

DESIGN OF RIGHT-TURN LANES

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ABSTRACT

This paper provides an expansion and explanation of the presentation of the “Design of Right-Turn Lanes” presented in Session 619 of the 2015 Annual Meeting of the Transportation Research Board. The paper addresses the operational issues and the design of right-turn lanes. As indicated in the paper, many issues relating to right- turn lanes are the same as for left-turn lanes. Deceleration rates reported in NCHRP Report 780 for left-turns are reasonably consistent with those previously assumed. The rationale for taper length as opposed to taper ratio is discussed. It is suggested that a “standard” short taper length be used. The paper also addresses a variety of issues such as, channelizing island/shape, use of “short” turn lanes, and pedestrian refuge.

INTRODUCTION

Right-two lanes (sometimes referred to as right-turn bays or speed change lanes) have received less attention than left-turn lanes. The reasons for this probably are: 1) The conflict between left-turns and opposing through traffic is more obvious than the conflict between right-turns and following through traffic; 2) Delay to advancing vehicles due to left-turns is also more apparent and longer than delay time to right-turning vehicles; and 3.) Crash rates and severity involving left-turns are higher than for right-turns.

The advantages for the use of right-turn lanes are:

1. Reduced delay to turning vehicles
2. Reduced delay through vehicles
3. Increased intersection capacity
4. Reduced vehicular emissions
5. Reduced fuel consumption
6. Fewer crashes/improved safety

These advantages are the same as those for a left-turn lane. However, the magnitude of the measured variable is typically less than for a right-turn lane than for a left-turn lane.

ELEMENTS OF A TURN LANE

The elements (d_1 , d_2 & d_3) shown in Exhibit 1 as the same for a left-turn lane and a right-turn lane. The essential difference in the treatment of the terminus of the turn lane. Whereas the issue with the design of a right-turn lane is the use, shape and design, of a channelizing island. The issue with a left-turn lane is the offset of opposing left-turn lanes of an intersection of the design of an opening in a non traversable median.

Distance d_1

The distance traveled during a drivers perception – reaction time is a function of: 1.) the time the driver uses to identify an intersection and to decide upon the maneuver to be executed; and 2.) the speed of traffic on the approach to the intersection – not the maneuver (right-turns through, or left turn) to be executed.

The perception-reaction time is probably a function of driver experience (age) and familiarity with the section of roadway on which the driver is traveling. There is no reason to expect that the perception-reaction time (and hence the distance d_1 traveled) is different from right-turns and left-turns.

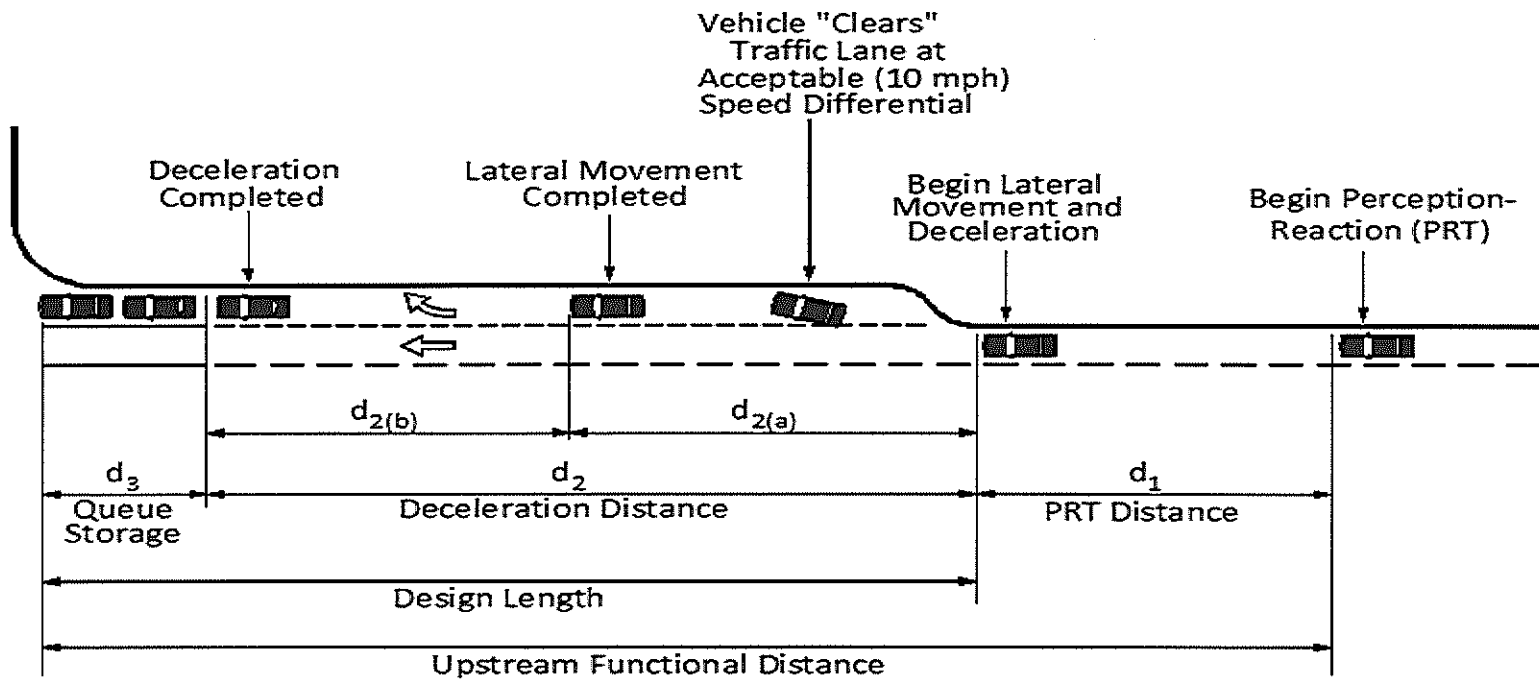
The perception-reaction time includes the identification of the beginning of taper at which point the driver begins the lateral movement from the through lane into the turn lane.

Distance d_2

Distance d_2 consists of the lateral maneuver from the through lane into the turn lane while decelerating to a stop before reaching the queue of stopped vehicles waiting in the turn lane. As shown in Exhibit 1, this distance consists of the following two components: d_{2a} the distance traveled while moving laterally from the through lane into the turn lane while decelerating (called “transition” distance in some manuals) and d_{2b} – the distance traveled while continuing to brake to a stop while steering straight-ahead. It may be anticipated that the deceleration rate while maneuvering from the through lane into the turn lane is less than the deceleration rate after the lateral movement into the turn lane has been completed and the driver is decelerating to a stop while steering straight-ahead. The rationale for this are: 1) lateral movement while decelerating is a more complex maneuver than simply decelerating while steering straight-ahead, and 2) the deceleration rate increases as speed decreases.

Distance d_3

Distance d_3 is the queue storage length. Nomographs and equations have been developed to provide estimates of storage length for left-turns and right-turns. Some agencies have included minimum queue storage requirement in their roadway design manual or access management manual.



Where:

$d_{2(a)}$ = Distance traveled while decelerating and transitioning from the through lane into the turn lane.

$d_{2(b)}$ = Distance traveled under full deceleration and lane change maneuver.

Exhibit 1: Elements of a Turn Lane

Determination/estimation of queue storage length is distinct topic and is not addressed in this paper. It's suggested that readers interested in the topic access agency design manuals or the ITE text Transportation in Land Development or Google the subject.

Deceleration Distance

On roadways other than freeways, it is commonly assumed that: 1.) the maneuver from the through lane into the turn lane starts at the beginning of the taper; and 2.) the turning vehicle the through lane before decelerating more than 10 mph. As illustrated in Exhibit 1, this lateral enrolment consists of two elements: d_{2a} which is the distance traveled while moving laterally and decelerating, and d_{2b} , the distance to complete deceleration is a stop before reaching the end of the queue (distance d_3).

Since moving literally while deceleration is a more capable maneuver than braking while turning straight-ahead, it is logical to assume that the deceleration route used in d_{2a} is less than that used in d_{2b} . (NCHRP Report 780 addresses this issue, and will be discussed later).

Research found that 85 % of drivers used an average deceleration rate of 6.0 fps^2 or greater; 50 % used a rate of 9.0 fps^2 or greater. In the conduct of NCHRP Project 3-13 (NCHRP Report 93) it was realized that the deceleration rate during distance d_{2a} should be less than that for distance d_{2b} . It was assumed that the deceleration during d_{2a} might be 1/2 to 2/3 of that driving distance d_{2b} . This suggest 6.0 fps^2 full deceleration while steering straight-ahead (a rate accepted by 85% of drivers) for distance d_{2b} ; and a deceleration of 3.0 fps^2 to 4.0 fps^2 for distance d_{2a} .

Research from NCHRP Project 3-52 (NCHRP Report 420) suggested that deceleration rates may be higher than the 6.0 fps^2 and 4.0 fps^2 previously assumed for d_{2b} and d_{2a} consequently an average of 5.8 fps^2 was used in the distance for d_{2a} and 6.7 fps^2 for distance d_{2b} . The 5.8 fps^2 deceleration rate while moving laterally from the through traffic lane to the turn lane was selected because a higher deceleration rate could be expected to result in a speed differential greater than 10 mph that is; the distance traveled longitudinally while decelerating to be less than the longitudinal distance traveled while moving laterally.

NCHRP Report 780 reported a two-stage deceleration of 4.2 fps^2 for distance d_{2a} and an average deceleration rate of 6.5 fps^2 for distance d_2 . The resulting deceleration distances are given Exhibit 2; AASHTO Greenbook distances are also shown. Research conducted under NCHRP Project 03-102 (NCHRP Report 780) confirms that the deceleration distances previously proposed (Transportation and Land Development, AASHTO Greenbook) and used by some agencies reasonably reflect current traffic operations.

Exhibit 2: Compression of Deceleration Distances

Deceleration Distance (d₂)

Speed (mph)	Two Stage Deceleration	Average Deceleration	Current
20	95	70	70
30	195	150	160
40	330	265	275
50	500	415	425
60	700	600	605
70	930	815	820

- 1.) NCHRP Report 780; also, presentation by Marcus Brewwer and Kay Fitzpatrick, 2015 annual TRB meeting
- 2.) d_{2a} @ 4.2 fps to d_{2b} @ 6.5 fps²
- 3.) average deceleration for $d_2 = 6.5$ fps²
- 4.) Transportation and Land Development
- 5.) AASHTO Greenbook

Exhibit 3: Deceleration Distance, d_2 , Feet

Transportation and Land Development			NCHRP Project 03-102 (NCHRP Report 780)	
Speed (mph)	Describable	Limiting	Two Stage Deceleration	Average Deceleration
20	70	70	95	70
25	110	105	140	105
30	160	145	195	150
35	215	190	260	205
40	275	245	330	265
45	345	300	410	240
50	425	365	500	415
55	510	435	595	505
60	605	510	700	600
65	710	590	810	700
70	820	680	930	815

- (1) Assumes turning vehicle has “cleared” the through lane and the following vehicle can pass without encroaching upon the adjacent through lane; this is assumed to be possible when the turning vehicle has moved laterally at least 9 ft.
- (2) 10 mph speed differential, 5.8 fps^2 deceleration while moving from the through lane into the turn lane (distance d_{2a}); 6.7 fps^2 average deceleration after completing lateral shift into the turn lane (distance d_{2b})
- (3) 10 mph speed differential; 5.8 fps^2 deceleration while moving from through lane into the turn lane; average deceleration after completing lateral shifts into the turn lane (distance d_{2b}) (distance d_{2a}) and 9.2 fps^2 deceleration
- (4) 4.2 fps^2 deceleration while moving laterally (distance d_{2a}) and 6.5 fps^2 full deceleration after completing lateral movement into the turn lane (distance d_{2b})

Exhibit 3 compares the deceleration/maneuver distances previously developed (Transportation and Land Development and other sources, such as the NHI course on Access Management, Location and Design developed by V.G. Stover and contained in the AASHTO

Greenbook) with those developed in NCHRP Project 03-102 (NCHRP Repaid 780). The distances for d_2 resulting from NSHRP Project 03-102 are based on extensive field data, whereas the distances previously developed were based on a deceleration rate used by drivers while steering straight-ahead, empirical observation, and a deceleration rate for distance d_{2a} that was expected to result in a speed differential.

The “desirable” distances shown in Exhibit 3 were expected to accommodate most drivers (eg 85% of drivers were expected to brake to a stop in this distance or less). Fifty percent of drivers were expected to brake to a stop in a distance less than the “limiting” distance and 50% requiring a longer distance.

The “two-stage” distances to for d_2 resulting from NCHRP Project 03-102 are based on a deceleration ratio of 4.2 fps^2 for distance d_{2a} and 6.5 fps^2 for distance d_{2b} . The resulting distance are surprisingly similar to those previously developed and adopted by several departments of transportation and local governments. Given the variations in the deceleration rates observed in NSHRP Project 03-102, the authors believe that the previously developed distances are still applicable. However, an agency that is considering adopting new or, revised standards should consider those developed in NCHRP Project 03-102.

Many agencies use distance for d_2 that less than these given in Exhibit 2. A few assume that the 10 mph speed differential occurs at the beginning of the taper (eg before the driver of a turning vehicle begins the lateral movement from the through lane into the turn lane). The expected speed differential can be estimated by comparing the adopted distance for d_2 with that in Exhibit 2. For example, a d_2 distance of 275 feet on a 50 mph roadway can be expected to result in a 20 mph (A d_2 distance of 275 ft will result in an expected 10 mph differential at 40 mph; given a 10 mph speed difference in speed roadway speed (50 mph) and the speed at which a d_2 distance of 275 ft is expected to result is a 10 mph speed differential (40 mph) the expected speed differential 10 mph plus 10 mph).

TAPER

Taper lengths were originally established using a taper ratio or a formula based on design speed and assumed rate of lateral movement from the through lane into the turn lane. The rate of lateral movement was commonly assumed to be about 3.0 to 4.0 feet per second—the lower rate for high speed rural conditions and the higher rate for urban conditions. (The authors are not aware of any research in support of this assumption.)

At 4 fps lateral movement a driver takes about 3 seconds to shift from the through lane into the turn lane at a speed of 30 mph while traveling about 133 ft resulting in a taper ratio of about 11:1 for a 12 ft turn lane. At 60 mph, a 12 ft lateral movement would be completed in about 4 seconds (a 3.0 fps lateral movement) while traveling 353 ft resulting a ratio of 29.4:1. It is to be expected that drivers will be decelerating while making the transition from the through lane into the turn lane. Therefore, the distance traveled will be less than for a constant speed.

Consequently the taper ratio could be less than the above values. Exhibit 4 shows typical taper ratios in many roadway design manuals.

Exhibit 4: Typical Taper Ratios

Speed(mph)	30	35	40	45	50	55	60	65
Taper Ratio	8:1:1	10:1	12:1	13:5:1	15:1:1	18:5:1	25:1	25:1

Source : Colorado

Some agencies have adopted a limited number of taper ratios. For example, the state of Maine uses the taper ratios given in Exhibit 5 where the through movement continues straight ahead and the turning vehicles move laterally into a turn lane as shown in Exhibit 4.

Exhibit 5: Example of a Limited Number of Taper Ratios

Design Speed (mph)	Taper Ratio	Taper Length (12 ft Lane)
30	8:1	96
40	10:1	120
50+	15:1	180

Source: Maine

The taper ratios are commonly based on design speed (posted speed in a few cases). The problem with this practice is that peak period speeds in urbanized areas are much lower than the design speed or the posted speed. Thus, the long taper based on design, or the posted speed, restricts the lateral movement of the turning vehicle.

Many agencies use formula based on speed (design speed or posted speed) and turn lane width to determine taper length. The following is an example:

$$L = WS, \text{ speed } 45 \text{ mph or higher}$$

$$L = WS^2/60, \text{ speed less than } 45 \text{ mph}$$

Where: W = turn lane width in feet

S = 85th percentile speed, design speed, or posted speed depending upon the agency

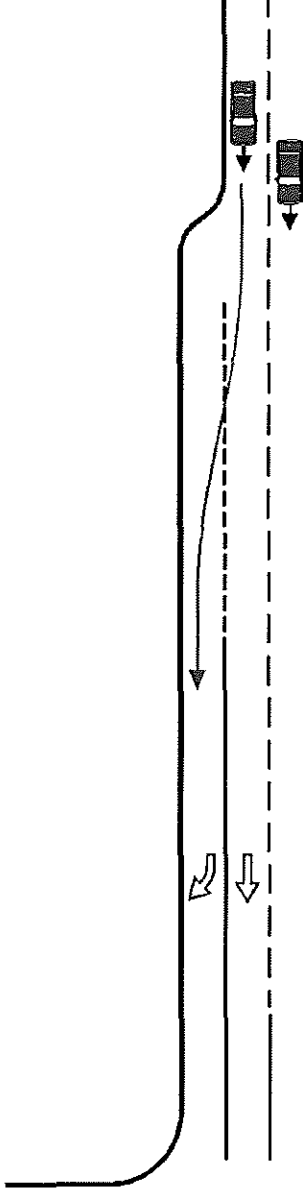
Such formula commonly results in excessively long taper lengths even when the peak period speed is used. For example, the above formula results in a 360 ft taper for a 12 ft wide lane and a speed of 30 mph. A 50ft or 60ft taper length would be much more appropriate for a turn lane taper in an urbanized area. As discussed later under “Other Considerations”, long tapers may confuse drivers where hill-climbing lanes are used and where turn lanes are located on a horizontal curve.

At slow speeds a long taper restricts lateral movement into the turn lane as illustrated in Exhibit 6. Hence, tapers based on design speed (or posted speed) result in high speed differential during peak periods when operating speeds are much lower than the design speed or posted speed.

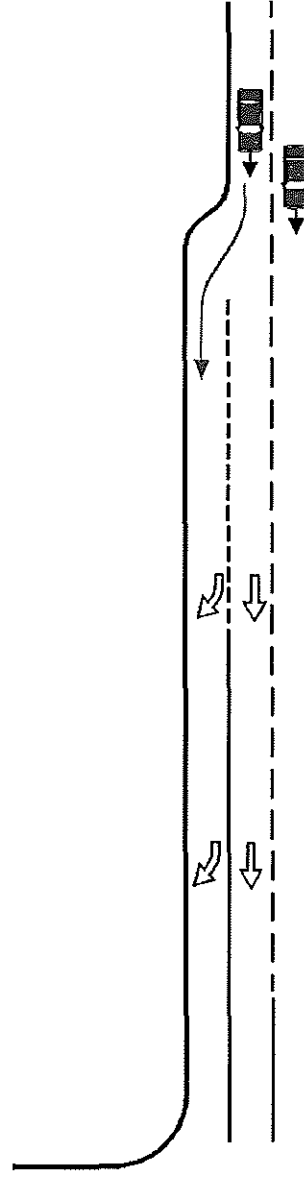
This in turn results in a high potential for collisions between the turning vehicle and following through vehicles or, more likely, between vehicles in the platoon some distance upstream from the turning vehicle. Where a long taper already exists, the turn lane should be redrafted a short taper should be constructed with the beginning of the taper and the same location as the existing taper (assuming that the turn lane does not need to be extended) and, thus, increasing the length of the full width section of the turn lane. During peak periods (high speed) drivers will transition from the through lane into the turn lane over a relatively long distance as illustrated in Exhibit 7a. During peak periods when speeds are slow (and volumes are higher) drivers will make the lateral movement over a much shorter distance as illustrated in Exhibit 7b.

It is becoming increasingly common to use a “standard” taper length (some agencies use a single taper length for all application while others use two or three lengths based on speed). Where speed is a parameter, peak period speed should be used. Exhibit 8 shows examples of standard short taper lengths used by various agencies. When taper length is a function of speed, the speed should be the lowest expected speed of traffic during peak hours. In urbanized areas this will be about 30 mph where traffic signal spacing and timing provide excellent traffic progression. In other situations, such as rural areas, the posted speed or the anticipated 85th percentile operating speed, not design speed, should be used.

The authors suggest that a short taper be adopted for urban and suburban application—50 ft for a single turn lane and 75 or 100 ft for a dual turn lane.



Off-Peak



Peak Period

Exhibit 7: Illustration of Vehicle Path with Short Taper

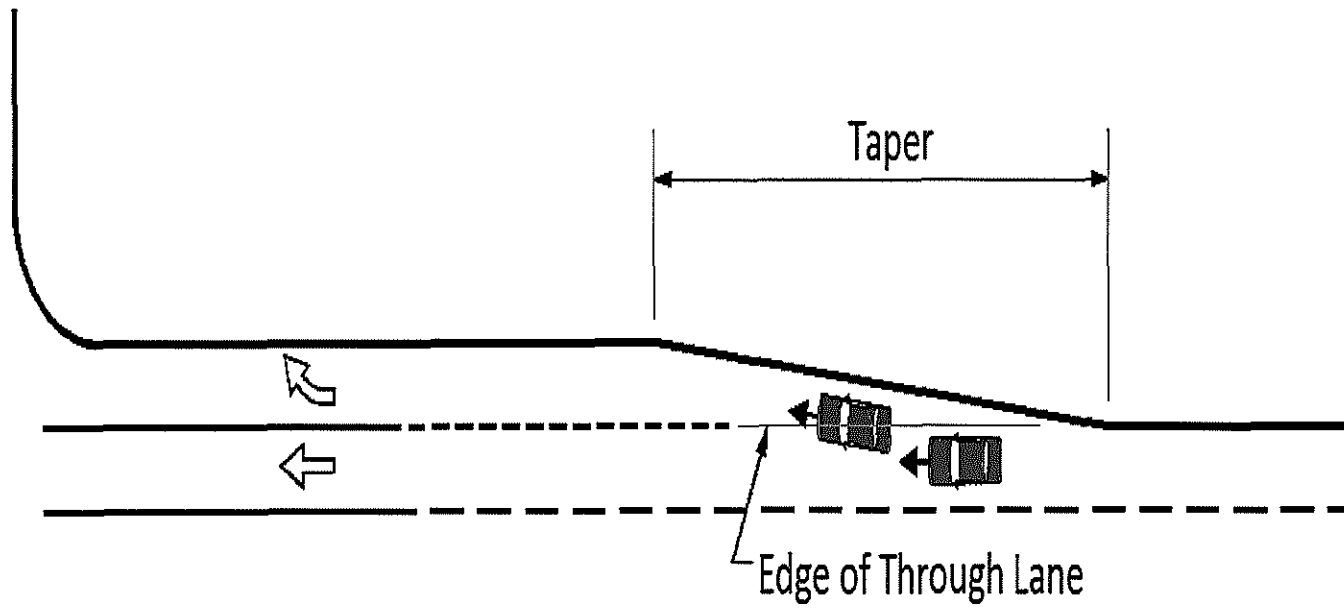


Exhibit 6: Schematic Illustration of the Effect of a Long Taper

Exhibit 8 Examples of “Standard” Taper Lengths

State	Condition	Taper Length
Arizona	Speed <40mph	60ft
	40-50mph	90ft
	>50mph	140ft
California	Urban, show speed	60ft
	Urban, other	90ft
	Rural high speed	120ft
Florida	Single turn lane, right or left	50ft
	Dual turn lane, right or left	100ft
Georgia	Speed ≤ 40 mph	50ft
	Speed ≥ 45mph	100ft
Kentucky	Speed < 40mph	50ft
	Speed ≥ 45mph	100ft
South Dakota	Minimum	50ft
	Maximum	100ft
Texas	Single lane, right or left: Speed ≤ 40mph	50ft
	Speed ≥ 45mph	100ft
	Dual lane, right or left: Speed ≤ 40mph	100ft
	Speed ≥ 45mph	150ft
Washington	Speed < 40mph	60ft
	Speed 40-50mph	90ft
	Speed > 50mph	140ft
Ohio	Single turn lane, right or left	50ft

TERMINAL TREATMENT

The elements (d_1 , d_2 , d_3) of a turn lane are the same for a right-turn lane as for a left-turn lane. The essential difference is the treatment of the terminus of the turn lane. For a left-turn lane, a positive offset of opposing left-turn lanes is desirable (or at least avoid a negative offset). For a right-turn lane, the issues are to: “enable drivers of right-turning vehicles to observe vehicles approaching from their left (assuming right-hand traffic) so as to safely complete the turn into the traffic accommodate pedestrians.”

The authors suggest that a channelizing island be used in the following applications only:
 1) A channelizing island is needed to provide pedestrian refuge so as to facilitate crossing the right-turning traffic, take refuge in the island, and then crossing the through traffic lanes, 2) when an island is needed to locate a traffic control device (traffic signal); or 3) it is necessary to

operate the through traffic and right-turning traffic under separate traffic control (ie signal control for the through and left-turning traffic and yield control for the right-turns).

In other situations (most cases) it is suggested that is simple radius (atops) or a three-centered radius (tracks, buses) be used.

The traditional equilateral triangular island is illustrated in Exhibit 9, this design requires a driver to make a change in sight line of at least 140 degrees in order to observe traffic approaching from the left. This presents a problem for older drivers as they have difficulty with an angle move them 90 degrees to, perhaps 100 degrees. Beyond that, they must rotate the upper body to achieve a greater angler change in Exhibit10 is suggested. This exhibit shows a maximum angle of 100 degrees (90-95 degrees is preferred) while the angle shown the literature is typically 112 degrees.

It is suggested that the equilateral channelizing island (Exhibit 9) be limited to applications where a traffic lane, or a long acceleration lane, is added downstream of the channelizing island.

Older drivers have difficulty in rotating there head more than about 90 degrees – a larger angle requires the individual to rotate the entire upper body. A preferred design is illustrated in Exhibit 10. Where high through traffic and right-turn volumes are encounter (and the pedestrian crossing distance is long) it may be desirable to enable pedestrians to cross the right-turn traffic, take refuge in an island, and then cross the through traffic lanes. A potential problems exists when a pedestrian is not present and the driver travels forward over the pedestrian crossing, resulting in an angle of more than 100 degrees.

OTHER CONSIDERATIONS

The following are other considerations that should be given to the design of right-turn lanes (as well as left-turn lanes).

Access Connection on a Crest Vertical Curve

When an access connection is located beyond the crest of a vertical curve, the turn lane should be visible to the driver for at least two seconds (TxDOT, 2014, pg. 3-17). This may require a turn lane that is longer than the deceleration distance (d_2) phs queue storage (d_3).

Turn Lane on a Horizontal Curve

A long taper length on a horizontal curve tends to misdirect drivers into the turn lane (right-turn lanes on a horizontal curve to the right and left-turn lanes on horizontal curves to the left). The following two practices will mitigate this problem: 1.) use a short taper (50ft) and 2.) use short, wide (18 inch strip and 24 inch gap) paint lines between the auxiliary lane and the through lane.

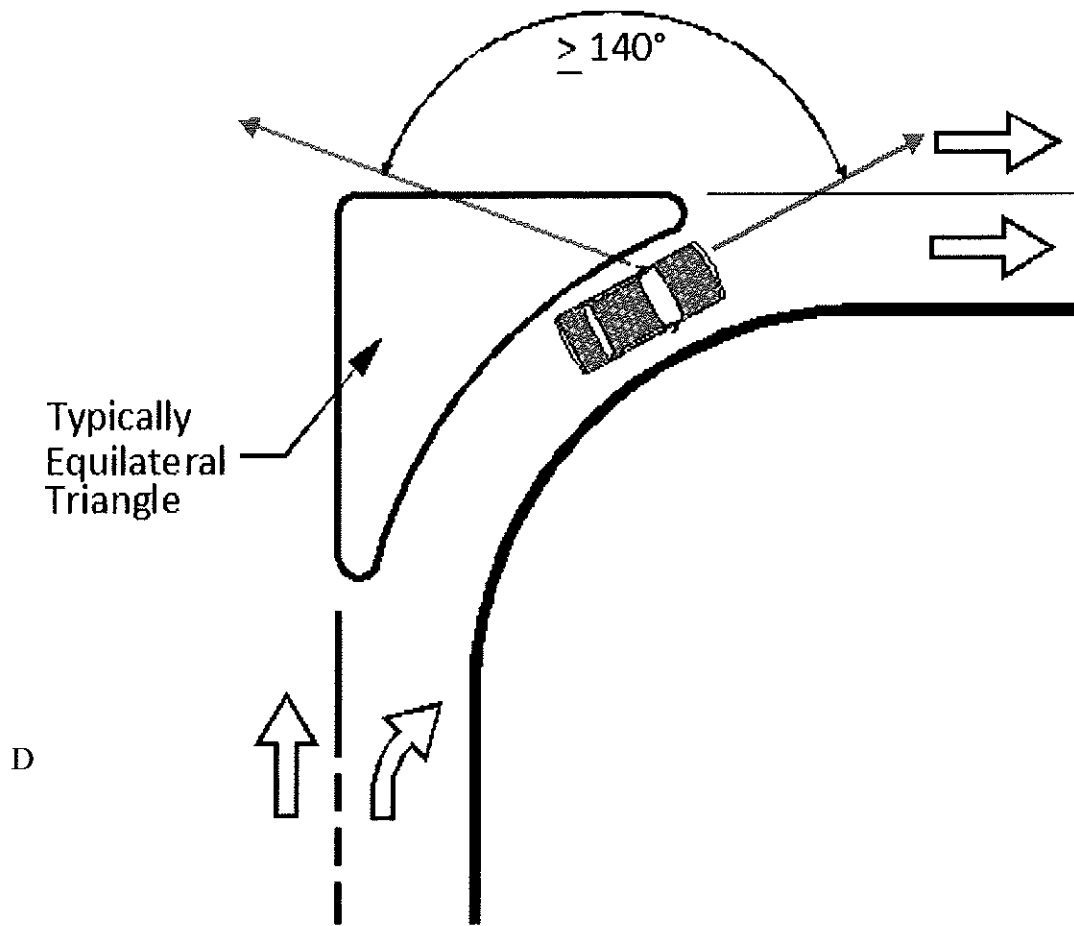


Exhibit 9: Illustration of Traditional Island

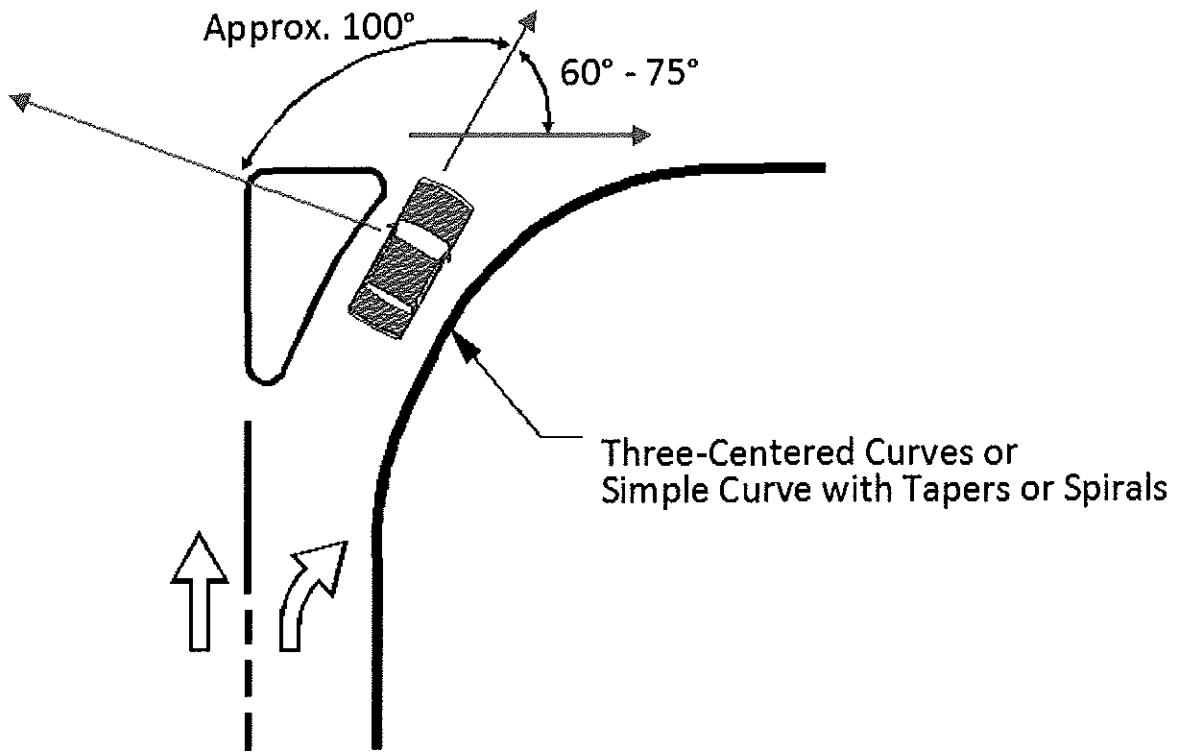


Exhibit 10: Illustration of Preferred Shape of Channelizing Island

Distinction Between Right-Turn Lane and a Hill-Climbing Lane

A long taper on a right-turn lane can confuse drivers in areas where hill-climbing lanes are used. Some drivers of slower moving vehicles followed closely by other traffic have been observed to mistake a right-turn lane with a long taper as a hill-climbing lane. And realizing then, making a abrupt re-entry into the through lane. Use of a very short taper and distinctive striping between the through lane and the turn lane will mitigate this problem. Also, posting a "Must Turn Right" (a sign common practice of the Minnesota DOT) as another mitigation measure.

Queue in Through Lane

In urbanized areas, signal timing and traffic volumes sometimes result in long queues in the through traffic lanes. In such situation the turn lane needs to be longer than the longer queue in the adjacent through lane. This allows drivers of turning vehicles arriving at the end of a long queue in the through lane to enter the turn lane. Gaps in the advancing through lane traffic resulting from turning vehicles moving from the through lane into the turn lane are thereby avoided and intersection capacity is increased.

Acceptable Speed Differential Greater Than 10mph

Speed differential greater than 10mph may be acceptable under the following:

- 1.) A high speed, low volume major roadway
- 2.) A minor arterial or collection
- 3.) Low to moderate volume driveway
- 4.) Geographical or cultural constraints restrict the turn lane length

Short Turn Lane

On occasions it is impractical or impossible to provide a turn of the desired length. While a "short" turn lane will result in a speed differential greater than that desired, "a short turn lane is better than no turn lane. Exhibit 11 provides examples of the expected speed differential based on the 6.5 fps² average deceleration rate from NCHRP Project 03-102."

Where the turn lane length is sufficient to store the longest expected queue, the following action should be considered for right-turns: Limit the maximum permitted driveway volume as a condition of the connection permit. For left-turns: 1.) limit the maximum driveway volumes as a condition of the permit, 2.) limit the access connection to right-in/right-out only by means of a non transversable median or divide. Where a short turn is used, the full width length should always be more than the former length. For example, if the standard taper length is 1000ft, the total turn lane length is only 200 ft, a 50 ft taper and a 150 ft full width is suggested.

Retrofit of a Roadway

When adding turn lanes to existing access connections, it may not be practical to provide a turn lane of sufficient length to limit the speed differential to the desired level. In these situations a short turn lane may be considered. Experience indicates that a turn lane length of 250 ft to 350 ft might be used, especially in lower volume roadways (ADT < 24,000). Although a high speed differential will result, the frequency of a conflict between a turning vehicle and a following vehicle is low.

Deceleration to a Stop -v- Right-Turn Without Stopping

Some agency regulations include turn lane lengths based on the right-turning vehicle coming to a stop as well as making the right-turn without stopping (ie executing the turn at 10, 15, 20, and even 25 or 30 mph). It should be recognized that some vehicles will need to brake to a stop even where a right-turn-on-red is permitted or a lane is added downstream from an intersection. Thus, all right-turn lane deceleration lane lengths should be designed for the stop condition and should have some queue storage (however, the queue storage length will be less where a right-turn-on-red is permitted than where it is prohibited).

Confusion with a Hill-Climbing Lane

Experience has found that where a long taper (using a taper ratio based on design speed) is used and hill-climbing lanes are also used, drivers confuse the right-turn lane with a hill-climbing lane—a driver shifts to the right, realizes he/she is in a right-turn lane and then makes an abrupt re-entry into the through lane. Adoption of a short taper as the standard (no larger than 75 or 100 ft) even on high speed roadways eliminates this problem.

Where a long taper already exists, the shorter taper should begin at the same point as the existing taper and the length of the full width portion of the right-turn lane increased.

Exhibit 11: Expected Speed Differential (mph) With a “Short” Turn Lane

Speed (mph)	Deceleration Length (distance d_2)			
	150ft	200ft	300ft	400ft
30	0	0	0	0
40	26	20	0	0
50	40	36	26	10
60	52	50	42	35
70	63	61	56	50

Based on 6.5 fps^2 average deceleration for NCHRP Project 03-102 (NCHRP Report 780)

Note: The speed differential is not hypersensitive to the deceleration rate. For example, for a 150 ft deceleration length, an average deceleration rate results on a speed differential of 44 mph at 50 mph compared to 40 mph for 150 ft length and 50 mph speed shown in the table.

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