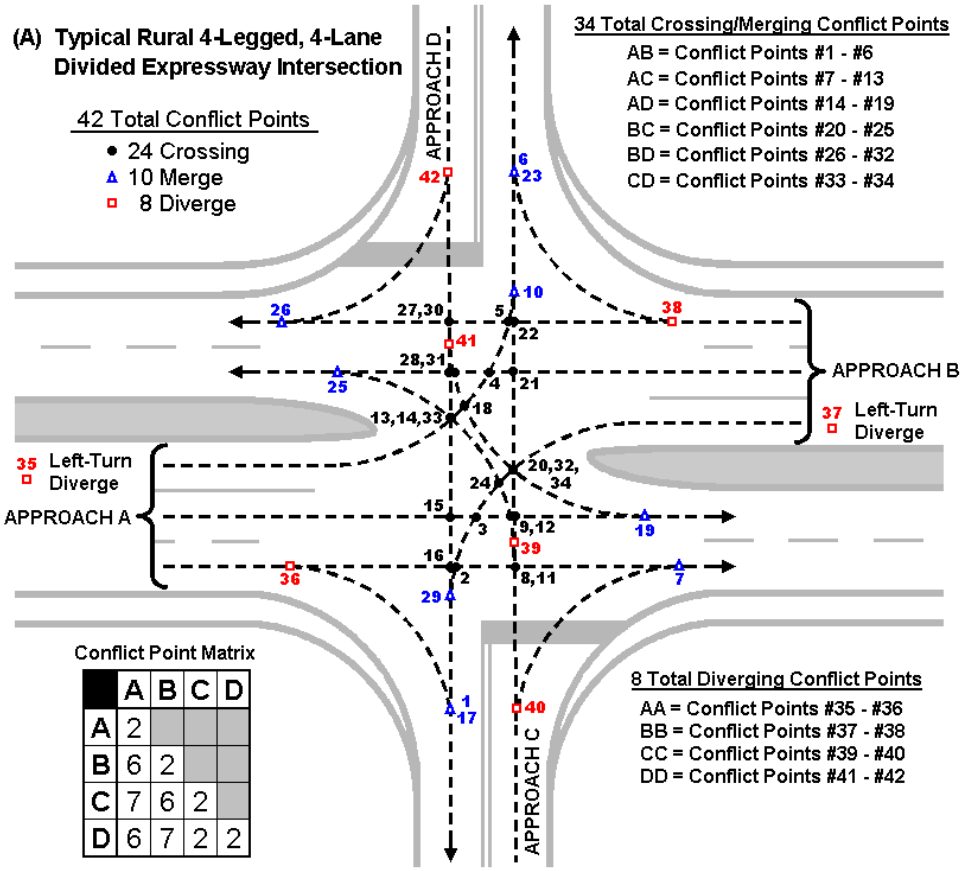


Figure 2-20. Conflict points in a median crossover intersection

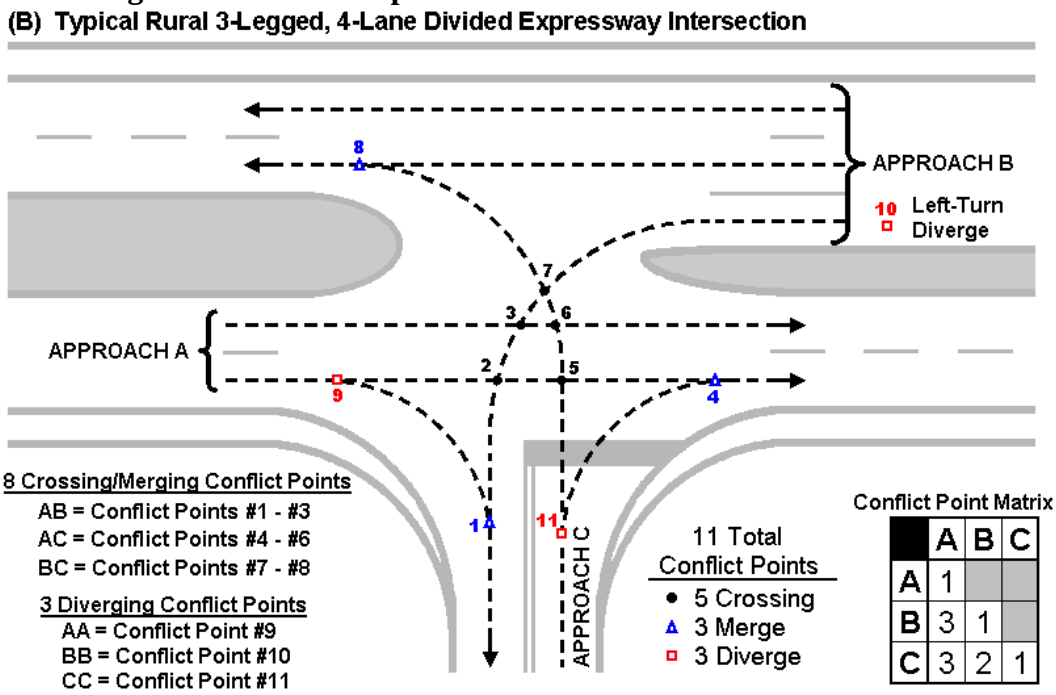


Figure 2-21. Conflict points for a T-intersection

Offset T-Intersections

It has long been acknowledged that three-legged intersections operate more safely than comparable four-legged intersections. Three-legged intersections are less complex, lead to less driver confusion, tend to have lower crossroad traffic volumes, and have fewer points at which conflicting traffic streams cross, merge, or diverge (4,54, 55). Crash models developed by Harwood et al. (4) revealed that crash rate and frequency at rural, three-legged, unsignalized divided highway intersections were substantially lower than at their four-legged counterparts. Therefore, converting a four-legged intersection into two three-legged intersections (an offset T-intersection, as in Figure 2-22) may improve intersection safety.

The conversion of a four-legged intersection into an offset T-intersection can be accomplished by separating the two minor road approaches by an appreciable distance, thus creating two T-intersections that operate independently. The AASHTO Strategy Highway Safety Plan on unsignalized intersections states that this method may be the best way to improve safety at four-legged unsignalized intersections at which the through volumes emanating from the minor road are low, since through vehicles on the minor road must turn onto and off of the major roadway rather than making a crossing maneuver (22).

Bared and Kaisar used intersection SPF models to estimate the safety benefit of converting a conventional intersection to an offset T-intersection. The benefit for very low volume conventional intersections is greatest (based on a percentage reduction in crashes), but the authors generally estimate that the conversion of a conventional intersection to an offset T-intersection should result in a 60percent to 40 percent reduction in crashes (53, p.12). The drawbacks of an offset T-intersection include the increased travel time and travel distances for minor road through movements, potential confusion for drivers making a through movement on the minor roadway, and the increased right-of-way.

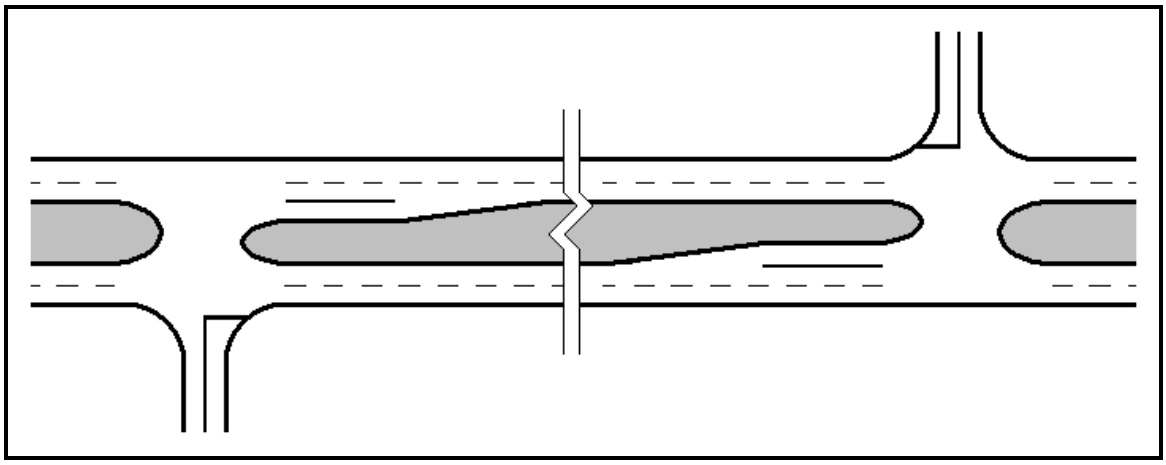


Figure 2-22. Offset T-intersection (right-left configuration)

The offset T-intersection configuration shown in Figure 2-22 is known as a right-left configuration because a through vehicle on the minor road must first turn right onto the major roadway and then turn left off of it. The right-left configuration is preferred because it is expected to reduce left turning maneuvers from the minor road, thereby diminishing delay and increasing capacity more than a left-right configuration (53).

Directional Medians and Right Turns follow by U-turns (J-turns)

J-turns, named by the Maryland State Highway Administration, describe this type of intersection. An actual rural J-turn intersection layout is shown in Figure 2-23. The J-turn has shared characteristics with Michigan's indirect left median U-turn design (Michigan lefts), but have some important dissimilarities, and the two should not be confused. The Michigan design shares the U-turn with the J-turn, but the Michigan design restricts all left turns (on both the minor and major roadway) and allows through traffic to move through the median crossover. A Michigan design is shown in Figure 2-24 (13, p. 709). Michigan has over 1,000 miles of highways with median U-turns in service and continues to include them as a preferred management and operations strategy on its primary arterial system (1).

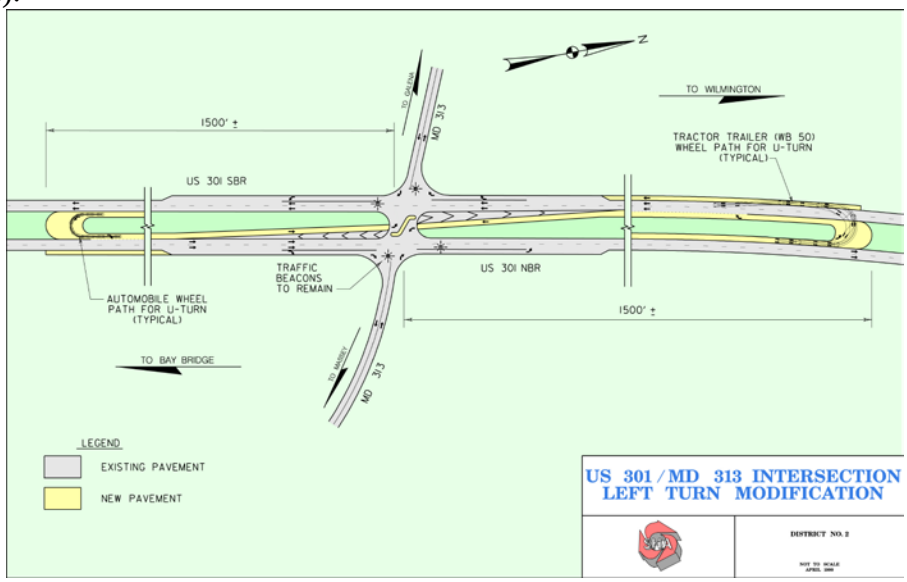


Figure 2-23. Directional median with median U-turns (Maryland J-turn)

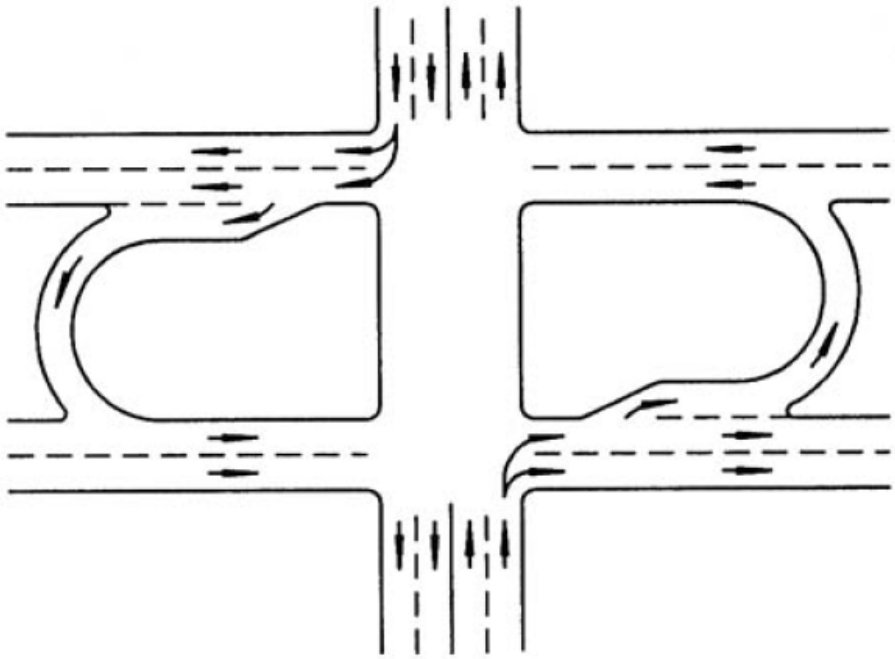


Figure 2-24. Michigan lefts, median U-turn design

The Michigan Department of Transportation (MDOT) first introduced the median U-turn design in the 1960s. Several rural highway corridors had been preserved through policies as early as the 1920s that provided large multi-lane highways with bi-directional openings in wide medians. Gradually, development built up along these corridors. By the 1960s, many corridors were largely urbanized and experienced capacity problems at intersections and at bi-directional crossover locations, largely due to interlocking left turns. To address this concern, MDOT engineers developed the median U-turn concept and moved all the left-turn movements to right turns or through movements followed by a median U-turn. One of the problems with type of intersection is that it requires a large median. If the design vehicle is a WB-50, AASHTO recommends a minimum of 59 feet of medians width (excluding U-turn bay width) (1).

One of the advantages of the MDOT design is that it often reduces the overall traffic delay through the intersection. Bared and Kaisar evaluated the operations of the Michigan design using a simulation modeling to compare the average delay associated with median U-turn intersections with that of conventional intersections (allowing direct lefts) (56). The authors found that "[a]lthough the average travel time for the U-turning traffic is higher than direct left turns, the overall reduction in the network travel time for the U-turn intersection is significant for balanced flows." (61, p. 54) The major factor contributing to these travel time savings for the U-turn intersection is the high total volumes entering the intersection with high left turning traffic volumes. The volume threshold at which the reduction in delay becomes noticeable will depend on the magnitude of left turning volumes and total volumes through the intersection. Although the total network travel time is about the same for both alternatives when simulations were attempted with 2,000 vehicles per hour (VPH) entering the intersection, increasing

the simulation to above 4,500 vehicles per hour showed that the U-turn intersection had a clear advantage.

Indirect left-turn treatments have generally not been applied at rural intersections because of the added travel distances for turning traffic. The added travel distance at rural and high-speed locations has not been perceived as compensating for any operational or safety improvements. When addressing indirect left turns and median U-turns, the Green Book states, “On high-speed or high-volume highways, the difficulty of weaving and the long lengths involved usually make this design pattern undesirable…” (13, p. 709).

Unlike the Maryland J-turn design, which has been applied at intersections with rural high-speed, four-lane divided highways, the Michigan design was largely created to increase capacity at signalized intersections. The Michigan design allows through movements at the median crossover and only requires left turning vehicles to use the median U-turns. The Maryland design does not allow minor roadway traffic through the median crossover, and the J-turn design is being used instead of improving an intersection through signalization or conversion to an interchange. The Maryland DOT found that “significant accident reductions were achieved” with the J-turn design in comparison to a conventional intersection (57). Maryland has been so pleased with the performance of this intersection layout that it has built four on different routes across the state.

One of the reasons this design achieves greater safety is that it reduces the number of conflict points further than an offset T-intersection. Figure 2-25 shows a drawing of the conflicts points for a J-turn intersection. The J-turn reduces conflict points by 43 percent in comparison to conventional intersection. Not only are the conflicts reduced, but the crossing conflicts are eliminated, reducing the opportunity for right-angle crashes. The majority of the remaining conflicts are merge and diverge conflicts, which may lead to lower severity sideswipe and rear-end crashes.

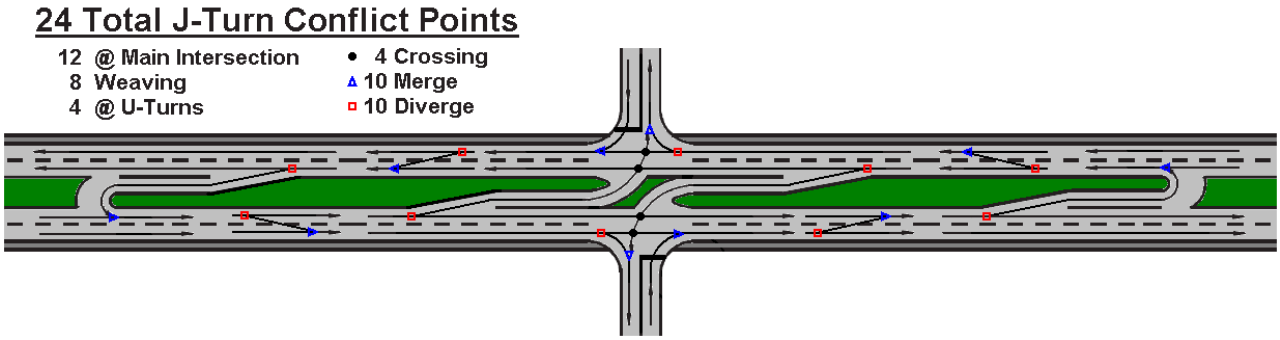


Figure 2-25. Conflict points for a J-turn intersection

The Florida Department of Transportation (FDOT) has implemented designs similar to the J-turn as an access management strategy at urban and suburban locations on median-divided highways. FDOT manages access by closing median crossovers, making a median crossover directional (only allowing left turns off the major road) or not permitting the construction of median crossovers at intersections with low-volume

roadways and driveways. Left turning drivers must turn right, followed by a U-turn through the median downstream (right turn followed by a U-turn [RTUT]). In 2001, Lu and other researchers at the University of South Florida reported the results of three studies that compared the crash, traffic conflicts, and operational characteristics of RTUT to the characteristics of direct left-turn (DLT) intersections in urban and suburban areas on four-, six-, and eight-lane divided highways in Florida (58, 59, 60). The researchers found that RTUT generally had superior safety performance (measured by crashes and conflicts) and that RTUT intersections had a smaller proportion of right-angle crashes but a higher proportion of sideswipe crashes. The sideswipe crashes are generally associated with weaving through traffic to the median opening and then merging after the U-turn, and are typically lower severity crashes than right-angle crashes. Similar to Bared and Kaisar's findings when they examined the Michigan design, the total average delay can be decreased by using RTUT intersections, but the delay depends on the volume of left turners and the traffic volume on the major roadway. Specifically, the authors found the following:

1. When the minor roadway left-turn volume equals 50 VPH, the average total delay of DLTs will be less than that of the RTUTs until the major roadway's traffic flow is greater than 4,500 VPD (in both directions).
2. When left-turn flow rates equal 100 VPH, the average total delay for DLTs will be less than that of the RTUT until the major roadway traffic flow is greater than 2,200 VPH.
3. When the left-turn rate is 150 VPH, the average total delay for DLTs will always be greater than that of the RTUT.

Lu et al. recommended the sign in Figure 2-23 at RTUT intersections with driveways or minor roadway (57).

Figure 2-23. Signing at right turn followed by a U-turn intersection

Lu and other researchers at the University of South Florida completed a similar series of evaluations in 2004 comparing RTUT intersections to DLT intersections on urban and suburban highways with six or more lanes (61,62). Lu and Liu also completed a study of traffic operations at RTUT intersections compared with those of DLT intersections on four-lane divided highways in 2004 (63). In this study, the authors compare the operational characteristics of three configurations: 1) a direct left-turn intersections (DLT), 2) a right turn followed by U-turn intersection (RTUT) where the U-turns are made upstream at a median opening, and 3) a RTUT where the U-turns are made upstream at a signalized intersection. The authors found that when the major roadway volume is allowed to vary from 1,000 to 4,000 VPH on the main line, for all volumes on the minor roadway the average delay time for the RTUT through a median opening is always least, and a RTUT through a signalized intersection always has the greatest average delay. However, left turning traffic always has more travel distance in either RTUT configurations than in a direct left-turn. Of course, all findings depend on the distance to the median opening and, at signalized intersections, the signal timing and signal phasing.

In their most recently reported evaluation of RTUT intersections, Lu et al. studied the safety impacts of the distance between the intersection mouth and the median opening (offset) (64). This study assumes that shorter offset distances will make the weave more difficult and risky. On the other hand, greater offset distance should make the weave less risky. The authors use conflict and crash analysis at 192 RTUT intersections with a U-turn through a median opening and with a U-turn through signalized intersections on four- and six-lane highways with speed limits of 40 mph or greater. The authors determined the 50th percentile crash rate and conflict rate (measured in conflicts per thousand vehicles). They then regressed the offset distance against crash rates and conflicts per thousand vehicles. Then, by working backwards through their regression equations, they selected the offset distance that equals the 50th percentile for crash and conflict rates. Because the distance is not always the same for each rate, they simply averaged the two distances and round to the nearest even 50 feet. Table 2-1 shows the authors' recommendations.

Table 2-1. Recommended offset distances

U-turn Location	Number of Lanes	Offset Distance Recommendation (ft.)
Median Opening	4	400
	6 or more	500
Signalized Intersection	4	550
	6 or more	750

Most of the known research about designs that are intended to move turning movements through an intersection from a direct left turn to a right turn followed by a median U-turn have been conducted in urban and suburban areas, and generally examined the traffic safety and operation of these treatments at very high volumes and at signalized

intersections. However, in a recent NCHRP study on median U-turns with a very limited crash database, Potts et al. found that “there is no indication that U-turns at unsignalized median openings constitute a major safety concern” (65). Based on Maryland’s experience, the J-turn intersection appears to be a promising strategy for rural multi-lane divided highways.

Jughandles, Loops, and other Indirect Lefts

Like intersection treatments where left turns are made by making a right turn followed by a median U-turn, jughandles in the United State have been predominately used at high-volume signalized intersections. By moving left turns to the jughandle (see Figure 2-24), left turns from the major roadway and a signal phase are eliminated. Another intersection configuration that achieves the same purpose as a jughandle is a loop following the intersection, as shown in Figure 2-25.

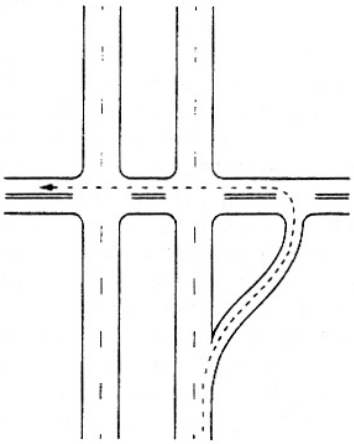


Figure 2-24. Intersection jughandle

Several studies comparing the jughandle operations, travel time, and capacities between conventional and unconventional intersection designs have showed that the jughandle was competitive with the conventional design for at least some volume combinations (66,67,68). Studies have shown that the jughandle design provides the greatest travel time savings on arterials that have high through movements, moderate or low left-turn volumes, and moderate to low cross-street volumes. If the left-turn or cross-street volumes are proportionately high, queues from the cross street may block the ramp terminal and outweigh any through-vehicle time savings.

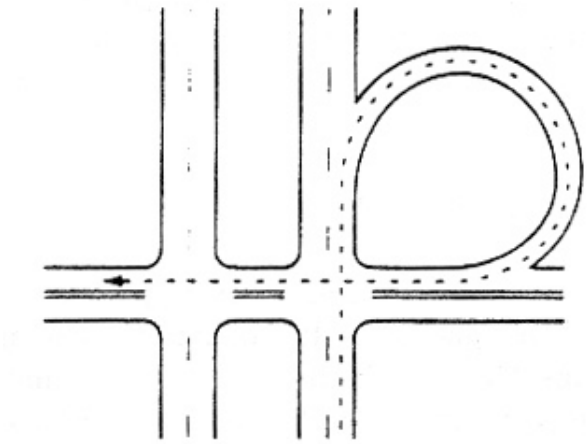


Figure 2-25. Loop following the intersection

The preferred design strategy of the New Jersey Department of Transportation (NJDOT) on high-volume arterials continues to be jughandles, referred to as “Jersey lefts.” New Jersey has built hundreds of miles of high-volume arterials with jughandle intersections over the last 30 years. The NJDOT “Roadway Design Manual” defines a jughandle as “an at-grade ramp provided at or between intersections to permit the motorists to make indirect left turns and/or U-turns” (69). The design manual defines three standard designs for jughandles: a forward jughandle (much like Figure 2-24), a jughandle to carry only U-turns, and a far-side jughandle (a loop). Some states in the Northeast use jughandles, and jughandles are occasionally used in other states outside of the Northeast.

Jagannathan et al. recently completed a study of the safety of New Jersey jughandle intersections (70). They conducted a cross-sectional study that included intersection characteristics from 44 jughandle intersections and 50 conventional intersections with similar traffic volumes, similar numbers of lanes, similar speed limits, and similar locations (rural/urban). However, some of the intersections are median-divided roadways and some are not.

In their descriptive analysis of the crash data, Jagannathan et al. noted that the distribution of crashes at conventional and jughandle intersections are different and that the conventional intersections have more head-on and left-turn (right-angle) crashes. The jughandle intersections also have a higher proportion of rear-end crashes. Part of the reason for the high incidences of head-on crashes at conventional intersections may be explained by the fact that only 40 percent of the conventional intersections have medians while 50 percent of the jughandle intersections had medians. Because rear-end crashes tend to be less severe, the overall severity of crashes at jughandle intersections tends to be lower (fewer injury and fatal crashes). Through the development of SPFs for conventional and jughandle intersections, the authors found that the jughandle intersections have lower property damage-only and severe (fatal and injury) crash frequencies than conventional intersections.

Gap Selection Assistance Devices

As shown at the beginning of this appendix in the descriptive analysis of crash data at median crossover intersections, right-angle crash frequencies increase and at increasing rate with minor roadway traffic volume. Right-angle crashes at two-way, stop-controlled intersections have been found to be most frequently a result of drivers failing to select an adequate gap rather than running the stop sign. To help drivers select a safe gap, both static (low-tech) and dynamic systems have been developed to help drivers select a safe gap.

Static Devices to Aid in Gap Acceptance

One proposed strategy is to use static devices to mark out a typical safe gap. The concept is that several devices or markings would be spaced along the uncontrolled approaches to mark a length along the major roadway where, if a vehicle is in this portion of the roadway, there is an insufficient gap (the hazard zone). The placement of the last device or marking identifies the threshold at which a vehicle may cross or turn safely. The size, number, and spacing of the devices or markings could be adjusted based on the posted speed limit and/or actual travel speeds.

Figure 2-26 shows a concept used by the Pennsylvania Department of Transportation (PennDOT) to help drivers identify safe gaps. The “+” symbols are painted on the major road, and white posts are placed along the side of the roadway to indicate the hazard zone. The advisory plate below the stop sign tells drivers that, if approaching vehicles are in this area, they should wait before crossing or turning onto the major roadway. This simple system delineates a distance with a sufficient gap to cross or merge with traffic safely. Although this system, shown in Figure 2-26, uses posts and pavement markings, alternatives might include the use of street lighting or a beacon to mark the hazardous zone.

PennDOT has deployed several variations of this strategy at approximately 20 rural intersections (71). The basis of the low-cost strategy uses pavement markings (“+” symbols) spaced out on the approaches (see Figure 2-27). Several different signs have been deployed at the intersections, including the sign in Figure 2-26 (72), which instructs drivers about using the pavement markings to aid with their gap selection decision. Other variations use a warning sign to remind drivers to look left-right-left before entering the intersection. However, that approach does not inform the driver of the purpose of the pavement markings.

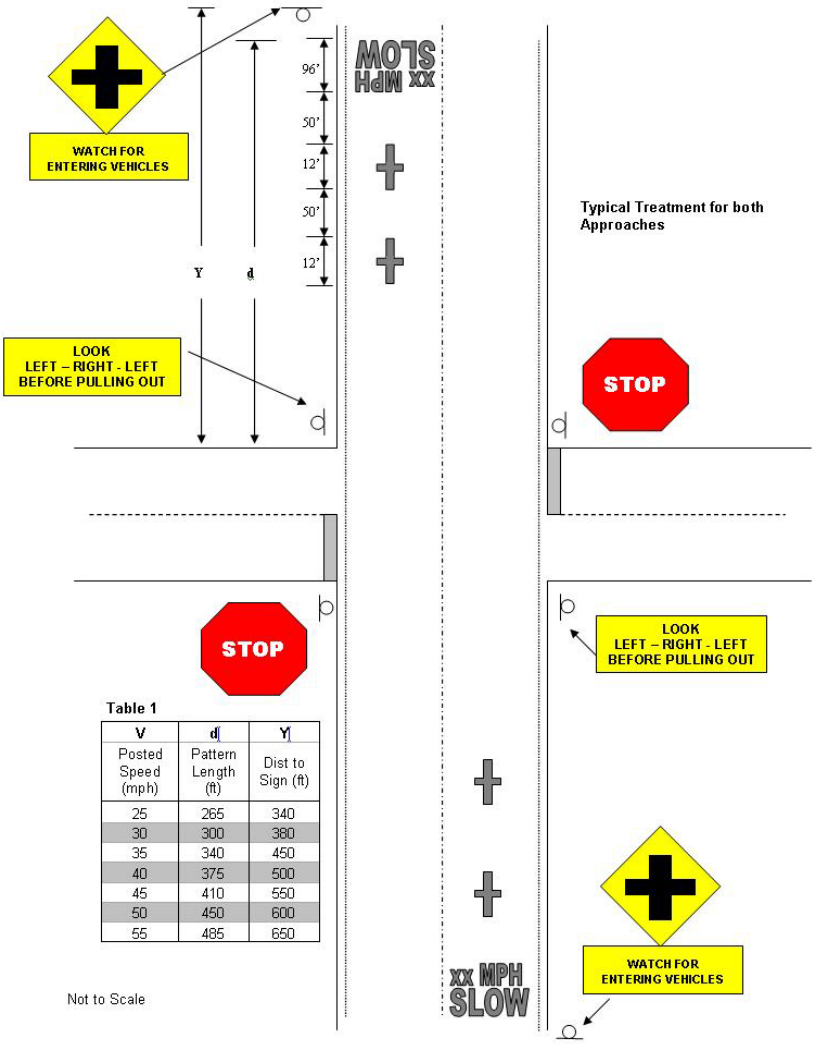
A rigorous evaluation of the PennDOT program has not been completed. However, the initial results of an evaluation of the look left-right-left sign are inconclusive. This may indicate that educating drivers on the intent of the pavement markings is needed, possibly through a driver education program such as a statewide program or the focused education of local residents.

Figure 2-26. Static gap selection assistance concept

The devices or markings used to identify the hazardous area could vary. Some states have chosen to use pavement markings, such as large "+" symbols. Another potential system would be spacing crashworthy poles or delineators along the road, possibly in conjunction with pavement markings. A final option would be to use street lighting, with the last light pole placed at the threshold location. Using street lighting at locations with a nighttime crash problem could be especially attractive, since it has been found to be effective in preventing these crash types (25).

PennDOT has deployed several variations of this strategy at approximately 20 rural intersections. Although these are all intersections of two-lane roads, similar concepts could be applied to intersections of multi-lane divided highways. PennDOT has tried several different signs at the intersections, including the sign in Figure 2-26. Other variations use a warning sign to remind drivers to look left-right-left before entering the intersection, as shown in Figure 2-27.

A rigorous evaluation of the PennDOT program has not been completed. However, initial results of the look left-right-left sign are inconclusive. This may indicate that educating drivers on the intent of the pavement markings and supplemental signs is needed, possibly through a driver education program such as a statewide program or the focused education of local residents.



V	d	Y
Posted Speed (mph)	Pattern Length (ft)	Dist to Sign (ft)
25	265	340
30	300	380
35	340	450
40	375	500
45	410	550
50	450	600
55	485	650

Figure 2-27. Example of static system to aid in gap selection (PennDOT, Bureau of Highway Safety and Traffic Engineering)

Dynamic devices to aid in the selection of safe gaps

Three examples have been found of devices that help drivers make a safe gap selection. Two of these are low-technology devices in which inductive loop detectors that sense the presence of a vehicle within the hazardous zone and a dynamic sign with a static message warns drivers on the minor approach that a vehicle is approaching. One has been field-tested in Prince William County, Virginia, at the intersection of two two-lane roads with a sight distance problems due to a vertical curve (73). Figure 2-28 shows the sign on the minor road approach, and the sign shows a car symbol. Figure 2-29 shows the sign on the major road approach, indicating that there is a vehicle on the minor approach near or at the intersection.

Figure 2-28. Dynamic sign on the minor road approach

Figure 2-29. Dynamic sign on major road approach

The system was operated from April 1998 through March 2000. The evaluation found that vehicles approaching the intersection when a vehicle was present on the minor approach reduced their speed. In other words, when a vehicle was sensed on the minor roadway, the vehicle on the major road tended to reduce its speed. The crash rate at the intersection also seemed to decline. Prior to installation of the system, the intersection averaged 2.6 crashes per year, and following the installation there were no crashes over the two-year test period.

A system similar to the Virginia system was implemented by the Maine Department of Transportation in Norridgewock, Maine (74). The major roadway is US 201A, and the subject intersection is just to the north of the touchdown point of the bridge over the Kennebec River. The bridge is an arched concrete bridge with large structural concrete columns and railings that limit site distances. To the south of the intersection on one of the bridge cross-members, a dynamic flasher sign lets northbound drivers on US 201A

know that a vehicle is on the cross street. On the minor roadway, dynamic signs indicate that a vehicle is approaching and the direction of the approaching vehicle. These signs are triggered by loop detectors on the major road approach.

The Maine system was evaluated by conducting a conflict analysis before and after the installation of the system and by surveying drivers. Two types of observational conflict analyses were conducted: the method outlined in the Federal Highway Administration's "Traffic Conflict Techniques for Safety and Operations" report, and a method developed by Per Gårder of the Swedish Royal Institute of Technology (75,76). Using the FHWA technique, conflicts were reduced by 35%, and conflicts were reduced by 40% when the Swedish method was applied. The evaluators also distributed 1,464 surveys to drivers, 541 of which were completed and returned. Sixty seven percent of the drivers surveyed felt that the signs could prevent crashes, and 64% recommended the signs' use at other intersections.

The third infrastructure system being tested is a system developed by the Intelligent Transportation Systems Institute at the University of Minnesota (77). Although it is not specifically designed for a crossover intersection on a divided highway, the first implementation and field test is on a rural median-divided highway (Trunk Highway 52 between Rochester and St. Paul, Minnesota). The intersection decision support (IDS) system is much more sophisticated than the Virginia or the Maine system. The IDS includes radar devices directed along the expressway in both directions, as shown in Figure 2-30, sending information about the location and speed of approaching vehicles back to a roadside computer unit. The computer controls a dynamic message sign on the minor roadway approach. The roadside computer then calculates when the conflicting vehicle will arrive at the intersection. Several concepts for the dynamic message sign are being considered. Figure 2-31 shows two alternative designs of the dynamic sign. The one on the left shows drivers the speed of the approaching vehicle from each direction; the speed indicator turns red when the gap is no longer safe. The sign on the right is similar, but shows the time before arrival rather than the speed; the time indication turns red when the gap is too small to turn with traffic or to cross the expressway.

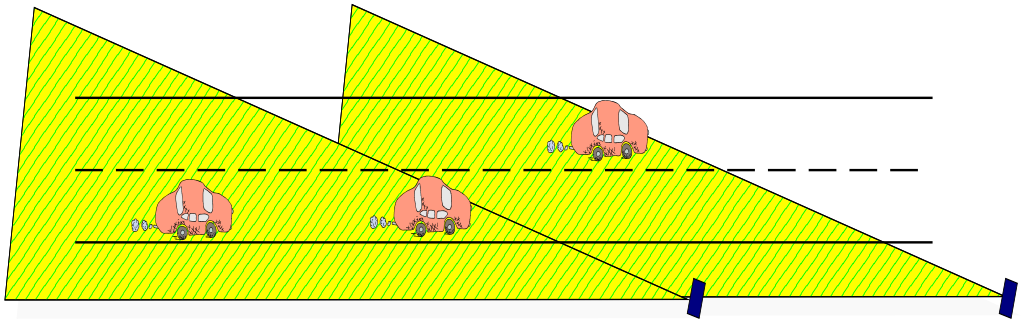


Figure 2-30. Radar directed upstream from the intersection (ITS Institute, University of Minnesota)

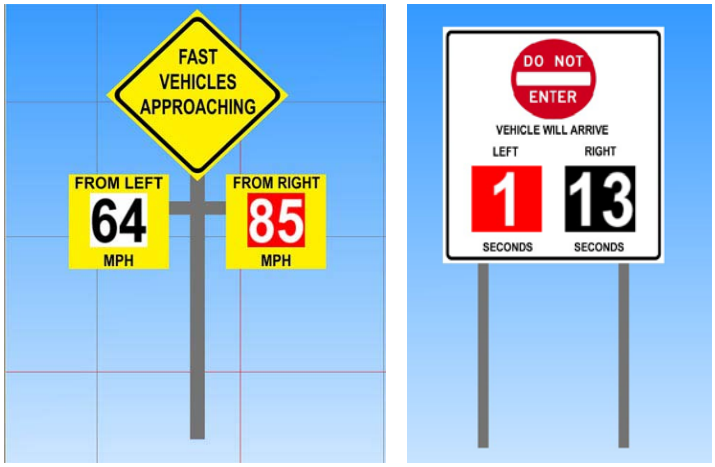


Figure 2-31. Alternative designs for dynamic signs (ITS Institute, University of Minnesota)

Signalization

Signalizing intersections is another method for reducing conflict points. With a simple two-phased signalized intersection, the only conflict points remaining are those involving left-turning vehicles. Although signalizing an expressway intersection is a common countermeasure consider to improve the safety performance of a conventional intersection, very little research has been conducted on the safety benefits of signalizing intersections on four-lane, median divided, high-speed highways.

The literature provides a diversity of studies on signalization of intersections in general, with results that either support or reject the assertion that the safety of an intersection will improve with signalization. For example, Voss performed a before-and-after crash reduction and benefit/cost analysis to measure safety improvements in the state of Kansas. New traffic signals were found to reduce crashes by 45 percent. However, type and severity of crash and selection bias were not accounted for in that study.(78) Thomas and Smith reported that installing 16 new traffic signals reduced overall crashes by 29 percent, with a 71 percent reduction in right-angle crashes but with increases of 44 percent in rear-end crashes and 41 percent in left-turn crashes.(79) This study was a simple before/after study of 16 intersection projects using 3 years of before and 3 years of after data. Contrast this to a study by Persaud, that reported on studies whose results ranged from a 24 percent reduction to a 51 percent increase in total crashes after signal installation.(80) Persaud concluded that a failure to account for regression to the mean and incorrectly interpreting the results of cross-sectional studies calls into question "…much of the knowledge about the safety impact of signal installation. In particular, the foundation of the belief that, where unwarranted, signal installation is likely to increase accidents appears to be shaky."

Signalization of expressways intersections

In a 1992 report for the Nebraska Department of Roads concerning how to determine when an interchange is economically justified, Bonneson and McCoy developed regression models for the safety of signalized and unsignalized (2-way stop control) expressway intersections as well as interchanges using generalized linear modeling.(81) They concluded that only the main and side road ADT values entered the crash prediction models for the intersections; the crashes at interchanges were related only to the expressway ADT. They also found that interchanges were economically justified (considering all costs) at a side road ADT of about 4,000. Comparing the crash frequencies predicted by their models for main line ADT values in the range of 7,000 to 15,000 and side road ADT values from 100 to 4,000 reveals that signals are expected to have more crashes until the side road ADT reaches a level about one fourth of the main line ADT, at which point the stop-controlled intersection would have more crashes.

Harwood, et. al., in NCHRP 375 reported crash rates for signalized and unsignalized divided highway intersections.(4) Rural 4-leg unsignalized intersections had an average crash rate of 0.17 crashes per million entering vehicles (0.10 fatal and injury crashes per MEV). Their urban counterparts had an average crash rate of 0.14 (0.07 fatal and injury crashes per MEV). While signalized rural intersections were not reported, signalized urban 4 leg intersections had an average crash rate of 0.16 (0.08 fatal and injury crashes per MEV). Little overall difference in crash rate was observed between signalized and unsignalized intersections in this study.

Souleyrette and Knox compared the results of a traditional (classical or naïve) before and after study of high-speed signalized expressway intersections to a study of the same intersections utilizing the Empirical Bayes method.(82) Where the classical study method showed a reduction of 11.7 percent in crash rates, the Empirical Bayes method found a 4.8 percent reduction in crash rate. They concluded that while crash rates are slightly lower, crash costs at signalized intersections are much higher. However, they noted that the models they developed do not have great explanatory power and that their statistical parameters are weak. Finally, they suggested that future researchers may wish to consider how site characteristics are related to accident modification functions.

Current research does not provide decisive conclusion regarding the safety benefits of signalization of rural expressway intersections. The finding of literature to date do not indicate that signization of an express intersection will necessarily improve safety performance of the intersection and signalization may even degrade safety performance.

Physical separation of conflicting movements

The ultimate in grade separation is to turn an intersection into an interchange. An interchange is the most expensive treatment for a problematic safety problem, and interchanges generally cost several million dollars to build, depending on the interchange design and the expense of clearing and purchasing the right of way for the interchange footprint. There are generally great cost savings if constructing an interchange can be avoided, so long as the intersection can be maintained at a reasonable safety performance. For example, the J-turn shown in Figure 2-22 (intersection of US 301 and Maryland 313) was eventually scheduled to be converted to an interchange, but the project was postponed due to a lack of resources. The safety and operational performance of the J-turn is viewed to be more than satisfactory by the district traffic engineer, and therefore the $618,000 J-turn intersection has made the construction of an interchange unnecessary.

Grade-separated intersection

In Iowa, two intersections have been constructed where the minor roadway crosses the median-divided highway on an overhead bridge. Turning traffic between the two roadways is carried on a turning roadway. Aerial photos of these two locations are shown in Figures 2-32 and 2-33. Both are intersections of primary highways. In both cases, the intersection may have originally been planned as a staged improvement, an intermediate step before building a full interchange. Additionally, in both cases traffic safety and traffic operation problems have not occurred, and therefore there is no need to upgrade the intersection to an interchange. This design eliminates the right-angle conflicts between through traffic on the two roadways, and only turning traffic travels through a median crossover T-intersection. In each case, the turning movements travel through two T-intersections. Since only turning movements travel through the T-intersection, the volume through the intersections is much lower than if the movement had been through the median crossover with a conventional design.

Both of these grade-separated intersections were built on US 59 (the north-south two-lane roadway) at intersections in western Iowa. The ADT on US 59 at both intersections is only about 1,300 VPD, while Iowa 92 (in Figure 2-32) has an ADT of 2,250 VPD, and US 34 (Figure 2-33) has an ADT of 3,270 VPD.

To evaluate the safety performance of these two intersections, Maze et al. used an SPF created for two-way, stop-controlled intersections using five years of crash data (1996–2000) (2). The SPF was used to estimate the intersections' safety performance had they been left as two two-way, stop-controlled intersections. The SPF was created using negative binomial regression, and the safety performance was measured through a crash severity rate. All crashes at each intersection were given a weight from 1 to 5, where 1 is a property damage-only crash, 2 is an unknown injury crash, 3 is a minor injury crash, 4 is a major injury crash, and 5 is a fatality. For each intersection, the severity weightings were totaled and averaged over the five-year period. These became the model's dependent variable. The model's independent variables were the minor and major roadways' ADT volume. The model was then used to estimate the expected crash

severity rate, when these two intersections were at-grade and stop-controlled, and the expected for the at-grade intersection was compared to the actual. The expected safety performance (crash severity rate) was about three times greater than the actual safety performance. Simply put, the actual safety performance of the grade-separated intersections was about three time better than the expected safety performance of a conventional intersection with the same volumes.

Figure 2-32. Intersection of US 59 and IA 92 in Pattawattamie County

Figure 2-33. Intersection of US 59 and US 34 in Mills County

In Iowa, the grade separation of the intersection was only intended to be a temporary step, with the intersection later being converted into a interchange. However, this strategy has worked well from a safety perspective, and volumes have not risen to a point where the intersection is experiencing operational problems. Therefore, there is no need at this time to make any further improvements.

We speculate that there are two conditions where this treatment would be appropriate. The first is similar to the condition experienced in Iowa where an intersection is eventually planned, but traffic volume does not yet require the use of ramps (as opposed to intersections and turning roadways), and the expense of building ramps can be postponed until later or even coordinated with a later comprehensive corridor improvement and corridor access control. The second case may simply be a location where an interchange is not planned and is unlikely to be warranted due to traffic volumes, but problematic geometric conditions (location on a horizontal or vertical curve) and/or traffic patterns (heavily peaked traffic or high percentages of heavy commercial vehicles) are likely to result in a hazardous at-grade intersection.

Grade-separated intersections are expensive treatments because they require the construction of an overhead bridge. Because the minor roadway is likely to be a two-lane roadway (as opposed to a multi-lane highway), the bridge cost can be minimized by building the bridge for the two-lane roadway. However, the treatment will cost less than a typical partial cloverleaf or diamond interchange and will require less right-of-way than an interchange. Because the intersections on the turning roadway are T-intersections, they

have far fewer conflict points than conventional intersections. Also, since the turning roadways only carry turning vehicles, the volumes are much lower than volumes through a conventional median crossover intersection. Lower volumes and fewer conflicts at the intersections generally result in fewer intersection crashes. As a result, the grade-separated intersection has a superior safety performance than a conventional intersection.

Policy and planning strategies

High-speed median crossover intersections as general improvements result from a reaction to an intersection that becomes a safety problem, as identified by the occurrence of crashes at the intersection. The conventional approach to intersection safety problems is to implement moderate-cost safety improvements to improve intersection recognition on the minor roadway approach and in the median. If intersection recognition strategies fail to reduce the frequency or severity of crashes, then traditionally the next step is to signalize the intersection and ultimately build an interchange at the intersection. However, this review of strategies has suggested that there is a continuum of possible strategies other than moving from a four legged, two-way, stopped-controlled intersection to a signal-controlled intersection to an interchange.

A few states were found to have strategies that proactively address intersection improvements rather than wait until volumes increase and safety performance degrades.. These can be divided into strategies that involve applying a treatment to an intersection or a group of intersections when a specific condition is met, and applying a treatment to an entire corridor when a condition is met.

Intersection-level policies

As illustrated in the descriptive crash statistical analysis at the beginning of this appendix, intersection safety performance declines quickly as minor roadway volumes increase. This suggests that a volume threshold could be established that indicates when it is prudent to start investigating improvement strategies. In the early 1990s, Bonneson and McCoy studied practices for determining whether to grade-separate intersections on divided multi-lane rural highways with other major highways for the Nebraska Department of Roads. Their study followed two general themes. The first was to conduct a survey of practices in other states, and the second was to formulate a benefit-cost model for use by the Nebraska Department of Roads to determine whether to improve a stop-controlled, at-grade intersection to a signalized intersection or a diamond interchange. Their findings are covered in two separate papers (83,84). Although they found no specific criteria used by other state transportation agencies for determining where a rural four-lane divided highway should be designed with grade-separated interchanges (with the exception of intersections with interstate highways), their benefit-cost analysis found that constructing an interchange is generally not cost-beneficial when minor roadway volumes are less than 2,000 VPD. However, interchanges are generally cost-beneficial when minor roadway volumes exceed 4,000 VPD. Intersections within minor roadways in the range of 2,000 and 4,000 VPD should, therefore, be candidates for potential improvement, and the decision whether to improve the intersection should then be based on an engineering evaluation of the intersection. Bonneson and McCoy also determined

that when two states built multi-lane divided highways bypassing a community, the intersections were constructed with complete access control, and all intersections were built as interchanges due to the high crash rates the states had experienced when conventional intersections were used on bypasses.

The Illinois Department of Transportation (ILDOT) has developed specific triggers for improvement strategies. These triggers are fairly simple but proactive for intersection improvements. When an intersection is projected to need a signal in the next nine years, it will be programmed for conversion into an interchange (2, p. 37). Any intersection projected to need a signal in the next 20 years will trigger the purchase of access rights for a future interchange.

Corridor-level policies

A few state transportation agencies, either through policy or through practice, improve an entire corridor at the same time. This involves converting all major intersections to interchanges and closing all other intersections as part of a contiguous project. The reason for conversion of all intersections at once is that mixing intersections with interchanges tends to violate driver expectations. In other words, if drivers travel through an interchange, they are likely to expect a freeway design standard facility and will not expect that cross-traffic will be entering the roadway through driveways and cross-streets, or they will expect that they will have to stop at traffic signals.

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