NCHRP 15-30 APPENDIX A

Detailed Green Book Review with Comments

Task 1: Summarize the guidance on median intersection and crossover design in the 2004 AASHTO Policy on Geometric Design of Highways and Streets (Green Book). Identify areas where guidance is lacking or needs to be expanded and/or supplemented.

The current guidance on median intersection design for high-speed (≥ 50 mph) divided highways with partial or no control of access, otherwise known as expressways, is spread throughout the 2004 "AASHTO Policy on Geometric Design of Highways and Streets" (Green Book). Guidance specific to expressway intersection/interchange design resides in Chapter 4 "Cross Section Elements", Chapter 7 "Rural and Urban Arterials", Chapter 9 "Intersections", and Chapter 10 "Grade Separations and Interchanges". This report summarizes the current guidance given in these chapters related to expressway intersection/interchange design. Throughout this document, comments have been provided in bold which identify areas where design guidance is lacking or needs to be expanded.

In addition, Chapter 8 of the Green Book entitled "Freeways" discusses the design of rural and urban freeways. This chapter was not summarized here because clearly, no guidance on intersection design is provided. However, a designer may refer to this chapter when designing the major features of an expressway. In the introduction to Chapter 7 on page 443, the Green Book states, "Although freeways are included in the functional description of an arterial, they have distinctive design requirements and are therefore treated separately in Chapter 8." Because expressways are really a hybrid design between a two-lane rural highway and a rural freeway, the spread of information regarding expressway intersection design in the current Green Book may create confusion among designers and better design guidance is necessary to alleviate this confusion. One way to solve this problem may be to reorganize all materials on expressways and expressway intersections into a comprehensive, all-inclusive chapter. After all, like freeways, expressways have distinctive design requirements and it may alleviate confusion if expressways were similarly addressed in a separate chapter. In discussions with Geometric design engineers at a half dozen State Transportation Agencies, they stated that it has long been recognized that the organization of Green Book may be cumbersome but reorganization will be very problematic.

The Green Book relates planning for the design of a facility around the design volume and the ability of the facility to provide and sustain a desired level of service over its life (In chapter 2). However, rural expressway corridors are often corridors of growth resulting from changes in adjacent land use and rural travel patterns. As a result, rural expressways typically outlast their at-grade intersections. Four-legged, two-way stop-controlled intersections may initially operate at an acceptable level of service and safely when cross traffic volumes are at a low level (e.g. 400 vpd); however, safety and operational performance may deteriorate when the cross traffic volumes increase to say 2,000 vpd. A recommended modification to the Green Book is to include a discussion regarding differences in intersection life-cycle and mainline life-cycle. What may be appropriate design initially may require incremental improvements. Expressway intersections are likely to have a different life cycle then the mainline. This is more of a philosophical where as the remainder of the recommendation are either editorial or technical.

Chapter 4

Chapter 4 of the AASHTO Green Book entitled “Cross Section Elements” contains short sections on median and frontage road design between pages 337 and 344. These sections state the following:

MEDIANS:

> *For maximum efficiency, a median should be highly visible both night and day and should contrast with the traveled way. Medians may be depressed, raised, or flush with the traveled way surface.* [p. 337]

> *Cost of construction and maintenance increases as median width increases, but the additional cost may not be appreciable compared with the total cost of the highway and may be justified in view of benefits gained.* [p. 337]

> *At unsignalized intersections on rural divided highways, the median should generally be as wide as practical. In urban and suburban areas, however, narrower medians appear to operate better at unsignalized intersections; therefore, wider medians should only be used in urban and suburban areas where needed to accommodate turning and crossing maneuvers by larger vehicles. Medians at unsignalized intersections should be wide enough to allow selected design vehicles to safely make a selected maneuver. The appropriate design vehicle for determining the median width should be chosen based on the actual or anticipated vehicle mix of crossroad and U-turn traffic. A consideration in the use of wider medians on roadways other than freeways is the provision of adequate storage area for vehicles crossing the highway at unsignalized intersections and at median openings serving commercial and private driveways. Such median openings may need to be controlled as intersections. Wide medians may be a disadvantage when signalization is needed. The increased time for vehicles to cross the median can lead to inefficient signal operation.* [p. 337]

The paragraph above could be simplified and written more clearly as follows: “At unsignalized intersections (and median openings serving commercial and private driveways) on rural divided highways where the need for future signalization is not projected, the median should generally be as wide as practical. A consideration in the use of wider medians is the provision of adequate storage for vehicles crossing the highway. However, excessively wide medians can lead to an increase in wrong-way entries. Therefore, the median should only be as wide as necessary to store the largest anticipated design vehicle. Wide medians may be a disadvantage where signalization is needed because they can lead to inefficient signal operation. [Guidance is lacking for selecting a median width where the need for future signalization is projected at a rural expressway intersection.] In urban

and suburban areas, narrower medians appear to operate better at unsignalized intersections; therefore, in urban and suburban areas, whether signalization is needed or not, the median should only be as wide as necessary to accommodate turning and crossing maneuvers by the appropriate design vehicle. The appropriate design vehicle for determining the median width should be chosen based on the anticipated vehicle mix of crossroad and U-turn traffic."

A depressed median is generally preferred on freeways for more efficient drainage and snow removal. Median side slopes should preferably be 1V:6H, but slopes of 1V:4H may be adequate. Raised medians have application on arterial streets where it is desirable to regulate left-turn movements. They are also frequently used where the median is to be planted, particularly where the width is relatively narrow. Flush medians are commonly used on urban arterials. Where used on freeways, a median barrier may be needed. The crowned type is frequently used because it eliminates the need for collecting drainage water in the median. In general, however, the slightly depressed median is preferred either with a cross slope of about 4 percent or with a minor steepening of the roadway cross slope. [p. 337, 338]

A depressed median is preferred on freeways, but what about expressways? How about near intersections on expressways? Depressed medians are commonly used on expressways, but which median type provides the safest operation at rural expressway intersections?

When medians are about 12 m [40 ft] or wider, drivers have a sense of separation from opposing traffic; thus, a desirable ease and freedom of operation is obtained, the noise and air pressure of opposing traffic is not noticeable, and the glare of headlights at night is greatly reduced. There is demonstrated benefit in any separation, raised or flush. Wider medians are desirable at rural unsignalized intersections, but medians as wide as 18 m [60 ft] may not be desirable at urban and suburban intersections or at intersections that are signalized or may need signalization in the foreseeable future. For further guidance in the selection of median widths for divided highways with at-grade intersections, refer to NCHRP Report 375, Median Intersection Design. [p. 339]

This information should be placed earlier and incorporated back on page 337 where median width was discussed so that all the information is together and so that the same information doesn't have to be repeated.

<u>FRONTAGE ROADS:</u>

Frontage roads serve numerous functions, depending on the type of arterial they serve and the character of the surrounding area. They may be used to control access to the arterial, function as a street facility serving adjoining properties, and maintain circulation of traffic on each side of the arterial. Frontage roads segregate local traffic from the higher speed through-traffic and intercept driveways of residences and commercial establishments along the highway.

Cross connections provide access between the traveled way and frontage roads and are usually located in the vicinity of the crossroads. Thus the through character of the highway is preserved and unaffected by subsequent development of the roadsides. [p. 339]

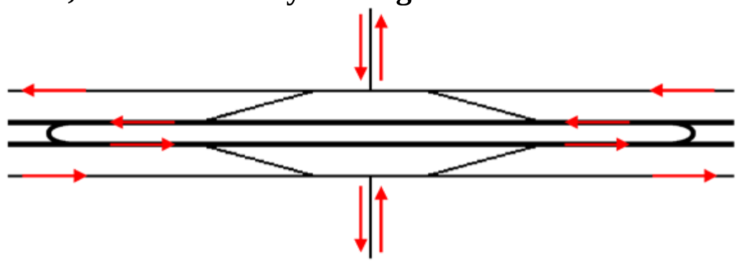
Frontage roads are used on all types of highways. Each chapter pertaining to a particular type of highway includes a discussion on the use of frontage roads with that highway type. Frontage roads not only provide more favorable access for commercial and residential development than the faster moving arterial street but also help to preserve the safety and capacity of the latter. In rural areas, development of expressways may need separated frontage roads that are somewhat removed from the right-of-way and serve as access connections between crossroads and adjacent farms or other development. [p.339]

Despite the advantages of using frontage roads on arterial streets, the use of continuous frontage roads on relatively high-speed arterial streets with intersections may be undesirable. Along cross streets, the various through and turning movements at several closely spaced intersections may greatly increase crash potential. Multiple intersections are also vulnerable to wrong-way entrances. Traffic operations are improved if the frontage roads are located a considerable distance from the mainline at the intersecting cross roads in order to lengthen the spacing between successive intersections along the crossroads. In urban areas, a minimum spacing of about 50 m [150 ft] between the arterial and the frontage roads is desirable. For further discussion on frontage roads at intersections, refer to the section in Chapter 9 on "Intersection Design Elements with Frontage Roads." [p.339, 340]

The first sentence in this paragraph should be worded differently. By initially saying the use of frontage roads may be undesirable, a designer may stop reading there and decide not to build frontage roads because the Green Book says they might be undesirable. The initial sentence should be qualified by stating, "The use of continuous frontage roads on relatively high-speed arterial streets with intersections may be undesirable if the frontage roads are not located a considerable distance from the mainline at the intersecting cross roads." This paragraph also infers that a "considerable distance" means a minimum spacing of about 50 m [150 ft] in urban areas. What about in rural areas? The same minimum spacing should apply in rural areas as well to preserve the integrity of operation on the crossroad as development occurs, which it is bound to.

From an operational and safety standpoint, one-way frontage roads are much preferred to two-way frontage roads. While one-way operation inconveniences local traffic to some degree, the reduction in vehicular and pedestrian conflicts at intersecting streets generally compensate for this inconvenience. In addition, there is some reduction in the roadway and right-of-way width required. Two-way frontage roads at busy intersections complicate crossing and turning movements. Where off-ramps join a two-way frontage road, the potential for wrong-way entry is increased. This problem is greatest where the ramp joins the *frontage road at an acute angle, thus giving the appearance of an onramp to the wrong-way driver.* [p. 340, 341]

The following rural expressway design with one-way frontage roads, one-way off/on-ramps, and downstream median U-turns could alleviate the need for at-grade intersections directly on the expressway and would be a cheaper alternative to grade separations and interchanges until the cross street through volumes increased to levels warranting an interchange. In less developed areas, the same design shown below could be used, but the one-way frontage road extensions could be dropped.



Two-way frontage roads may be appropriate for suburban or rural areas where points of access to the through facility are infrequent, where only one frontage road is provided, or where roads or streets connecting with the frontage roads are widely spaced. [p. 341]

Connections between the arterial and frontage roads are an important element of design. On freeways and other arterials with high operating speeds, the ramps and their terminals should be liberally designed to provide for speed change and storage. Details of ramp design are covered in later chapters. Exhibits 4-10 and 4-11 each illustrate an arrangement of frontage roads with entrance and exit ramps that are applicable to freeways and other high speed arterials. [p. 341]

The design of a frontage road is influenced by the type of service it is intended to provide. Refer to Chapter 6 for guidelines on the widths of two-lane frontage roads for rural and urban collectors. [p. 342]

The area between the traveled way of a through traffic roadway and a frontage road or street is referred to as the "outer separation." Such separations function as buffers between the through traffic on the arterial and the local traffic on the frontage road and provide space for a shoulder for the through roadway and ramp connections to or from the through facility. The wider the outer separation, the less influence local traffic will have on through traffic. A substantial width of outer separation is particularly advantageous at intersections with cross streets because it minimizes vehicle and pedestrian conflicts. Where ramp connections are provided between the through roadway and the frontage road, the outer separation should be substantially wider than typical. The needed width will depend mostly upon the design of the ramp termini. [p. 342, 343]

Where two-way frontage roads are provided, a driver on the through facility faces approaching traffic on the right (opposing frontage road traffic) as well as opposing arterial traffic on the left. Desirably, the outer separation should be *sufficiently wide to minimize the effects of approaching traffic, particularly the potentially confusing and distracting nuisance of headlight glare at night.* [p. 343]

On page 339, 40 ft or wider was mentioned as the required median width to minimize the effects of opposing traffic. Therefore, the outer separation should be at least 12 m (40 ft). In the vicinity of intersections, the outer separation distance should still be ≥ 50 m (150 ft) to maintain adequate crossroad intersection spacing.

With one-way frontage roads the outer separation need not be as wide as with two-way frontage roads. [p. 343]

In the vicinity of intersections, the outer separation should still be ≥ 50 m (150 ft) to maintain crossroad intersection spacing.

The cross section and treatment of an outer separation depend largely upon its width and the type of arterial and frontage road. Typical cross sections of outer separations for various types of arterials are illustrated in Exhibit 4-13. [p. 343]

Chapter 7

Chapter 7 of the AASHTO Green Book is entitled "Rural and Urban Arterials." The section on "Rural Arterials" (pp. 443 – 469) contains three noteworthy subsections: 1) General Design Considerations (pp. 443 – 450), 2) Ultimate Development of Four-Lane Divided Arterials (pp. 450 – 452), and 3) Divided Arterials (pp. 454 – 469). When only looking at the section on divided arterials, it is unclear if this section is discussing rural or urban divided arterials. The only indications that it is discussing rural divided arterials are 1) the header on odd numbered pages in this section says "rural" in parenthesis and 2) this section is bookmarked underneath the "Rural Arterials" heading in the table of contents. To clarify that this section is discussing rural divided arterials, it should be entitled, "Rural Divided Arterials" or even "Rural Expressways" rather than just "Divided Arterials."

Chapter 7 begins with a general discussion of the design considerations for rural arterials. Because rural arterials cover a broad range of roadway cross-sections, from two-lane to multilane both undivided and divided, it is difficult to critique this section regarding specific expressway design guidance. However, statements could be added in this section to more clearly distinguish between undivided and divided rural arterials where differences exist.

GENERAL DESIGN CONSIDERATIONS (*RURAL ARTERIALS*):

This chapter considers rural and urban arterials separately because each has distinctive features. However, the designer should be prepared to use design features from both arterial types to provide for suitable transitions as an arterial moves between rural and urban settings. [p. 443]

The remainder of this chapter contains a section on rural and a section on urban arterials. There is not a section specifically for suburban arterials, even

though the text recognizes design differences would exist for an arterial in a suburban area versus one in a rural or urban area. Design guidance should be provided to help the designer integrate the design when an arterial is located in a suburban setting. Further research is likely necessary in order to provide the appropriate guidance.

> *The appropriate design geometrics for an arterial may be readily determined from the selected design speed and the design traffic volumes, with consideration of the type of terrain, the general character of the alignment, and the composition of traffic.* [p. 443]
>
> *Rural arterials, excepting freeways, should be designed for speeds of 60 to 120 km/hr [40 to 75 mph] depending on terrain, driver expectancy, and, in the case of reconstruction projects, the alignment of the existing facility. Design speeds in the higher range (100 to 120 km/hr [60 to 75 mph]) are normally used in level terrain, design speeds in the mid-range (80 to 100 km/hr [50 to 60 mph]) are normally used in rolling terrain, and design speeds in the lower range (60 to 80 km/hr [40 to 50 mph] are used in mountainous terrain. Where a lower design speed is used, refer to Chapters 2, 3, and 4 to select appropriate design features.* [p. 444]
>
> *Before an existing rural arterial is improved or a new rural arterial is constructed, the design traffic volume should be determined. The design of low-volume rural arterials is normally based on ADT values alone because neither capacity nor intersection operations typically govern the overall operation. Such roadways normally provide free flow under all conditions. By contrast, it is usually appropriate to design high-volume rural arterials using an hourly volume as the design traffic volume. The design hourly volume (DHV) that should generally be used in design is the 30th highest hourly volume of the year, abbreviated as 30 HV, which is typically about 15 percent of the ADT on rural roads. For further information on the determination of design traffic volumes, see the section on "Traffic Characteristics" in Chapter 2.* [p. 444]

The above statement discusses design based on the design traffic volume of the arterial. However, there is little mention of the design traffic volume of the crossroad. Especially on expressways, intersection operations do play an important role in the overall safety and operation of the facility. The design of a divided rural arterial and its intersections should take into account the design traffic volume and vehicle mix on the crossroads when designing certain geometric features (i.e., median width, median acceleration lanes (MALs), etc.).

> *Level-of-service characteristics are discussed in Chapter 2 and summarized in Exhibit 2-31. For acceptable degrees of congestion, rural arterials and their auxiliary facilities (i.e., turning lanes, passing sections, weaving sections, intersections, and interchanges) should generally be designed for level-of-service B, except in mountainous areas where level-of-service C is acceptable.* [p. 444]

Stopping sight distance, a key safety-related design element, should be provided through the length of the roadway. Passing and decision sight distances influence roadway operations and should be provided wherever practical. Providing decision sight distance at locations where complex decisions are made greatly enhances the chances that drivers will be able to safely accomplish maneuvers. Examples of locations where complex decisions are required include high-volume intersections, transitions in roadway width, and transitions in the number of lanes. Provision for adequate sight distance on rural arterials, which may combine both high speeds and high traffic volumes, can be complex. Exhibit 7-1 presents the recommended minimum values of stopping and passing sight distance. Refer to Chapter 3 for a comprehensive discussion of sight distance and for tabulated values for decision sight distance. [p. 445]

The paragraph above states that high-volume intersections are an example of a location where complex decisions are made and where providing decision sight distance along the arterial will increase the chances that drivers will be able to safely accomplish maneuvers. What volume level qualifies as high-volume? Why even specify high-volume intersections here? Complex decisions are required at all intersections, especially those on divided arterials. Providing decision sight distance on an expressway approach to an intersection should increase the probability that an expressway driver will be able to accomplish a crash avoidance maneuver if a minor road driver misjudges a gap in the expressway traffic stream. Therefore, why not include decision sight distance in Exhibit 7-1 as well?

Ideally, intersections and railroad crossings should be grade separated or provided with adequate sight distance. Intersections should be placed in sag and/or tangent locations, where practical, to allow maximum visibility of the roadway and pavement markings. [p. 445]

What constitutes adequate sight distance; stopping or decision? Placing intersections in sag curve locations could especially pose problems for large trucks if they are required to stop at an intersection (i.e., if the intersection is signalized or stop-controlled) or make a required crash avoidance maneuver. Intersections in sag or crest curve locations should be avoided. Also, horizontal curvature has been shown to be detrimental to intersection safety when present in the vicinity of expressway intersections. Instead of stating, "Intersections should be placed in tangent locations, where practical" the statement should say that intersections should not be placed in the vicinity of horizontal curves. Further research is necessary to determine where an intersection can be safely placed relative to horizontal curvature (i.e., what constitutes a "safe" distance from a horizontal curve? The term vicinity needs to be more specifically defined).

Exhibit 7-2 presents recommended maximum grades for rural arterials. When vertical curves for stopping sight distance are considered, there are seldom advantages to using the maximum grade values except when grades are long. [p. 446]

The number of lanes on an arterial roadway should be determined based on consideration of volume, level-of-service, and capacity conditions. [p. 446]

The logical approach to determining appropriate lane and shoulder widths is to provide a width related to the traffic demands. Exhibit 7-3 provides values for the width of traveled way and usable shoulder that should be considered for the volumes indicated. [p. 448]

The right-of-way should be wide enough to accommodate all of the cross-sectional elements throughout the project. Local conditions such as drainage and snow storage should be considered in determining right-of-way widths. Where additional lanes may be needed in the future, the initial right-of-way width should be adequate to provide the wider roadway section. It may be desirable to construct the initial two lanes off center within the right-of-way, so the future construction will cause less interference with traffic and the investment in initial grading and surfacing can be salvaged. [p. 449]

This discussion of right-of-way is basically repeated in the next section on the ultimate development of four-lane divided arterials and could possibly be removed.

ULTIMATE DEVELOPMENT OF FOUR-LANE DIVIDED ARTERIALS:

There are numerous instances, particularly near urban areas, where two-lane arterials will require ultimate development to a higher type arterial to handle the expected traffic. Where it is anticipated that the DHV for the design year will be in excess of the service volume of the two-lane arterial for its desired level of service, the initial improvement should be patterned to the ultimate development of a four-lane divided arterial and provision made for acquisition of the needed right-of-way. The eventual need for additional lanes should be considered during the design of a two-lane arterial. Even where right-of-way is restricted, some form of separator should be used in the ultimate facility, with a median at least 1.2 m [4 ft] wide and preferably much wider. [p. 450, 451]

This section discusses the ultimate development of a four-lane divided arterial from a two-lane highway. However, it does not specify whether the four-lane arterial is an expressway (partially access-controlled) or a freeway (fully access-controlled). Perhaps this section should be entitled "Ultimate Development of a Freeway" and the process of upgrading a two-lane highway to an expressway and ultimately to a freeway (if necessary) be described. The Illinois DOT designs expressways as an intermediate step in the ultimate development of freeways and has specific volume warrants to identify when to start planning for the next level of intersection design.

The Green Book philosophy (described in the quote above) for planning the design of a facility around the design volume assumes that the facility will be able to provide and sustain a desired level of service over its life. This may hold true for the corridor, but not for the at-grade intersections if the facility is an expressway. Rural expressways typically outlast their at-grade intersections. Four-legged, two-way stop-controlled, rural expressway intersections may initially operate at an

acceptable level of service and safety when cross road traffic volumes are at a low level (e.g., 400 vpd); however, safety and operational performance may deteriorate when the cross road traffic volumes increase to higher levels. Illinois has recognized that although the mainline may be able to sustain design volumes over the course of its life cycle, the at-grade intersections have shorter life spans that need to be taken into account during the corridor planning process. This section of the Green Book does not address planning for intersection modifications that may be required before the end of the design or functional life of the expressway. Ultimately there should be some guidance on traffic volumes and land use attributes that individual agencies can use as triggers for implementing improved intersection designs. Guidance is also needed in determining what intersection design treatments/levels are effective and appropriate to use prior to constructing costly grade separations/interchanges.

The majority of state DOTs consider interchanges as a corrective measure for at-grade expressway intersections with high crash rates and convert at-grade intersections to interchanges on a case-by-case basis. A 1992 study conducted by Bonneson and McCoy (1) for the Nebraska Department of Roads showed that a diamond interchange is generally warranted when expressway volumes exceed 4000 vpd and minor road approach volumes exceed 4000 vpd. The inherent problem with this approach is that it will lead to a facility with a mix of at-grade intersections and interchanges, which plays with driver expectancies. Uniformity in highway design features plays an important role in making the driver aware of what to expect on a certain type of highway. Therefore, a few state DOTs do not build new rural expressways. Instead, they design all new rural divided arterials as freeways and upgrade their current expressways to freeways on a corridor basis. In addition to design consistency, freeways provide improved safety, up-front dedication of right-of-way, and surplus capacity for future traffic growth.

(1) Bonneson, J.A. & McCoy, P.T., *Interchange versus At-Grade Intersection on Rural Expressways: Final Report*, Nebraska Department of Roads Project No. RES1(0099) P453, University of Nebraska-Lincoln, May 1992.

In the ultimate development of a four-lane divided arterial, the initial two-lane roadway should be constructed so that it can eventually form one of the two-lane, one-way roadways. The advantages of this approach over building the initial two lanes in the center of the right-of-way are as follows: [p. 451]

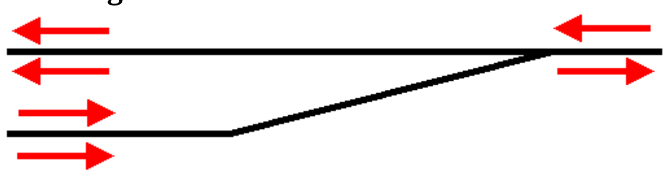
1) *There is no loss of investment in existing surfacing and in highway and railroad overcrossings when the second roadway is constructed.*
2) *This approach allows grading of the entire roadway and/or the construction of undercrossings and overcrossings to accommodate the ultimate improvement when a decision to do so is warranted. The economics of such a decision need to be carefully considered, as do the benefits associated with minimization of future impacts. If the entire roadway is graded initially, traffic will be subjected to little restriction or delay when the additional two-lane surfacing is constructed. The two-lane surfacing originally constructed continues in use as a two-way highway,*

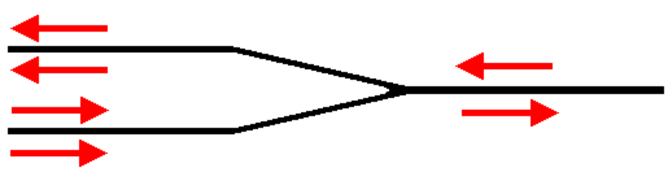
no detours are needed, and contact with construction operations is restricted to intersections and turnouts on one side. If the decision is to construct undercrossings and overcrossings, similar benefits also occur.

This approach also allows the alignments of the two one-way roadways to be readily coordinated, which is especially important in the vicinity of at-grade intersections to prevent intersection sight distance restrictions created when the separate one-way roadways have independent profiles.

3) *It is often desirable to initially acquire sufficient right-of-way for the ultimate development, including that required for future intersection improvements and grade separations. The economics of such a decision are important to consider, but the preservation of the right-of-way for the ultimate improvement is typically the compelling factor. Increase in land value, particularly after the construction or improvement of the arterial may more than offset the investment in additional right-of-way.*
4) *Later adjustment of minor road structures and plant growth are reduced to a minimum. When the entire grade for the ultimate four-lane divided arterial is constructed initially, all structures such as drains and culverts usually are completed and remain undisturbed when the final two lanes are added. If grading for only one of the two-lane roadways is economically advisable, road structures may be completed on one side, and temporary headwalls and open drains may be provided on the side where additional lanes will be placed later.*
5) *By grading the entire roadway for four lanes, future impacts to wetlands created by roadside ditches and recharge basins are avoided.*

Another advantage of this approach includes the construction of a single taper (as shown in the top figure below) to transition from a two-lane section to a four-lane divided section rather than using a splitting taper design (as shown in the bottom figure below). The single taper is easier to construct and relocate as the second set of lanes is being constructed.





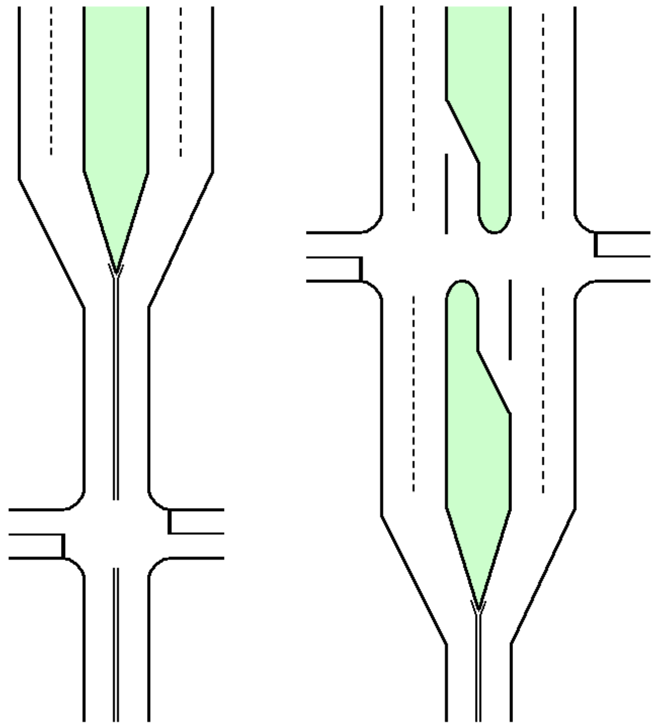
Where divided highway transitions (DHTs) like those shown above occur, care should be taken to place the transition as far as practical from nearby intersections. It is often convenient to place a DHT near an intersection. The need

for a DHT is often due to a drop in traffic volume along the divided highway such that the four-lane section is no longer justified. This situation typically arises where a rural divided highway intersects a joining state highway. The desire for placing a DHT near an intersection may also arise out of administrative convenience for defining job descriptions when a rural two-lane highway is being converted to an expressway in a piecewise manner over multiple construction seasons. The piecewise project ends typically terminate at intersections or county lines where intersections exist. If project funding doesn't come through or if other projects take priority, these DHTs may remain in place for much longer than expected.

Where DHTs are placed near intersections, operational and safety problems may occur. Unfamiliar motorists may not be expecting this complex situation and in general, a high crash frequency can be expected. Drivers need more time, space, and visibility to safely transition from high-speed, multi-lane divided operations that they have been conditioned to for several miles to two-lane undivided conditions. The driving task becomes even more complicated when a DHT is combined with an intersection, especially if the through roadway alignment is not clearly visible or if significant reverse curvature is required to make the DHT fit the through roadway's horizontal alignment and/or the intersection's geometrics. To further complicate the situation, traffic warning signs for the DHT will overlap the intersecting roadway's guide signing. Unfortunately, DHTs combined with intersections currently exist on rural highways.

If one must be constructed, throughout the DHT, the design speed should remain consistent, paved shoulders should be maintained, visibility should be maximized by providing decision sight distance, and only natural flowing alignment of 3^{o} or less should be used (2). Also, the intersection should be placed on the undivided two-lane portion (as shown at left below) rather than on the divided four-lane portion (as shown at right below). For the case on the right with travel from the undivided to the divided portion, it follows that the intersection's turning traffic will be slowing while the through traffic will be trying to accelerate to the divided highway speed, creating a large speed differential between vehicles and a high conflict potential. Also, vehicles may be weaving in the transition area, especially if caught behind a large truck, creating a dangerous situation. Imagine a queue of vehicles has built up behind a truck on the two-lane undivided portion. As soon as these vehicles reach the transition area, they are going to weave around the truck and begin to accelerate to the divided highway speed. Now imagine a vehicle sitting at the intersection attempts to cross or turn left because the driver feels he or she can beat the truck and does not see the weaving vehicle(s) coming around the truck. Hence, a severe right-angle collision may occur.

For the case on the right with travel from the divided to the undivided portion, a queue in the merge area may build up and create a queue through the intersection, thus interfering with intersection operations.



2) Messer, C.J., Mounce, J.M., & Brackett, R.Q., *Highway Geometric Design Consistency Related to Driver Expectancy, Vol. III: Procedures for Determining Geometric Design Consistency*, Report No. FHWA-RD-81-037, Federal Highway Administration, Washington, D.C., April 1981.

Care should be exercised, however, to ensure that an appropriate clear zone is provided in the initial stage. A similar procedure may be adopted for topsoiling, seeding, planting, and any other work that is done to prevent soil erosion, the value of which increases with time. [p. 451]

When upgrading to an expressway facility, careful consideration of intersection placement in regard to horizontal/vertical alignment and skew should also be exercised. Placing expressway intersections in tangent, flat areas on the mainline as well as at 90^{o} to the mainline is ideal for safe intersection operation. On expressways, intersection operations play a large part in the facility's overall operation and safety.

Two lane arterials planned for ultimate conversion to a divided arterial usually have sufficient volume initially to warrant a traveled way of 7.2 m [24 ft] wide and usable shoulders, 2.4 m [8 ft] wide, as shown in Exhibit 7-5A. These traveled way and shoulder dimensions are commensurate with those recommended for four-lane divided arterials, as discussed later in this chapter. Where an arterial will ultimately be developed to a four-lane divided arterial with a wide median and the initial roadway is offset to one side of the right-of-way centerline, the roadway generally is crowned to drain both ways. Ultimately, the wide median is depressed to be self-draining and may receive surface runoff from one-half of *each roadway (Exhibit 7-5B). Grading for the future development generally is deferred when the median is wide.* [p. 452]

How wide does a median have to be for it to be considered wide?

Where the right-of-way for the future four-lane arterial is restricted, a narrow median, which should be not less than 1.2 m [4 ft] wide, may need to be used. If provision of a median barrier is anticipated for the ultimate improvement, space for a wider median should be provided to accommodate the width of the barrier plus the appropriate clearance between the edge of the traveled way and the face of the barrier. As in the case of a wide median, the initial two-lane construction should be offset so that the ultimate development is centered on the right-of-way. To economize on the cost of drainage structures and to simplify construction, the initial and future two-lane roadways may be positioned to drain to the outside (Exhibit 7-5C). Future grading may or may not be deferred, depending on local conditions and on the probable length of time to the full development. [p. 452]

On most two-lane arterials constructed many years ago, no provision was made for future improvement to a higher roadway type. In such instances, where practical, a new two-lane, one-way roadway should be provided approximately parallel to the first, which is then converted to one-way operation to form a divided arterial. [p. 452]

The new two-lane, one-way, parallel roadway's alignment should be coordinated (i.e., at the same elevation as the first), if practical, to prevent intersection sight distance restrictions.

Where there is adjacent development, it may be more practical to construct another one-way, two-lane roadway nearby without disturbing the existing development. This method also may be advantageous where topography is not favorable to direct widening of the existing roadway section. If this construction cannot be accomplished, it may be practical to obtain a divided section by widening 4.2 m [14 ft] on each side of the existing roadway (Exhibit 7-5D). When none of these methods is practical, it may be necessary to find a new location. The old road then becomes a local facility and may also serve as an alternate route. From the standpoint of adequacy and service provided to through traffic, the last method is preferred because the arterial on a new location will not be influenced by the old facility and can be built to modern design criteria, preferably with some control of access. [p. 452]

For roadways that will ultimately be developed with narrow medians (Exhibits 7-5C and 7-5D), all of the cross sections shown have minimum combined widths of roadways and median of 20 m [70 ft]. About 3.6 m [12 ft] or more of additional width should be obtained so that median lanes for left turns may be provided at intersections. [p. 452]

DIVIDED ARTERIALS (*RURAL*):

General Features:

> *The width of the median may vary and is governed largely by the type of area, character of terrain, intersection treatment, and economics. An arterial is not normally considered to be divided unless two full lanes are provided in each direction of travel and the median has a width of 1.2 m [4 ft] or more and is constructed or marked in a manner to preclude its use by moving vehicles except in emergencies or for left-turns.* [p. 454]

An arterial is not considered divided unless the median is marked in a manner to preclude its use by moving vehicles except in emergencies or for left-turns? What about crossing maneuvers from a cross road at an intersection? The way this is currently worded, a divided arterial would not allow crossing maneuvers at a cross road!

> *A four-lane rural facility should have adequate median width to provide for protected left turns, which is a very important safety consideration. For example, vehicles making left turns should not be required to stop in the passing lane of a roadway designed for high volumes and speeds.* [p. 454]

At first read, a protected left turn may be interpreted only as a left-turn off the mainline, indicating a minimum median width required to install a left-turn bay on the mainline. This statement should be clarified. A protected left-turn also includes a vehicle making a left-turn from a cross road that can safely stop in the median without encroaching on the through lanes of the divided arterial. If the minor road driver is provided with this median refuge, he or she can make the desired left-turn or crossing maneuver in two steps while watching traffic coming from one direction at a time rather than trying to make a single, much more complex maneuver. This maneuver is the critical maneuver in determining the minimum median width because it requires a wider median.

> *Where median lanes for left turns are provided, rear-end collisions and other inconveniences* **[delay]** *to through traffic resulting from left-turn movements are greatly reduced.* [p. 454]

I'm sure this statement is only referring to median lanes for left-turn deceleration, but it could be interpreted as a statement indicating the benefits of left-turn median acceleration lanes (MALs) as well.

> *Where the median is wide enough, crossing and left-turning vehicles can slow down or stop between the one-way roadways to take advantage of breaks in traffic and cross when it is safe to do so.* [p. 454]

As stated earlier, the minimum median width on expressways should allow this condition. Driver education efforts should teach drivers that this is the way to

properly navigate a divided highway intersection. Median centerlines, stop-bars, and yield signs may help communicate this to the minor road drivers.

Headlight glare is reduced somewhat by narrow medians but can almost be eliminated by wide medians or glare screens on a median barrier. [p. 455]

<u>Lane Widths:</u>

Roadways on divided arterials should be designed with lanes 3.6 m [12 ft] wide. On reconstructed arterials, it may be acceptable to retain 3.3 m [11 ft] lanes if the alignment and safety record are satisfactory. [p. 455]

<u>Cross Slope:</u>

Each roadway of a divided arterial may be sloped to drain to both edges, or each roadway may be sloped to drain to its outer edge, depending on climatic conditions and the width of median. Roadways on divided arterials should have a normal cross slope of 1.5 to 2 percent. Traveled ways with unidirectional slope may have the outer lane on a steeper slope than the inner lane. On an auxiliary lane, the cross slope should not normally exceed 3 percent on tangent alignment. In no case should the cross slope of an outer and/or auxiliary lane be less than the adjacent lane. [p. 455]

<u>Shoulders:</u>

Arterials with sufficient traffic volume to justify the construction of four lanes also justify the provision of full-width shoulders. The width of usable outside shoulders should be at least 2.4 m [8 ft] and be usable during all seasons. Paving of the usable width of shoulder is preferred. The normal roadway section, including usable shoulders, should be extended across all structures except for long bridges (over 60 m [200 ft] in length, which may have 1.2 m [4 ft] shoulders). [p. 455]

Shoulder space on the left side of the individual roadways of a four-lane divided arterial (i.e., within the median) is not intended to serve the same purpose as the right shoulder. The shoulder on the right, through customary use on undivided arterials, is accepted by all drivers as a suitable refuge space for stops. Where the median is flush with the roadway or has sloping curbs, vehicles may encroach or drive on it momentarily when forced to do so to avoid a crash. Only on rare occasions should drivers need to use the median for deliberate stops. On divided arterials with two lanes in each direction, a paved shoulder strip 1.2 m [4 ft] wide should satisfy the needs for a shoulder within the median. Such a shoulder strip will preclude rutting at the edge-of-traveled way and will alleviate possible loss of driver control of vehicles that inadvertently encroach on the median. On divided arterials with three or more lanes in each direction, a driver in distress in the lane nearest the median may have difficulty maneuvering to the right-hand shoulder. Consequently, a full-width shoulder within the median is desirable on divided arterials having six or more lanes. In cases where a wall or median barrier is used in the median, the AASHTO Roadside Design Guide should be *consulted for guidance in selecting an appropriate lateral clearance from the normal edge of the traveled way to the base of the wall or barrier and the type of barrier to be used.* [p. 455, 456]

Medians:

Where intersections are to be provided, special concern should be given to median width. NCHRP Report 375 has found that most types of undesirable driving behavior in the median areas of divided highway intersections are associated with competition for space by vehicles traveling through the median in the same direction. The potential for such problems is limited where crossroad and U-turn volumes are low, but may increase at higher volumes. Types of undesirable driving behavior observed include side-by-side queuing, angle stopping, and encroaching on the through lanes of a divided highway. At rural unsignalized intersections, the frequency of undesirable driving behavior and crashes was observed to decrease as the median width increased; this implies that medians should be as wide as practical. It was also found that the frequency of undesirable driving behavior increased as the median opening length increased. [p. 456]

Side-by-side queuing and angle stopping might also be reduced by providing a median centerline.

While medians as narrow as 1.2 to 1.8 m [4 to 6 ft] may be used under very restricted conditions, medians 3.6 to 9 m [12 to 30 ft] wide provide protection for left-turning vehicles at intersections. Medians of 1.2 to 2.4 m [4 to 8 ft] wide should be avoided, if practical, where left turns are common. Such widths do not provide sufficient space for turning vehicles and may encourage other motorists to encroach into the adjacent lane when attempting to pass a turning vehicle that is only partially in the median. [p. 456]

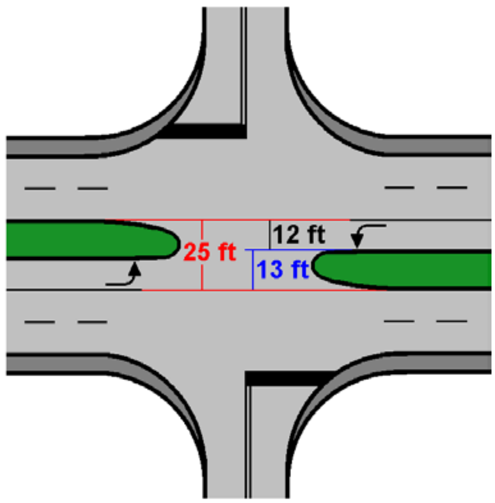
Medians 3.6 m [12 ft] wide only provide protection for vehicles turning left from the mainline at intersections and do not provide protection for vehicles turning left or crossing from a minor cross road. Such widths also may encourage motorists to encroach into the adjacent lane when attempting to go around a cross road vehicle that is only partially in the median.

In many cases, the median width at rural unsignalized intersections is a function of the design vehicle selected for turning and crossing maneuvers. [p. 456]

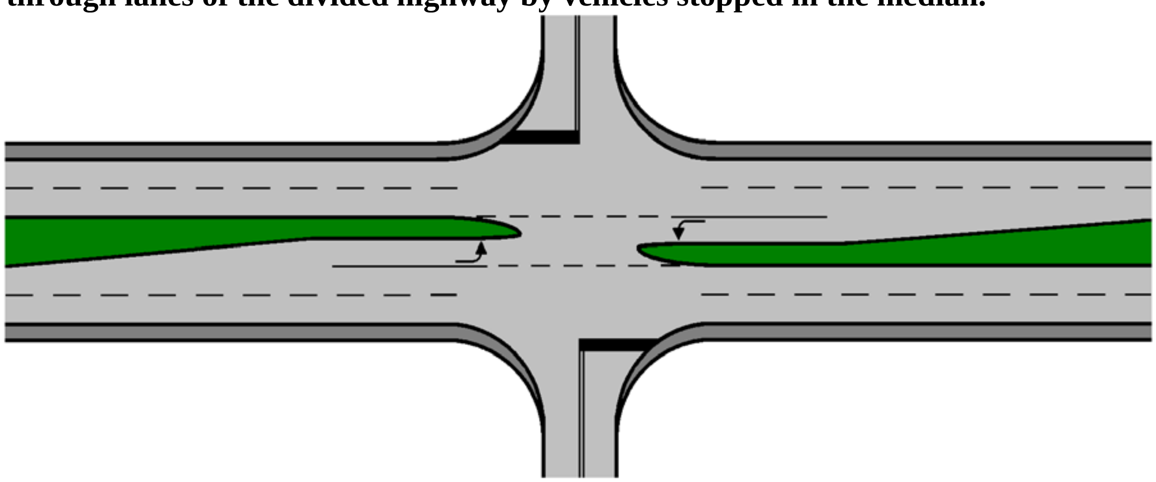
Adequate median storage for the design (crossing or turning) vehicle from the minor road should be the design minimum.

Where a median width of 7.5 m [25 ft] or more is provided, a passenger car making a turning or crossing maneuver will have space to stop safely in the median area. Medians less than 7.5 m [25 ft] wide should be avoided at rural intersections because drivers may be tempted to stop in the median with part of their vehicles unprotected from through traffic. [p. 456, 457]

What if mainline left-turn bays are provided? Consider a four-legged intersection with traditional 3.6 m [12 ft] wide left-turn bays on each mainline approach. If the total median width is 7.5 m [25 ft] there is technically room to store a 5.8 m [19 ft] passenger car. However, to the cross road driver waiting to cross or turn left, it may appear that there is only a 3.9 m [13 ft] storage area which would not be enough. Thus, the driver may try to cross or turn left in a single maneuver. In this case, placing a median centerline and stop-bars would not be appropriate. With this traditional left-turn bay design, an 11.1 m [37 ft] median width would be the minimum width required to place a median centerline and stop-bars for use by passenger cars. However, if mainline offset left-turn bays are provided, this discussion could change depending on the type of offset left-turn bays provided.



Extending the left edge-lines of the divided highway across the median may also help define the boundary of the median roadway and help the minor road driver judge the available storage space within the median and minimize the chances of encroachment on the through lanes of the divided highway by vehicles stopped in the median.



The school bus is often the largest vehicle to use the median roadway frequently. The selection of a school bus as the design vehicle results in a median width of 15 m [50 ft]. [p. 457]

A conventional school bus is 10.9 m [35.8 ft] long. A large school bus is 12.2 m [40 ft] long. How did they come up with a minimum 15 m [50 ft] median width? Using the same rational they used to get a minimum 7.5 m [25 ft] median width for a 5.8 m [19 ft] passenger car (i.e., a 0.85 m [3 ft] clearance), the median widths for conventional and large school buses should be 12.6 m [41.8 ft] and 13.9 m [46 ft], respectively. My guess is that a minimum 15 m [50 ft] median width is stated because it is adequate (rounded up) for either school bus type and is an integer of 7.5 m [25 ft] so that it will also hold multiple passenger cars. However, how the 15 m [50 ft] minimum median width for a bus was determined should be stated in the Green Book.

With traditional 3.6 m [12 ft] wide mainline left-turn lanes present, a four-legged intersection would need an minimum median width of 16.2 m [53.8 ft] and 17.5 m [58 ft] to adequately store a conventional and large school bus, respectively.

Larger design vehicles, including trucks, may be used at intersections where enough turning or crossing trucks are present; median widths of 25 m [80 ft] or more may be needed to accommodate large tractor-trailer trucks without encroaching on the through lanes of a major road. [p. 457]

If there is a large percentage of minor road left-turning trucks, but a low percentage of minor road crossing trucks, left-turn median acceleration lanes (MALs) can be used at divided highway intersections to minimize the required minimum median width because left-turning trucks can use the MAL as median storage.

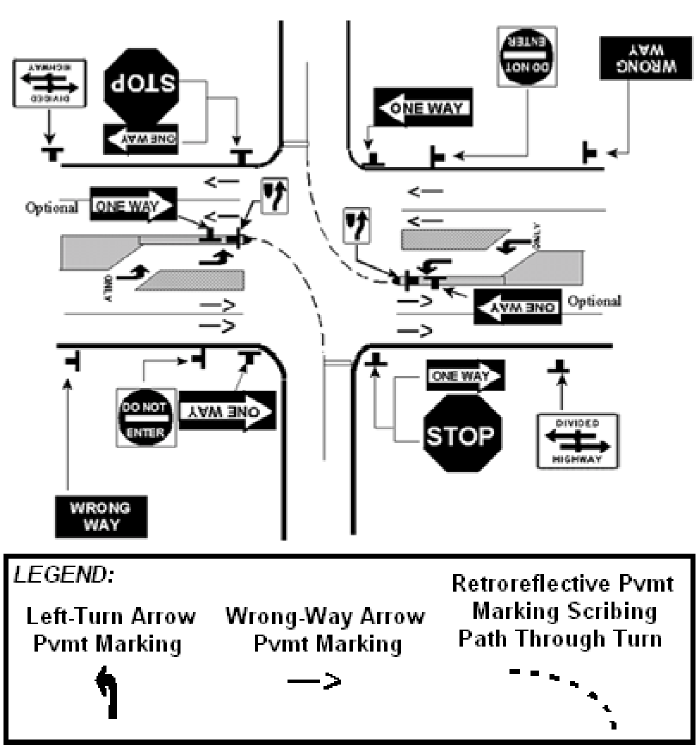
There was concern that median widths in the range of 15 to 25 m [50 to 80 ft] at divided highway intersections could cause some drivers to become confused. No evidence of such confusion at rural intersections has been found. However, an intersection with a wider median may become confusing to some drivers if the median is so wide that a driver on the crossroad approach cannot see the far roadway of the divided highway. Such designs should be avoided and, where they are used, signing should be provided to discourage wrong-way movements. [p.457]

Why wouldn't medians of greater than 25 m [80 ft] be of concern as far as causing driver confusion when the wider the median is, the more trouble a driver would have seeing the far roadway?

The statement "No evidence of such confusion at rural intersections has been found" is referenced to NCHRP 375; however, NCHRP 375 did not study this issue in great detail; therefore, I feel this statement should be removed.

Earlier the Green Book stated that medians at rural unsignalized intersections should be as wide as practical. The statement here is that extremely wide medians should be avoided. At what median width does as wide as practical become should be avoided?

Where these designs are used, intersection lighting should also be provided to help discourage wrong-way movements. In 1997, Staplin et al., (3) recommended the use of wrong-way arrow pavement markers and left-turn pavement marking extensions where offset left-turn bays are used in order to prevent wrong-way entry as shown below.



(3) Staplin, L., Harkey, D.L., Lococo, K.H., & Tarawneh, M.S., *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Vol. I: Final Report*, Report No. FHWA-RD-96-132, Federal Highway Administration, McLean, VA, June 1997.

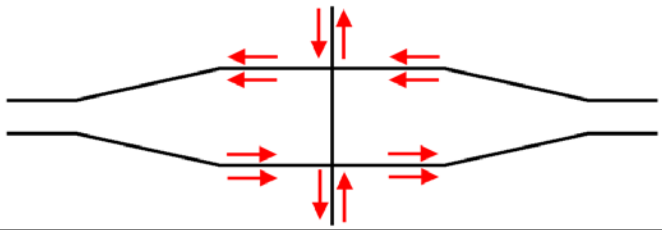
Median widths of more than 18 m [60 ft] are undesirable at intersections that are signalized or may need signalization in the foreseeable future. The efficiency of signal operations decreases as the median width increases, because drivers need more time to traverse the median and special detectors may be needed to avoid trapping drivers in the median at the end of the green phase for traffic movements that pass through the median. Furthermore, if the median is so wide that separate signals are needed on the two roadways of the divided highway, delays to motorists will increase substantially and careful attention should be given to vehicle storage needs on the median roadway between the two signals. Because wider medians at intersections on urban arterials may increase crashes and lead to undesirable driving behavior, consideration should be given to limiting use of wider medians at rural intersections that are likely to undergo urban or suburban development in the foreseeable future. [p. 457]

Undesirable driving behavior at rural unsignalized intersections increases as the median opening length increases. The median opening length should be equal to at least that described in Chapter 9, but median openings at rural unsignalized intersections should not be unnecessarily long. [p.457]

Alignment and Profile:

A divided arterial generally serves high-volume and high-speed traffic for which a smooth flowing alignment should be provided. Because a divided arterial consists of two *separated roadways, there may be instances where median widths and roadway elevations can be varied. Special topographic or intersection considerations may necessitate such treatments for economic or operational reasons. Precaution should be taken that such variations do not adversely affect operations. Potential problems associated with sharp reverse curves, headlight glare, roadside design, and grades of intersection crossings should be considered.* [p. 457/458]

In order to preserve intersection sight distance, roadway elevations of the two divided roadways should not be varied in the vicinity of intersections. However, varying median width in the vicinity of intersections (as shown below) may help draw the expressway driver's attention to the upcoming intersection and may help the minor road driver safely navigate the intersection (select safe gaps). The tangent legs of the expressway extending from the intersection could be made long enough so that if an expressway vehicle is in this area, the minor road driver should know not to proceed. Conversely, the median width could be narrowed in the vicinity of the intersection, but since unsignalized rural expressway intersections have been found to operate better with wider medians, this is not shown here.



With two or more lanes for travel in each direction, the profile grade is generally governed by stopping sight distance, except at intersections. For volumes well below capacity, grades may be steeper and longer on multilane highways than on two-lane arterials, because there is a continuous lane for passing of heavy, slow vehicles on upgrades. [p. 458]

What governs the profile grade at intersections? The answer is in Chapter 9, so a statement like, "For intersections, see Chapter 9" should be provided here.

<u>Superelevated Cross Sections:</u>

A divided arterial on a curve should be superelevated to ensure safe traffic operation, pleasing appearance, and economy. Care should be taken in the superelevation transition to fit site conditions and to meet controls of intersection design. [p. 459]

Intersections should NOT be placed on or near horizontal curves. The distance from a horizontal curve at which an intersection can be safely placed needs to be determined through research.

General methods of attaining superelevated cross sections for divided arterials are discussed in Chapter 3 (see Exhibit 3-40). In the design of arterials, the inclusion of a median in the cross section alters the manner in which superelevation is attained. Depending on the width of median and its cross section, there are three general cases for attaining superelevation:

Case I *– The whole of the traveled way, including the median, is superelevated as a plane section. Case I should necessarily be limited to narrow medians and moderate superelevation rates to avoid substantial differences in elevation of the extreme edges of the traveled way arising from the median tilt. Specifically, Case I should be applied only to median with widths of 4.5 m [15 ft] or less.* [p. 459]

Case II *– The median is held in a horizontal plane and the two traveled ways are rotated separately around their median edges. Case II can apply to any width of median, but is most appropriate for medians with widths between 4 and 18 m [15 and 60 ft]. By holding the median edges level, the difference in elevation between the extreme traveled way edges can be limited to that needed to superelevate the roadway. Superelevation transition design for Case II usually has the median-edge profiles as the control. One traveled way is rotated about its lower edge and the other about its higher edge.* [p. 459]

Case III *– The two traveled ways are treated separately for superelevation with a resulting variable difference in elevation at the median edges. Case III design can be used on wide medians (i.e., those with widths of 18 m [60 ft] or more). For this case, the difference in elevation of the extreme edges of the traveled way is minimized by a compensating slope across the median. With a wide median, it is possible to design the profiles and superelevation transition separately for the two roadways.* [p. 459]

Exhibit 7-6 demonstrates treatment of cross sections for narrow and wide medians with superelevated roadway in relation to the width of median for the three cases noted. [p. 459]

I personally do not like the way the rest of this section, "Superelevated Cross Sections" (pp. 459 – 462) is written. Following the basic descriptions of the three cases for attaining superelevation, further details are given for each case in reference to Exhibit 7-6. However, much of the text could be removed by simply referencing case numbers (I, II, or III) during the discussion. In Exhibit 7-6, cross sections A and D represent Case I, cross sections B and E represent Case II, and cross sections C and F represent Case III; however this is never really stated.

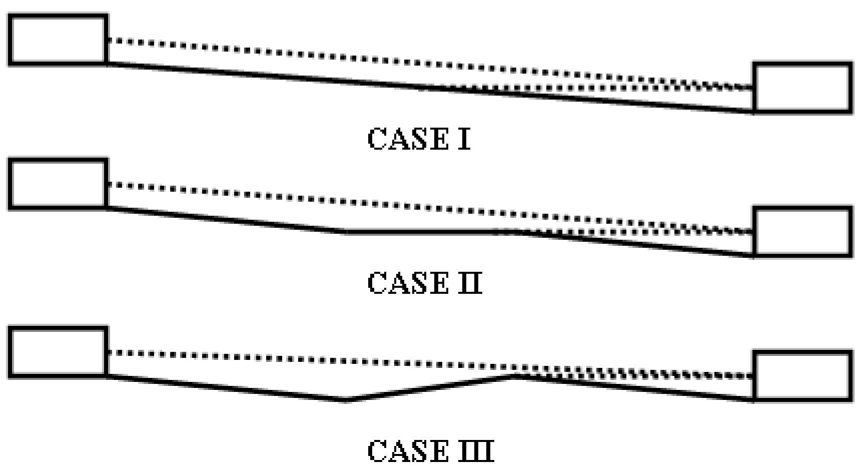
Where cross section A of Exhibit 7-6 is used, the median should be designed so that surface water from the higher roadway does not drain across the lower roadway. On tangent alignment, a shallow drainage swale can be provided in a median about 4.5 m [15 ft] wide and a well-rounded drainage channel with a **(median)** *width of about 18 m [60 ft] as shown in Exhibit 7-7F. On a superelevated section rotated about the median centerline, as in Cross Section A of Exhibit 7-6, approximately 9 m [30 ft] of median width is needed for a rounded drainage channel and adequate left shoulders. In a median less than 9 m [30 ft] wide, a channel with flat sideslopes can be provided if the superelevation rate is small, or a paved channel can be used in conjunction with higher rates of superelevation.* [p. 460]

The basic description of Case I states, "Case I should be applied only to medians with widths of 4.5 m [15 ft] or less." Why then is the discussion of wider median widths in conjunction with this cross section necessary? I suppose this is because this recommendation is not always followed. If it isn't, then the preceding info could be useful

to designers; however, the recommendation to use Case I with narrow medians should be reinforced.

The projection of superelevation across wide medians may be fitting in some instances as in Cross Section A of Exhibit 7-6, but its general use in conjunction with large rates of superelevation is not satisfactory in appearance and generally not economical. It may fit at highway intersections where the profile of the intersecting road approximates the superelevated slope. Occasionally, it may fit the natural slope of the terrain. However, unless these conditions prevail, the large difference in elevation between the outer shoulder edges is likely to be objectionable. For example, the difference in elevation between the outer shoulder edges of a four-lane divided arterial with a median of 12 m [40 ft] and a superelevation rate of 8 percent is about 2.4 m [8 ft]. [p. 460]

This paragraph indicates that Case I CAN be used in conjunction with wide medians (> 4.5 m [15 ft]) at intersections where the intersecting roadway's profile matches the superelevated slope. The large difference in elevation between vehicles on opposite approaches of the minor road may be a concern (another reason why horizontal curves and intersections don't mix), but this may actually be the best method of superelevation at any intersection with median pavement markings so that the minor road driver on the low side can adequately see the markings. This cross section (Case I) may also help minor road drivers recognize the divided highway and prevent wrong-way entry. Which superelevated cross section is best for intersection safety and operations?



In level terrain and in terrain where the natural slope of the land is adverse to the cross-sectional slope, substantial improvement in appearance and economy in earthwork results if the wide median is made level as in Cross Section B of Exhibit 7-6 **(Case II)***, or sloped opposite to the superelevation plane as in Cross Section C* **(Case III)**. [p. 460]

Superelevation runoff lengths may vary for each of the three cases (refer to Exhibit 3-32). [p. 460]

In Cross Sections B and E of Exhibit 7-6 **(Case II)***, the edges of roadways on the median sides are at the same elevation. Designs on this basis are pleasing in appearance and generally are desirable for safe operation. With a wide separation between the one-way* *roadways, Cross Section B* **(Case II)** *has considerable advantage over Cross Section A* **(Case I)** *in reducing the difference in elevation across the entire roadbed. On roadways having a superelevation rate near 10 percent, the treatment in Cross Section B* **(Case II)** *requires a minimum median width of about 9 m [30 ft] to provide fully effective shoulder areas and a well-rounded traversable swale.* [p. 460]

In Cross Sections C and F of Exhibit 7-6 **(Case III)***, the two one-way roadways have a common centerline grade. The difference in elevation of the outer extremities of the superelevated roadways is minimal, being the product of the superelevation rate and the width of one of the one-way roadways. With a wide median, the treatment of Cross Section C of Exhibit 7-6* **(Case III)** *allows the desired appearance to be maintained and permits economy in the wide-graded cross section. The roadway as a whole will appear fairly level to the motorist, who will not readily perceive the difference in elevation of the inside edges of roadway. This cross section generally is not suitable for important at-grade intersections unless the median is very wide. The median should be sufficiently wide in relation to superelevation to afford a smooth S-shaped profile across its width. About 12 m [40 ft] is needed, with a superelevation rate of 10 percent and adequate shoulder areas. This width can be reduced to about 9 m [30 ft] when a paved channel is provided.* [p. 461]

With cross section C, will the median roadway appear fairly level to the cross road motorist at an intersection? Will the cross road driver readily perceive the difference in elevation between the inside edges of the median roadway?

On a divided arterial with variable width of median and difference in elevation between the two roadways, each roadway is designed with a separate profile. With a reasonably wide median, each roadway can be superelevated in any manner suitable for a single roadway with little effect on the median slope.
[p. 461]

As previously mentioned, it is not a good idea to vary the elevations of the two one-way roadways making up the divided arterial in the vicinity of at-grade intersections unless the median is very wide.

Exhibit 7-7 shows various median configurations that may be used on rural arterials, excepting Configurations C, D, and E, which are more appropriate for urban situations as described later in this chapter. [p. 461, 462]

In reference to this figure, the Green Book later states the following:

Exhibit 7-7 shows some sections with curbs **(Configurations C, D, and E)***, which are generally not recommended along rural roadways. Sloping curbs may be used in restricted areas where needed to control drainage, or where special treatment is needed at locations such as intersections.* [p. 463]

This entire statement regarding Exhibit 7-7 (both parts) should be combined within the next section, "Cross Section and Right-of-Way Widths" rather than having a part of it in the "Superelevated Cross Sections" section where it seems out of place.

<u>Cross Section and Right-of-Way Widths:</u>

The appropriate right-of-way widths **(layouts)**, *including all elements in a composite arterial cross section, are presented in Exhibit 7-8.* [p. 462]

Exhibit 7-8 does not provide actual dimensions. It just shows three different cross-sectional arrangements for divided arterials.

In an ideal situation, the topography, other physical constraints, and economic feasibility permit the design of a well balanced cross section of desirable dimensions for which an adequate width of right-of-way is established and procured. On the other hand, the constraints may be so tight that if a divided arterial is to be provided at all, it should be designed within a limited width of right-of-way, using minimum or near minimum dimensions for each element of the arterial cross section. In the first instance, the right-of-way is based on the most favorable design criteria for the cross-sectional elements; in the latter case, the cross section is determined on the basis of the available width of right-of-way. [p. 462, 463]

If the right-of-way is restricted, the border area or median width, rather than the lane or shoulder width, should be reduced. The extent to which the border area and/or median width is reduced respectively should be decided carefully. Consideration should be given to achieving approximately the same clear-zone width for both the median and roadside. [p. 463]

Exhibit 7-8C shows a desirable divided arterial cross section warranted for a high-type facility where liberal width of right-of-way is attainable. Where these wider widths cannot be obtained, attempts should be made to provide a right-of-way width that permits the use of a median 9 m [30 ft] or more and sufficient borders to provide for the needed clear zone. Sometimes, the right-of-way may be so restricted that minimum or near minimum widths of cross-sectional elements must be used. If at all practical, the right-of-way should be wide enough to permit the use of median and borders of not less than 4.5 m [15 ft] (see Exhibit 7-8A). A 4.5 m [15 ft] median is near the minimum median width within which a median lane can be provided at intersections. [p. 463]

The cross sections and right-of-way widths shown in Exhibit 7-8 pertain to four-lane facilities. Where provision is to be made for ultimate conversion to a six or eight lane facility, the right-of-way widths should be increased by the width of lanes to be added. It is preferable to include this additional width in the median. [p. 463]

The above statement should be located in the section, "Ultimate Development of Four-Lane Divided Arterials" if that section is changed to "Ultimate Development of a Freeway." A lot of the material in this section could and maybe should be moved to that section as well.

The right-of-way width need not be uniform and may be varied along the course of the arterial as needed for grading, for safe roadside design, and other conditions. Where controls become rigid, the two roadways may have to be brought closer together. Where physical conditions are favorable and land is readily available, the roadways of a divided *highway may be spread farther apart. Where future grade separations and ramps are envisioned, provision for the initial acquisition of additional rights-of-way should be considered.* [p. 463]

The cross sections depicted in Exhibit 7-8 represent normally divided facilities in rural areas. Sometimes in rural areas, and particularly in and near urban districts, it is appropriate to separate through traffic from local traffic. Where such is the case, frontage roads may be provided along the outer limits of the highway cross section (Exhibit 7-9). The component parts of a typical cross-section with frontage roads in generally flat terrain are shown in Exhibit 7-9A. The frontage roads are shown within the right-of-way limits, which is the typical arrangement. [p. 464]

Grade separation on divided arterials may be appropriate at some crossroads, but not at others. A typical cross section at a separated crossroad with a depressed arterial is depicted in Exhibit 7-9B. Where frontage roads are provided, the outer separations should be wider on arterials with two-way frontage roads and on arterials with grade separations than on arterials crossing at grade to allow for roadside slopes and ramps. Further discussion on interchanges is presented in Chapter 10. [p. 465]

The outer separation of frontage roads on arterials with at-grade intersections still needs to be large enough to allow for efficient intersection operations. This information was presented earlier in Chapter 4. A statement such as "For further discussion of frontage roads at intersections, refer to the section in Chapter 4 on "Frontage Roads" or the section in Chapter 9 on "Intersection Design Elements with Frontage Roads" should be located here.

<u>Sections with Widely Separated Roadways:</u>

Occasionally, it is practical to widely separate the one-way roadways of a divided arterial. This design may be appropriate where an existing two-lane arterial proves inadequate and is improved to a four-lane section, but for which direct widening is not practical because of topography or adjacent development. In such a case, the old roadway is not disturbed, but is converted to one-way operation and another, completely separate, one-way roadway is constructed. This action sometimes results in acquisition of two separate rights-of-way to contain the individual roadways of the divided arterial. [p. 465]

Widely separated one-way roadways may be particularly appropriate for certain topographic conditions. **(Examples are given)**. *Such arrangements simplify location problems because only one roadway is considered at a time. With reduced roadway prisms, construction scars are kept to a minimum and more of the natural growth is retained, particularly between the separate roadways. In areas where right-of-way is not restricted, designs involving widely separated roadways often result in lower construction costs.* [p. 465, 466]

Intersections between a crossroad and a one-way roadway are greatly simplified in design and operation. Crash potential is generally reduced and the capacity of intersections is increased. Moreover, operation on widely separated roadways provides *the maximum in driver comfort. Strain is lessened by largely eliminating the view and influence of opposing traffic. Substantial reduction or elimination of headlight glare at night is especially helpful in easing driver tension. [p. 466]*

Operational problems of intersections on roadways with very wide medians should be considered. Desirably, a wide median is adequate to store the longest legal vehicles. To determine the number of intersection lanes needed, all movements and their volumes should be considered. The need for turn-arounds, connecting roadways, and frontage roads should be considered along with the effect on adjacent property owners. Signing to prevent wrong-way operation should be provided in accordance with the MUTCD, particularly when both roadways of the divided highway are not visible to drivers stopped at the crossroad. Additional discussion on wide medians is presented in the earlier section of this Chapter on "Medians." [p. 466]

If arterials of appreciable length have roadways separated so widely that each roadway cannot be seen from the other, drivers may assume that they are on a two-way instead of a one-way roadway and hesitate to pass slow moving vehicles. This situation can be alleviated by an occasional open view between the two roadways. [p. 466]

If drivers cannot see the opposite direction roadway due to their wide separation, how will providing an open view between the two roadways help? "Separated so widely" should be changed to something that indicates continuously blocked views of the other roadway, via terrain or vegetation, then it would make sense.

<u>Intersections:</u>

The liberal use of high-type intersections and interchanges is highly desirable on arterials that do not have full control of access. Adequate turning widths **(lanes)** *with acceleration and deceleration tapers will provide a minimum design for minor intersections on a minor* **(major/principal)** *arterial. Where practical, principal arterials that intersect should be served by interchanges, possibly of the free-flow type. A comprehensive study of all intersections is needed for new and reconstruction projects, and a suitable design, consistent with the desired level of service, should be selected.* [p. 466]

What constitutes a high-type intersection? High-type is never defined in the Green Book, but is used to refer to pavements, arterials, and intersections.

The mix of low-type intersections, high-type intersections, and interchanges can pose driver expectancy issues. Therefore, closing the low-type at-grade intersections on expressways and providing frontage roads with access to fewer high-type intersections and interchanges may lead to safer expressway operation.

Rural intersection control by traffic signals is not desirable. Drivers generally do not anticipate signals in rural areas that have high operating speeds, especially when traffic volumes are relatively low. [p. 466]

A 1992 study conducted by Bonneson and McCoy (1) showed that the costs of stopping expressway traffic are so high that a very heavy minor road demand must be

present to economically justify installing a traffic signal. They also showed that when the minor road demand grows to these levels, making two-way stop-controlled intersections operationally unsafe and inefficient, a diamond interchange is more economically viable than a signalized intersection. This study should be cited here in support of the above statement that rural divided arterial intersection control by traffic signals is not desirable.

(1) Bonneson, J.A. & McCoy, P.T., *Interchange versus At-Grade Intersection on Rural Expressways: Final Report*, Nebraska Department of Roads Project No. RES1(0099) P453, University of Nebraska-Lincoln, May 1992.

Curbed islands present an obstacle to drivers and may become snow traps in regions that receive frequent snowfalls. Therefore, curbs at intersections should be avoided in high-speed areas. [p. 466]

This statement could be placed earlier (back on page 462/463) where Exhibit 7-7 was discussed to place all of the same information together.

If interchanges are intermixed with intersections, adequate merging distances should be provided to allow ramp traffic to operate freely. The merging driver should not have to be concerned with cross traffic at a downstream intersection while making a merging maneuver. Design of intersections and interchanges should be in accordance with Chapters 9 and 10, respectively. [p. 466/467]

This is good guidance, but the intermixing of at-grade intersections and interchanges in a corridor should be avoided to improve driver expectancy.

<u>Access Management:</u>

A lot of the information provided in this section could appear in the section entitled, "Ultimate Development of Four-Lane Divided Arterials."

Arterials are designed and built with the intention of providing better traffic service than is available on local roads and streets. Although an arterial may not have more traffic lanes, its ability to carry greater volumes is usually related to the amount of crossroad interference or side friction to which it is subjected. One of the most important considerations in arterial development is the amount of access control, full or partial, that can be acquired. Controlling access is vital to maintaining operations and safety and to preserving the level of service for which the arterial was initially designed. [p. 467]

Therefore, the provision of frontage roads with fewer direct expressway access points is a vital safety measure.

Access control is usually not too difficult to obtain in a rural area where development is light. Adequate access can normally be provided without great interference to traffic operations. However, rural areas do pose distinct access-related problems. The movement of large, slow-moving farm machinery is not uncommon and numerous field entrances are also requested by land owners. Because of these unique problems, access *points* **(intersections)** *should be situated to minimize their detrimental effects to through traffic.* [p. 467]

Where numerous field entrances are requested by farmers, gravel frontage roads are the perfect solution, thereby removing the large slow-moving farm machinery from the expressway. Intersections/access points should also be placed to maximize safety. Placing expressway intersections in tangent, flat areas on the mainline as well as at 90^{o} to the mainline is ideal for safe intersection operation.

If access points are needed on opposite sides of the roadway, they should be situated directly opposite each other to allow vehicles to cross the arterial in the shortest possible time. [p. 467]

This statement is not necessarily correct. Offset T-intersections may provide safer intersection operation by reducing the number of conflict points. NCHRP 375 showed that three-legged intersections tend to operate more safely than comparable four-legged intersections. Also, the Alabama DOT has experienced positive safety benefits by minimizing the number of four-legged expressway intersections by using T-intersections instead.

If access points are requested directly opposite each other, another method of improving safety may be to close the median and force a downstream U-turn to prevent the dangerous direct crossing and left-turn movements.

Where access is needed for two adjacent properties or where different land uses adjoin one another, providing one driveway to serve both properties will reduce the number of access locations needed. Adequate and uniform spacing between access points will also help eliminate many conditions where a large vehicle at an intersection hides another vehicle on a nearby approach. Consideration should also be given to the location of access points in relationship to intersection sight distance restrictions and other intersections. High-volume access points can lead to particular operational problems if not properly situated. Short sections of rural frontage roads may be used to combine access points and minimize their operational effect to the arterial. [p. 467]

Uniform spacing of intersections on the expressway will also help driver expectancy. Again, where frontage roads are used, the outer separation should be adequately spaced for efficient intersection operations.

Anticipation of future land use is a critical factor in determining the degree of access control. Provision of access management is vital to the concept of an arterial route if it is to provide the service life for which it is designed. For additional guidance on access management techniques for arterials, refer to NCHRP Report 420, "Impacts of Access Management Techniques." [p. 467]

Anticipation of future land use is also a critical factor in determining median width as well as other intersection design parameters. Also, access management on a minor road near an expressway intersection is also important for efficient intersection operation.

Chapter 9

Chapter 9 of the AASHTO Green Book is entitled "Intersections" and covers a very broad range of at-grade intersection types and designs. The chapter mainly speaks in terms of intersection design in general; however, much of this discussion can be applied to expressway intersection design. Statements of this nature as well as specific guidance regarding intersection design on expressways/divided highways are quoted and commented on herein.

The information in this chapter needs to be better organized, possibly by intersection types, to facilitate more efficient design guidance and information retrieval. The TRB Joint Subcommittee on Intersection Safety, Design, and Operations has identified categories of intersection types that may be helpful in this task.

<u>General Design Considerations and Objectives:</u>

> *The main objective of intersection design is to facilitate the convenience, ease, and comfort of people traversing the intersection while enhancing the efficient movement of motor vehicles, buses, trucks, bicycles, and pedestrians. Intersection design should be fitted closely to the natural transitional paths and operating characteristics of its users. Five basic elements should be considered in intersection design: human factors, traffic considerations, physical elements, economic factors, and the functional intersection area.* [p. 555/556]

What about safety? Safety must be a higher priority than efficiency in intersection design.

> *An intersection is defined by both its functional and physical areas, as illustrated in Exhibit 9-1. The functional area of an intersection extends both upstream and downstream from the physical intersection area and includes any auxiliary lanes and their associated channelization. The functional area on the approach to an intersection or driveway consists of three basic elements: perception-reaction distance, maneuver distance, and queue-storage distance. These elements are shown in Exhibit 9-2. Ideally, driveways should not be located within the functional area of an intersection.* [p. 556 – 558]

<u>Types and Examples of Intersections (General Considerations):</u>

> *The basic types of intersections are the three-leg or T, the four-leg, and the multi-leg. At each particular location, the intersection type is determined primarily by the number of intersecting legs, the topography, the character of the intersecting highways, the traffic volumes, patterns, and speeds, and the desired type of operation. Any of the basic intersection types can vary greatly in scope, shape, and degree of channelization.* [p. 558]

> *Once the intersection type is established, the design controls and criteria discussed in Chapter 2 and the elements of intersection design presented in Chapter 3, as well as in this chapter, should be applied to arrive at a suitable geometric plan.* [p. 558]

Chapter 2, "Design Controls and Criteria," discusses the selection of vehicles, speeds, volumes, level of service, etc. to be used for design. Chapter 3, "Elements of Design" discusses general elements used in design such as sight distance and horizontal/vertical alignment. As far as I can tell, Chapter 3 does not address any specific elements of intersection design. One possible idea for Green Book reorganization may be to move the discussion of general intersection design elements (i.e., intersection sight distance) that currently reside in Chapter 9 into Chapter 3 as elements of design, and reserve Chapter 9 for intersection design configuration options/issues.

> *In this section, each type of intersection is discussed separately, and likely variations of each are shown. It is not practical to show all possible variations, but those presented are sufficient to illustrate the general application of intersection design. Many other variations of types and treatment may be found in the NCHRP Report 279, "Intersection Channelization Design Guide," which shows detailed examples that are not included in this policy.* [p. 558]

Most of the examples currently shown are intersections on two-lane undivided roadways. More examples of typical expressway intersection designs need to be shown in this section. Typical intersections could be shown and then modifications to the typical designs could be discussed separately.

> *Although many of the intersection design examples are located in urban areas, the principles involved apply equally to design in rural areas. Some minor design variations occur with different kinds of traffic control, but all of the intersection types shown lend themselves to cautionary or non-stop control, stop control for minor approaches, four-way stop control, and both fixed-time and traffic-actuated signal control.* [p. 558]

Chapter 7 considers rural and urban arterials separately because "each has distinctive features." Rural and urban intersections also have distinctive features, rather than "minor design variations" and should also be considered separately.

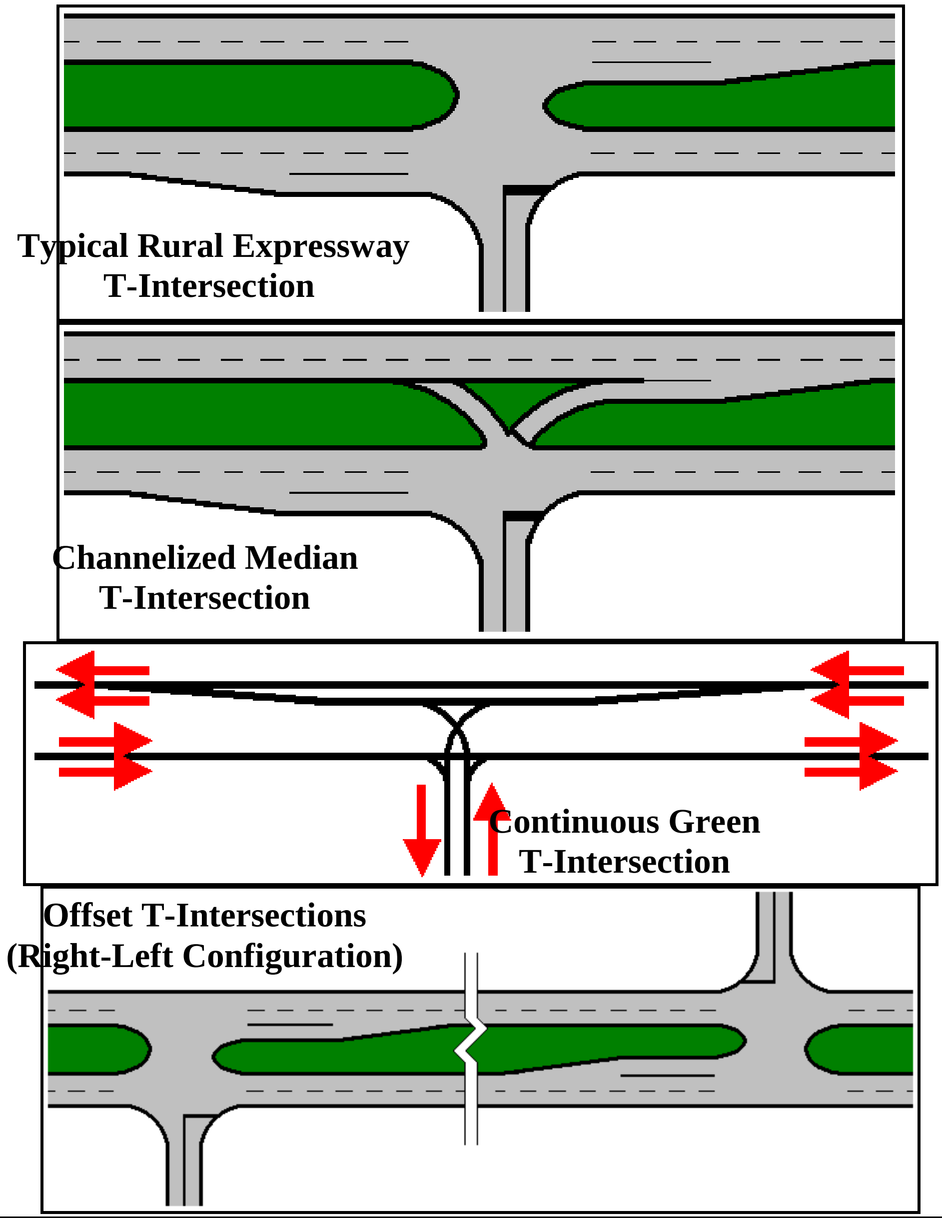
> *Right turns without stop or yield control are sometimes provided at channelized intersections. Such free-flow right turns should be used only where an adequate merge is provided. In built-up areas, the use of free-flow right-turn lanes should be considered only where significant traffic capacity or safety problems may occur without them and adequate pedestrian crossings can be provided.* [p. 558]

At rural expressway intersections, the "pork-chop" right-turn design is used on minor road approaches. Although the maneuver is usually yield or stop-controlled and is therefore not a "free-flow" right turn, it is similar. These designs can present a number of problems if an acceleration/merge lane is not provided on the high-speed mainline. These designs increase the skew for the waiting or stopped right-turn driver and can create an intersection sight distance issue if a through or left-turning vehicle occupies the same approach. Providing an acceleration lane would alleviate these issues and should improve the safety of the intersection design.

Four basic intersection types (three-leg, four-leg, multi-leg, and modern roundabouts) are presented and elements of their design discussed between pages 559 and 579.

Types and Examples of Intersections (Three-Leg Intersections):

Basic forms of three-leg or T-intersections are discussed and illustrated between pages 559 and 565. No examples of three-legged expressway intersections are shown or discussed. Figures of a typical expressway T-intersection, a channelized median T-intersection, and a continuous green T-intersection could be shown and their use discussed in detail at this point. Further research is necessary to determine which of these three T-intersection designs performs the best in terms of safety and operations. In addition, offset T-intersections can be used to replace four-legged intersections and could also be discussed at this point.



Types and Examples of Intersections (Four-Leg Intersections):

Basic types of four-leg intersections are shown in Exhibits 9-9 through 9-13. [p. 565]

Of these exhibits, Exhibits 9-12 and 9-13 show four examples of four-legged expressway intersections labeled as "Channelized High-Type" intersections. However, the example shown in Exhibit 9-13B is anything but "basic." These examples are discussed in more detail in a subsequent section.

Parallel auxiliary lanes are essential where traffic volume on the major highway is near the uninterrupted-flow capacity of the highway or where through and cross traffic volumes are sufficiently high to warrant signal control. Auxiliary lanes are also desirable for lower volume conditions. The length of added pavement should be determined as it is for speed-change lanes, and the length of uniform lane width, exclusive of taper, should normally be greater than 45 m [150 ft] on the approach side of the intersection. The length of added pavement on the exit side of the intersection should be 60 m [200 ft] as shown in Exhibit 9-12B. [p. 565]

An island marked on the pavement is not as positive a separator as a curbed divisional island, but it is appropriate where sand or snow may be a maintenance problem and where any curbed island may be an obstruction, as on high-speed rural highways. [p. 566]

Except at minor intersections, right-turning roadways are often provided, as shown in Exhibit 9-10A, for the more important turning movements, where large vehicles are to be accommodated, and at minor intersections in quadrants where the angle of turn greatly exceeds 90 degrees. [p. 566]

Exhibit 9-11B illustrates an intersection with divisional islands on the crossroad. This configuration fits a wide range of volumes, and its capacity is governed by the roadway widths provided through the intersection. The form of channelization on the crossroad should be determined based on the cross and turning volumes and the sizes of vehicles to be accommodated. [p. 568]

Divisional (splitter) islands on the crossroad are typically used at rural expressway intersections; however, maintenance crews do not like them where snow removal is necessary if they are raised. There is no mention of their safety effectiveness and the only guidance provided for their use is on page 564 where Exhibit 9-8 (a channelized T-intersection) is discussed. This guidance states:

Space for this island is made by flaring the pavement edges of the intercepted road and by using larger-than-minimum pavement edge radii for the right-turning movements. To fit the paths of left-turning vehicles, the end of the island should generally be located about 2.4 to 3.6 m [8 to 12 ft] from the pavement edge of the through highway. [p. 564]

The simplest form of intersection on a divided highway has paved areas for right turns and a median opening conforming to designs shown in later discussions in this chapter.

Often the speeds and volumes of through and turning traffic justify a higher type of channelization suitable for the predominant traffic movements. [p. 568]

This statement tells me that all expressway intersections, where a right-turn is possible, should have right-turn lanes.

Exhibit 9-12A shows a high-type intersection on a divided highway. The approach on the right has a heavy left-turn volume that can utilize the auxiliary lane provided in the median. The lower leg of the intersection has a significant right-turn volume that is channelized with a triangular island and added auxiliary lane. [p. 568]

Exhibit 9-12A is flawed. In the lower right-hand corner of the intersection, the channelizing island is blocking the outside through lane, thus there is only one through lane. The right-turn movement from the lower leg has an auxiliary lane the way it is drawn, but there should be two through lanes and an extra auxiliary lane provided for the right-turn movement in Exhibit 9-12A. These "pork-chop" designs on the minor road can present problems at expressway intersections, as discussed earlier, where an auxiliary acceleration lane is not provided.

Exhibit 9-12B illustrates another configuration for the intersection of a high-speed divided highway and a major crossroad. Right-turning roadways with speed-change lanes and median lanes for left-turns afford both a high degree of efficiency in operation and high capacity and permit through traffic on the highway to operate at reasonable speed. Traffic signal controls should be properly used. [p. 568]

Here it states that traffic signal controls should be properly used. A reminder should be placed here as to what was stated earlier (Chapter 7, p. 466) that rural divided arterial intersection control by traffic signals is not desirable.

Exhibit 9-13A shows an intersection configuration with dual left-turn lanes for one of the left-turning movements. This configuration needs traffic signal control with a separate signal phase for the dual left-turn movement and is particularly suitable for locations in urban areas where there is a heavy turning movement in one quadrant of the intersection. The auxiliary lanes in the median should be separated from the through lanes by either an elongated island, as shown, or by pavement markings. Furthermore, pavement markings, contrasting pavements, and signs should be used to discourage through drivers from entering the median lane inadvertently. Left-turning vehicles typically leave the through lane to enter the median lane in single file but, once within it, are stored in two lanes. On receiving the green signal indication, left-turn maneuvers are accomplished simultaneously from both lanes. The median opening and the crossroad pavement should be sufficiently wide to receive the two side-by-side traffic streams. [p. 571]

Exhibit 9-13B shows a suitable configuration for an intersection with unusually heavy through volumes and a high left-turning volume in one quadrant. The high-volume left-turn movement is removed from the main intersection by providing a separate diagonal roadway and creating two additional intersections. A high degree of traffic operational efficiency can be attained by a system of progressively synchronized traffic signals and proper signal timing based on the distances and pavement widths between the three *intersections. The three intersections should be at least 60 m [200 ft] and preferably 90 m [300 ft] or more, apart. A median lane for the left-turning movement onto the diagonal roadway should be two lanes wide. The right-turning movement using the diagonal roadway may flow continuously, and an auxiliary lane along each of the major roadways may be desirable. This design may be used where a grade separation is not practical, as in flat terrain with traffic having a high volume of heavy trucks, or where it is desired to defer the construction of a grade separation. Where movements in the other quadrants reach the proportions of through movements, additional diagonal roadways might be provided, but with major turning movements in more than one quadrant, a grade separation is generally preferred. Before using the configuration shown in Exhibit 9-13B, careful consideration should be given to its overall operational performance (i.e., delay to motorists) since this design, in effect, creates two additional intersections.* [p. 571]

This expressway intersection design is not a typical design and is probably not practical in most situations. Ask yourself, have you every seen one like this constructed? The Green Book states that Exhibits 9-9 through 9-13 are basic intersection types. This example is far from basic.

This design could also be problematic. Before using this configuration, its safety performance should be considered as well. By relocating the left-turn movement in advance of the intersection, only a couple of minor conflict points are actually removed. This design also creates two additional skewed intersections, one of which is on the mainline. Neither the skew nor the extra mainline intersection are desirable for safe operation.

A few other questions remain about this design. Why does the median lane for the left-turning movement onto the diagonal roadway need to be two lanes wide? It is not shown this way in Exhibit 9-13B. Also, as pictured, the right-turner using the diagonal roadway may flow continuously onto it, but not off of it. An acceleration lane should be provided on the mainline.

This example intersection should be replaced with one which may serve a similar purpose (i.e., a design to defer the construction of a grade separation), but is more practical.

This is the last example shown of a four-legged intersection. Other examples of four-leg intersections from later in Chapter 9 could potentially be brought forward and placed in this location. See General Intersection Types [p. 682-686], Indirect Left-Turns and U-Turns [p. 705-712], Offset Left-Turn Lanes [p. 723], and Intersection Designs with Frontage Roads [p. 725-728]. Other examples of innovative four-legged intersection treatments that are not currently shown in the Green Book could also be shown here.

<u>Types and Examples of Intersections (Multileg Intersections):</u>

Multileg intersections, those with five or more intersection legs, should be avoided wherever practical. [p. 571]

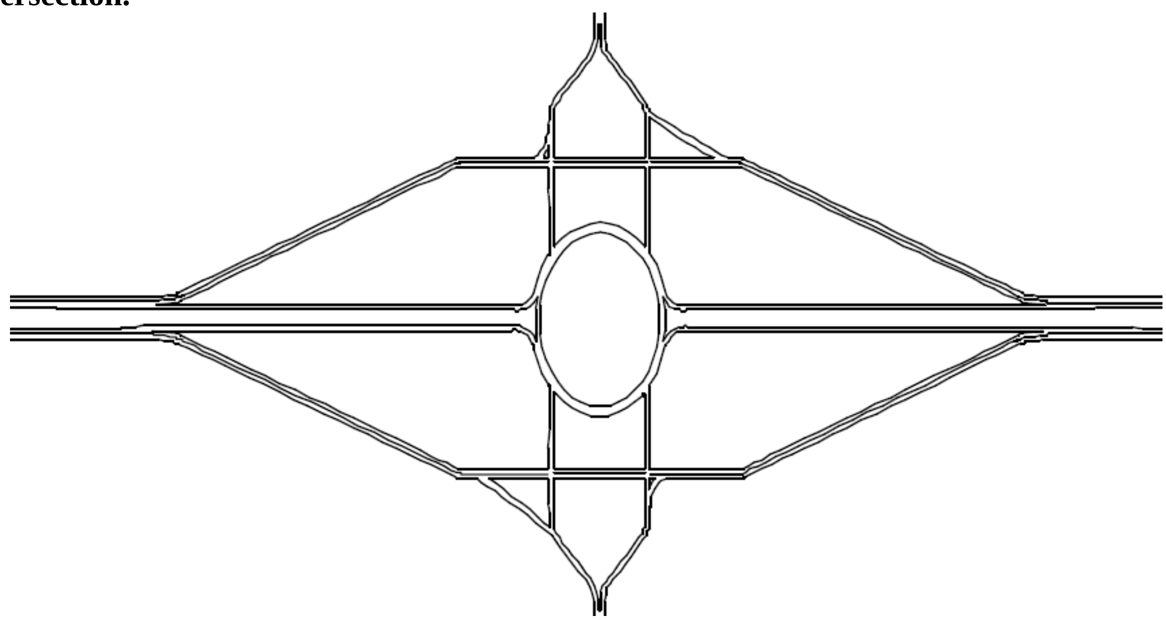
This short section discusses options for realigning multi-leg intersections at other than minor intersections. Clearly, multi-leg intersections should not be used on

expressways, making this section irrelevant to the discussion of expressway intersection design.

Types and Examples of Intersections (Modern Roundabouts):

The greater speeds permitted by larger roundabouts, inscribed circle diameters greater than 75 m [246 ft], may reduce their safety benefits to some degree. Roundabouts operate most safely when their geometry forces traffic to enter and circulate at slow speeds. Designing a roundabout is a process of determining the optimal balance between safety provisions, operational performance, and accommodation of over-sized vehicles. [p. 575, 576]

This section currently is not applicable to expressway intersections because expressway intersections are not mentioned. However, there is an expressway "semi-roundabout" intersection design (shown below) that has been proposed by Edwin Lagergren of the Washington Department of Transportation, whose purpose is to be an interim measure for a diamond interchange (4). As proposed, only expressway left-turning and minor road left-turning/cross-traffic use the roundabout in the center of the intersection.



(4) Lagergren, E.A., *Expressway Semi-Roundabout Intersection*, Presented, Annual Meeting of ITE, Orlando, FL, August 2004.

Capacity Analysis:

Capacity and level-of-service analysis is one of the most important considerations in the design of intersections. This subject is discussed at length in Chapter 2 and is discussed throughout this chapter as it relates to the various elements of intersection design. Optimum capacities and levels of service can be obtained when intersections include auxiliary lanes, appropriate channelization, and traffic control devices. For more complete discussion of capacity and level-of-service analysis for intersections, including operational analysis procedures, refer to the Highway Capacity Manual (HCM) and to Chapter 2 for guidance for its use. [p. 579]

<u>Alignment and Profile:</u>

The alignment and grade of intersecting roads should permit users to recognize the intersection and the other vehicles using it, and readily perform the maneuvers needed to pass through the intersection with minimum interference. To these ends, the alignment should be as straight and the gradients as flat as practical. The sight distance should be equal to or greater than the minimum values for specific intersection conditions, as derived and discussed later in this chapter. If design objectives are not met, users may have difficulty in discerning the actions of other users, in reading and discerning the messages of traffic control devices, and in controlling their operations. Site conditions generally establish definite alignment and grade constraints on the intersecting roads. It may be practical to modify the alignment and grades, however, in order to improve traffic operations. [p. 579]

The presence of vertical and horizontal curves on intersection approaches reduces the ability of drivers to perceive the actions taking place both at the intersection and on its approaches. Therefore, as stated above, expressway intersections should not be placed on or near horizontal/vertical curves. The statement above also states that it may be practical to modify alignments and grades to improve operations. However, it is extremely costly to correct alignment deficiencies after the highway is constructed, usually making this option impractical; therefore, initial intersection approach alignments should be carefully considered during expressway intersection design.

Regardless of the type of intersection, for safety and economy, intersecting roads should generally meet at or nearly at right angles. Roads intersecting at acute angles need extensive turning roadway areas and tend to limit visibility, particularly for drivers of trucks. When a truck turns on an obtuse angle, the driver has blind areas on the right side of the vehicle. Acute-angle intersections increase the exposure time for the vehicles crossing the main traffic flow. The practice of realigning roads intersecting at acute angles in the manner shown in Exhibits 9-18A and 9-18B has proved to be beneficial. The greatest benefit is obtained when the curves used to realign the roads allow operating speeds nearly equivalent to the major highway approach speeds. [p. 580]

Skewed intersections can also be problematic for older drivers. This should be mentioned here. Again, initial intersection approach alignment/skew should be carefully considered during design because realignment at a later time is extremely costly.

The above states that the realigning curves should be designed for speeds nearly equivalent to the major highway approach speeds. If these curves are on the minor road, which is typical, then it makes more sense that they should be designed for a design speed equivalent to the minor road design speed, not the major road. From Figure 9-18, it is hard to tell if the major or minor road is being realigned. This should be made more clear.

The practice of constructing short-radius horizontal curves on side road approaches to achieve right-angle intersections should be avoided whenever practical. Such curves result in increased lane encroachments because drivers tend to reduce their path radius using a portion of the opposing lane. Also, the traffic control devices at the intersection *may be located outside the driver's line of sight, resulting in the need to install advanced signing.* [p. 580]

Later, in the middle of page 581, the Green Book states:
The width of the roadway on the approach curves should be consistent with Exhibit 9-31 in order to reduce the potential for encroachment on adjacent lanes.
This statement seems out of place and should be moved up following the earlier statement on page 580 regarding lane encroachments. Also, Exhibit 9-31 is talking about low speed turns and off-tracking is not the issue here. Rather, drivers trying to "cut the corner" to maintain speed. In this case, there is no need to cut the corner if they are going to have to stop anyway. This may be more of a problem on departure rather than approach.

Another method of realigning a road that originally intersected another road at an acute angle is to make an offset intersection, as shown in Exhibits 9-18C and 9-18D. Only a single curve is introduced on each crossroad leg, but crossing vehicles must turn onto the major road and then reenter the minor road. Realignment of the minor road, as shown in Exhibit 9-18C, provides poor access continuity because a crossing vehicle must reenter the minor road by making a left turn off the major highway. This design arrangement should only be used where traffic on the minor road is moderate, the anticipated minor road destinations are local, and the through traffic on the minor road is low. Where the alignment of the minor road is as shown in Exhibit 9-18D, access continuity is better because a crossing vehicle first turns left onto the major road (e.g., a maneuver that can be done by waiting for an opening in the through traffic stream) and then turns right to reenter the minor road, thus interfering little with through traffic on the major road. [p. 581]

This is really the only place in the Green Book where the use of offset T-intersections is discussed. On page 400, in the section on intersection design for urban streets, it states that closely spaced offset intersections are undesirable; however the Green Book provides no guidance for rural offset intersection spacing. More guidance is necessary in terms of the appropriate offset distance to use and at what minor road through volume they should be avoided, if at all. Even if minor road through volumes are high, the offset T could potentially still work as long as the offset distance is large enough. The two minor road approaches should be separated by an appreciable distance to allow the two T-intersections to operate independently.

Some of the information presented here is flawed. Exhibit 9-18C is considered a right-left offset configuration because a crossing minor road driver must first turn right onto the major road and then turn left off of it. Conversely, Exhibit 9-18D is a left-right configuration. For expressway intersections, the right-left configuration (Exhibit 9-18C) would be preferred over the left-right configuration (Exhibit 9-18D) because a left-turn off of the expressway is a safer maneuver than a left-turn onto the expressway. The right-left configuration would therefore be expected to cause less delay and provide higher capacity. Bared and Kaisar (5) did some research showing that interference between vehicles on a 65 mph expressway and accelerating/decelerating vehicles from the minor roads is minimized when the intersections are offset by a maximum of 141 feet for a right-left configuration and by a maximum of 235 feet for a left-right configuration.

For some reason, the Green Book discussion of offset T-intersections is picked up one paragraph later on page 581. Here the Green Book states:

Where a large portion of the traffic from the minor road turns onto the major road, rather than continuing across the major road, the offset-intersection design may be advantageous regardless of the right or left entry.

Where a large portion of traffic turns onto the major road, you would certainly want them to have a right-turn entry onto an expressway instead of a high crash risk left-turn maneuver. Therefore, the traffic volumes of the various minor road movements should ultimately determine the best configuration.

(5) Bared, J.G. & Kaisar, E.I., *Advantages of Offset T-Intersections with Guidelines*, International Conference: Traffic Safety on Three Continents, Moscow, Russia, September 2001.

Once a decision has been made to realign a minor road that intersects a major road at an acute angle, the angle of the realigned intersection should be as close to 90 degrees as practical. Although a right-angle crossing is normally desired, some deviation from a 90 degree angle is permissible. Reconstructing an intersection to provide an angle of at least 60 degrees provides most of the benefits of a 90 degree intersection angle while reducing the right-of-way takings and construction costs often associated with providing a right-angle intersection. [p. 581]

The end of this statement makes it sound like a hardship to provide a 90 degree intersection and beneficial to provide an intersection angle of 60 degrees instead because it will save on construction costs and right-of-way. Actually, providing a 90 degree intersection would probably be less difficult and require less right-of-way. In addition, there is no research cited here which found that a 60 degree intersection provides most of the benefits of a 90 degree intersection. If a statement like this is made it should be backed up by research. Also, if you're reconstructing an intersection, you might as well do it right and provide a 90-degree angle.

Intersections on sharp curves should be avoided wherever practical because the superelevation and widening of pavements on curves complicate the intersection design and may reduce sight distance. [p. 581]

Intersections on or near horizontal curves should be avoided altogether, not just on/near sharp curves. How is a "sharp" curve defined anyway? I assume one that requires superelevation, which can vary from state to state.

Where the major road curves and a minor road is located along a tangent to that curve, it is desirable to realign the minor road, as shown in Exhibit 9-18E, to guide traffic onto the main highway and improve the visibility at the point of intersection. This practice may have the disadvantage of adverse superelevation for turning vehicles and may need further study where curves have high superelevation rates and where the minor road approach has adverse grades and a sight distance restriction due to the grade line. [p. 581]

First, the Green Book just got through saying that intersections on horizontal curves should be avoided and then here it shows Exhibit 9-18E where an intersection is realigned and placed directly on a horizontal curve. Second, it states that the new alignment guides traffic onto the main highway. I think the original alignment did a better job of that. Exhibit 9-18E should be replaced by a figure providing better design guidance.

Combinations of grade lines that make vehicle control difficult should be avoided at intersections. Substantial grade changes should be avoided at intersections, but it is not always practical to do so. Adequate sight distance should be provided along both intersecting roads and across their included corners, as discussed below, even where one or both intersecting roads are on vertical curves. The gradients of intersecting roads should be as flat as practical on those sections that are to be used for storage of stopped vehicles, sometimes referred to as "storage platforms." [p. 582]

The calculated stopping and accelerating distances for passenger cars on grades of 3 percent or less differ little from the corresponding distances on the level. Grades steeper than 3 percent may need changes in several design elements to sustain operations equivalent to those on level roads. Most drivers are unable to judge the effect of steep grades on stopping or accelerating distances. Their normal deductions and reactions may thus be in error at a critical time. Accordingly, grades in excess of 3 percent should be avoided on the intersecting roads in the vicinity of the intersection. Where conditions make such designs too expensive, grades should not exceed about 6 percent, with a corresponding adjustment in specific geometric design elements. [p. 582]

Stopping and accelerating distances for passenger cars on grades of 3% or less differ little from the corresponding distances on level roads. What about for trucks? A separate standard from 3% grades for trucks may be necessary. Professional truck drivers are presumably more aware of the effects of grades on the performance of their vehicles.

Grades steeper than 3% may need changes in several specific geometric design elements to sustain operations equivalent to those on level roads. What design elements are those? They should be specified here.

Grades steeper than 3% should be avoided in the vicinity of an intersection. What distance defines intersection vicinity?

The profile gradelines and cross sections on the legs of an intersection should be adjusted for a distance back from the intersection proper to provide a smooth junction and proper drainage. Normally, the gradeline of the major road should be carried through the intersection and that of the minor road should be adjusted to it. This design involves a transition in the crown of the minor road to an inclined cross section at its junction with the major road. For simple unchannelized intersections involving low design speeds and stop or signal control, it may be desirable to warp the crowns of both roads into a plane at the intersection; the appropriate plane depends on the direction of drainage and other conditions. Changes from one cross slope to another should be gradual. Intersections at which a minor road crosses a multilane divided highway with a narrow median on a superelevated curve should be avoided whenever practical because of the difficulty in adjusting grades to provide a suitable crossing. Gradelines of *separate turning roadways should be designed to fit the cross slopes and longitudinal grades of the intersection legs.* [p. 582]

The alignment and grades are subject to greater constraints at or near intersections than on the open road. At or near intersections, the combination of horizontal and vertical alignment should provide traffic lanes that are clearly visible to drivers at all times, clearly understandable for any desired direction of travel, free from the potential for conflicts to appear suddenly, and consistent in design with the portions of the highway just traveled. The combination of vertical and horizontal curvature should allow adequate sight distance at an intersection. As discussed in Chapter 3, "Combinations of Horizontal and Vertical Alignment," a sharp horizontal curve following a crest vertical curve is undesirable, particularly on intersection approaches. [p. 582]

Types of Turning Roadways (General):

The widths of turning roadways for intersections are governed by the volumes of turning traffic and the types of vehicles to be accommodated. In almost all cases, turning roadways are designed for use by right-turning traffic. There are three typical types of right-turning roadways at intersections: (1) a minimum edge-of-traveled-way design, (2) a design with a corner triangular island, and (3) a free-flow design using a simple radius or compound radii. The turning radii and the pavement cross slopes for free-flow right turns are functions of design speed and type of vehicles. For an in-depth discussion of the appropriate design criteria, see Chapter 3. [p. 583]

The widths of turning roadways are governed by design vehicle and design volume. What about the type of turning roadway? What governs its selection?

A fourth type of right-turning roadway used at intersections that could be added here is the offset right-turn bay design. There is no guidance provided in the Green Book on their use or design.

Types of Turning Roadways (Minimum Edge-of-Traveled-Way Designs):

Where it is appropriate to provide for turning vehicles within minimum space, as at unchannelized intersections, the corner radii should be based on minimum turning path of the selected design vehicles. The sharpest turn that can be made by each design vehicle is shown in Chapter 2, and the paths of the inner rear wheel and the front overhang are illustrated. The swept path widths indicated in Chapter 2 are the minimum paths attainable at speeds equal to or less than 15 km/hr [10 mph] and consequently offer some leeway in driver behavior. These turning paths of the design vehicles shown in Exhibits 2-3 through 2-23 are considered satisfactory as minimum designs. Exhibits 9-19 and 9-20 summarize minimum-edge-of-traveled-way designs for various design vehicles. [p. 583]

In the design of the edge of the traveled way based on the path of a given design vehicle, it is assumed that the vehicle is properly positioned within the traffic lane at the beginning and end of the turn (i.e., 0.6 m [2 ft] from the edge of traveled way on the *tangents approaching and leaving the intersection curve). Curve designs for edge of traveled way conforming to this assumption are shown in Exhibits 9-21 through 9-28. Although not shown explicitly in the figures, the edge designs illustrated also apply to left-turn maneuvers, such as a left-turn by a vehicle leaving a divided highway at a very low speed. Where the alignment includes a horizontal curve at the beginning or end of a return radius, the design should be modified accordingly. The most expeditious way to customize a design for such special conditions is to use the appropriate design vehicle as an overlay on a plan of the intersection.* [p. 592]

Using something like Autoturn® is a more up to date method of customizing a design for special conditions.

At an intersection with a low right-turn volume, the designer may determine that a deceleration and right-turn lane is not warranted. In this instance, the composition of the shoulder may be improved for greater load capacities to permit right-turning vehicles to utilize the shoulder. In turn, where right-turning volumes are high, consideration should be given to providing a right-turn lane along with appropriate provisions for vehicle deceleration. In rural areas, the appropriate shoulder width should be considered in conjunction with the design of right-turn lanes. [p. 592]

The designs illustrated in Exhibits 9-21 through 9-28 are those that accommodate the sharpest turns for specific design vehicles. Combinations of curves with radii other than those shown may also provide satisfactory operations. The selection of any specific design depends on the type and size of vehicles that will be turning and the extent to which they should be accommodated. In addition, the appropriate design may depend on other factors such as the type, character, and location of the intersecting roads, the vehicular and pedestrian traffic volumes, the number and frequency of the larger vehicles involved in turning movements, and the effect of these larger vehicles on other traffic. [p. 592]

Minimum designs are appropriate for locations with low turning speeds, low turning volumes, and high property values. The selection of a design vehicle for minimum edge-of-traveled-way designs depends on the designer's judgment upon consideration of the site conditions and analysis of the operational needs of larger vehicles. Generally, the SU design vehicle (Exhibit 9-22) provides the recommended minimum edge-of-traveled-way design for rural highways. Important turning movements on major highways, particularly those involving a large percentage of trucks, should be designed with larger radii, speed-change lanes, or both. [p. 592, 593]

Minimum designs are also appropriate in areas where designers are trying to avoid environmental impacts.

It is not practical to fit simple circular arcs to the minimum design paths for semitrailer combination design vehicles. To fit the edge of traveled way more closely to the minimum path of these design vehicles, an asymmetrical arrangement of three-centered compound curves should be used. A simple curve with tapers is shown in Exhibit 9-24 for the WB-15 [WB-50] vehicle. Although not as efficient in the use of pavement area as *the asymmetrical curve layout, it may be a preferred design because of its ease of construction.* [p. 610]

Jointing details should also be considered in selecting the preferred curve layout.

For oblique-angle turns, minimum designs for the edge of the traveled way are developed in the same manner as those for right-angle intersections by plotting the paths of the design vehicles on the sharpest turns and fitting curves or combinations of curves to the paths of inner rear wheels. Suggested minimum designs in which three-centered compound curves are used for each design vehicle are given in Exhibit 9-20 for various angles of turn. This angle is the same as that commonly called the delta or central angle in surveying terminology. The designs shown in Exhibit 9-20 are those suggested to fit the sharpest turns of the different design vehicles. Some other combinations of curves may also be used with satisfactory results. The use of tapers with simple curves is another method for design of the edge of the traveled way for turns at intersections, and dimensions for such combinations are shown in Exhibit 9-19. Any of the designs shown in Exhibits 9-19 or 9-20 may be chosen, depending on the type and size of vehicles that will be turning and the extent to which those vehicles should be accommodated. On major highways intersecting at oblique angles, separate turning roadways with a corner island for right-turning traffic should be provided in quadrants where vehicles turn more than about 120 degrees. [p. 610, 611]

The effect of curb radii on the right-turning paths of various design vehicles turning through an angle of 90 degrees is shown in Exhibits 9-29 and 9-30. Exhibit 9-31 shows the effect of the angle of intersection on turning paths of various design vehicles. Exhibit 9-31 also shows that a very large radius should be used or the streets should be very wide to accommodate the longer vehicles, particularly where the central angle is greater than 90 degrees. For this reason, three-centered curves (or offset, simple curves in combination with tapers to fit the paths of vehicles properly) are much preferred. [p. 611, 614]

<u>Islands (General Characteristics):</u>

An island is a defined area between traffic lanes used for control of vehicle movements. Within an intersection, a median or an outer separation is also considered an island. This definition makes evident that an island is no single physical type. It may range from an area delineated by a raised curb to a pavement area marked out by paint or thermoplastic markings. Where traffic entering an intersection is directed into definite paths by islands, this design feature is termed a channelized intersection. [p. 621, 622]

Channelizing islands generally are included in intersection design for one or more of the following purposes: separation of conflicts, control of angle of conflict, reduction in excessive pavement areas, regulation of traffic and indication of proper use of intersection, arrangements to favor a predominant turning movement, protection of pedestrians, protection and storage of turning and crossing vehicles, and location of traffic control devices. [p. 622]

Islands serve three primary functions: (1) channelization – to control and direct traffic movement, usually turning; (2) division – to divide opposing or same direction traffic streams, usually through movements; and (3) refuge – to provide refuge for pedestrians. Most islands combine two or all of these functions. [p. 622]

Islands should be located and designed to offer little obstruction to vehicles, be relatively inexpensive to build and maintain, and occupy a minimum of roadway space; however, they should be commanding enough that motorists will not drive over them. The dimensions and details depend on the particular intersection design and should conform to the general principals that follow. [p. 622]

At this point, no list of general principles is provided. Instead, four short paragraphs are written here which mainly provide guidance regarding island type. These general principles should be organized in a list format and stated more clearly.

Curbed islands are sometimes difficult to see at night because of the glare from oncoming headlights or from distant luminaires or roadside businesses. Accordingly, where curbed islands are used, the intersection should have fixed-source lighting or appropriate delineation such as curb-top reflectors. [p. 622]

Where various intersections are involved along a route and the warrants are sufficiently similar to enhance driver expectancy, it is desirable to provide a common geometric design for each intersection. Reference can also be made to the MUTCD for design guidance. [p. 622]

This is very difficult to do along a rural expressway corridor because each intersection has its own unique needs which may require special designs or channelization. An earlier idea that can be restated here is to use frontage roads as a means to close minor intersections and provide more high-type expressway intersections.

This statement is located in between two statements regarding island/median type and should either be moved to the first or the last general principal stated for better organization.

Under certain conditions, painted, flush medians and islands or traversable type medians may be preferable to the raised curb type islands. These conditions include the following: lightly developed areas that will not be considered for access management; intersections where approach speeds are relatively high; areas where there is little pedestrian traffic; areas where fixed-source lighting is not provided; median or corner islands where signals, signs, or luminaire supports are not needed; areas requiring significant snow plowing; and areas where extensive development exists along a street and may demand left-turn lanes into many entrances. [p. 622]

There are three basic median types that are typically used at rural expressway intersections: 1) turf/depressed, 2) surfaced/painted/flush, and 3) raised. Most of the conditions listed here are applicable at rural expressway intersections. Therefore, it seems that types 1 and 2 are preferred over raised medians. However, more guidance is necessary here as DOTs have used raised medians at rural expressway intersections as a tool to communicate the presence of the intersection to approaching expressway drivers.

No studies have been found that examined the issue of which median type design leads to the best safety performance at rural expressway intersections.

Painted islands may be used at the traveled way edge. At some intersections, both curbed and painted islands may be desirable. All pavement markings should be reflectorized. The use of thermoplastic striping, raised dots, spaced and raised retroreflective markers, and other forms of long-life markings also may be desirable. This subject is discussed in the MUTCD. [p. 623]

Islands (Channelizing/Divisional/Refuge):

The three general types of islands (channelizing, divisional, and refuge) are each discussed in more detail at this point. The discussion on refuge islands is not applicable to rural expressway intersections since pedestrians and bicyclists would not be expected at these locations; therefore, no comments have been made regarding this text.

Channelizing islands that control and direct traffic movements into the proper paths for their intended use are an important part of intersection design. Confusing traffic movements resulting from spacious areas may be eliminated by the conversion of unused areas into islands that leave little to driver discretion. Channelizing islands may be of many shapes and sizes, depending on the conditions and dimensions of the intersection. Some of those conditions are illustrated in Exhibit 9-35. A common form is the corner triangular shape that separates right-turning traffic from through traffic. [p. 623]

Exhibit 9-35 shows two instances where a corner triangular island separates minor approach right-turning traffic from minor through/left-turning traffic. These "pork-chop" channelization designs on the minor road approach can present problems at rural expressway intersections, as discussed earlier, where an auxiliary acceleration lane is not provided on the high-speed mainline. However, further research is necessary to support or discontinue their use.

Channelizing islands should be placed so that the proper course of travel is immediately obvious, easy to follow, and of unquestionable continuity. When designing an island, attention should be given to the fact that the driver's eye view is different from the plan view. Particular care should be taken where the channelization is on or beyond a crest of a vertical curve, however slight, or where there is substantial horizontal curvature on the approach to or through the channelized area. Where islands separate turning traffic from through traffic, the radii of curved portions should equal or exceed the minimum for the turning speeds expected. Drivers should not be confronted suddenly with an unusable area in the normal vehicle path. Islands first approached by traffic should be indicated by a gradually widening and marking or a conspicuously rumble strip that directs traffic to each side. [p. 623]

With the possibility of confusion, a few large islands are preferable to a greater number of smaller islands. [p. 623]

The use of curbed islands generally should be reserved for multilane highways or streets and for the more important intersections on two-lane highways. Curbed islands *generally should not be used in rural areas and at isolated locations unless the intersection is lighted and curbs are delineated.* [p. 624]

As mentioned previously, DOTs have used raised curb medians (a median is considered an island) for the more important intersections on rural expressways, similar to what is done on two-lane highways, in order to communicate the presence of the intersection to approaching expressway drivers. No studies have been found that examined the issue of which median type design leads to the best safety performance at rural expressway intersections.

Marked channelization (painting or striping) can be made to increase efficiency and has the advantage of easy modification when warranted by driver behavior. If a more positive barrier is needed, curbed islands may be constructed, but the marked channelization may well serve initially to establish the best layout arrangement before permanent construction is established. However, it should be noted that inclement weather decreases the effectiveness of flush channelization. [p. 625]

This section on channelizing islands does not discuss channelized medians or median delineation at all. The use of channelized medians at T-intersections on rural expressways may have potential to improve rural expressway intersection safety. Also, channelizing the median at a four-legged expressway intersection so that crossing/left-turning minor road traffic are forced to turn right at the intersection and only left-turns off the mainline are allowed can provide safety benefits based on Maryland DOT experience.

Delineation of the median at a rural expressway intersection with a centerline and stop bars can also improve intersection safety by reducing undesirable driving behavior in the median (i.e., side-by-side queuing, angle stopping, and expressway lane encroachment). Median delineation clearly has the potential to communicate to a minor road driver 1) how the median should be navigated and 2) the median's storage capacity. In doing so, this strategy can reduce competition for space within the median and tell the minor road driver that it is OK to stop in the median in order to cross/turn-left from the minor road.

Divisional islands often are introduced on undivided highways at intersections. They alert the drivers to the crossroad ahead and regulate traffic through the intersection. A variety of divisional islands that separate opposing traffic are illustrated in Exhibit 9-36. Where an island is introduced at an intersection to separate opposing traffic on a four-lane road or on a major two-lane highway carrying high volumes, particularly where future conversion to a wider highway is likely, two full lanes should be provided on each side of the dividing island. [p. 625]

If dividing an undivided highway in the vicinity of an intersection helps to alert mainline drivers of the crossroad ahead and to regulate mainline traffic through the intersection, maybe undividing a divided highway/expressway could have the same effect? Or, an alternate approach may be to divide the expressway more widely in the vicinity of the intersection (as shown earlier).

It may be an interesting research project to compare the safety of rural expressway intersections with intersections that have similar geometrics, but where the intersection is divided by a divisional island on an undivided highway. A project such as this may help

determine if the expressway intersection safety problem lies in minor road gap selection or major road intersection recognition.

Exhibit 9-36 shows four figures with divisional islands on the mainline. The use and safety benefits of using divisional/splitter islands on minor road approaches at expressway intersections is not discussed or shown in this section. Also, it is interesting to note that two of the four figures in Exhibit 9-36 show intersections on horizontal curves. There should also be some guidance on how long the divided section should be as shown in Exhibit 9-36.

Widening a roadway to include a divisional island (Exhibit 9-36) should be done in such a manner that the proper paths to follow are unmistakably evident to drivers. Often the highway is on a tangent, and to introduce dividing islands, reverse curve alignment would be needed. Tapers can be used, but should be consistent with lane shifts at the design speed. In rural areas, where speeds are generally high, reversals in curvature should preferably be with radii of 1165 m [3825 ft] or greater. [p. 625]

Some guidelines are specified here for widening the roadway when using a divisional island. These guidelines can be applied at the beginning or end of an expressway segment. However, it is unclear if these same guidelines would apply when designing a divisional/splitter island on a minor stop-controlled approach at an expressway intersection.

*Usually, the roadway in each direction of travel is bowed out, more or less symmetrically about the centerline as shown in Exhibit 9-36***(A)**. *Widening may also be affected on one side only with one of the roadways continuing through the intersection on a straight course* **(as shown in Exhibit 9-36B)**. *When this arrangement is used for a two-lane road that is planned for future conversion to a divided highway, the traveled way on tangent alignment will become a permanent part of the ultimate development.* [p. 625]

<u>Island Size and Designation:</u>

Island sizes and shapes vary materially from one intersection to another, as shown in Exhibit 9-35. Further variations occur at multiple and acute-angle intersections. Islands should be sufficiently large to command attention. The smallest curbed corner island normally should have an area of approximately 7 m^2 [75 ft^2] for rural intersections. However, 9 m^2 [100 ft^2] is preferable. Accordingly, corner triangular islands should not be less than about 3.5 m [12 ft] and preferably 4.5 m [15 ft], on a side after the rounding of corners. [p. 627]

Divisional islands should be not less than 1.2 m [4 ft] wide and 6 to 8 m [20 to 25 ft] long. In general, introducing curbed divisional islands at isolated intersections on high-speed highways is undesirable unless special attention is directed to providing high visibility for the islands. Curbed divisional islands introduced at isolated intersections on high-speed highways should be 30 m [100 ft] or more in length. [p. 627]

It is not clear whether or not splitter islands used on minor roads at expressway intersections are considered divisional islands and if they must conform to these design specifications. I would think so, but it is not clear.

In a physical sense, islands can be divided into three groups: (1) raised-curb islands, (2) islands delineated by pavement markings or reflectorized markers placed on paved areas, and (3) islands formed by the pavement edges and possibly supplemented by delineators on posts or other guideposts beyond and adjacent to the pavement edges. Group 1 provides the greatest positive guidance. In rural areas, this treatment often is limited to corner islands of small to intermediate size. In rural areas, Group 2 treatments may be used to minimize maintenance problems on high approach speeds or where snow removal is more difficult with curbed islands. The Group 3 treatment by its nature applies to other than small channelizing islands and is primarily used at rural intersections where there is space for large-radius intersection curves and wide medians. The central area of large channelizing islands in most cases has a turf or other vegetative cover. Turf provides excellent contrast with the paved areas, assuming that the ground cover is cost-effective and can be properly maintained. Where pavement cross-slopes are outward, large islands should be depressed to avoid draining water and snow melt across the pavement. [p. 627, 628]

The use of turf cover to provide contrast with paved areas will be discussed in more detail when the section on offset left-turn bay design is critiqued.

<u>Island Delineation and Approach Treatment:</u>

In rural areas, island curbs should usually be a sloping type. Chapter 4 indicates different curb types. The amount that a curbed island is offset from the through-traffic lane is influenced by the type of edge treatment and other factors such as island contrast, length of taper, or auxiliary pavement preceding the curbed island. Since curbs influence the lateral placement of a vehicle in a lane, they should be offset from the edge of through-traffic lanes even if they are sloping. Curbs need not be offset from the edge of a turning roadway, except to reduce their vulnerability to turning trucks. Details of curbed corner island designs used in conjunction with turning roadways are shown in Exhibits 9-37 and 9-38. [p. 628]

Why is speed not stated as a factor in the amount that a curbed island is offset from the through traffic lanes?

The approach nose of a curbed island should be conspicuous to approaching drivers and should be definitely clear of vehicle paths, physically and visually, so that drivers will not shy away from the island. The offset from the travel lane to the approach nose should be greater than that to the face of the curbed island, normally about 0.6 m [2 ft]. For curbed median islands, the face of curb at the approach island nose should be offset at least 0.6 m [2 ft] and preferably 1.0 m [3 ft] from the normal median edge of the traveled way. Where a curbed corner island is proposed on an approach roadway with shoulders, the face of curb on the corner island should be offset by an amount equal to the shoulder width. If the corner island is preceded by a right-turn deceleration lane, the shoulder offset should be at least 2.4 m [8 ft]. [p. 629]

Curbed corner islands and median noses should be ramped down as shown in Exhibit 9-39 and provided with devices to give advance warning to approaching drivers, especially for nighttime driving. Delineation is especially pertinent at the approach nose of a *divisional island. In rural areas, the approach should consist of a gradual widening of the divisional island as indicated in Exhibit 9-40. The transition section should be as long as practical. The cross sections in Exhibit 9-40 demonstrate the transition. The face of curb at the approach island nose should be offset at least 0.5 m [2 ft] and preferably 1 m [3 ft] from the normal edge of traveled way and gradually transitioned to the normal width toward the crossroad.* [p. 629]

Exhibit 9-40 shows the transition from a four-lane undivided road to a four-lane divided road on an intersection approach. No dimensions are given for the transition, it is just stated that it should be as long as practical. Better guidance is necessary for transitions such as these and those from a two-lane highway to a four-lane divided highway. What distances are necessary for the transition as well as from the transition to the nearest intersection?

<u>Turning Roadways with Corner Islands:</u>

Where the inner edges of the traveled way for right turns are designed to accommodate semitrailer combinations, where the design permits passenger vehicles to turn at speeds of 15 km/h [10 mph] or more, or where oblique angle crossings occur, the pavement area within the intersection may become excessively large and consequently does not provide for the proper control of traffic. To avoid this condition, a corner island can be provided to form a separate turning roadway between the two intersection legs. [p. 634]

As mentioned previously, when these "pork-chop" island designs are used on minor road approaches at rural expressway intersections without adequate acceleration lanes provided on the expressway, safety problems may arise.

<u>Turning Roadways with Corner Islands (Right-Angle Turns):</u>

The principal controls for the design of turning roadways are the alignment of the traveled way edge and the turning roadway width. These design features ensure that a vehicle can be accommodated while turning at the selected turning roadway speed. With radii greater than the minimum edge of traveled way, controls result in an area large enough for a triangular island to be designed. Such an island is desirable for delineating the path of through and turning traffic, for the placement of signs, and for providing a refuge for pedestrians and bicycles. [p. 634]

Based on general observations, such island designs are more desirable for exiting the expressway than for entering the expressway, especially if a right-turn acceleration lane from the minor road onto the expressway is not provided. Without such acceleration lanes, these designs increase skew for the waiting or stopped right-turning minor road driver and can create sight distance obstructions if a through or left-turning minor road vehicle is stopped on the same approach.

A turning roadway should be designed to provide at least the minimum size island and the minimum width of roadway. Generally, the turning roadway width should not be less than 4.2 m [14 ft]. When the turning roadway is designed for a semitrailer combination, a much wider roadway is needed. Exhibit 9-41 shows minimum turning roadway designs *for a 90-degree right turn. At locations where a significant number of semitrailer combinations, particularly the longer units, will be turning, the arrangement shown in Exhibit 9-41C should be used. The designer should reference the truck turning templates in Chapter 2 to meet his or her design needs. In rural areas, the use of painted corner islands may be considered. For each minimum design shown in Exhibit 9-41, a three-centered compound curve is recommended.* [p. 634, 637]

Turning Roadways with Corner Islands (Oblique-Angle Turns):

The minimum design dimensions for oblique-angle turns are determined on a basis similar to that for right-angle turns and values are given in Exhibit 9-42. For a particular intersection, the designer may choose from the three minimum designs shown in accordance with vehicle size, the volume of traffic anticipated, and the physical controls at the site. If practical, angles of intersection less than 75 degrees should not be used. For flat angles of turn, the design of turning roadways involve relatively large radii and are not considered in the minimum class. Such turning angles should have individual designs to fit site controls and traffic conditions. [p. 637, 639]

The information provided here contradicts the information provided earlier regarding intersection angle. Earlier, the Green Book stated that angles of 60 degrees provide most of the benefits of a 90 degree angle. Here it states that angles less than 75 degrees should not be used, if practical.

Free-Flow Turning Roadways at Intersections:

An important part of the design on some intersections is the design of a free-flow alignment for right turns. Ease and smoothness of operation can result when the free-flowing turning roadway is designed with compound curves preceded by a right-turn deceleration lane, as indicated in Exhibits 9-43B and 9-43C. The shape and length of these curves should be such that they: (1) allow drivers to avoid abrupt deceleration, (2) permit development of some superelevation in advance of the maximum curvature, and (3) enable vehicles to follow natural turning paths. The design speed of a free-flow turning roadway for right turns may vary between the end of the right-turn deceleration lanes and the central section. The design speed of the turning roadway may be equal to, or possibly within 20 to 30 km/h [10 to 20 mph] less, than the through roadway design speed. Refer to Exhibits 3-25 through 3-29 for minimum radii for right-turning traffic. Turning roadways at intersections should use the "upper range" design speeds whenever practical although the "middle range" speeds may be used in constrained situations. [p. 639]

The safety effects of installing free-flow right-turn lanes at expressway intersections are unknown. Warrants or considerations for their use at expressway intersections need to be developed.

Superelevation for Turning Roadways at Intersections:

The general factors that control the maximum rates of superelevation for open highway conditions as discussed in Chapter 3 also apply to turning roadways at intersections.

When speed is not affected by other vehicles, drivers on turning roadways anticipate the sharp curves and accept operation with higher side friction than they accept on open highway curves of the same radii. This behavior stems from their desire to maintain their speed through the curve. In designing for safe operation, periods of light traffic volumes and corresponding speeds will generally control. [p. 639, 642]

Designs with gradually changing curvature, affected by the use of compound curves, spirals, or both, permit desirable development of superelevation. For these designs, the design superelevation rates and corresponding radii listed in Exhibits 3-25 through 3-29 are desirable and can be used when conditions justify the conservative use of superelevation. [p. 642]

The principles of superelevation runoff design discussed in Chapter 3 generally apply to free-flowing turning roadways at intersections. In general, the rate of change in cross slope in the runoff section should be based on the maximum relative gradients listed in Exhibit 3-30. The values listed in this table are applicable to a single lane of rotation. The effective maximum relative gradients that can be used for a range of turning roadway widths are listed in Exhibit 9-44. Usually, the profile of one edge of the traveled way is established first, and the profile on the other edge is developed by stepping up or down from the first edge by the amount of desired superelevation at that location. [p. 642]

Superelevation commensurate with curvature and speed seldom is practical at terminals where: 1) a flat intersection curve results in little more than a widening of the traveled way, 2) it is desirable to retain the cross slope of the traveled way, and 3) there is a practical limit to the difference between the cross slope on the traveled way and that on the intersection curve. [p. 642]

For design of a highway, the through traffic lanes may be considered fixed in profile and cross slope. Shortly beyond the point where the full width of the turning roadway is attained, an approach nose separates the two pavements. Where the exit curve is relatively sharp and without taper or transition, little superelevation in advance of the nose can be developed in the short distance available. Beyond the nose substantial superelevation usually can be attained, the amount depending on the length of the turning roadway curve. The method of developing superelevation at turning roadway terminals is illustrated diagrammatically in Exhibits 9-45 through 9-48. The discussion and arrangements illustrated in Exhibits 9-45 through 9-48 for exit terminals are also directly applicable to entrance terminals, except that the details at the merging end are different from those of an approach nose. [p. 643, 647]

The design control at the crossover line (not to be confused with the crown line normally provided at the centerline of a roadway) is the algebraic difference in cross slope rates of the two adjacent lanes. The suggested maximum differences related to the speed of turning traffic are given in Exhibit 9-49. The attainment of superelevation over the gradually widening auxiliary lane and over the whole of the turning roadway terminals should not be abrupt. The design should be in keeping with the cross-slope controls, given in Exhibit 9-49. [p. 648]

Traffic Control Devices:

Traffic control devices are used to regulate, warn, and guide traffic and are a primary determinant in the efficient operation of intersections. It is essential that intersection design be accomplished simultaneously with the development of signal, signing, and pavement marking plans to ensure that sufficient space is provided for proper installation of traffic control devices. Geometric design should not be considered complete, nor should it be implemented until it has been determined that needed traffic devices will have the desired effect in controlling traffic. [p. 649, 650]

This is another reason why traffic signals should not be installed at rural expressway intersections. It has not yet been determined whether their installation will have the desired effect in controlling traffic and improving safety. More research needs to be conducted to determine under what conditions traffic signals will improve safety at rural expressway intersections.

Most of the intersection types illustrated and described in the following discussions are adaptable to either signing control, signal control, or a combination of both. At intersections that do not need signal control, the normal roadway widths of the approach highways are carried through the intersection with the possible addition of speed-change lanes, median lanes, auxiliary lanes, or pavement tapers. Geometric features that may be affected by signalization are number of lanes, length and width of storage areas, location and position of turning roadways, spacing of other subsidiary intersections, access connections, and the possible location and size of islands to accommodate signal posts or supports. [p. 650]

In the first sentence, what does a combination of both mean?

All of these geometric features may be affected by signalization, but no guidance is given in the Green Book as to how these features should be modified to accommodate signalization. Is this given in the MUTCD?

At high volume intersections, the design of the signals should be sophisticated enough to respond to the varying traffic demands, the objective being to keep the vehicles moving through the intersection. An intersection that needs traffic signal control is best designed by considering jointly the geometric design, capacity analysis, design hour volumes, and physical controls. Details on the design and location of most forms of traffic control signals, including the general warrants, are given in the MUTCD. [p. 650]

Signals that respond to varying traffic demands are also important at low volume signalized intersections.

Intersection Sight Distance (General Considerations):

Each intersection has the potential for several different types of vehicular conflicts. The possibility of these conflicts actually occurring can be greatly reduced through the *provision of proper sight distances and appropriate traffic controls. The provision of stopping sight distance at all locations along each highway or street, including intersection approaches, is fundamental to intersection operation. Sight distance is provided at intersections to allow drivers to perceive the presence of potentially conflicting vehicles. This should occur in sufficient time for a motorist to stop or adjust their speed, as appropriate, to avoid colliding in the intersection. The methods for determining the sight distances needed by drivers approaching intersections are based on the same principles as stopping sight distance, but incorporate modified assumptions based on observed driver behavior at intersections.* [p. 650, 651]

The driver of a vehicle approaching an intersection should have an unobstructed view of the entire intersection, including any traffic control devices, and sufficient lengths along the intersecting highway to permit the driver to anticipate and avoid potential collisions. The sight distance needed under various assumptions of physical conditions and driver behavior is directly related to vehicle speeds and to the resultant distances traversed during perception-reaction time and braking. Sight distance is also provided at intersections to allow the drivers of stopped vehicles a sufficient view of the intersecting highway to decide when to enter the intersecting highway or to cross it. If the available sight distance for an entering or crossing vehicle is at least equal to the appropriate stopping sight distance for the major road, then drivers have sufficient sight distance to anticipate and avoid collisions. However, in some cases, this may require a major road vehicle to stop or slow to accommodate the maneuver by a minor road vehicle. To enhance traffic operations, intersection sight distances that exceed stopping sight distances are desirable along the major road. [p. 651]

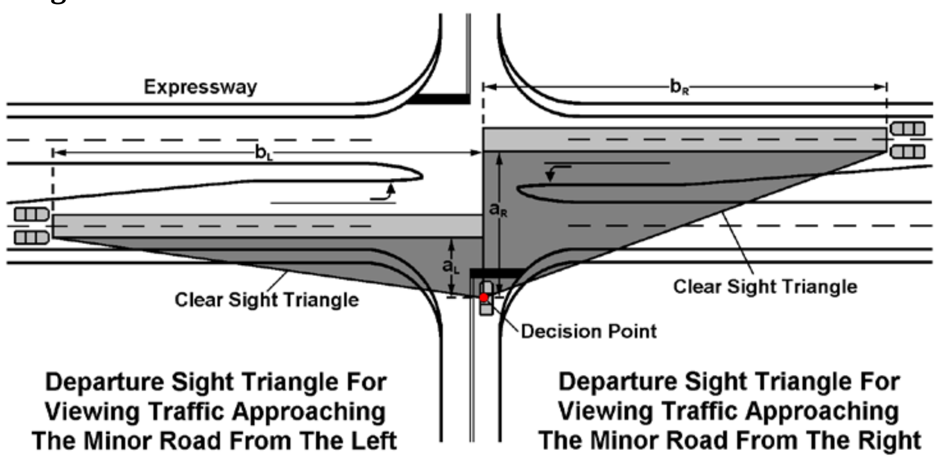
At two-way stop-controlled expressway intersections, it would seem that a minor road driver needs more sight distance than the stopping sight distance for the major road, especially where adequate vehicle storage is not provided in the median and the minor road driver attempts to cross both one-way roadways in one maneuver. The stopping sight distance of the major road driver is calculated based on the distance that a major road driver travels during their perception-reaction time plus their required braking distance. The minimum intersection sight distance that the minor road driver actually needs should be based on the distance the major road driver will travel in the time that the minor road driver takes to decide to enter the intersection and accelerate through the major road driver's projected path.

Intersection Sight Distance (Sight Triangles):

Specified areas along intersection approach legs and across their included corners should be clear of obstructions that might block a driver's view of potentially conflicting vehicles. These specified areas are known as clear sight triangles. The dimensions of the legs of the sight triangles depend on the design speeds of the intersecting roadways and the type of traffic control used at the intersection. These dimensions are based on observed driver behavior and are documented by space-time profiles and speed choices of drivers on intersection approaches. Two types of clear sight triangles are considered in intersection design; approach sight triangles and departure sight triangles. [p. 651]

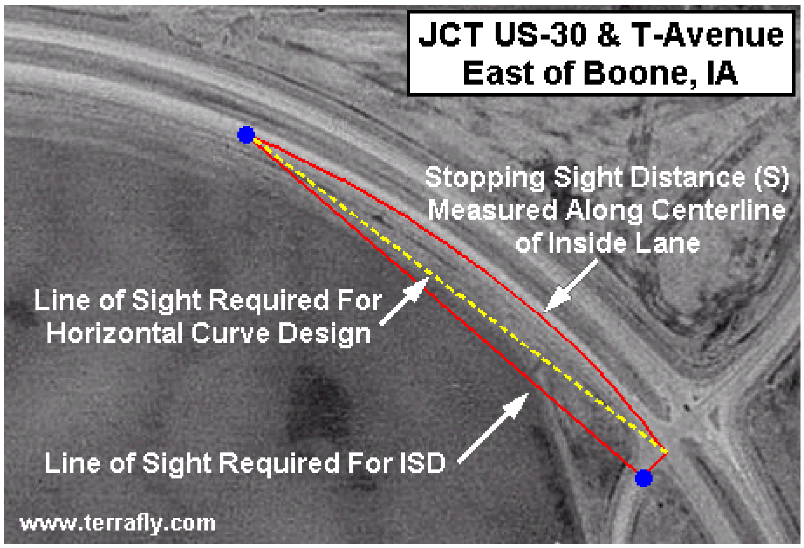
Although desirable at higher volume intersections, approach sight triangles like those shown in Exhibit 9-50A are not needed for intersection approaches controlled by stop signs or traffic signals. Departure sight triangles, as shown in Exhibit 9-50B, provide sight distance sufficient for a stopped driver on a minor road approach to depart from the intersection and enter or cross the major road. Departure sight triangles should be provided in each quadrant of each intersection approach controlled by stop or yield signs. Departure sight triangles should also be provided for some signalized intersection approaches. The recommended dimensions of the clear departure sight triangle for desirable traffic operations where stopped vehicles enter or cross a major road are based on assumptions derived from field observations of driver gap-acceptance behavior. The provision of clear departure sight triangles also allow the drivers of vehicles on the major road to see any vehicles stopped on the minor road approach and to be prepared to slow or stop, if necessary. [p. 652, 653]

The intersection departure sight triangles shown in Exhibit 9-50B are for a two-lane undivided major road. The departure sight triangles to consider at an expressway intersection are slightly different and the following figure should be added within Exhibit 9-50 for better guidance.



The profiles of the intersecting roadways should be designed to provide the recommended sight distances for drivers on the intersection approaches. Within a sight triangle, any object at a height above the elevation of the adjacent roadways that would obstruct the driver's view should be removed or lowered, if practical. The determination of whether an object constitutes a sight obstruction should consider both the horizontal and vertical alignment of both intersecting roadways, as well as the height and position of the object. In making this determination, it should be assumed that the driver's eye is 1080 mm [3.5 ft] above the roadway surface and that the object to be seen is 1080 mm [3.5 ft] above the surface of the intersecting road. This object height is based on a vehicle height of 1330 mm [4.35 ft], which represents the 15th percentile of vehicle heights in the current passenger car population less an allowance of 250 mm [10 in]. This allowance represents a near maximum value for the portion of a passenger car height that needs to be visible for another driver to recognize it as the object. The use of an object height equal to the driver eye height makes intersection sight distances reciprocal (i.e., if one driver can see another vehicle, then the driver of that vehicle can also see the first *vehicle). Where the sight distance value used in design is based on a single-unit or combination truck as the design vehicle, it is also appropriate to use the eye height of a truck driver in checking sight obstructions. The recommended value of a truck driver's eye height is 2330 mm [7.6 ft] above the roadway surface.* [p. 653, 654]

The presence of horizontal curvature on the major approach changes the shape of the required clear departure sight triangle and can increase the area in which roadside obstructions need to be removed. Roadway designers should check actual site conditions at intersections on horizontal curves to make sure adequate intersection sight distance has been provided because designing horizontal curves using the stopping sight distance criteria presented in Exhibit 3-54 does not guarantee that intersection sight distance requirements will be met as shown in the following figure:



<u>Intersection Sight Distance (Intersection Control):</u>

The recommended dimensions of the sight triangles vary with the type of traffic control used at an intersection because different types of control impose different legal constraints on drivers and, therefore, result in different driver behavior. Procedures to determine sight distances at intersections are presented according to different types of traffic control, as follows: [p. 654]

Case A: Intersections with no control
Case B: Intersections with stop control on the minor road
- *Case B1: Left turn from the minor road*
- *Case B2: Right turn from the minor road*
- *Case B3: Crossing maneuver from the minor road*

Case C: Intersections with yield control on the minor road
- *Case C1: Crossing maneuver from the minor road*
- *Case C2: Left or right turn from the minor road*

Case D: Intersections with traffic signal control
Case E: Intersections with all-way stop control
Case F: Left turns from the major road

Case A is not applicable at expressway intersections; therefore no comments have been made on this case.

Case B – Intersections with Stop Control on the Minor Road:

Intersection sight distance criteria for stop-controlled intersections are longer than stopping sight distance to ensure that the intersection operates smoothly. Minor road vehicle operators can wait until they can proceed safely without forcing a major road vehicle to stop. [p. 657]

Case B1 – Left Turn from the Minor Road (Stop Control):

Departure sight triangles for traffic approaching from either the right or the left should be provided for left turns from the minor road onto the major road for all stop-controlled approaches. The length of the leg of the departure sight triangle along the major road in both directions is the recommended intersection sight distance for Case B1. The vertex (decision point) of the departure sight triangle on the minor road should be 4.4 m [14.5 ft] from the edge of the major road traveled way. Field observations of vehicle stopping positions found that, where necessary, drivers will stop with the front of their vehicle 2.0 m [6.5 ft] or less from the edge of the major road traveled way. Measurements of passenger cars indicate that the distance from the front of the vehicle to the driver's eye for the current U.S. passenger car population is nearly always 2.4 m [8 ft] or less. Where practical, it is desirable to increase the distance from the edge of the major road traveled way to the vertex of the clear sight triangle from 4.4 m to 5.4 m [14.5 ft to 18 ft]. This increase allows 3.0 m [10 ft] from the edge of the major road traveled way to the front of the stopped vehicle, providing a larger sight triangle. The length of the sight triangle along the minor road (distance a in Exhibit 9-50B) is the sum of the distance from the major road plus 1/2 lane width for vehicles approaching from the left, or 1-1/2 lane width for vehicles approaching from the right. [p. 657, 659]

Field observations found that drivers will stop with the front of their vehicle 6.5 ft or less from the edge of the major road traveled way. Is this distance different at a divided highway where shoulder widths are typically 8 to 10 ft and where stop-bars are sometimes located much further from the edge of the divided highway through lanes? For departure sight triangles at expressway intersections the 18 ft distance from the edge of the major road traveled way to the vertex should be a minimum standard in design. This assumes the front of the minor road vehicle will come to a stop near the edge of the expressway shoulder.

At the same time, the minor road stop-bars at expressway intersections should be located as close to the through lanes of the divided highway as is safe to do so. In doing so, the actual base distance, a, of the departure sight triangle will be minimized and the available intersection sight distance will be maximized.

The description of the base distance, a, given above could be better described as follows: The total length of the departure sight triangle leg along the minor road for viewing traffic approaching from the left is the distance from the decision point to the center of the nearest left to right through travel lane. For viewing traffic approaching from the right, the base distance, a, is the total distance from the decision point to the center of the nearest right to left through lane.

Field observations of the gaps in major road traffic actually accepted by drivers turning onto the major road have shown that the values in Exhibit 9-54 provide sufficient time for the minor road vehicle to accelerate from a stop and complete a left turn without unduly interfering with major road traffic operations. The time gap acceptance time does not vary with approach speed on the major road. Studies have indicated that a constant value of time gap, independent of approach speed, can be used as a basis for intersection sight distance determinations. Observations have also shown that major road drivers will reduce their speed to some extent when minor road vehicles turn onto the major road. Where the time gap acceptance values in Exhibit 9-54 are used to determine the length of the leg of the departure sight triangle, most major road drivers should not need to reduce speed to less than 70 percent of their initial speed. The intersection sight distance in both directions should be equal to the distance traveled at the design speed of the major road during a period of time equal to the time gap. In applying Exhibit 9-54, it can usually be assumed that the minor road vehicle is a passenger car. However, where substantial volumes of heavy vehicles enter the major road, the use of tabulated values for single-unit or combination trucks should be considered. [p. 659]

Take a moment and think about how you select a gap at an expressway intersection. In reality, gap selection is probably a combination of speed judgment and distance judgment (depth perception) that leads to a quasi speed/distance/time gap acceptance. The method described above maintains that minor road drivers select gaps based on their <u>perceived</u> distance to oncoming vehicles as opposed to their judgment of the speed of

oncoming vehicles. This method of determining sight distance is flawed because there is also a lot of variability in the gaps that minor road drivers are willing to accept depending on driver age, driver experience, driver stress, location, traffic volume levels, trip purpose, and many other factors. I feel a better method is to determine the required sight distance based on comfortable acceleration rates of the minor road vehicle. There is less uncertainty in this method.

In addition, on expressways, left-turning minor road drivers merge with high-speed traffic in the passing lane if median acceleration lanes are not provided. Expressway drivers in the passing lane are probably not as likely, willing, or expecting to reduce their speed when minor road vehicles turn in front of them. To provide a factor of safety, sight distance should be determined based on the assumption that those oncoming expressway vehicles will maintain their speeds.

Exhibit 9-54 includes appropriate adjustments to the gap times for the number of lanes on the major road and for the approach grade of the minor road. The adjustment for the grade of the minor road approach is needed only if the rear wheels of the design vehicle would be on an upgrade that exceeds 3 percent when the vehicle is at the stop line of the minor road approach. The intersection sight distance along the major road is determined by Equation 9-1 in combination with Exhibit 9-4. No adjustment of the recommended sight distance values for the major road grade is generally needed because both the major and minor road vehicle will be on the same grade when departing from the intersection. However, if the minor road design vehicle is a heavy truck and the intersection is located near a sag vertical curve with grades over 3 percent, then an adjustment to extend the recommended sight distance based on the major road grade should be considered. [p. 659, 660]

Does this approach treat the gap acceptance behavior of drivers at undivided and divided highways separately? Not really. The gap acceptance behavior of the minor road driver is most likely different on these two roadway types. This described method of determining sight distance treats them the same with an adjustment factor for median width that treats the median as extra through lanes to be crossed. If the median width is large enough to store the design vehicle, then this method is probably appropriate. However, the gap acceptance behavior of the minor road driver is probably much different if forced to cross the near lanes and merge onto the far lanes all in one maneuver.

The approach grade of the major road would also play a role because the sight distance required is the distance the major road driver will travel during the gap time. Most of this travel distance is most likely on the intersection approach rather than on intersection departure.

Sight distance design for left turns at divided highway intersections should consider multiple design vehicles and median width. If the design vehicle used to determine sight distance for a divided highway intersection is larger than a passenger car, then sight distance for left turns will need to be checked for the selected design vehicle and for smaller design vehicles as well. [p. 661]

If the divided highway median is wide enough to store the design vehicle with a clearance to the through lanes of approximately 1 m [3 ft] at both ends of the vehicle, no separate *analysis for the departure sight triangle for left turns is needed on the minor road approach for the near roadway to the left. In most cases, the departure sight triangle for right turns (Case B2) will provide sufficient sight distance for a passenger car to cross the near roadway to reach the median. Possible exceptions are addressed in the discussion of Case B3. If the design vehicle can be stored in the median with adequate clearance to the through lanes, a departure sight triangle to the right for left turns should be provided for that design vehicle turning left from the median roadway. Where the median is not wide enough to store the design vehicle, a departure sight triangle should be provided for that design vehicle to turn left from the minor road approach.* [p. 661]

The way this statement is worded is confusing. It should be worded more like this:

If the median is wide enough to store the design vehicle, a separate analysis should be conducted for determining the sight distance required to the left and to the right. In this situation, the critical departure sight triangle to the left in most cases will be that for right turns onto the divided highway (Case B2). Possible exceptions are addressed in the discussion of Case B3. The departure sight triangle to the right for left turns from the median can be determined as in Case C2. Where the median is not wide enough to store the design vehicle, the minor road vehicle is forced to turn left in a single maneuver. Therefore, a departure sight triangle to the left and to the right should be provided for that design vehicle to turn left from the minor road approach. This is the critical case in terms of expressway intersection safety and median storage should be provided for the design vehicle if at all possible.

The problem with this approach is that, even if there is enough room to store a vehicle in the median, a minor road driver may still decide that they are going to cross/turn left in one maneuver, without stopping in the median. Therefore, to be conservative, a designer should provide enough sight distance (to the left and right) for a minor road driver to cross or turn left from the minor road approach, without stopping in the median.

The median width should be considered in determining the number of lanes to be crossed. The median width should be converted to equivalent lanes. For example, a 7.2 m [24 ft] median should be considered as two additional lanes to be crossed in applying the multilane highway adjustment for time gaps in Exhibit 9-54. [p. 661]

This only needs to be done in determining the departure sight triangle to the right when the median is not wide enough to store the design vehicle, forcing the minor road driver to cross the near lanes and turn left onto the far roadway in one maneuver. This is a unique situation and the gap acceptance behavior of this situation should be studied more thoroughly to see if it differs from the gap selection behavior assumed in Exhibit 9-54.

Furthermore, a departure sight triangle for left turns from the median roadway should be provided for the largest design vehicle that can be stored on the median roadway with adequate clearance to the through lanes. If a divided highway intersection has a 12 m [40 ft] median width and the design vehicle for sight distance is a 22 m [74 ft] combination truck, departure sight triangles should be provided for the combination truck turning left from the minor road approach through the median. In addition, a *departure sight triangle should also be provided to the right for a 9 m [30 ft] single unit truck turning left from a stopped position in the median.* [p. 661, 663]

This statement and example should be placed a little earlier on page 661 where median storage was discussed. It would make it easier to understand. Also, the actual sight distances required for this hypothetical situation could be calculated and the calculations shown, leaving little doubt as to how to conduct this procedure.

If the sight distance along the major road shown in Exhibit 9-55, including any appropriate adjustments, cannot be provided, then consideration should be given to installing regulatory speed signing on the major road approaches. [p. 663]

<u>CASE B2 – Right Turn from the Minor Road (Stop Control):</u>

A departure sight triangle for traffic approaching from the left should be provided for right turns from the minor road onto the major road. The intersection sight distance for right turns is determined in the same manner as for Case B1, except that the time gaps in Exhibit 9-54 can be decreased by 1.0 s for right-turn maneuvers without undue interference with major road traffic. These adjusted time gaps are shown in Exhibit 9-57. When the minimum recommended sight distance for a right-turn maneuver cannot be provided, consideration should be given to installing regulatory speed signing or other traffic control devices on the major road approaches. [p. 663]

<u>CASE B3 – Crossing Maneuver from the Minor Road (Stop Control):</u>

In most cases, the departure sight triangles for left and right turns onto the major road, as described for Cases B1 and B2, will also provide more than adequate sight distance for minor road vehicles to cross the major road. However, in the following situations, it is advisable to check the availability of sight distance for crossing maneuvers: [p. 663]

- *Where left and/or right turns are not permitted from a particular approach and the crossing maneuver is the only legal maneuver;*
- *Where the crossing vehicle would cross the equivalent width of more than six lanes; or*
- *Where substantial volumes of heavy vehicles cross the highway and steep grades that might slow the vehicle while its back portion is still in the intersection are present on the departure roadway on the far side of the intersection.*

The formula for intersection sight distance in Case B1 is used again for the crossing maneuver, except that time gaps are obtained from Exhibit 9-57. At divided highway intersections, depending on the relative magnitudes of the median width and the length of the design vehicle, intersection sight distance may need to be considered for crossing both roadways of the divided highway or for crossing the near lanes only and stopping in the median before proceeding. The application of adjustment factors for median width and grade is discussed under Case B1. [p. 666]

Where adequate sight distance is only provided for the design vehicle to cross the near lanes and then stop in the median before proceeding, median centerlines and stop bars should be provided to communicate this navigation scheme to the minor road driver.

CASE C – Intersections with Yield Control on the Minor Road:

This type of control is not used at expressway intersections on the minor road. However, yield control is used in the median and it is therefore relevant in determining intersection sight distance for left-turn or crossing maneuvers from the median roadway when adequate median storage is provided.

Drivers approaching yield signs are permitted to enter or cross the major road without stopping, if there are no potentially conflicting vehicles on the major road. Therefore, the sight distances needed by drivers on yield-controlled approaches exceed those for stop-controlled approaches. [p. 666]

CASE C1 – Crossing Maneuver from the Minor Road (Yield Control):

If the major road is a divided highway with a median wide enough to store the design vehicle for the crossing maneuver, then only crossing of the near lanes needs to be considered and a departure sight triangle for accelerating from a stopped position in the median should be provided based on Case B3. For median widths not wide enough to store the design vehicle, the crossing width should be adjusted as discussed in Case B1. [p. 667]

This statement is not clearly written and it is confusing. It is hard to determine what the Green Book is saying here and the designer must make his or her own interpretation as a result. Based on a direct interpretation of the words and the context in which they are written, it seems like the minor road has yield control and where the design vehicle can be stored in a stop-controlled median, then sight distance to the left for crossing the near lanes of the divided highway needs to be determined based on yield control. Sight distance to the right for accelerating from a stopped position in the median is then determined based on Case B3. If there is not enough storage space in the median, then sight distances to the left and right from the minor road are determined based on Case B1.

I would hope that this scenario where the minor road at a divided highway intersection is yield-controlled never occurs. Therefore, I think the Green Book is trying to describe how to determine the sight distance from a yield-controlled median here, but has failed to get the point across. I think what the Green Book wants to say here is that if the median has adequate storage space and it is yield-controlled, the sight distance to the right from the median for a crossing maneuver should be determined using Case B3 (i.e., treat the yield-controlled median as a stop-controlled median). However, there is no explanation given as to why this should be done. It was previously stated that sight distances on yield-controlled approaches should exceed what is required on stop-controlled approaches. The fact that accelerating from a complete stop in the median would be the most critical condition is the most likely explanation for this.

In addition, how should the sight distance to the right be determined for a left-turn from a yield-controlled median with adequate storage? In the next section, Case C2 –

left/right turn maneuvers from yield control, there is no mention of determining the sight distance for a left-turn from a yield-controlled divided highway median. This may be because it should be treated as Case B1, but it is not clear.

CASE C2 – Left and Right-Turn Maneuvers (Yield Control):

The leg of the approach sight triangle along the major road is similar to the major road leg of the departure sight triangle for a stop-controlled intersection in Cases B1 and B2. However, the time gaps in Exhibit 9-54 should be increased by 0.5 s to the values shown in Exhibit 9-63. The minor road vehicle needs 3.5 s to travel from the decision point to the intersection. This represents additional travel time that is needed at a yield-controlled intersection, but is not needed at a stop-controlled intersection (Case B). However, the acceleration time after entering the major road is 3.0 s less for a yield sign than for a stop sign because the turning vehicle accelerates from 16 km/h [10 mph] rather than from a stop condition. The net 0.5 s increase in travel time for a vehicle turning from a yield-controlled approach is the difference between the 3.5 s increase in travel time and the 3.0 s reduction in travel time. [p. 671]

Yield-controlled approaches generally need greater sight distance than stop-controlled approaches, especially at four-leg yield-controlled intersections where the sight distance needs of the crossing maneuver should be considered. If sight distance sufficient for yield control is not available, use of a stop sign instead of a yield sign should be considered. [p. 671]

Again, determining sight distance to the right for a left-turn from a yield-controlled median at a divided highway intersection is not addressed in this section. The case explained here is for a vehicle to turn left or right onto a two-lane undivided highway from a yield-controlled approach. Turning left from a yield-controlled median may be similar to turning right from a yield-controlled minor road. How should the sight distance to the right be determined for a left-turn from a yield controlled median?

CASE D – Intersections with Traffic Signal Control:

At signalized intersections, the first vehicle stopped on one approach should be visible to the driver of the first vehicle stopped on each of the other approaches. Left-turning vehicles should have sufficient sight distance to select gaps in oncoming traffic and complete left turns. Apart from these sight conditions, there are generally no other approach or departure sight triangles needed for signalized intersections. Signalization may be an appropriate crash countermeasure for higher volume intersections with restricted sight distance that have experienced a pattern of sight distance related crashes. [p. 671]

Signalization may or may not be an appropriate crash countermeasure at rural expressway intersections. Signalization has not been proven to be an effective crash countermeasure at these locations.

However, if the traffic signal is to be placed on two-way flashing operation (i.e., flashing yellow on the major road approaches and flashing red on the minor road approaches) *under off-peak or nighttime conditions, then the appropriate departure sight triangles for Case B, both to the left and to the right, should be provided for the minor road approaches. In addition, if right turns on red are permitted from any approach, then the appropriate departure sight triangle to the left for Case B2 should be provided to accommodate right turns from that approach.* [p. 674]

CASE E – Intersections with All-Way Stop Control:

At intersections with all-way stop control, the first stopped vehicle on one approach should be visible to the drivers of the first stopped vehicles on each of the other approaches. There are no other sight distance criteria applicable to intersections with all-way stop control and, indeed, all-way stop control may be the best option at a limited number of intersections where sight distance for other control types cannot be attained. [p. 674]

All-way stop control at rural expressway intersections is rarely used. As signals are not expected on rural expressways, stop control similarly would not be expected and would be less visible to approaching drivers than signals. This visibility issue could be remedied by the installation of flashing beacons, however. There are locations on rural expressways where all-way stop control has been installed and seemingly works well; however, the volume conditions that make this type of control workable are most likely rare on rural expressways.

CASE F – Left Turns from the Major Road:

All locations along a major highway from which vehicles are permitted to turn left across opposing traffic, including intersections and driveways, should have sufficient sight distance to accommodate the left turn maneuver. Left turning drivers need sufficient sight distance to decide when it is safe to turn left across the lane(s) used by opposing traffic. Sight distance design should be based on a left-turn by a stopped vehicle, since a vehicle that turns left without stopping would need less sight distance. The sight distance along the major road to accommodate left turns is the distance traversed at the design speed of the major road in the travel time for the design vehicle given in Exhibit 9-66. The table contains appropriate adjustment factors for the number of major road lanes to be crossed by the turning vehicle. [p. 674]

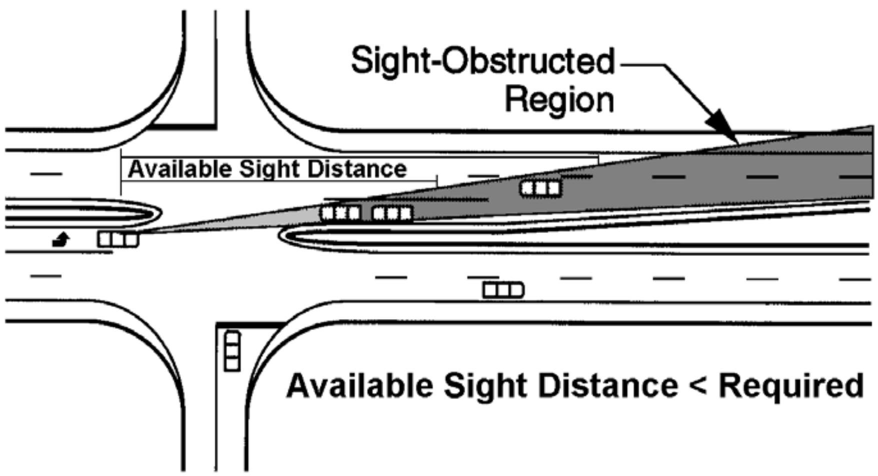
Earlier, where sight distance from a yield controlled median was discussed, it should have been worded in a similar way. That is, sight distance should be based on a stopped vehicle (left-turn or crossing), since a vehicle that does not stop would need less sight distance.

It should also be specified that the sight distance along the <u>opposing</u> major road approach required to accommodate left turns from the major road is the distance traversed at the design speed of the major road during the time gap required for the <u>left-turning</u> design vehicle given in Exhibit 9-66.

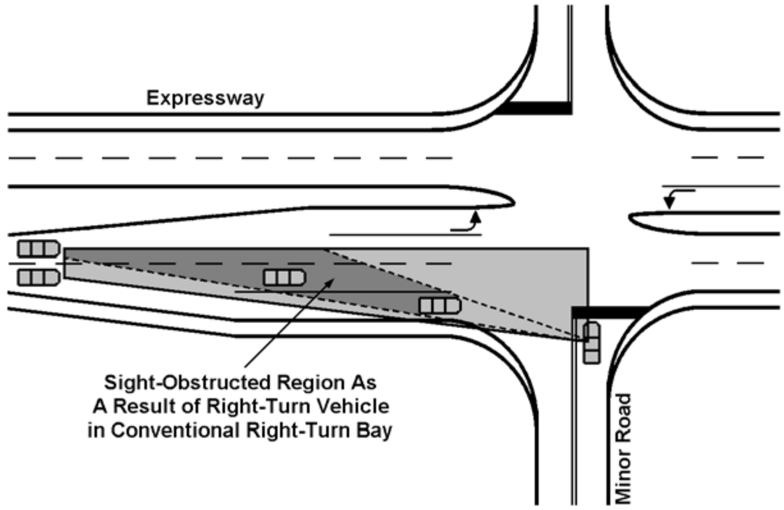
At three-leg intersections or driveways located on or near a horizontal curve or crest vertical curve on the major road, the availability of adequate sight distance for left turns from the major road should be checked. In addition, the availability of sight distance for *left turns from divided highways should be checked because of the possibility of sight obstructions in the median. At four-leg intersections on divided highways, opposing vehicles turning left can block a driver's view of oncoming traffic. Exhibit 9-98, presented later in this chapter, illustrates intersection designs that can be used to offset the opposing left turn lanes and provide left-turning drivers with a better view of oncoming traffic.* [p. 675]

At the beginning of this statement, why are three-legged intersections specified? The availability of adequate sight distance for left turns from the major road should be checked at all intersections, especially those located on horizontal and vertical curves.

Opposing left-turn vehicles can block each other's sight distance. A diagram like the one shown below may be appropriate here to clarify this condition. However, this condition does not only occur at divided highway intersections. This can occur wherever opposing left-turn lanes are constructed if the lanes are not properly offset. The goal of offsetting opposing left-turn lanes is to push the left-turn vehicles to the left as far as possible in order to improve the available sight distance. At divided highways, this can be done by offsetting the left-turn bays as shown in Exhibit 9-98. At other intersections it can be done by widening the pavement marking on the right-side of the left-turn lane.



During the Green Book's discussion of intersection sight distance, there is no mention of the sight distance problem that can be created by a right-turn vehicle positioned in a conventional right-turn lane on the mainline. This poses a problem for crossing and left/right-turning minor road vehicles on a stop-controlled approach. This problem should be presented with Case B and the solution, offset right-turn bays should be presented as well.



<u>Intersection Sight Distance (Effect of Skew):</u>

When two highways intersect at an angle less than 60 degrees, and when realignment to increase the angle of intersection is not justified, some of the factors for determination of intersection sight distance may need adjustment. Each of the clear sight triangles described are applicable to oblique-angle intersections. As shown in Exhibit 9-69, the legs of the sight triangle will lie along the intersection approaches and each sight triangle will be larger or smaller than the corresponding sight triangle would be at a right-angle intersection. The area within each sight triangle should be clear of potential sight obstructions as described previously. [p. 677]

The statement below describes the adjustment of the sight triangles for oblique angle intersections. Are these adjustments only required when the angle of intersection is less than 60 degrees? That is what the paragraph above makes it sound like. However, the need for adjustment should probably be checked at all skewed intersections, no matter the angle.

At an oblique-angle intersection, the length of the travel paths for some turning and crossing maneuvers will be increased. The actual path length for a turning or crossing maneuver can be computed by dividing the total widths of the lanes (plus the median width, where appropriate) to be crossed by the sine of the intersection angle. If the actual path length exceeds the total widths of the lanes to be crossed by 3.6 m [12 ft] or more, then an appropriate number of additional lanes should be considered in applying the adjustment for the number of lanes to be crossed shown in Exhibit 9-54 for Case B1 and in Exhibit 9-57 for Cases B2 and B3. For Case C1, the w term in the equation for the major road leg of the sight triangle to accommodate the crossing maneuver should also be divided by the sine of the intersection angle to obtain the actual path length. In the obtuse angle quadrant of an oblique-angle intersection, the angle between the approach leg and the sight line is often so small that drivers can look across the full sight triangle with only a small head movement. However, in the acute angle quadrant, drivers are often required to turn their heads considerably to see across the entire clear sight triangle. For this reason, it is recommended that the sight distance criteria for

Case A not be applied to oblique angle intersections and that sight distances at least equal to those for Case B should be provided, whenever practical. [p. 677]

This adjustment method adjusts for the increased path length (i.e., travel time) required at a skewed intersection. This adjustment increases the time-gap used in the sight distance calculation as a result. However, it does not take into account a longer decision time most likely required by drivers making a crossing or turning maneuver at an oblique angle intersection. The intersection skew introduces a complexity that makes decision-making more difficult and should be somehow accounted for in the skew adjustment factor.

No adjustments for Case C2 (left/right turn from yield controlled approach), Case D (signal control), Case E (all-way stop control), or Case F (left-turn from major road) are mentioned. No adjustment is likely necessary for Cases D or E, but this should at least be mentioned here. The adjustment for Case C2 would involve adjustment of the time gaps in Exhibit 9-63. For Case F, even though the skew doesn't affect the geometry of the sight triangle toward the opposing major approach, a longer time gap may be necessary (an adjustment to the time gaps in Exhibit 9-66) for decision-making where the left-turner is making an oblique angle turn.

<u>Stopping Sight Distance at Intersections for Turning Roadways:</u>

This section should really be entitled, "Stopping Sight Distance for Turning Roadways at Intersections" because it discusses the design of turning roadways at intersections in terms of their required stopping sight distance. This section should be relocated so that it directly follows or is placed within the section on turning roadway design (pp. 634 – 649).

The values for stopping sight distance as computed in Chapter 3 for open highway conditions are applicable to turning roadway intersections of the same design speed and are shown in Exhibit 9-70. These sight distances should be available at all points along a turning roadway; wherever practical, longer sight distances should be provided. They apply as controls in design of both vertical and horizontal alignment. [p. 678]

Because the design speed of most turning roadways is governed by the horizontal curvature and the curvature is relatively sharp, a headlight beam parallel to the longitudinal axis of the vehicle ceases to be a vertical control. Where practical, longer lengths for both crest and sag vertical curves should be used. The sight distance control as applied to horizontal alignment has an equal, if not greater, effect on design of turning roadways than the vertical control. The sight line along the centerline of the inside lane around the curve, clear of obstructions, should be such that the sight distance measured on an arc along the vehicle path equals or exceeds the stopping sight distance given in Exhibit 9-70. [p. 678, 679]

<u>Design to Discourage Wrong-Way Entry [p. 679 – 682]:</u>

This section discusses a few techniques for preventing wrong-way entry onto a freeway at an interchange terminal. This section should be moved into Chapter 10, "Grade Separations and Interchanges." However, this section in Chapter 9 could be used to describe the techniques used to prevent wrong-way entry onto a divided highway at a

divided highway intersection. This tends to be more of a problem where medians are wide. The presence of offset left-turn lanes may also increase the probability of wrong-way entry, but this has not been studied. Most of the techniques to prevent wrong-way entry involve signing, pavement marking, and intersection lighting, as discussed in the section on medians in Chapter 7, and should also be included in the MUTCD; thus, this section may not be necessary in Chapter 9 after all.

General Intersection Types:

This section discusses two different topics: 1) the factors that influence the choice of intersection type and 2) the need for left-turn lanes. The information provided regarding the selection of intersection type should be moved and/or integrated into the section at the beginning of Chapter 9 entitled, "Types and Examples of Intersections; General Considerations." The information on the need for left-turn lanes should be moved later in Chapter 9 into the section entitled, "Speed-Change Lanes at Intersections" or the section entitled, "Auxiliary Lanes; General Design Considerations."

General types of intersections and terminology are indicated in Exhibits 9-73 and 9-74. [p. 682]

Exhibit 9-73 shows an "Unchannelized T-Intersection" which was presented previously in Exhibit 9-5A as a "Plain T-Intersection." Exhibit 9-73 also shows a "T-Intersection with Right-Turn Lane" previously presented in Exhibit 9-5B. Therefore, Exhibit 9-73 is not necessary and should be removed because it does not present any new information.

The intersection presented at the top right of Exhibit 9-74 was also previously displayed in Exhibit 9-11A as a "Channelized Four-Leg Intersection." The intersection presented at the bottom right of Exhibit 9-74 was also previously displayed in Exhibit 9-9A as an "Unchannelized Four-Leg Intersection." This demonstrates the fact that Exhibit 9-74 could also be removed.

Many factors enter into the choice of type of intersection and the extent of design of a given type, but the principal controls are the design-hour traffic volume, the character or composition of traffic, and the design speed. The character of traffic and design speed affect many details of design, but in choosing the type of intersection they are not as significant as the traffic volume. Of particular significance are the actual and relative volumes of traffic involved in various turning and through movements. [p. 682]

Maybe the design speed should be a larger factor affecting the choice of intersection type. The high speed of expressways may be the decisive factor in selecting an intersection type that does not allow direct left-turns or crossing maneuvers from a minor road at an expressway intersection.

When designing an intersection, left-turning traffic should be removed from the through lanes, whenever practical. Therefore, provisions for left turn lanes have widespread application. Ideally, left turn lanes should be provided at driveways and intersections along major arterial and collector roads wherever left turns are permitted. In some *cases or at certain locations, providing for indirect left turns (jughandles, U-turn lanes, and diagonal roadways) may be appropriate to improve safety and preserve capacity. The provision of left turn lanes has been found to reduce crash rates anywhere from 20 to 65 percent. Left turn facilities should be established on roadways where traffic volumes are high enough or safety considerations are sufficient to warrant them. They are often needed to ensure adequate service levels for the intersections and the various turning movements.* [p. 682]

This paragraph transitions this section from discussing the factors that go into selecting the intersection type to a discussion of deciding when to provide left-turn lanes. This paragraph is relevant to selecting intersection type because it mentions the possibility of providing indirect left-turn treatments, but the few paragraphs that follow provide more detailed guidelines for when left-turn lanes should be provided. Later, this section goes back to discussing the selection of intersection type. All of the information on selecting intersection type should be presented together.

Where this section discusses left-turn lanes, it does not specify whether it is talking about left-turn deceleration or acceleration lanes. The reader would most likely assume deceleration, but this should be specified.

Here, the Green Book states that providing for indirect left-turns may be appropriate to improve safety and preserve capacity, but it does not specify in what cases or locations this might occur. Expressway intersections seem like a very appropriate location for the use of indirect left-turn treatments due to the high speed of expressway traffic. A later section of Chapter 9 discusses indirect left-turn treatments in more detail and more comments are provided there.

Guidelines for when left-turn lanes should be provided are set forth in several documents for both signalized and unsignalized intersections. These guidelines key the need for left-turn lanes to (a) the number of arterial lanes, (b) design and operating speeds, (c) left-turn volumes, and (d) opposing traffic volumes. The HCM indicates that exclusive left-turn lanes at signalized intersections should be installed as follows: 1) where fully protected, left-turn phasing is to be provided, 2) where space permits, left turn lanes should be considered when left-turn volumes exceed 100 vph (left-turn lanes may be provided for lower volumes on the basis of judged need and state of local practice, or both), and 3) where left-turn volumes exceed 300 vph, a double left-turn lane should be considered. Exhibit 9-75 is a guide to traffic volumes where left-turn facilities should be considered on two-lane highways. For the volumes shown, left-turns and right turns from the minor street can be equal to, but not greater than, the left-turns from the major street. Additional information on left-turn lanes, including their suggested lengths, can be found in published sources. [p. 682, 685]

Exhibit 9-75 is a guide for determining the need for left-turn lanes on two-lane highways based on volume. A similar exhibit should be created and provided for high-speed divided highways (expressways).

Local conditions and the cost of right-of-way often influence the type of intersection selected as well as many of the design details. In general, traffic service, highway design designation, physical conditions, and cost of right-of-way are considered jointly in *choosing the type of intersection. For the general benefit of through traffic movements, the number of crossroads, intersecting roads, or intersecting streets should be minimized. Traffic analysis is needed to determine whether the road or street pattern is adequate to serve normal traffic plus the traffic diverted from any terminated road or street.* [p. 685, 686]

The major functional purpose of rural high-speed expressways is mobility rather than access. Thus, minimizing the number of intersections would improve both the safety and efficiency of the facility. This can be accomplished through the provision of frontage roads as previously mentioned.

The functional classification of the road, the patterns of traffic movement at the intersections, and the volume of traffic on each approach during one or more peak periods of the day, are indicative of the type of traffic control devices necessary, the roadway widths needed (including auxiliary lanes), and the degree of channelization needed to expedite the movement of all traffic. The differing arrangement of islands and the shape and length of auxiliary lanes depend on whether signal control is provided. [p. 686]

The composition and character of traffic are a design control. Movements involving large trucks need larger intersection areas and flatter approach grades than those needed at intersections where traffic consists predominantly of passenger cars. Approach speeds of traffic also have a bearing on the geometric design as well as on control devices and markings. The number and locations of the approach roadways and their angles of intersection are major controls for the intersection geometric pattern, the location of islands, and the types of control devices. Two or more crossroads intersecting an arterial highway in close proximity should be combined into a single crossing. The distances between intersections influence the degree of channelization at any one particular intersection. Where crossroads are widely spaced, each intersection should accommodate all crossing, turning, and pedestrian movements. [p. 686]

Combining two crossroads in close proximity (how is close defined?) into a single crossing may or may not be a good idea at expressway intersections. If you have two four-legged intersections in close proximity, it probably would be a good idea to combine them into a single crossing or convert them into offset T-intersections. However, if you already have offset T-intersections, it would probably be beneficial to leave them offset and not combine them into a single crossing.

It may not be a good idea to accommodate all crossing and turning movements at widely spaced expressway intersections. Closing the median and adding U-turns downstream for crossing and left-turning traffic may improve both the safety and efficiency of the expressway. All movements would technically still be accommodated, but not directly.

<u>Channelization:</u>

This section should be placed closer to the beginning of Chapter 9, prior to the sections on turning roadways and channelizing islands, as more of an introduction to intersection design principles.

Channelization is the separation or regulation of conflicting traffic movements into definite paths of travel by traffic islands or pavement marking to facilitate the orderly movements of both vehicles and pedestrians. Proper channelization increases capacity, provides maximum convenience, and instills driver confidence. Improper channelization has the opposite effect and may be worse than none at all. Channelization of intersections is generally considered for one or more of the following factors: [p. 686, 687]

- *The paths of vehicles are confined so that not more than two paths cross at any one point.*
- *The angle and location at which vehicles merge, diverge, or cross are controlled.*
- *The amount of paved area is reduced, thereby decreasing vehicle wander and narrowing the area of conflict.*
- *Clearer indications are provided for the proper path in which movements are to be made.*
- *The predominant movements are given priority.*
- *Areas are provided for pedestrian refuge.*
- *Separate storage lanes permit turning vehicles to wait clear of through traffic lanes.*
- *Space is provided for traffic control devices so that they can be more readily perceived.*
- *Prohibited turns are controlled.*
- *The speeds of vehicles are restricted to some extent.*

Proper intersection channelization also should improve intersection safety. Rather than factors, this is more of a list of the purposes or advantages of channelization.

Design of a channelized intersection usually involves the following significant controls: the type of design vehicle, the cross sections on the crossroads, the projected traffic volumes in relation to capacity, the number of pedestrians, the speed of vehicles, and the type and location of traffic control devices. Furthermore, the physical controls such as right-of-way and terrain have an effect on the extent of channelization that is economically practical. Certain principles should be followed in the design of a channelized intersection, but the extent to which they are applied will depend on the characteristics of the total design plan. These principles are: [p. 687, 688]

- *Motorists should not be confronted with more than one decision at a time.*

Turning left onto or crossing a divided highway involves more than one decision if median storage is not provided as minor road drivers must look both ways and decide when to proceed. This is more difficult at a divided highway intersection due to the large scan area created.

- *Unnatural paths that involve turns greater than 90 degrees or sudden and sharp reverse curves should be avoided.*
- *Areas of vehicle conflict should be reduced as much as practical. However, merging and weaving areas should be as long as conditions permit. Channelization should be used to keep vehicles within well-defined paths that minimize the area of conflict.*

The "J-Turn" intersection design concept follows these principles as long as the U-turns are located far enough downstream to maximize the merging and weaving areas.

- *Traffic streams that cross without merging and weaving should intersect desirably at right angles with a range of 60 to 120 degrees acceptable.*
- *The angle of intersection between merging streams of traffic should be appropriate to provide adequate sight distance.*
- *The points of crossing or conflict should be studied carefully to determine if such conditions would be better separated or consolidated to simplify design with appropriate control devices added to ensure efficient operation.*
- *Refuge areas for turning vehicles should be provided clear of through traffic.*

This includes median storage for both major and minor road traffic.

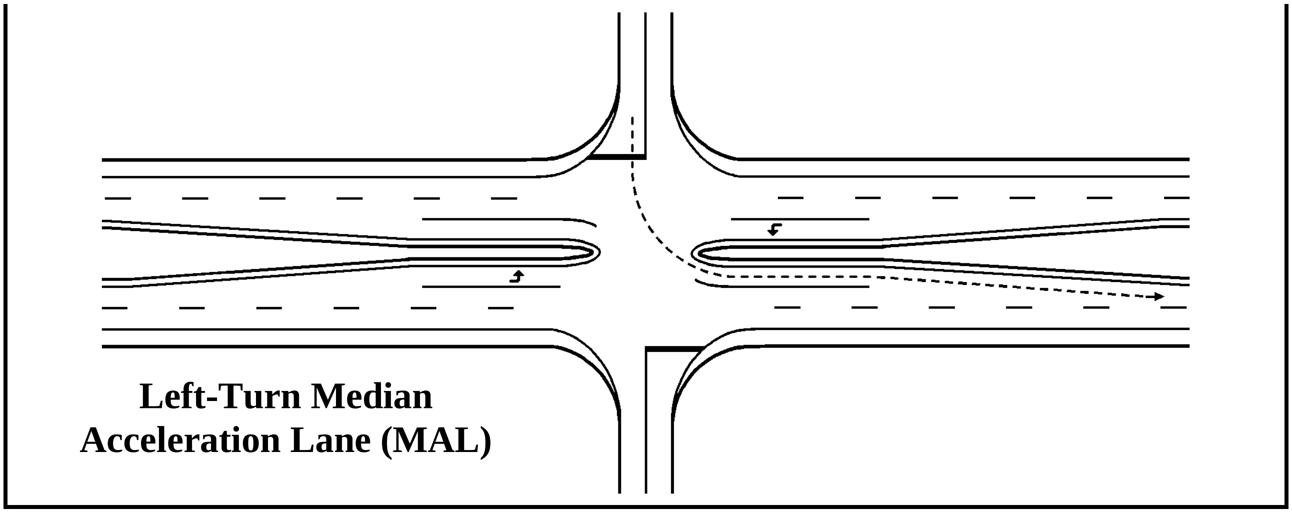
- *Islands used for channelization should not interfere with or obstruct bicycle lanes at intersections.*
- *Prohibited turns should be blocked wherever practical.*
- *Location of essential control devices should be established as part of the design of a channelized intersection.*
- *Channelization may be desirable to separate the various traffic movements where multiple phase signals are used.*

Speed-Change Lanes at Intersections:

This section is out of place and needs to be moved later in Chapter 9 and integrated into the section entitled, "Auxiliary Lanes."

This "Speed-Change Lanes" section discusses both acceleration and deceleration lanes as a single entity. However, in the context of this section, it seems more like left-turn deceleration lanes are being discussed. Within this section, deceleration and acceleration lanes should be discussed separately. A clear list of the types of lanes included in the "speed-change" lane category should be provided. Such lanes include left-turn deceleration lanes, right-turn deceleration lanes, left-turn median acceleration lanes, and right-turn acceleration lanes. Figures showing an example of each would be helpful, especially for left-turn median acceleration lanes, since designers may be least familiar with their usage and since a figure of one is not currently presented in the Green Book.

The section entitled, "Auxiliary Lanes" later in Chapter 9 primarily focuses on left-turn deceleration lanes. Left-turn median acceleration lanes probably should be discussed within a separate subsection of the "Auxiliary Lanes" section.



Drivers leaving a highway at an intersection are usually required to reduce speed before turning. Drivers entering a highway from a turning roadway accelerate until the desired open-road speed is reached. When undue deceleration or acceleration by leaving or entering traffic takes place directly on the highway traveled way, it disrupts the flow of through traffic. To preclude or minimize these undesirable aspects of operation at intersections, speed-change lanes are provided on highways having expressway characteristics and are frequently used on other main highway intersections. A speed-change lane is an auxiliary lane, including tapered areas, primarily for the acceleration or deceleration of vehicles entering or leaving the through traffic lanes. The terms "speed-change lane," "deceleration lane," or "acceleration lane," as used here, apply broadly to the added pavement joining the traveled way of the highway or street with that of the turning roadway and do not necessarily imply a definite lane of uniform width. A speed-change lane should be of sufficient width and length to enable a driver to maneuver a vehicle into it properly, and once into it, to make the necessary change between the speed of operation on the highway or street and the lower speed on the turning roadway. Deceleration and acceleration lanes may be designed in conjunction with each other, the relationship depending on the arrangement of the intersection and traffic needs. They may be designed as parts of intersections, but are especially important at ramp junctions where turning roadways meet high-speed traffic lanes. [p. 688]

Hanson (6) recommended a minimum 1000 foot length for left-turn median acceleration lanes where the mainline speed is 55 mph or greater. However, the standard length recommended by the study was 1500 feet. The length guidelines recommended by this study were based on peak hour volumes in the mainline through lane the left-turning vehicle was merging into. Lengths of deceleration lanes are discussed in more detail later in Chapter 9 in the section entitled, "Auxiliary Lanes."

(6) Hanson, C., *Median Acceleration Lane Study Report*, Minnesota Department of Transportation, District 6 Traffic Office, Rochester, MN, July 2002.

Warrants for the use of speed-change lanes cannot be stated definitely. Many factors should be considered, such as speeds, traffic volumes, percentage of trucks, capacity, *type of highway, service provided, and the arrangement and frequency of intersections.* [p. 688]

NCHRP 375 (7) recommended that left-turn median acceleration lanes be considered where adequate median width is available and the following conditions exist: 1) limited gaps available in the divided highway traffic stream, 2) left-turning traffic merges with high speed divided highway through traffic, 3) significant history of rear-end or sideswipe collisions involving left-turn vehicles entering the divided highway, 4) intersection sight distance is inadequate for left-turning vehicles entering the divided highway, and 5) there is a high volume of left-turning trucks entering the divided highway.

More specific warrants for their use should be developed. In the first condition stated, how are "limited gaps" defined? In the third condition, what is a "significant" history of collisions? In the fifth condition, what is considered a "high volume" of left-turning trucks? In addition, the second condition stated should not be included since those conditions exist at most, if not all, expressway intersections.

(7) Harwood, D.W., Pietrucha, M.T., Wooldridge, M.D., Brydia, R.E., & Fitzpatrick, K., *NCHRP 375: Median Intersection Design*, TRB, National Research Council, Washington, D.C., 1995.

Observations and considerable experience with speed change lanes have led to the following general conclusions: [p. 688, 689]

- *Speed-change lanes are warranted on high-speed and on high volume highways where a change in speed is necessary for vehicles entering or leaving the through traffic lanes.*
- *All drivers do not use speed change lanes in the same manner; some use little of the available facility. As a whole, however, these lanes are used sufficiently to improve highway operation.*

Hanson (6) studied how median acceleration lanes are utilized by left-turning drivers entering the divided highway and found similar results. Some drivers use little of the available facility, while others will use the entire length.

- *Use of speed-change lanes varies with volume, the majority of drivers using them at high volumes.*
- *The directional type of speed change lane consisting of a long taper fits the behavior of most drivers and does not require maneuvering on a reverse-curve path.*
- *Deceleration lanes on the approaches to intersections that also function as storage lanes for turning traffic are particularly advantageous, and experience with them generally has been favorable.*

Median acceleration lanes also 1) help minor road left-turning drivers select safe gaps in the expressway traffic stream by reducing their need to consider the availability of gaps in the far traffic lanes, and 2) provide additional median storage for left-turners to prevent expressway through lane encroachments. Driver education and extra signage may need to be provided so that left-turn median acceleration lanes are used properly.

A median lane provides refuge for vehicles awaiting an opportunity to turn, and thereby keeps the highway traveled way clear for through traffic. The width, length, and general design of median lanes are similar to those of any other deceleration lane, but their design includes some additional features discussed in the section on "Auxiliary Lanes" later in this chapter. [p. 689]

Deceleration lanes are always advantageous, particularly on high-speed roads, because the driver of a vehicle leaving the highway has no choice but to slow down on the through traffic lane if a deceleration lane is not provided. The failure to brake by the following drivers because of a lack of alertness causes many rear-end collisions. [p. 689]

Acceleration lanes are not always desirable at stop-controlled intersections where entering drivers can wait for an opportunity to merge without disrupting through traffic. Acceleration lanes are advantageous on roads without stop control and on all high volume roads even with stop control where openings between vehicles in the peak-hour traffic streams are infrequent and short. (For additional design guidance relative to lengths of deceleration and acceleration auxiliary lanes, refer to Chapter 10). [p. 689]

When statements like, "Acceleration lanes are not always desirable" or "Acceleration lanes are advantageous" are made, research should be referenced and an explanation given as to why this is the case.

<u>Median Openings (General Design Considerations):</u>

Medians are discussed in Chapter 4 chiefly as an element of the cross section. General ranges in width are given, and median width at intersections is treated briefly. For intersection conditions the median width, the location and length of the opening, and the design of the median end are developed in combination to fit the character and volume of through and turning traffic. Median openings should reflect street or block spacing and the access classification of the roadway. In addition, full median openings should be consistent with traffic signal spacing criteria. In some situations, median openings should be eliminated or directionalized. [p. 689]

In what situations should median openings be eliminated or directionalized?

Spacing of openings should be consistent with access management classifications or criteria. Where the traffic pattern at an intersection shows that nearly all traffic travels through on the divided highway and the volume is well below capacity, a median opening of the simplest and least costly design may be sufficient. This type of opening permits vehicles to make cross and turning movements, but in doing so, they may encroach on adjacent lanes and usually will not have a protected space clear of other traffic. Where a traffic pattern shows appreciable cross and turning movements or through traffic of high speed and high volume, the shape and width of the median opening should provide for turning movements to be made without encroachment on adjacent lanes and with little or no interference between traffic movements. [p. 689]

Where nearly all traffic travels through on the divided highway, and the median is not wide enough to store the design vehicle, this situation may lend itself to elimination of the median opening and providing a downstream U-turn. However, this recommendation should be based on research and a benefit-cost assessment. As turning movements increase from the divided highway, a median opening could be added for left-turns off the mainline only.

The design of a median opening and median ends should be based on traffic volumes, urban/rural area characteristics, and type of turning vehicles as discussed in Chapter 2. Crossing and turning traffic should operate in conjunction with the through traffic on the divided highway. Design should be based on the volume and composition of all movements occurring simultaneously during the design hours. The design of a median opening becomes a matter of considering what traffic is to be accommodated, choosing the design vehicle to use for layout controls for each cross and turning movement, investigating whether larger vehicles can turn without undue encroachment on adjacent lanes, and finally checking the intersection for capacity. If the capacity is exceeded by the traffic demand, the design must be expanded, possibly by widening or otherwise adjusting widths for certain movements. Urban/rural characteristics may influence the median width selected. Intersections in urban/suburban areas have been found to operate more safely with narrow medians, while unsignalized intersections in rural areas have been found to operate more safely with wider medians. Traffic control devices such as yield signs, stop signs, or traffic signals may be needed to regulate the various movements effectively and improve the effectiveness of operations. However, wide medians may lead to inefficient traffic signal operation. [p. 689, 690]

Urban/rural characteristics may also influence the median opening length selected. NCHRP 375 (7) found that the rate of undesirable median maneuvers significantly increased as the median opening length increased at rural unsignalized divided highway intersections. Therefore, the median opening length should be minimized at rural expressway intersections.

<u>Median Openings (Control Radii for Minimum Turning Paths):</u>

An important factor in designing median openings is the path of each design vehicle making a minimum left turn at 15 to 25 km/h [10 to 15 mph]. Where the volume and type of vehicles making the left-turn movement call for higher than minimum speed, the design may be made by using a radius of turn corresponding to the speed deemed appropriate. However, the minimum turning path at low speed is needed for minimum design and for testing layouts developed for one design vehicle for use by an occasional larger vehicle. [p. 690]

The paths of design vehicles making right turns are given in Chapter 2 and are discussed in this chapter in the section on "Types of Turning Roadways." Any differences between the minimum turning radii for left turns and those for right turns are small and are insignificant in highway design. Minimum 90 degree left-turn paths for design vehicles are shown in Exhibit 9-76. Exhibit 9-76A shows these paths positioned as they would govern median end design for vehicles leaving a divided highway. Exhibit 9-76B shows *them positioned for left turns to enter a divided highway. In both cases, it is assumed that the inner wheel of each design vehicle clears the median edge and centerline of the crossroad by 0.6 m [2 ft] at the beginning and end of the turn. The traveled way edges that most closely fit the paths of turning vehicles are transitional; however, for sharp turns at intersections, designs closely fitting these paths are three-centered curves. Design guidance for three-centered curves is discussed in the section on "Types of Turning Roadways" in this chapter. The same curves are applicable to left turns and should be used where there is a physical edge of traveled way for left turns, as in a channelized intersection and on ramps for the predominant highway.* [p. 690]

The customary intersection on a divided highway does not have a continuous physical edge of traveled way delineating the left-turn path. Instead, the driver has guides at the beginning and at the end of the left-turn operation: 1) the centerline of an undivided crossroad or the median edge of a divided crossroad, and 2) the curved median end. For the central part of the turn, the driver has the open central intersection area in which to maneuver. Under these circumstances for minimum design of the median end, the precision of compound curves does not appear necessary, and simple curves for the minimum assumed edge of left turn have been found satisfactory. The larger the simple curve radius used, the better it will accommodate a given design vehicle, but the resulting layout for the larger curve radius will have a greater length of median opening and greater paved areas than one for a minimum radius. These areas may be sufficiently large to result in erratic maneuvering by small vehicles, which may interfere with other traffic. To reduce the effective size of the intersection for most motorists, consideration should be given to providing an edge marking corresponding to the desired turning path for passenger cars, while providing sufficient paved area to accommodate the turning path of an occasional large vehicle. [p. 690, 693]

Minimizing the median opening length at rural expressway intersections has shown to improve intersection safety performance (7). Therefore, at rural expressway intersections, the minimum simple turning radius for the given left-turning design vehicle should be used in design.

By considering the range of radii for minimum right turns and the need for accommodation of more than one type of vehicle at the usual intersections, the following control radii can be used for minimum practical design of median ends: 12 m [40 ft] accommodates P vehicles suitably and occasional SU vehicles with some swinging wide, 15 m [50 ft] accommodates SU vehicles and occasional WB-12 [WB-40] vehicles with some swinging wide, and 23 m [75 ft] accommodates WB-12 [WB-40] and WB-15 [WB-50] vehicles with only minor swinging wide at the end of the turn. These relations are shown generally in Exhibits 9-77 through 9-83. [p. 693]

Median Openings (Shape of Median End):

One form of a median end at an opening is a semicircle, which is a simple design that is satisfactory for narrow medians. However, the several disadvantages of semicircular ends for medians greater than about 3.0 m [10 ft] in width are widely recognized, and other more desirable shapes are generally used. Alternate minimum designs for median ends are shown in Exhibits 9-78, and 9-81 through 9-83. The alternate minimum *designs are a semicircular end and a bullet nose form. The indicated PC of the control radius on the median edge is a common PC for both forms of median end. The bullet nose is formed by two symmetrical portions of control radius arcs and an assumed small radius (e.g., 0.6 m [2 ft] is used, to round the nose). The bullet nose design closely fits the path of the inner rear wheel and results in less intersection pavement and a shorter length of opening than the semicircular end. These advantages are operational in that the driver of the left-turning vehicle channelized for a greater portion of the path has a better guide for the maneuver, and the elongated median is better positioned to serve as a refuge for pedestrians crossing the divided highway. For medians about 1.2 m [4 ft] wide, there is little or no difference between the two forms of median end. For a median width of 3.0 m [10 ft] or more, the bullet nose is superior to the semicircular end and preferably should be used in design. On successively wider medians, the bullet nose end results in shorter lengths of openings. For median widths greater than 4.2 m [14 ft] and a 12 m [40 ft] control radius (Exhibit 9-78), the minimum length of opening to provide for cross traffic becomes a positive control. The bullet nose curves are such as to position the left-turning vehicles to turn to or from the crossroad centerline, whereas the semicircular end tends to direct the left off movement onto the opposing traffic lane of the crossroad.* [p. 697]

There is a section later in Chapter 9 (p. 722) entitled, "Median End Treatment." That section should be brought forward from its current location and integrated somewhere here during this discussion of median end design.

<u>Median Openings (Minimum Length of Median Opening):</u>

For any three or four-leg intersection on a divided highway the length of median opening should be as great as the width of crossroad traveled way plus shoulders. Where the crossroad is a divided highway, the length of opening should be at least equal to the width of the crossroad traveled ways plus that of the median. The use of a minimum length of opening without regard to the width of median or the control radius should not be considered except at very minor crossroads. Care should be taken not to make the median opening longer than necessary at rural unsignalized intersections. The minimum length of opening for U-turns is discussed later in this chapter in the section, "Indirect Left Turns and U-Turns." [p. 697, 698]

NCHRP 375 (7) should be referenced where it is stated that, "Median openings should not be longer than necessary at rural unsignalized intersections."

<u>Median Openings (Median Openings Based on Control Radii for Design Vehicles):</u>

Exhibit 9-78 shows minimum median opening designs based on a control radius of 12 m [40 ft] for a 90 degree intersection. The control radius is made tangent to the upper median edge and to the centerline of the undivided crossroad, thereby locating the semicircular median end or forming a portion of a bullet nose end. The resulting lengths of opening vary with the width of median, as shown in the tabulation on the figure **(Exhibit 9-77)**. *For each of the median widths indicated, the channelizing and area differences between the semicircular and bullet nose ends are apparent. The control radius of 12 m [40 ft] accommodates passenger vehicles making turns somewhat above* *minimum. The paths of the WB-12 [WB-40] and WB-15 [WB-50] design vehicles making minimum left turns both off and onto the divided highway are shown in Exhibit 9-78 to indicate how these large vehicles can turn at an intersection designed for passenger cars. Exhibit 9-78 indicates that minimum median openings based on a control radius of 12 m [40 ft] are not well suited for lengths of opening for two-lane crossroads because trucks cannot turn left without difficult maneuvering and encroachment on median ends or outer shoulders, or both, depending on the median width.* [p. 698, 699]

Exhibit 9-81 shows minimum median opening designs for a 90 degree intersection, based on a control radius of 15 m [50 ft]. The control radius of 15 m [50 ft] accommodates the SU design vehicle making minimum left turns without encroachment on adjacent lanes. Exhibit 9-81 indicates that minimum lengths of median openings based on a control radius of 15 m [50 ft] are suited for truck operation, except that WB-15 [WB-50] vehicles will encroach on adjacent lanes. For these cases, additional advantage is gained by using a control radius greater than 15 m [50 ft] where WB-15 [WB-50] semitrailers are expected to turn. [p. 699]

Exhibit 9-82 shows minimum median opening designs for a 90 degree intersection, which are based on a control radius of 23 m [75 ft] while Exhibit 9-83 is based on a control radius of 30 m [100 ft]. The 23 m [75 ft] control radius is sufficiently large to accommodate a WB-12 [WB-40] design vehicle, and the minimum path of the WB-15 [WB-50] vehicle indicates that it can also use this design without undue encroachments. The left-turn to leave the divided highway can be made within a two-lane crossroad. In the left-turn to enter the divided highway, the WB-15 [WB-50] vehicle would encroach on the adjacent lane about 0.5 m [2 ft]. [p. 700]

<u>Median Openings (Effect of Skew):</u>

A control radius for design vehicles as the basis for minimum design of median openings results in lengths of openings that increase with the skew angle of the intersection. Although the bullet nose end remains preferable, the skew introduces other variations in the shape of median end. At a skewed crossing, the control radius should be used in the acute angle to locate the PT on the median edge (point 1 in Exhibit 9-84). With this PT as a design control, several alternate designs that depend on the skew angle, median width, and control radius may be considered. [p. 700, 701]

Semicircular ends (A in Exhibit 9-84) result in very long openings and minor channelizing control for vehicles making a left turn with less than 90 degrees in the turning angle. A symmetrical bullet nose B with curved sides determined by the control radius and tangent at points 1 and 2 is a layout similar to those in Exhibits 9-78 and 9-81 through 9-83. This design also has little channelizing control for vehicles turning left less than 90 degrees from the divided highway. An asymmetrical bullet nose (C in Exhibit 9-84) has the most positive control and less paved area than designs A and B. The length of the opening of these alternates for a given median width decreases in the order discussed, A to C. For wide medians and a large skew, the length of openings may *not be sufficient to accommodate the crossroad and flattened ends, or an above-minimum design should be used.* [p. 701]

Exhibit 9-86 shows typical values obtained for the minimum median ends designed with a control radius of 15 m [50 ft] (the same as in Exhibit 9-81) for a range of skew angles and median widths. Lengths of openings, measured normal to the crossroad, are shown for median ends A, B, and C, as shown in Exhibit 9-84. In general, median openings longer than 25 m [80 ft] should be avoided, regardless of skew. This plan may call for special channelization, left-turn lanes, or adjustment to reduce the crossroad skew, all of which result in above minimum designs. Preferably, each skew crossing should be studied separately with trial graphical solutions on a suitable scale to permit the designer to make comparisons and choose the preferred layout. In general, the asymmetrical bullet nose end (C in Exhibit 9-84) is preferable. [p. 701, 702]

Exhibit 9-86 shows minimum lengths of median openings designed with a control radius of 15 m [50 ft] for various skew angles, median widths, and median end designs. It is stated that the median opening is measured normal to the crossroad. It may not make much of a difference, but normal to the crossroad is not the precise measurement of median opening when the intersection is skewed because the median opening is actually measured parallel to the divided highway.

For the preceding discussion the design controls for minimum median openings for left turns are summarized in Exhibit 9-85. [p. 702]

<u>Median Openings (Above-Minimum Designs for Direct Left Turns):</u>

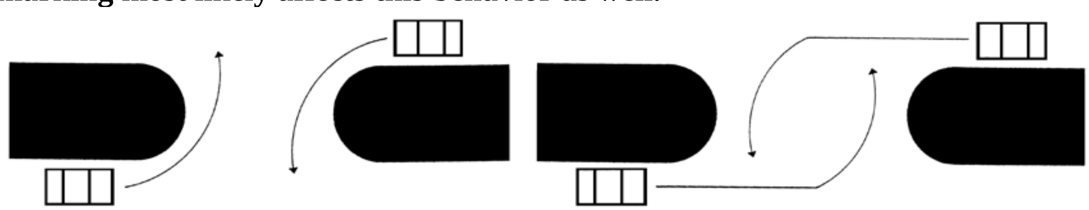
Median openings that enable vehicles to turn on minimum paths are adequate for intersections where traffic, for the most part, proceeds straight through the intersection. Where through traffic volumes and speeds are high and left-turning movements are important, undue interference with through traffic should be avoided by providing median openings that permit turns without encroachment on adjacent lanes. This arrangement would enable turns to be made at speeds above that for the minimum vehicle paths and provide space for vehicle protection while turning or stopping. The general pattern for minimum design can be used with larger dimensions. [p. 702]

A variety of median opening arrangements may be considered that depend on the control dimensions (width of median and width of crossroad, or other) and the size of vehicle to be used for design control. Median openings having above minimum control radii and bullet nose median ends are shown in Exhibit 9-87. The design controls are the three radii R, R_1, and R_2. Radius R is the control radius for the sharpest portion of the turn, R_1 defines the turnoff curve at the median edge, and R_2 is the radius of the tip. Radius R_1 may vary from about 25 to 120 m [80 to 400 ft], or more. The tabulated values shown, 30, 50, and 70 m [90, 170, and 230 ft], are established minimum radii for turning speeds of 30, 40, and 50 km/h [20, 25, and 30 mph], respectively. Radius R_2 can vary considerably, but is pleasing in proportion and appearance when it is about one-fifth of the median width. Radius R cannot be smaller than the minimum control radius for the *design vehicle, or these vehicles will be unable to turn to or from the intended lane, even at low speed. To avoid a large opening, R should be held to a reasonable minimum (e.g., 15 m [50 ft]), as used in Exhibit 9-87.* [p. 702]

The length of median opening is governed by the radii. The tabulation of values in Exhibit 9-87 shows the resultant lengths of median openings over a range of median widths for three assumed values of R_1 *and for R assumed to be 15 m [50 ft]. The median end designs in Exhibit 9-87 do not positively provide protection areas within the limits of the median width. A design using* R_1*=30 m [100 ft] or more provides space for at least a single passenger vehicle to pause in an area clear of both the through-traffic lanes and the crossroad lanes with wide medians; such radii may provide enough protection space for larger design vehicles. At skewed intersections, above minimum designs with bullet nose median ends can be applied directly. Where the skew is 10 degrees or more, adjustments in R and* R_2 *from the values shown are needed to provide the appropriate length of opening.* [p. 704]

There is a very short section (three sentences plus Exhibit 9-99) later in Chapter 9 (p. 723) entitled, "Simultaneous Left Turns." Since allowing this traffic pattern would most likely increase the median opening length, it would be considered an above minimum design. Consideration of simultaneous left-turns should be discussed at this point in the Green Book. More detail needs to be provided on when simultaneous left-turns should be considered in design and the minimum median opening length required for its implementation.

The simultaneous left-turn shown in Exhibit 9-99 assumes turn-in-front driver behavior. NCHRP 375 (7) found that opposing left-turn vehicles tend to turn in front of one another at intersections with median widths of up to 50 feet, but turn behind one another at intersections with median widths greater than 50 feet. Undoubtedly, the median opening length plays a role in this behavior as well. More research needs to be conducted on the effect of median opening length on driver behavior and whether or not turn-in-front or turn-behind left-turn maneuvers are more desirable. The presence of median pavement marking most likely affects this behavior as well.



Turn-In-Front Behavior **Turn-Behind Behavior**

More Green Book reorganization is recommended at this point. Since direct median left-turns are being discussed here, the section entitled, "Auxiliary Lanes" (p. 713–723) which mainly focuses on median left-turn lanes should be brought up to this point, preceding the section on "Indirect Left-Turns and U-Turns."

Indirect Left Turns and U-Turns (General Design Considerations):

Divided highways need median openings to provide access for crossing traffic in addition to left-turning and U-turning movements. The discussions to follow deal with *the various design methods that accommodate these movements predicated on median width. At intersections where the median is too narrow to provide a lane for left-turning vehicles and the traffic volumes, speeds, or both are relatively high, safe and efficient operation is particularly troublesome. Vehicles that slow down or stop in a lane primarily used by through traffic to turn left greatly increase the potential for rear-end collision. Other factors that should receive special consideration in design for left and U-turning movements are the turning paths of the various design vehicles in conjunction with narrow medians.* [p. 705]

The three design options presented in this section (Exhibits 9-88, 9-89, and 9-90) are for divided highway intersections where the median is not wide enough to construct left-turn lanes on the mainline. This situation would most likely occur in urban and suburban areas where right-of-way is more restricted. The purpose of these designs is to force an indirect left-turn, thereby removing left-turning traffic from the high-speed and/or high volume mainline. These designs would most likely not be successful at rural expressway intersections in terms of improving safety and should not be considered at these locations. The safety problem at these intersections seems to be gap selection by the minor road crossing and left-turning drivers. These designs attempt to replace a left-turn from the mainline with a higher risk crossing maneuver from the minor road. In addition, these designs do not prohibit the left-turn from the mainline through geometrics and the maneuver may still occur.

The design plans shown in Exhibits 9-88 and 9-89 offer two options with respect to indirect left turns and also provide for indirect U-turning movements. Exhibit 9-88 involves a jug-handle-type ramp or diagonal roadway that intersects a secondary crossing roadway. The motorist exits via the jug-handle-type ramp and makes a left turn onto the crossroad. For a U-turn maneuver, the motorist makes an additional left-turn onto the divided highway. [p. 705]

On rural expressways, the intersection design presented in Exhibit 9-88 should only be used where median widths are too narrow to construct exclusive mainline left-turn deceleration lanes. Care should be taken so that the diagonal roadway terminal at the crossroad is adequately spaced from the divided highway to allow for vehicle storage on the crossroad and efficient signal operations if future signalization is required. In addition, the diagonal roadway terminal should intersect the crossroad at as close to a right-angle as possible.

Exhibit 9-89 shows an at-grade loop that can serve as an alternate to the jug-handle-type ramp. The loop design might be considered when the jug-handle-type ramps would need costly right-of-way, the opposite quadrant being less costly. There might be other justifications in selecting the loop instead of the ramp, such as improved vertical alignment and comparative grading costs. [p. 705]

The at-grade loop option also has the disadvantage that the mainline driver wishing to make a left-turn must pass through the intersection twice; thus increasing the intersection's entering volume and increasing the probability of collisions. Again, this design should not be used in conjunction with wide medians.

Exhibit 9-90 illustrates a design that provides for indirect left turns to be made from the right, via separate turning roadways connected to a crossroad. Such arrangements have the advantage of eliminating left turns from the through lanes and providing storage for left turning vehicles not available on the highway itself. The left turning vehicles, with little extra travel distance, are able to cross the main highway with appropriate traffic control devices. Exhibit 9-90 illustrates three design options that might be adaptable to various roadway patterns. The turn from bottom to left is accomplished via the added left-turn slip ramp at the lower right (similar to previous discussions). This arrangement permits left turns onto the minor road under traffic signal protection and prevents cars making left turns from blocking the lane adjacent to the medians. Where there is a parallel roadway nearby, the added ramp may connect to it, as shown in the upper left or alternately as shown by the dashed-line connection. However, this design is less desirable because the vehicles must pass through the intersection twice and create delays by reducing speed in turning right. This delay might be overcome by the introduction of auxiliary lanes if space is available. [p. 705]

Again, this design should only be used with narrow medians that do not allow room for the construction of left-turn deceleration lanes. If an indirect left-turn is accomplished via a connection to a parallel frontage road, the frontage road should be adequately spaced from the mainline to allow for efficient intersection operations. The three intersections along the crossroad shown in Exhibit 9-90 should be spaced so that they are each able to operate independently.

<u>Indirect Left Turns and U-Turns (Using Local Streets):</u>

Highways without control of access that involve narrow non-traversable medians and where the adjacent property owners enter the divided highway by right turn only must gain access to the opposite traveled way by one of three types of operation and control. The first option is to use the interconnecting street patterns. The second alternative is to provide median openings for the individual properties. This option would defeat a major purpose of the median and would lead to complete erosion of this control feature. The third alternative is use of the design principles previously described with respect to constructing jug-handle type ramps or at-grade intersecting loops. [p. 707, 708]

This section is really not relevant to rural expressway intersections because in the case where a median opening is not directly provided at an intersection, rural expressways will normally have a median wide enough to provide a median U-turn downstream.

However, a couple of corrections are needed here. First, the first sentence here should say, "Highways with partial control of access" because that would be the purpose of a non-traversable median. Second, it should be clarified that the use of the third alternative (providing jug-handles or loops) would occur at a downstream intersection in order to provide the U-turn option.

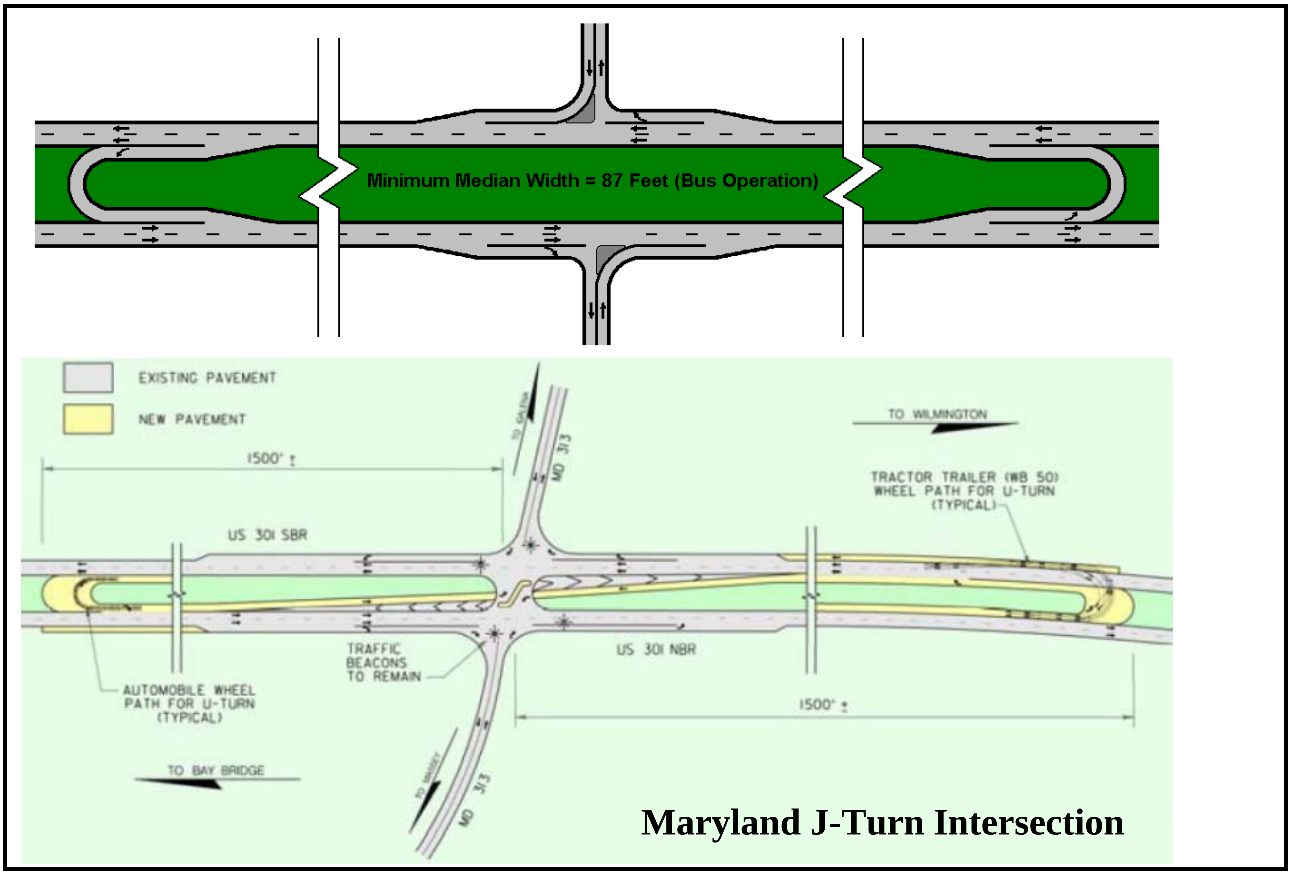
Wherever practical, a newly designed divided highway should have a median width that can accommodate normal left turns and U-turns by using a median storage lane that will protect and store the design-hour turning volume. [p. 708]

Indirect Left Turns and U-Turns (Wide Medians):

> *Exhibit 9-91 illustrates an indirect left-turn for two arterials where left-turns are heavy on both roads. The north-south roadway is undivided and the east-west roadway is divided with a wide median. Because left turns from the north-south road would cause congestion because of the lack of storage, left turns from the north-south road are prohibited at the main intersection. Left-turning traffic turns right onto the divided road and then makes a U-turn at a one-way crossover located in the median of the divided road. Auxiliary lanes are highly desirable on each side of the median between the crossovers for storage of turning vehicles. The crossover should be 120 to 180 m [400 to 600 ft] away from the intersection to allow the left-turn traffic to approach the intersection on a green signal. This scheme provides a slight increase in capacity at very little cost with no additional acquisition of right-of-way. The main disadvantage is that the left-turn traffic has to pass through the same intersection twice. This maneuver may also be confusing to motorists unfamiliar with the design and thus needs special signing. Special left-turn considerations may also be needed at major crossroads where one or more of the left-turning movements are so large that they cannot be handled by the conventional median lanes and where there is insufficient width to install two median lanes.* [p. 708, 709]

The design shown in Exhibit 9-91 should be slightly modified to be successfully used at rural expressway intersections. Two possible modified designs are shown below. As currently shown, the design in Exhibit 9-91 may prohibit direct left-turns and crossing from the minor road through signing, but it does not prohibit these maneuvers through its geometry. The major safety issue at rural expressway intersections is gap selection for minor road left-turning and crossing maneuvers. The two modified designs shown below prohibit these risky maneuvers through roadway design and force the minor road driver to turn right instead.

The first modified design shown here could be used at minor intersections where there isn't a great deal of left-turning traffic leaving the expressway. As these volumes increase, offset left-turn bays with a raised median island could be constructed as shown in the second design. Ideally, deceleration and acceleration lanes would be provided for all turning movements, the U-turns would allow the design vehicle to make the turn without encroaching on adjacent expressway lanes, and the U-turns would be spaced far enough from the main intersection to allow for safe weaving areas. The 400 to 600 feet recommended for Exhibit 9-91 most likely is not enough space for safe weaving to occur on a high speed expressway. The J-Turn Intersection, a design successfully implemented in Maryland, uses 1500 foot spacing. This issue may require further study. The J-Turn shown provides extra shoulder width to accommodate a U-turn by a WB-50 design vehicle since the median is not wide enough to do so. According to the criteria presented in Green Book Exhibit 9-92, a WB-50 design vehicle would need 71 feet (equivalent to a 95 foot median) to execute a U-turn from a 12 foot deceleration lane to a 12 foot acceleration lane.



Maryland J-Turn Intersection

<u>Indirect Left Turns and U-Turns (Location and Design of U-Turn Median Openings):</u>

Median openings designed to accommodate vehicles making U-turns only are needed on some divided highways in addition to openings provided for cross and left-turning movements. Separate U-turn median openings may fit at the following locations: [p. 709, 710]

- *Locations beyond intersections to accommodate minor turning movements not otherwise provided in the intersection or interchange area. The major intersection area is kept free for the important turning movements, in some cases, obviating expensive ramps or additional structures.*
- *Locations just ahead of an intersection to accommodate U-turn movements that would interfere with through and other turning movements at the intersection. Where a fairly wide median on the approach highway has few openings, U-turns are necessary for motorists to reach roadside areas. Advance separate openings to accommodate them outside the intersection proper will reduce interference.*
- *Locations occurring in conjunction with minor crossroads where traffic is not permitted to cross the major highway but instead is required to turn right, enter the through traffic stream, weave to the left, U-turn, and then return. On high-speed or high-volume highways, the difficulty of weaving and the long lengths involved usually make this design pattern undesirable unless the volumes intercepted are light and the median is of adequate width. This condition may occur where a crossroad with high volume traffic, a shopping area, or other*

traffic generator that needs a median opening nearby and additional median openings would not be practical.

The above seems confusing and contradictory. First it states that the design of a separate U-turn median opening is usually undesirable on high-speed or high volume highways, unless the volumes intercepted are light. Then it states that this condition may occur where a crossroad with high volume traffic needs a nearby median opening. Which is it, low intercepting traffic volumes or high?

Regardless, Maryland has successfully implemented this type of U-turn design, shown previously, on a high-speed, high volume facility. As long as the weaving areas are of adequate length and the median is wide enough, this design should be the preferred intersection design in terms of safety on rural expressways. Further research on its safety performance needs to be conducted, however.

- *Locations occurring where regularly spaced openings facilitate maintenance operations, policing, repair service of stalled vehicles, or other highway-related activities. Openings for this purpose may be needed on controlled-access highways and on divided highways through undeveloped areas.*
- *Locations occurring on highways without control of access where median openings at optimum spacing are provided to serve existing frontage developments and at the same time minimize pressure for future median openings. A preferred spacing at 400 to 800 m [0.25 to 0.50 mi] is suitable in most instances. Fixed spacing is not necessary, nor is it fitting in all cases because of variations in terrain and local service needs.*

For a satisfactory design for U-turn maneuvers, the width of the highway, including the median, should be sufficient to permit the design vehicle to turn from an auxiliary left-turn lane in the median into the lane next to the outside shoulder or outside curb and gutter on the roadway of the opposing traffic lanes. [p. 710]

Using Exhibit 9-92 and assuming 12 foot lanes with two lanes in each direction, the median width would have to be a minimum of 30 feet for a passenger car and 63 feet for a single unit truck to meet the satisfactory U-turn design criteria presented above.

Medians of 5.0 m [16 ft] and 15 m [50 ft] or wider are needed to permit passenger and single-unit truck traffic, respectively, to turn from the inner lane on one roadway to the outer lane of a two-lane opposing roadway. A median left-turn lane is highly desirable in advance of the U-turn opening to eliminate stopping on the through lanes. This scheme would increase the median width by approximately 3.6 m [12 ft]. [p. 710]

The values given here do not jive with Exhibit 9-92. Exhibit 9-92 shows medians of 18 feet and 51 feet for passenger cars and single-unit truck traffic, respectively, are required to turn from the inner lane on one roadway to the outer lane of a two-lane opposing roadway. The use of these values lead to the 30 foot and 63 foot minimum median widths given in my previous comment if left-turn deceleration lanes are provided.

Wide medians are uncommon in highly developed areas. Consequently, special U-turn designs should be considered where right-of-way is restricted, speeds are low, and signal *control is used downstream to provide sufficient gaps in the traffic stream. Median widths of 2 to 12 m [7 to 40 ft] may be used for U-turn openings to permit passenger vehicles or single unit trucks to turn from the inner lane in one direction onto the shoulder of a four lane divided highway in the other direction. This special U-turn feature can be incorporated into the design of an urban roadway section by constructing a short segment of shoulder area along the outside edge of the traveled way across from the U-turn opening. The outside curb and gutter section would then be carried behind the shoulder area and the shoulder would be designed as a pavement.* [p. 710]

This statement makes it sound like the inner lane to shoulder U-turn design path should only be considered in urban areas, where speeds are low, right-of-way is restricted, and signal control is provided downstream. The shoulder U-turn treatment shown on the Maryland J-Turn, a left-turn lane to shoulder path for a WB-50 vehicle, has seemed to work well in a rural application where speeds are high and signal control is not provided downstream. The guidance here should just be that these special U-turn designs may be used where right-of-way is restricted and wider medians cannot be provided.

Once again, the English unit values given here do not jive with Exhibit 9-92. Exhibit 9-92 shows 8 and 41 feet for a passenger car and a single-unit truck to turn from the inner lane in one direction to the shoulder of a four-lane divided highway in the other direction.

Where U-turn openings are proposed for access to the opposite side of a multilane divided street, they should be located 15 to 30 m [50 to 100 ft] in advance of the next downstream left-turn lane. [p. 710]

Does this apply for both urban and rural areas? Does this apply for all speeds? Clarification is needed.

For U-turn openings designed specifically for the purpose of eliminating left-turn movement at a major intersection, they should be located downstream of the intersection, preferably midblock between adjacent cross road intersections. This type of U-turn opening should be designed with a median left-turn lane for storage. [p. 710]

On rural expressways, intersections are typically spaced about 1 mile (5280 ft) apart, but this may vary based on DOT policy. If the U-turns are placed “mid-block”, then they will be placed approximately 2600 feet downstream. The Maryland J-Turn design used 1500 feet. Further research is necessary to determine the optimum spacing (in terms of safety and operations) between the intersection and the downstream U-turn.

Normally, U-turns should not be permitted from the through lanes. However, where medians have adequate width to shield a vehicle stored in the median opening, through volumes are low, and left-turns/U-turns are infrequent, this type of design may be permissible. Minimum widths of median to accommodate U-turns by different design vehicles turning from the lane adjacent to the median are given in Exhibit 9-92. These dimensions are for a four-lane divided facility. If the U-turn is made from a median left-turn/U-turn lane, the total median width needed would include an additional 3.6 m [12 ft] for a single median turn lane. [p. 710]

Exhibit 9-93 illustrates special U-turn designs with narrow medians. In Exhibit 9-93A, the U-turning vehicle swings right from the outer lane, loops around to the left, stops clear of the divided highway until a suitable gap in the traffic stream develops, and then makes a normal left turn onto the divided highway. In Exhibit 9-93B, the U-turning vehicle begins on the inner lane of the divided highway, crosses the through-traffic lanes, loops around to the left, and then merges with the traffic. To deter vehicles from stopping on through lanes, a left-turn lane with proper storage capacity should be provided to accommodate turning vehicles. [p. 712]

The designs presented here are not necessarily limited to use at "narrow" medians. Consider the J-Turn design shown earlier. The difference between the minimum median width required to accommodate a passenger car and a WB-50 design vehicle is significant (41 feet for all maneuvers). In order to accommodate a WB-50 design vehicle in making a U-turn from a left-turn deceleration lane (LTDL) to the opposite outside shoulder, a minimum median width of 61 feet is required. If the volumes on the mainline are large, a truck may experience significant delay when attempting to merge in this manner. The alternative designs presented in Exhibit 9-93 could be used in conjunction with the J-Turn design with a narrower median to better accommodate truck traffic. If necessary, separate U-turn lanes for cars and trucks could be provided with careful consideration of sight distance.

Minimum Median Width for U-Turn Maneuvers (Feet)				
Design Vehicle	LTDL to LTAL	LTDL to Inner Lane	LTDL to Outer Lane	LTDL to Shoulder
PC	54	42	30	20
WB-50	95	83	71	61

However, the design presented in Exhibit 9-93A should not be used at rural expressway intersections. This design would defeat the purpose of providing a J-Turn intersection because a truck would still have to make a traditional left-turn maneuver onto the expressway. The design in Exhibit 9-93B would be more conducive to intersection safety because a truck would only have to cross one set of expressway lanes and could use the diagonal portion of the jug-handle for acceleration.

<u>Flush or Traversable Medians:</u>

The foregoing discussion of design for indirect left turns and indirect U-turns with raised curb medians brings into focus the difficulties involved in providing access to abutting property, especially where such access is by commercial vehicles. These conditions are very common in commercial and industrial areas where property values are high and rights-of-way for wide medians are difficult to acquire. Under such conditions, paved flush or traversable-type medians 3.0 to 4.8 m [10 to 16 ft] wide may be the optimum type of design for left-turning vehicles. [p. 712]

<u>Auxiliary Lanes (General Design Considerations):</u>

From the foregoing discussions it is appropriate to deal with the design elements of auxiliary lanes as they relate to median openings with left-turning movements. In *general, auxiliary lanes are used preceding median openings and are also used at intersections preceding right-turning movements. Auxiliary lanes may also be added to increase capacity and improve safety at an intersection. In many cases, an auxiliary lane may be desirable after completing a right-turn movement to provide for acceleration, maneuvering, and weaving.* [p. 713]

The design elements of auxiliary lanes should be dealt with separately for each type of lane because each serves a different purpose. It should also be mentioned here that an auxiliary lane may be desirable after completing a left-turn movement onto a high-speed divided highway to provide for acceleration, maneuvering, and weaving.

Auxiliary lanes should be at least 3 m [10 ft] wide and desirably should equal that of the through lanes. Where curbing is to be used adjacent to the auxiliary lane, an appropriate curb offset should be provided. [p. 714]

What is the appropriate curb offset distance?

The length of the auxiliary lanes for turning vehicles consists of three components: 1) entering taper, 2) deceleration length, and 3) storage length. Desirably, the total length of the auxiliary lane should be the sum of the length for these three components. Common practice, however, is to accept a moderate amount of deceleration within the through lanes and to consider the taper length as a part of the deceleration within the through lanes. [p. 713, 714]

The Green Book uses the term, "Auxiliary Lanes" which would include both deceleration and acceleration lanes. Therefore, the length of auxiliary lanes consist of 1) entering/exiting taper, 2) deceleration/acceleration length, and 3) storage/ merge length. The design of acceleration and deceleration lanes and their components should differ because they serve different purposes. As such, they should be addressed separately in the Green Book.

The design of entering and exiting tapers should differ. The sole purpose of an entering taper is to guide the driver safely into a deceleration lane. While an exiting taper for an acceleration lane also guides the driver into an adjacent lane, it requires more distance to provide for a safe merging movement. Similarly, the necessary deceleration length would be different from the necessary acceleration length. Deceleration lengths should be based on friction factors and comfortable driver deceleration rates. Acceleration lengths should be based on the comfortable driver acceleration rates. Therefore, a separate discussion should be provided for the components of a deceleration lane versus an acceleration lane.

The common practice described in the above quotation goes against driver expectations on rural expressways. The expectation of drivers in the left-hand lane on rural expressways is that the lane is a passing lane and that they should not be required to slow down in that lane. This expectation is particularly pronounce when traffic volumes exceed 6000, at which point a four-lane facility is warranted (8). The question becomes how much deceleration/speed differential is allowable in the left-hand lane of a high-speed expressway in terms of safety and efficient operations? A conservative design practice should allow all of the deceleration to take place in a full width deceleration lane.

Similarly, a conservative design practice would allow all necessary acceleration to take place in a full width acceleration lane. However, to be more economical, perhaps a 10 mph difference in speed could be allowed.

(8) Nebraska Department of Roads Roadway Design Division, *Length of Deceleration Lanes Meeting Minutes*, November 2, 2005.

Auxiliary Lanes (Deceleration Length):

> *Provision for deceleration clear of the through traffic lanes is a desirable objective on arterial roads and streets and should be incorporated into design, whenever practical. The approximate total lengths needed for a comfortable deceleration to a stop from the full design speed of the highway are as follows: for design speeds of 50, 60, 70, 80, and 90 km/h [30, 40, 45, 50, and 55 mph`], the limiting deceleration lengths of auxiliary lane are 50, 70, 95, 120, and 150 m [170, 275, 340, 410, and 485 ft], respectively. These approximate lengths are based on grades of less than 3 percent.* [p. 714]

The values given here are stated as the limiting deceleration lengths and referenced to a National Highway Institute Course entitled, "Access Management, Location, and Design." The information provided here is different than what was in the 2001 Green Book, although referenced to the same source. The 2001 Green Book gives much longer deceleration lengths and states that they are the desirable deceleration lengths. It is unclear why the 2004 values are different. What has changed? It is also unclear how these values were determined. In an attempt to figure this out, the table below shows the required breaking distances based on various design speeds, a level road, and a "comfortable deceleration for most drivers" of 11.2 ft/s^2. The corresponding stopping sight distances are also shown for a reaction time of 2.5 seconds. The 2001 deceleration lengths given exceed the required stopping sight distances by 25 to 185 feet. The 2004 deceleration lengths given are less than the required stopping sight distances by 10 to 30 feet. Maybe this has something to do with the assumption of constant deceleration. It may be that people accept higher deceleration rates at lower speeds.

In the Green Book quotation above, no values are given for design speeds above 55 mph. Most rural expressways have 65 mph speed limits with larger design speeds. More guidance needs to be provided clarifying what deceleration lengths are necessary on high-speed rural expressways.

Design Speed (mph)	Braking Distance (ft) on level (< 3%) [GB EQ 3-1]	Stopping Sight Distance (ft) on level (< 3%) [GB EQ 3-2]	Stopping Sight Distance (ft) Rounded for Design [GB Exhibit 3-1]	Deceleration Length (ft) [2001 GB]	Deceleration Length (ft) [2004 GB]
30	86.4	196.6	200	230	170
40	153.6	300.6	305	330	275
45	194.4	359.7	360	430	340
50	240.0	423.7	425	550	410
55	290.3	492.5	495	680	485
65	405.5	644.4	645	Not Given	Not Given

On many urban facilities, it is not practical to provide full length auxiliary lanes for deceleration and, in many cases, the storage length overrides the deceleration length. In such cases, at least part of the deceleration must be accomplished before entering the auxiliary lane. Inclusion of the taper length as part of the deceleration distance for an auxiliary lane assumes that an approaching turning vehicle can decelerate comfortably up to 15 km/h [10 mph] in a through lane before entering the auxiliary lane. Shorter auxiliary lane lengths will increase the speed differential between turning vehicles and through traffic. A 15 km/h [10 mph] differential is commonly considered acceptable on arterial roadways. Therefore, the lengths given above should be accepted as a desirable goal and should be provided where practical. The deceleration lengths stated above are applicable to both left and right turning lanes, but the approach speed is usually lower in the right lane than in the left lane. [p. 714]

Is a 10 mph speed differential acceptable in the passing lane on a rural expressway? This may or may not meet driver expectations and therefore, the minimum lengths of the deceleration lanes should allow all of the deceleration to be accomplished within the lane and off of the through lanes. It is unclear if the deceleration length values given in the 2004 Green Book have already taken the 10 mph speed drop into account because how the values were derived is not stated. However, the values given in the 2004 Green Book may be appropriate as they are longer than the required braking distance, but shorter than stopping sight distance based on a 2.5 second reaction time. Because the deceleration maneuver is most likely planned in advance, a driver may not need a 2.5 second reaction time, and therefore, may not need the entire stopping sight distance to come to a complete stop.

<u>Auxiliary Lanes (Storage Length):</u>

The auxiliary lane should be sufficiently long to store the number of vehicles likely to accumulate during a critical period and avoid the possibility of left-turning vehicles stopping in the through lanes waiting for a signal change or for a gap in the opposing traffic flow. [p. 714]

The auxiliary lane length should also be sufficiently long so that a queue of through vehicles at a signalized intersection does not block entry into the left-turn lane. The storage length should provide sufficient space so that neither turning nor through traffic blocks the other. Maybe this condition is not economical, but it should at least be considered in design.

At unsignalized intersections, the storage length, exclusive of taper, may be based on the number of turning vehicles likely to arrive in an average two minute period within the peak hour. Space for at least two passenger cars should be provided. With over 10 percent truck traffic, provisions should be made for at least one car and one truck. The two minute waiting time may need to be changed to some other interval that depends largely on the opportunities for completing the left turn maneuver. These intervals, in turn, depend on the volume of opposing traffic. [p. 714, 715]

At signalized intersections, the storage length needed depends on the signal cycle length, the signal phasing arrangement, and the rate of arrivals and departures of left-turning *vehicles. The storage length should usually be based on 1 ½ to 2 times the average number of vehicles that would store per cycle, which is predicated on the design volume. This length will be sufficient to serve heavy surges that occur from time to time. As in the case of unsignalized intersections, provision should be made for storing at least two vehicles. Traffic signal design fundamentals are discussed further in the MUTCD.* [p. 715]

Auxiliary Lanes (Taper):

On high-speed highways, it is common practice to use a taper rate that is between 8:1 and 15:1 (longitudinal: transverse). Long tapers approximate the path drivers follow when entering an auxiliary lane from a high-speed through lane. However, long tapers tend to entice some through drivers into the deceleration lane, especially when the taper is on a horizontal curve. Long tapers constrain the lateral movement of a driver desiring to enter the auxiliary lanes. This problem primarily occurs on urban curbed roadways. [p. 715]

Which problem primarily occurs on urban curbed roadways? Long tapers entice through drivers into the deceleration lane, long tapers constrain the lateral movement of a driver desiring to enter the auxiliary lane, or both? Some states have used longer tapers on rural expressways. For example, according to the Nebraska Department of Roads Roadway Design Manual, a 20:1 taper ratio is typically used for left-turn lanes on expressways, while a 15:1 taper ratio is used for right-turn lanes on expressways. Better design guidance is necessary for the selection of an appropriate taper rate on rural expressways.

Some agencies permit the tapered section of deceleration auxiliary lanes to be constructed in a "squared-off" section at full paving width and depth. This configuration involves a painted delineation of the taper. The abrupt squared-off beginning of deceleration exits offers improved driver commitment to the exit maneuver and also contributes to driver security because of the elimination of the unused portion of long tapers. The squared-off design principle can be applied to median deceleration lanes, and it can also be used at the beginning of deceleration right-turn exit terminals when there is a single exit lane. [p. 715]

The longitudinal location along the highway where a vehicle will move from the through lane to a full-width deceleration lane will vary depending on many factors. These factors include vehicle type, driver characteristics, speeds, weather conditions, and lighting conditions. [p. 716]

Straight line tapers are frequently used, as shown in Exhibit 9-95A. The taper rate may be 8:1 for design speeds up to 50 km/h [30 mph] and 15:1 for design speeds of 80 km/h [50 mph]. A short curve is desirable at either end of long tapers as shown in Exhibit 9-95B, but may be omitted for ease of construction. Where curves are used at the ends, the tangent section should be about one-third to one-half of the total length. Symmetrical reverse curve tapers (Exhibit 9-95C) are commonly used on curbed urban streets. A more desirable reverse-curve taper is shown in Exhibit 9-95D where the turnoff curve radius is about twice that of the second curve. All the dimensions and configurations *shown in Exhibit 9-95 are applicable to right-turn lanes as well as left-turn lanes.* [p. 716]

What should the taper rate be for design speeds above 50 mph? Symmetrical reverse curve tapers have also been commonly used at rural expressway intersections. Which design performs the best in terms of safety and operations at rural expressway intersections, the straight line taper, the symmetrical reverse curve taper, or the asymmetrical reverse curve taper? The most important question here is which design most effectively guides a left-turn driver into the left-turn lane without causing undue deceleration on the through lanes? What about for a right-turn lane?

<u>Auxiliary Lanes (Median Left-Turn Lanes):</u>

A median left-turn lane is an auxiliary lane for storage or speed change of left-turning vehicles located at the left of a one-directional roadway within a median or divisional island. Inefficiencies in operations may be evident on divided highways where such lanes are not provided. Median lanes, therefore, should be provided at intersections and at other median openings where there is a high volume of left turns or where the vehicular speeds are high. Minimum designs of median openings are shown in Exhibits 9-77 through 9-84. Median lane designs for various widths of median are shown in Exhibits 9-96 and 9-97. Median widths of 6 m [20 ft] or more are desirable at intersections with single median lanes, but widths of 4.8 to 5.4 m [16 to 18 ft] permit reasonably adequate arrangements. [p. 716]

A left-turn median acceleration lane (MAL) qualifies as a median left-turn lane and should at least be mentioned at this point.

For medians 5.4 m [18 ft] wide or more, a flush, color-contrasted divider is recommended to delineate the area between the turning lane and the adjacent through lane in the same direction of travel. Pavement markings, contrasting pavement texture, signs, and physical separators may be used to discourage the through driver from inadvertently entering the wrong lane. [p. 722]

At this point, the Green Book has not yet introduced the concept of offset left turn lanes. Therefore, the statement, "A flush divider is recommended to delineate the area between the turning lane and the adjacent through lane in the <u>same</u> direction of travel" does not make sense. Do they mean the opposite direction of travel, implying that the median should be flush, or are they implying the concept of offset left turn lanes?

Later, when offset left-turn lanes are discussed, comments will be provided regarding different materials used to effectively delineate left-turn lanes.

<u>Auxiliary Lanes (Median End Treatment):</u>

The form of treatment given the end of the narrowed median adjacent to lanes of opposing traffic depends largely on the available width. The narrowed median may be curbed to delineate the lane edge, to separate opposing movements, to provide space for signs, markers, and luminaire supports, and to protect pedestrians. To serve these purposes satisfactorily, the minimum narrowed median width of no less than 1.2 m [4 ft] *is recommended and is preferably 1.8 to 2.4 m [6 to 8 ft] wide. For curbed dividers 1.2 m [4 ft] or more in width at the narrowed end, the curbed nose can be offset from the opposing through traffic lane 0.6 m [2 ft] or more with gradual taper beyond to make it less vulnerable to contact by through traffic as shown in Exhibit 9-96B. The shape of the nose for curbed dividers 1.2 m [4 ft] wide usually is semicircular, but for a wider width the ends are normally shaped to a bullet nose pattern to conform better with the paths of turning vehicles.* [p. 722, 723]

The median may also be flush or depressed and serve the same purposes. Which median type performs best in terms of rural expressway intersection safety?

Auxiliary Lanes (Offset Left-Turn Lanes):

For medians wider than about 5.4 m [18 ft], it is desirable to offset the left-turn lane so that it will reduce the width of the divider to 1.8 to 2.4 m [6 to 8 ft] immediately before the intersection, rather than to align it exactly parallel with and adjacent to the through lane. This alignment will place the vehicle waiting to make the turn as far to the left as practical, maximizing the offset between the opposing left-turn lanes, and thus providing improved visibility of opposing through traffic. The advantages of offsetting the left-turn lanes are 1) better visibility of opposing through traffic, 2) decreased possibility of conflict between opposing left-turn movements within the intersection, and 3) more left-turn vehicles served in a given period of time, particularly at a signalized intersection. [p. 723]

At some wider median width, which should be determined and stated here, the use of offset left-turn bays becomes pointless in terms of improving sight distance because left-turning expressway vehicles could simply use the conventional left-turn lane to turn onto the median roadway and wait perpendicular to the opposing expressway through lanes (see the picture of the expressway on the back cover of the Green Book for an example of this wide median condition). In this case, opposing left-turn vehicles would be stored side-by-side and would not pose a sight distance issue to each other while waiting for gaps in expressway traffic unless excessive median queues build up. Offset left-turn bays would still help increase vehicle storage areas if dealing with excessive queues in this scenario.

Besides improving sight distance, two other advantages of using offset left-turn lanes are as follows: 1) they move a stopped left-turning vehicle waiting to turn off the expressway further away from high-speed expressway through traffic, reducing the potential for same direction sideswipe or rear-end collisions, and 2) they can increase the available storage area within the median (without increasing the median width) for both left-turning traffic from the expressway and for through/left-turning traffic from the minor road.

The safety effectiveness of providing offset left-turn lanes on high-speed expressways has not been studied. Research needs to be conducted to determine the safety benefits of installing these lanes. More specific warrants for their use need to be developed, which would most likely be based on left-turn volumes, opposing expressway volumes, truck percentages, left-turn leaving crash history, and approach geometrics.

Three disadvantages of the use of offset left-turn lanes should also be mentioned. First, their use may make it more difficult for minor road drivers to recognize the divided

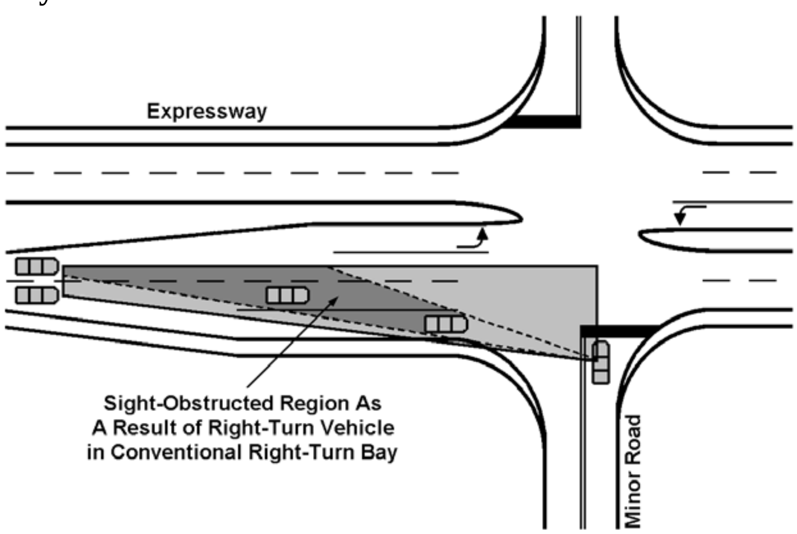
highway, thus increasing the probability of wrong-way entries onto the expressway. As previously mentioned, the use of intersection lighting, wrong-way pavement markers, proper signage, and left-turn pavement extensions from the minor approach may be required in conjunction with their use at rural expressway intersections to prevent wrong way entry. A second disadvantage to the use of offset left-turn bays was discovered by Schurr et al. (9). This study showed that offset left-turn bays seem to encourage left-turn drivers to slow down more in the passing lane of the expressway prior to entering the bay than traditional left-turn bays do. The larger speed differentials on the expressway mainline created by this behavior are expected to lead to an increase in rear-end crashes as compared to conventional left-turn bay designs. Geometrics (as will be discussed a little later), signage, and driver education could possibly be used to encourage left-turning expressway traffic to decelerate in the offset left-turn bay rather than in the passing lane of the expressway. A final disadvantage of the use of offset left-turn bays may be improper usage of the lanes as shown in the next figure. This operational issue may be corrected through driver education, improved advance signage, and better delineation of the offset with improved pavement marking or the use of materials that provide better contrast, such as turf.

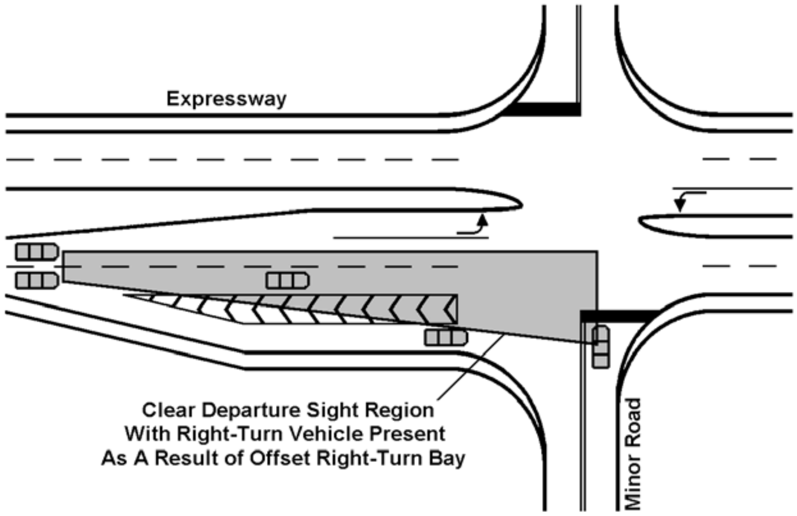
(9) Schurr, K.S., McCoy, P.T., Pesti, G., Egelhoff, A.T., & Burdick, R., *Deceleration Lanes on Left-Turn Bays of Four-Lane Expressways: Final Report*, Nebraska Department of Roads Project No. SPR-PL-1(038) P537, University of Nebraska-Lincoln, December 2003.

Parallel offset left-turn lanes may be used at both signalized and unsignalized intersections. This left-turn lane configuration is illustrated in Exhibit 9-98A. An offset between opposing left-turn vehicles can also be achieved with a left-turn lane that *diverges from the through lanes and crosses the median at a slight angle. Exhibit 9-98B illustrates a tapered offset left-turn lane of this type. Tapered offset left-turn lanes provide the same advantages as parallel offset left-turn lanes in reducing sight distance obstructions and potential conflicts between opposing left-turn vehicles and in increasing the efficiency of signal operations. Tapered offset left-turn lanes are normally constructed with a 1.2 m [4 ft] nose between the left turn lane and the opposing through lanes. Tapered offset left turn lanes have been used primarily at signalized intersections. This type offset is especially effective for turning radii allowance where trucks with long rear overhangs are turning from the mainline roadway. This same type of offset geometry may also be used for trucks turning right with long rear overhangs.* [p. 723]

Both parallel and tapered offset left-turn lane designs have been used at rural expressway intersections, signalized and unsignalized. Which design is preferred at rural expressway intersections in terms of safety and operations? If there is no difference, which design is cheaper to construct? Further study is necessary to make these determinations.

Both the parallel and tapered offset designs can be used to create offset right turn lanes. Offset right turn lanes are eluded to here, but their use and benefits are not discussed in the Green Book. A figure of a conventional versus an offset right turn bay is presented below. Expressway vehicles using a conventional right turn lane to exit the expressway can obstruct a minor road driver's view of oncoming expressway traffic approaching from the left. The offset right-turn bay is designed to remove this intersection sight distance issue. Further research is necessary to determine the safety benefits of using offset right-turn bays.

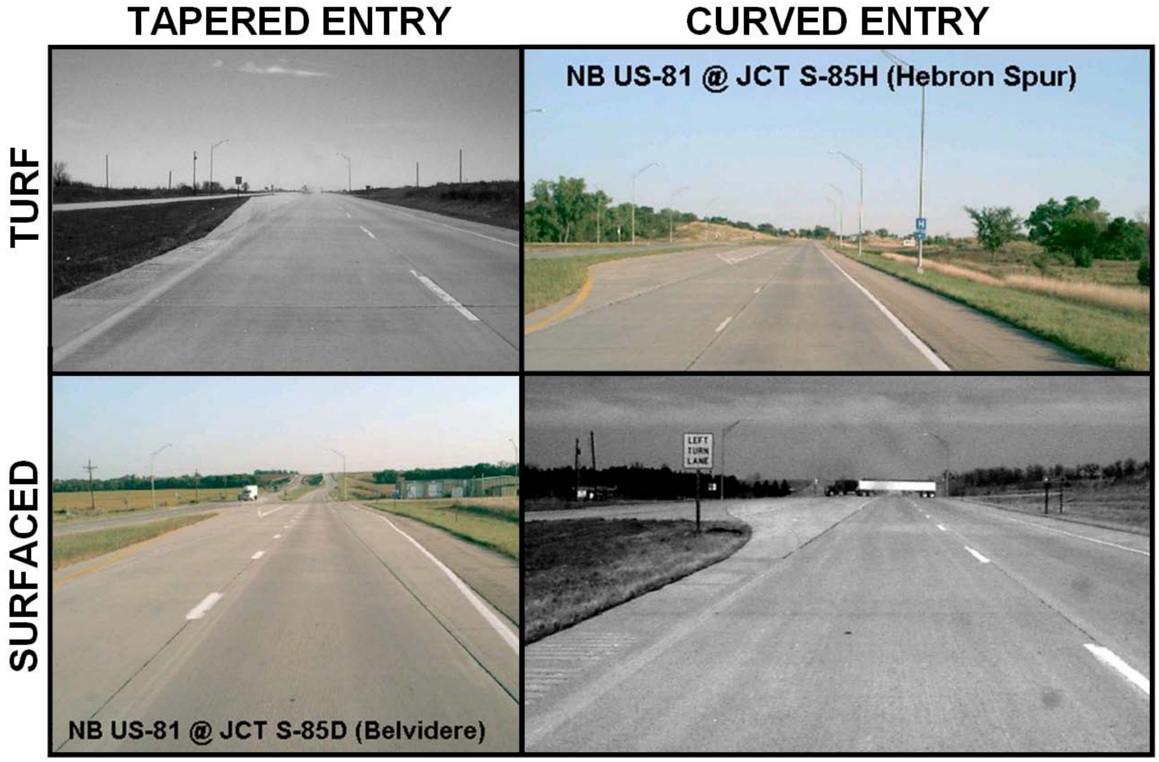




Parallel and tapered offset left-turn lanes should be separated from the adjacent through traffic lanes by painted or raised channelization. [p. 723]

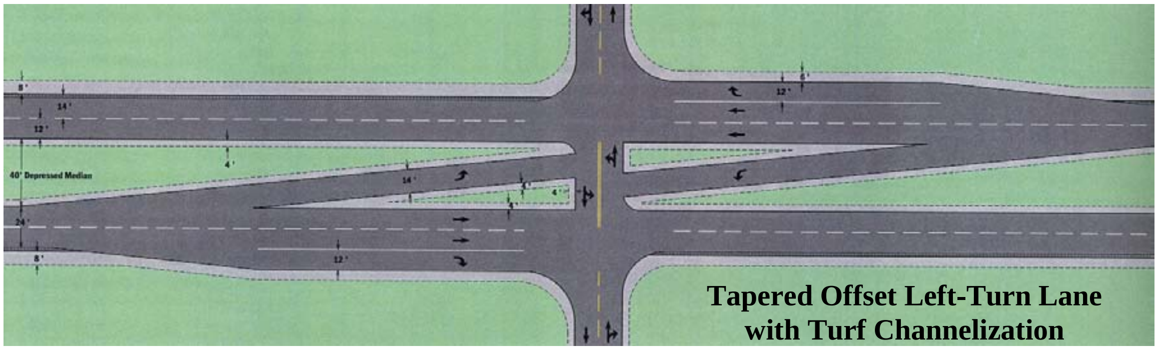
It is unclear if this statement is recommending that painted/raised channelization should be used in the area separating the offset left-turn lanes from the same direction adjacent through lanes, the opposite direction adjacent through lanes, or both. In both cases, turf channelization may provide better contrast and a better perspective for the approaching, left-turning expressway driver. As stated earlier in the Green Book, raised channelization should be avoided in high speed areas.

Different offset left-turn bay designs can be created from both the parallel and tapered designs by using different lane entry treatments and channelizing materials. In Nebraska, four different applications of offset left-turn lanes have been observed as shown in the figure below. These four applications are the result of a combination of tapered/reverse-curve entry and surfaced/turf channelization between the offset left-turn bay and the through lanes in the opposite direction.



Although it is hard to see, the design in the lower left is a tapered offset left-turn bay as shown in Exhibit 9-98B and the design in the upper left is a parallel offset left-turn bay with a tapered entry, as shown in Exhibit 9-98A. Both designs on the right are parallel lanes with reverse-curve entry. This figure shows how different entry treatments and different materials can produce a drastic difference in driver perception regarding the distance to the intersection ahead. The surfaced designs in the bottom row may lead the approaching, left-turning expressway driver to think that the intersection is closer than it really is and may cause them to decelerate unnecessarily in the passing lane of the expressway (*9*). The curved entry into the offset left-turn bay as shown on the right may also cause left-turning expressway drivers to slow down in the passing lane so that they can safely navigate the reverse-curve path. The turf designs in the top row and the tapered designs on the left seem to give the approaching expressway driver a better target (i.e., a better sense of where the intersection is located) and makes them realize that they will be able to use the left-turn lane for all of their deceleration. Therefore, offset left-turn lane designs with tapered entry and turf channelization (as shown in the upper left of the previous figure) would be recommended here based solely on these observations, regardless of whether the storage area of the left-turn lane is parallel or tapered.

Imagine if the picture in the upper left also had a turf offset area (i.e., turf channelization between the offset left turn bay and the adjacent through lanes in the same direction). This would improve the delineation of the offset left-turn bay and provide an even better target for approaching left-turn expressway drivers.



Tapered Offset Left-Turn Lane with Turf Channelization

Turf channelization between the offset left-turn bays and the through lanes in the opposite direction also provide better delineation for opposing expressway drivers proceeding through the intersection as shown in the picture below.

Parallel Offset Left-Turn Lane with Surfaced Channelization as Viewed from an Opposing Through Driver's Perspective

<u>Auxiliary Lanes (Simultaneous Left Turns):</u>

Simultaneous left turns may be considered at an intersection of two major highways. Exhibit 9-99 indicates traffic patterns that should be considered in the design. Marking details are given in the MUTCD. [p. 723]

As mentioned earlier, this section should be moved into or closer to the section entitled, "Above Minimum Designs for Direct Left-Turns" (p. 702). Comments were provided about simultaneous left turns back where that section was discussed.

<u>Intersection Design Elements with Frontage Roads:</u>

Frontage road cross-sectional elements, functional characteristics, and service value as collectors are discussed in Chapters 4, 6, and 7. The discussion to follow concerns frontage road design elements with respect to the operational features where the frontage road intersects the major highway. Frontage roads are generally needed adjacent to arterials or freeways where adjacent property owners are not permitted direct access to the major facility. Short lengths of frontage roads may be desirable along urban arterials to preserve the capacity of the arterial through control of access. Much of the improvement in capacity may be offset by the added conflicts introduced where the frontage road and arterial intersect the crossroad. Not only is there an increase in the number of conflicting movements, but the confusing pattern of roadways and separations can lead to wrong-way entry. Inevitably, where an arterial is flanked by frontage roads, the problems of design and traffic control at intersections are far more complex than where the arterial consists of a single roadway. Three intersections (two if there is only one frontage road) actually exist at each cross street. [p. 725]

The second sentence in this paragraph states, "Where the frontage road intersects the major highway." The frontage road does not intersect the major highway. The crossroad intersects the major highway, connecting it to the frontage road; therefore, this sentence should be reworded.

Frontage roads are also used along rural arterials to preserve the capacity of the arterial through the control of access. More importantly however, frontage roads can be used as a means to improve rural expressway intersection safety. McDonald (10) observed that low minor road volume (≤ 2400 vpd) expressway intersections had a higher average crash frequency per minor road vehicle than did higher minor road volume intersections. A more recent model developed by Maze et al. (11) showed similar results. This observation led McDonald to the conclusion that the concentration of minor road traffic via the closing of low minor road volume intersections and the provision of frontage roads may be an effective means of reducing collisions on rural expressways.

The additional conflict points added along the crossroad due to the intersections with the frontage roads should not be a concern as long as the intersections along the crossroad are adequately spaced. Adequate spacing should also alleviate driver confusion, reduce wrong-way entries, and simplify intersection design.

(10) McDonald, J.W., *Relation Between Number of Accidents and Traffic Volume at Divided Highway Intersections,* Highway Research Board Bulletin 74: Traffic-Accident Studies, National Research Council, Washington, D.C., 1953, pp. 7-17.

(11) Maze, T.H., Hawkins, N.R., & Burchett, G., *Rural Expressway Intersection Synthesis of Practice and Crash Analysis: Final Report,* Center for Transportation Research & Education Project 03-157, Iowa State University, October 2004.

The preferred alternative is to design the intersection with expanded dimensions, particularly the width of outer separation. This design permits the intersections between the crossroad and frontage roads to be well removed from the crossroad intersection with the main lines. For satisfactory operation with moderate to heavy traffic volumes on the frontage roads, the outer separation should be 50 m [150 ft] or more in width at the *intersection. The 50 m [150 ft] dimension is derived on the basis of the following considerations:* [p. 726]

- *This dimension is about the shortest acceptable length needed for placing signs and other traffic control devices to provide proper direction to traffic on the crossroad.*
- *It usually affords acceptable storage space on the crossroad in advance of the main intersection to avoid blocking the frontage road.*
- *It enables turning movements to be made from the main lanes onto frontage roads without seriously disrupting the orderly movement of traffic.*
- *It facilitates U-turns between the main lanes and two-way frontage roads. (Such a maneuver is geometrically possible with a somewhat narrower separation but is extremely difficult with commercial vehicles).*
- *It alleviates the potential of wrong-way entry onto through lanes of the predominant highway.*

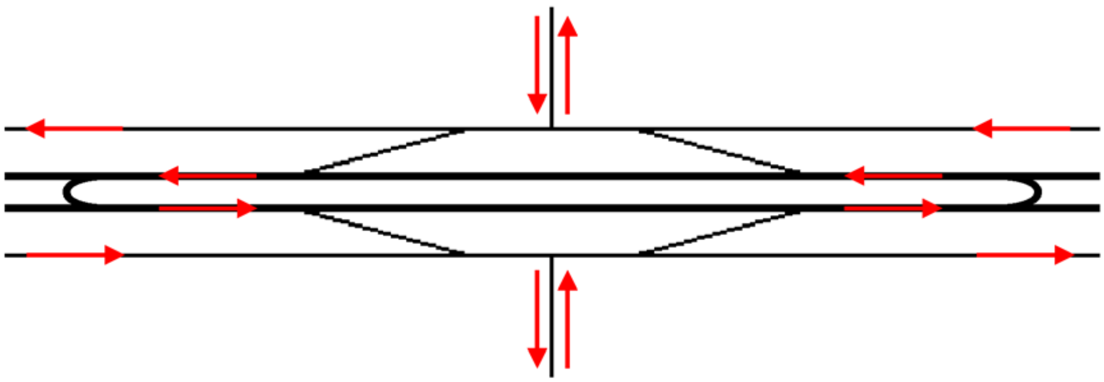
Because right-of-way is expensive, volumes may actually play a role in selecting the outer separation distance; however, it would seem like if there is enough volume to justify a frontage road (by the way, what would that be?) then there would be enough volume to justify adequate outer spacing. Furthermore, where frontage roads pop-up, development may soon follow, thereby increasing volumes rather quickly. Therefore, no matter the frontage road traffic volumes, the outer separation should be a minimum of 150 feet, but larger if practical for safety reasons.

Wider separations can enhance operations significantly. Outer separations of 100 m [300 ft] allow for overlapping left-turn lanes and provide a minimal amount of vehicle storage. The design year traffic volumes, turning movements, signal phasing, and storage requirements should determine the ultimate outer separation distance. Narrower separations are acceptable where frontage road traffic is very light, where the frontage road operates one-way only, or where some movements can be prohibited. Turning movements that are affected most by the width of outer separation are: 1) left-turns from the frontage road onto the crossroad, 2) U-turns from the through lanes of the predominant highway onto a two-way frontage road, and 3) right turns from the through lanes of the predominant highway onto the crossroad. [p. 726]

"Outer separations of 300 feet allow for overlapping left-turn lanes and provide a minimal amount of vehicle storage." Where? What does that mean? The bullet points stated previously that an outer separation of 150 feet usually provides acceptable storage on the crossroad between the main highway and the frontage road. Now they are saying 300 feet is necessary for minimal vehicle storage. Are they talking about the same storage area here?

Except for the width of the outer separation, the design elements for intersections involving frontage roads are much the same as those for conventional intersections. Exhibit 9-100 shows two arrangements of highways with frontage roads intersecting cross streets. Because traffic turning right must cross the path of traffic on the frontage road, the need for right-turn storage lanes on the mainline is usually greater in this case than in the case of conventional intersections. Exhibit 9-100A shows a simple *intersection design with an outer separation of 50 m [150 ft] or more in width. The intersections of the two-way frontage roads and the crossroad are sufficiently removed from the through roadways that they might operate as separate intersections. Exhibit 9-100B shows a design that would be adaptable for two-way frontage roads in areas where right-of-way considerations would preclude the design shown in Exhibit 9-100A. The width of outer separation at the crossroad opening should be at least 18 m [60 ft], which might be acceptable for light to moderate frontage road traffic, but preferably it should be 50 m [150 ft] or more.* [p. 726 – 728]

Exhibit 9-100 shows two examples of intersection design with two-way frontage roads. An example of the use of one-way frontage roads in combination with intersection design should be shown as well. The design shown here is just an idea of the author and has not been constructed or tested.



<u>Lighting At Intersections:</u>

Lighting may affect the safety of highway and street intersections, as well as efficiency of traffic operations. Statistics indicate that the nighttime crash rates are higher than that during daylight hours. This fact, to a large degree, may be attributed to impaired visibility. Whether or not rural intersections should be lighted depends on the planned geometrics and the turning volumes involved. Intersections that are not channelized are seldom lighted. However, for the benefit of non-local highway users, lighting at rural intersections **(destination lighting)** *is desirable to aid the driver in ascertaining sign messages during non-daylight periods. Intersections with channelization, particularly multiple-road geometrics, should include lighting. Large channelized intersections especially need illumination because of the higher range of turning radii that are not within the lateral range of vehicular headlight beams.* [p. 729]

Whether or not rural intersections are lit should also probably depend on minor road traffic volumes as well as night-time crash history. Most rural expressway intersections should include lighting because they have multiple-road geometrics and lighting may be the best way to prevent wrong-way entry.

<u>Driveways:</u>

Driveways are, in effect, intersections and should be designed consistent with their intended use. For further discussion of driveways, refer to Chapter 4. The number of *crashes is disproportionately higher at driveways than at other intersections; thus their design and location merit special consideration.* [p. 729]

Access management policies should prohibit the construction of driveways along rural expressways. Instead, frontage roads should be used to gain direct access to driveways.

Ideally, driveways should not be located within the functional area of an intersection or in the influence area of an adjacent driveway. The functional area extends both upstream and downstream from the physical intersection area and includes the longitudinal limits of auxiliary lanes. [p. 729]

The functional area of an intersection extends both upstream and downstream, along both the major and minor roads. This should be emphasized here. Driveways should not be allowed within the functional area of a rural expressway intersection. Driveways along the minor road within the functional area of rural expressway intersections have been consistently observed and should be removed or relocated.

The regulation and design of driveways are intimately linked with the type of road and zoning of the roadside. On new highways, right-of-way can be obtained to provide the desired degree of driveway regulation and control. The main objectives of driveway regulation are to provide desirable spacing of driveways and to ensure that a proper internal layout is being proposed. [p. 730]

Chapter 10

Chapter 10 of the AASHTO Green Book is entitled “Grade Separations and Interchanges.” This chapter is relevant to the decision-making process when it comes time to decide whether or not to grade separate an expressway intersection. This chapter also describes an alternative hybrid at-grade intersection design (a “one-quadrant interchange configuration”) that has been successfully used on rural expressways in Iowa. This design alternative may get overlooked as a design option because it is included in Chapter 10 as an interchange configuration. It may be beneficial to present, or at least mention, this intersection design concept within Chapter 9.

Introduction and General Types of Interchanges:

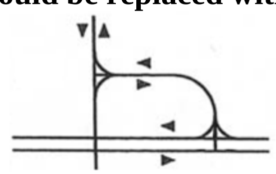
The ability to accommodate high volumes of traffic safely and efficiently through intersections depends largely on the arrangements provided for handling intersecting traffic. The greatest efficiency, safety, and capacity are attained when the intersecting traveled ways are grade separated. An interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways on different levels. The selection of the appropriate type of grade separation and interchange, along with its design, is influenced by many factors, such as highway classification, character and composition of traffic, design speed, and degree of access control. In addition to these controls, signing needs, economics, terrain, and right-of-way are of great importance in *designing facilities with adequate capacity to safely accommodate traffic demands.* [p. 743]

The first sentence in this paragraph should be stressed in Chapter 9. Grade separations/interchanges provide the greatest efficiency, safety, and capacity because they limit the number of conflict points. The ideal intersection design alternatives are those that limit the number of high-risk conflict points while being economical. For rural expressway intersections, that means limiting crossing and left-turn movements from the minor road because these movements are associated with the highest and most severe crash rates.

The basic interchange configurations are shown in Exhibit 10-1. Any one configuration can vary extensively in shape and scope, and there are numerous combinations of interchange types that are difficult to designate by separate names. The practical aspects of topography, culture, and cost may be determining factors in the configuration and nature of ramps, but the desired traffic operation should predominate in design. With ramps in one quadrant, the interchange in Exhibit 10-1C is not suitable for freeway systems, but becomes very practical for an interchange between a major highway and a parkway. This design is appropriate for parkways because design speeds are usually lower, large trucks are prohibited, and turning movements are light. [p. 743]

The "Ramps in one quadrant" interchange shown in Exhibit 10-1C is a very practical design option for replacing a four-legged intersection on a rural expressway with a grade separation and a three-legged intersection. This configuration reduces the number of conflict points much like an offset T-intersection and can provide an interim step between an at-grade intersection and a full interchange. This design option is discussed in more detail later in Chapter 10.

Looking at Exhibit 10-1, Exhibit 10-1C is the only figure that does not show a divided highway. Exhibit 10-1C should be replaced with something like this:



Warrants for Interchanges and Grade Separations:

An interchange can be a useful and an adaptable solution for many intersection problems either by reducing existing traffic bottlenecks or by improving safety. However, the high cost of constructing an interchange limits its use to those cases where the additional expenditure can be justified. An enumeration of the specific conditions or warrants justifying an interchange at a given intersection is difficult and, in some instances, cannot be conclusively stated. Because of the wide variety of site conditions, traffic volumes, highway types, and interchange layouts, the warrants that justify an interchange may differ at each location. The following six conditions, or warrants, should be considered when determining if an interchange is justified at a particular site: [p. 745, 746]

1) *Design designation. The determination to develop a highway with full control of access between selected terminals becomes the warrant for providing highway*

grade separations or interchanges for all intersecting roadways. Once it has been decided to develop a route as a freeway, it should be determined whether each intersecting highway will be terminated, rerouted, or provided with a grade separation or interchange. The chief concern is the continuous flow on the major road.

A few state DOTs design all new rural expressways as freeways and upgrade their existing expressways to freeways on a corridor basis rather than grade separating on intersection at a time.

2) *<u>Reduction of bottlenecks or spot congestion</u>. Inability to provide essential capacity with an at-grade facility provides a warrant for an interchange where development and available right-of-way permit. Even on facilities with partial control of access, the elimination of random signalization contributes greatly to improvement of free-flow characteristics.*

Bonneson and McCoy (1) showed that the costs associated with stopping expressway traffic are so high that a very large minor road demand must be present to economically justify installing a traffic signal. When the minor road demand grows to these levels, a diamond interchange is more economically feasible than a signalized intersection.

3) *<u>Safety improvement</u>. Some at-grade intersections have a disproportionate rate of serious crashes. If inexpensive methods of eliminating crashes are likely to be ineffective or impractical, a highway grade separation or interchange may be warranted. Crash prone intersections are frequently found at the junction of comparatively light-traveled highways in rural areas where speeds are high. In such areas, structures can usually be constructed at little cost compared with urban areas, right-of-way is not expensive, and lower cost improvements can be justified by the elimination of only a few serious crashes. Serious crashes at heavily traveled intersections, of course, also provide a warrant for interchange facilities. In addition to greater safety, the operational efficiency for all traffic movements is also improved at the interchange.*

Uniformity in highway design features plays an important role in making a driver aware of what to expect on a certain type of highway. The majority of State DOTs consider interchanges to be a corrective measure for intersections with high crash rates and convert at-grade intersections to interchanges on a case-by-case basis (11, 12). However, on rural expressways, this policy can create a setting that conflicts with driver expectancies (i.e., a mix of at-grade and grade separations on the same corridor) and can lead to driver confusion and error, especially at other at-grade intersections in the area of a newly converted interchange. If grade separations cannot be justified along an entire corridor, this policy is probably alright because it trades off driver expectancy for safety improvements at high crash risk intersections.

(12) Bonneson, J.A., McCoy, P.T., & Truby, J.E., *Safety Improvements at Intersections on Rural Expressways: A Survey of State Departments of Transportation*, Transportation Research Record 1385, TRB, National Research

Council, Washington D.C., 1993, pp. 41-47.

4) *<u>Site topography</u>. At some sites, grade separations are the only type of intersection that can be constructed economically due to the topography at the site. The topography at the site may be such that any other type of intersection is physically impossible to develop or is equal to or greater than the cost of a grade-separated design.*

5) *<u>Road-user benefits</u>. The road-user costs such as fuel and oil usage, wear on tires, repairs, delay to motorists, and crashes that result from speed changes, stops, and waiting, at at-grade intersections are well in excess of those for interchanges permitting uninterrupted or continuous operation. The relation of road user benefits to the cost of improvement indicates an economic warrant for that improvement. Comparison of these ratios for design alternatives is an important factor in determining the type and extent of improvement to be made. Furthermore, interchanges usually are adaptable to stage construction and initial stages may produce incremental benefits that compare even more favorably with incremental costs.*

6) *<u>Traffic volume warrant</u>. A traffic volume warrant for interchange treatment may be the most tangible of any interchange warrant. Although a specific volume of traffic at an intersection cannot be completely rationalized as the warrant for an interchange, it is an important guide, particularly when combined with the traffic distribution pattern. However, volumes in excess of the capacity of an at-grade intersection would certainly be a warrant. Interchanges are desirable at cross streets with heavy traffic volumes because the elimination of conflicts due to high crossing volume greatly improves the movement of traffic.*

A more specific volume warrant should be provided. Bonneson and McCoy (1) developed a volume warrant for converting a two-way stop-controlled rural expressway intersection to a full diamond interchange based on a benefit-cost analysis. This analysis showed that a diamond interchange is generally warranted when expressway volumes exceed 4000 vpd and minor road volumes exceed 4000 vpd. How much higher do expressway volumes have to be to warrant an interchange if the minor road is at, say 2000 vpd?

Not all warrants for grade separations are included in the warrants for interchanges. Additional warrants for grade separations include grade separations that would: [p. 746]

- *Serve local roads or streets that cannot practically be terminated outside the right-of-way limits of freeways.*
- *Provide access to areas not served by frontage roads or other means.*
- *Eliminate a railroad-highway grade crossing.*
- *Serve unusual concentrations of pedestrian traffic.*
- *Serve bikeways and routine pedestrian crossings.*
- *Provide access to mass transit stations within the confines of a major arterial.*

- *Assure free-flow operation of certain ramp configurations and serve as part of an interchange.*

Adaptability of Highway Grade Separations and Interchanges:

The three general types of intersections are: at-grade, highway grade separations without ramps, and interchanges. For each type, there is a range of situations for which the intersection is practical, but the limits of that range are not sharply defined. Furthermore, there is much overlapping between these ranges, and the final selection of intersection type is frequently a compromise after joint consideration of design traffic volume and pattern, cost, topography, and availability of right-of-way. [p. 747]

Each intersection type accommodates through traffic to varying degrees of efficiency. Where traffic on the minor cross road is considerably less than on the major road, through traffic on the major road is minimally inconvenienced on at-grade intersections, particularly where topography is flat. Where the minor crossroad traffic volume is sufficient to justify a signal, delay is experienced by all through traffic. Through traffic has no delay at highway grade separations except where approach gradients are long and steep and many heavy trucks are included in the traffic stream. [p. 747]

Turning movements can affect traffic operations at an intersection and are accommodated to varying degrees, depending on the type of intersection or interchange. Where turning movements are light and some provision is made for all turning movements, a one-quadrant ramp design may suffice. However, left-turning movements on both highways may be no better accommodated than at an intersection at-grade. Where traffic on the minor road is sufficient to justify the expenditure to eliminate the at-grade left-turns, a cloverleaf or higher type interchange should be considered. [p. 747]

Except on freeways, interchanges usually are provided only where crossing and turning traffic cannot readily be accommodated by an at-grade intersection. Interchanges are adaptable to various traffic mixes. The presence of a high proportion of heavy trucks in the traffic stream makes interchanges especially desirable. Interchanges help to maintain the capacity of the intersecting highways by minimizing vehicle delays caused by heavy trucks that do not have the accelerating ability that passenger cars have. [p. 748]

In rolling or hilly topography, interchanges usually can be well fitted to the existing ground, and the through roads often can be designed more generously than if an at-grade intersection were provided. Interchanges are practical for all types of intersecting highways and for any range of design speeds. Conflicts from vehicles stopping and turning at an intersection increase with the design speed such that high-design-speed highways warrant interchange treatment earlier than low-design-speed roads with similar traffic volumes. The ramps on a high-design-speed highway should permit suitably high turning speeds and include sufficiently long speed-change lanes. The extent to which local service should be maintained or provided is also a consideration in selecting the intersection type. Whereas local service can be provided readily on certain types of at-grade intersections, it may be difficult to provide for some types of interchanges. [p. 748, 749]

<u>Safety:</u>

> *Elimination or minimization of crossing and turning conflicts can be very effective in improving safety, especially at intersections. Regardless of design, signing, and signalization, at-grade intersections have a potential for crashes resulting from vehicle-vehicle conflicts. This is due, in part, to conflicting crossing and turning movements that occur within a limited area. By separating the grades of the intersecting roadways, crashes caused by crossing and turning movements can be reduced. Where access between intersecting roadways will be provided, an interchange is appropriate for providing the maximum degree of safety.* [p. 751]

<u>Grade Separations without Ramps:</u>

> *There are many situations where grade separations are constructed without the provision of ramps. For example, some major arterials intersecting the existing highway must be kept open for access but carry only low traffic volumes. Lacking a suitable relocation plan for the crossroad, a highway grade separation without ramps may be provided. All drivers desiring to turn to or from that road are required to use other existing routes and enter or leave the highway at other locations. In some instances, these vehicles may have to travel a considerable extra distance, particularly in rural areas. In other situations, despite sufficient traffic demand, ramps may be omitted 1) to avoid having interchanges so close to each other that signing and operation would be difficult, 2) to eliminate interference with large highway traffic volumes, and 3) to increase safety and mobility by concentrating turning traffic where it is practical to provide adequate ramp systems. On the other hand, undue concentration of turning movements at one location should be avoided where it would be better to provide several interchanges.* [p. 769, 770]

<u>Ramps in One Quadrant:</u>

> *Interchanges with ramps in only one quadrant have application for an intersection of roadways with low traffic volumes. Where a grade separation is provided at an intersection because of topography, even though volumes do not justify the structure, a single two-way ramp of near minimum design usually will suffice for all turning traffic. The ramp terminals may be simple T-intersections. Appropriate locations for this type of interchange are very limited. A typical location would be at the intersection of a scenic parkway and a state or county two-lane highway where turning movements are light, there is minimal truck traffic, and the terrain and preservation of natural environment typically take precedence over providing additional ramps.* [p. 776]

One-quadrant interchanges also have application at rural expressway intersections. This design should work equally well at intersections with low and higher traffic volume levels, but would be warranted where through volumes on the minor road are large. The major benefit to this design is that it provides an intermediate step to a full interchange and provides improved safety until volumes become large enough to warrant a full interchange.

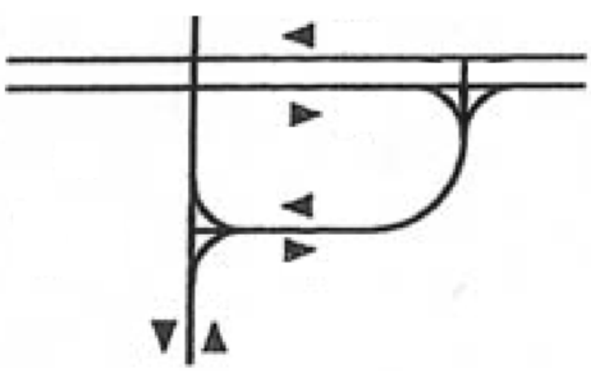
The T-intersection on the expressway could be designed as one of the three T-intersection types discussed back in Chapter 9 (typical, channelized, or continuous green). Whichever design is expected to provide the best safety performance could be constructed.

Proper spacing should be provided on the expressway between the T-intersection and the grade separation so that adequate sight distance is provided at the T-intersection.

At some interchanges it may be appropriate to limit ramp development to one quadrant because of topography, culture, or other controls, even though the traffic volumes justify more extensive turning facilities. With ramps in only one quadrant, a high degree of channelization at the ramp terminals, at the median, and at the left-turn lanes on the through facilities is normally needed to control turning movements properly. In some instances, a one quadrant interchange may be constructed as the first step in a stage construction program. In this case, the initial ramps should be designed as a part of the ultimate development. [p. 777]

Exhibit 10-15A illustrates a one-quadrant interchange at the intersection of a state highway and a scenic parkway located in a rural mountainous area. Exhibit 10-15B is a one-quadrant interchange designed to function as an early phase of stage construction. On future construction, it is readily adaptable to become a part of a full or partial cloverleaf interchange without major renovation. The channelization, although elaborate, is conducive to safety and attractive landscaping. [p. 777]

Another figure in Exhibit 10-15 should be provided showing the application of a one-quadrant interchange on a rural expressway, like the one shown here. This design replaces a four-legged intersection with a grade separation and a three-legged intersection. The three-legged intersection should operate more safely than the four legged intersection did (7). In the photo at the right, the expressway is the horizontal roadway.



A two-quadrant interchange like the one shown below could also be used at a rural expressway intersection in order to restrict median crossings by entirely closing the median. Again, the expressway is the horizontal roadway in this photo.