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16. Abstract

Right-turn lanes are used to provide space for the deceleration and storage of turning vehicles and to separate the turning vehicles from the through movement. When larger corner radii are used at the right turn, vehicles can turn at higher speeds (thereby minimizing the speed differential between turning and through vehicles) and can more efficiently merge with the cross-street traffic. A concern with the higher operating speed is the challenge it provides pedestrians attempting to cross the street. Equations are available for predicting speeds on a horizontal curve; however, these equations should not be used for predicting speeds in a right turn. This project analyzed the impact of right-turn lane treatments on vehicle speeds and vehicle safety using nine intersections for the safety study and 18 approaches for the speed study. Each approach for the speed study had an exclusive right-turn lane that was separated from the through lane with either a lane line or with a raised corner island. The corner radii ranged between 27 and 86 ft. The speed study included only free-flow right-turning vehicles. The 85^{th} percentile speed near the middle of the right turn ranged from 13 to 21 mph while on the approach it ranged from 17 to 29 mph. Speed prediction equations were developed. For the nine intersections included in the crash study, the monthly crash rate for a shared lane with island (0.67 right-turn crashes per approach per year) was the highest of the treatments studied. The next highest was the right-turn lane with island design with 0.21 right-turn crashes per approach per year.

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TURN SPEEDS AND CRASHES WITHIN RIGHT-TURN LANES

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DISCLAIMER

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CHAPTER 1

INTRODUCTION

Right-turn lanes provide space for the deceleration and storage of turning vehicles and separate the turning vehicles from the through movement. They have been used to improve safety and/or operations at intersections. A number of factors can enter into the decision regarding whether right-turn lanes should be used including speeds, pedestrian volumes, traffic volumes, percentage of trucks, capacity, type of highway, and the arrangement and frequency of intersections.

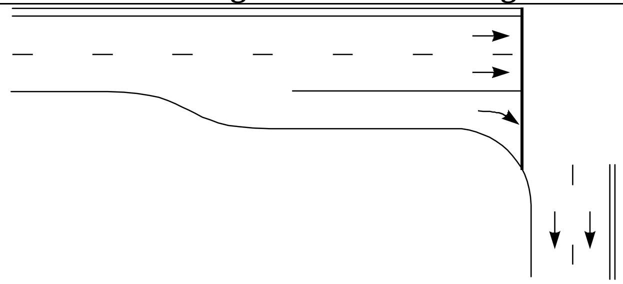
Right-turn lanes can have many forms, based on the design elements used and method of control on the right turn. Table 1 shows common configurations for right turns along with their pluses and minuses.

RESEARCH NEED

The pedestrian's path is affected when a large radius is selected at the intersection. Crosswalk lengths increase with larger curb radii if the crosswalk is located inside the corner radius (see Figure 1), increasing pedestrian crossing time and, subsequently, traffic signal timing. Larger radii can increase the distance pedestrians are exposed to traffic. They also can result in crosswalks and curb ramps being farther from the intersection. The selection of a radius should be weighed in light of these effects, and may result in a compromise between pedestrian needs and vehicle needs.

Another challenging issue is the speed of the turning vehicles. Resources are currently not available to estimate the speed of turning vehicles. Equations are available for horizontal curves (see Chapter 2); however, these equations are not appropriate for the angle of turns present within a right turn. Previous research has indicated that when the angle of intersection between the right-turn lane and the crossroad is small (say about 112 degrees) speeds are on the order of 14 to 18 mph as compared to 20 to 40 mph when the angle of intersection is near 142 degrees *(1)*.

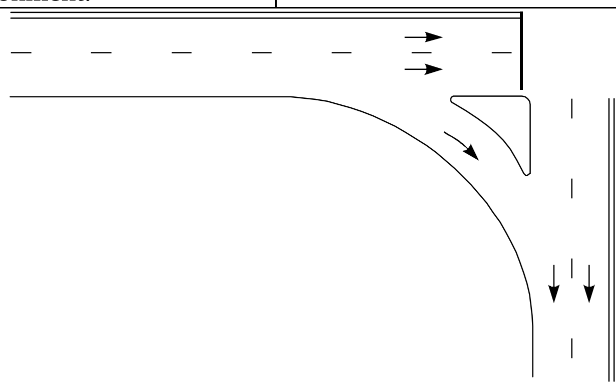
Table 1. Right-Turn Lane Designs.



Right-Turn Lane

Plus	Minus

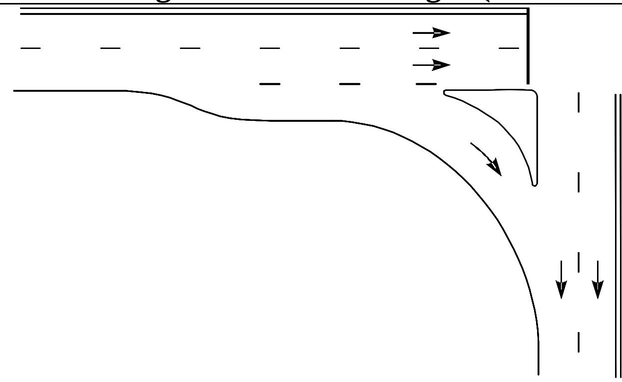
• Allows right-turn-on-red (unless prohibited), reducing right-turn queues.
• Removes turning vehicles from through-vehicle lane for improved intersection operations.
• Lower turning speeds provide a safer pedestrian environment.
	• All vehicles must stop on red, potentially increasing the right-turn queue.
	• The absence of an island eliminates its use for:
	  ◦ Placement of traffic control devices, and
	  ◦ A pedestrian refuge.



Shared Lane With Island

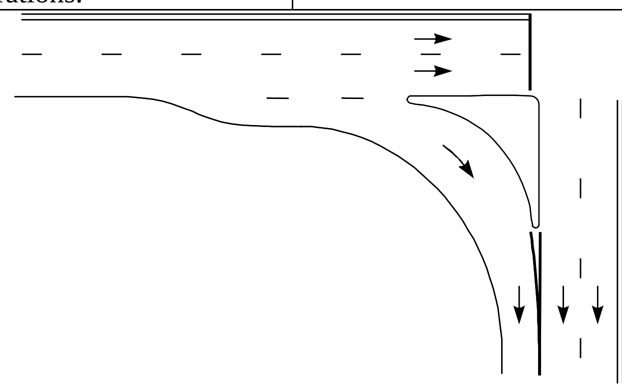
Plus	Minus
• Provision of islands permits its use for placement of traffic control devices or as a pedestrian refuge. • Removes turning vehicle from head of queue.	• May encourage higher speeds. • If signal support is located on island, pedestrians will need to cross uncontrolled lane to reach pedestrian push button. • Design may result in small island size. • The through movement queue may obstruct the throat of the right-turn lane, reducing capacity of the intersection.

Table 1. Right-Turn Lane Designs (continued).



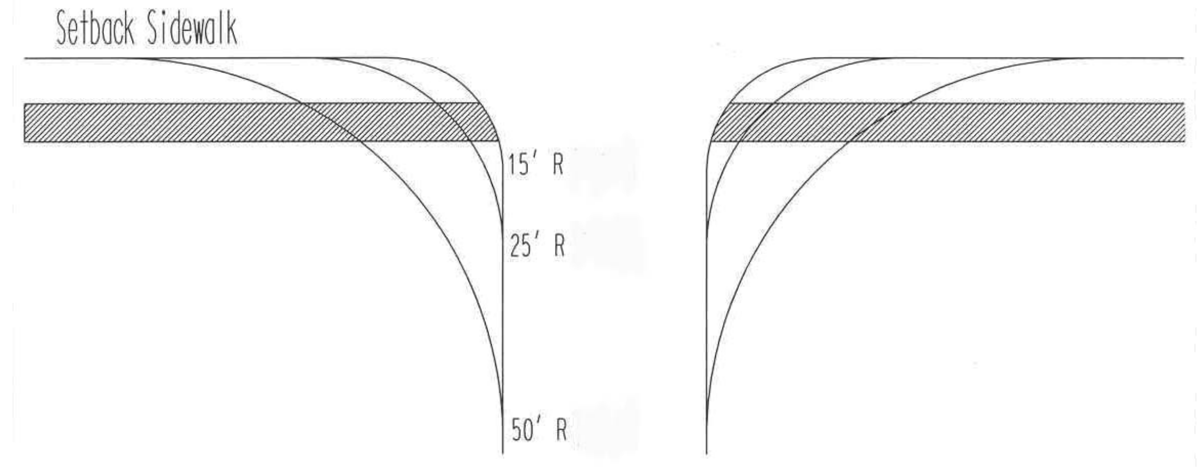
Right-Turn Lane with Island

Plus	Minus
• Provides relatively free movement for vehicles after yielding to pedestrians and opposing traffic, reducing right-turn queues. • Removes turning vehicles from through-vehicle lane for improved intersection operations.	• Higher turning speeds may present a hazard to pedestrians. • Driver attention is split between looking back to merging traffic and looking forward to pedestrian crossing points that may be present in front of the vehicle.

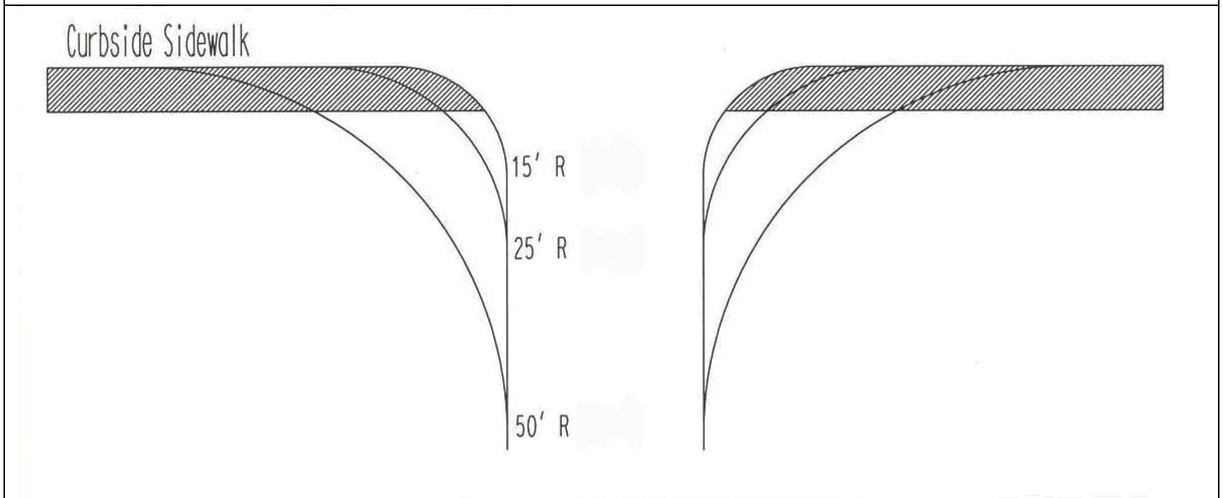


Right-Turn Lane with Island and Dedicated Downstream Lane

Plus	Minus
• Benefits motorized vehicles by lowering emissions and increasing capacity. • Provides free flow of turning vehicles, reducing right-turn queues. • Eliminates need to look for merging vehicles (attention may be focused ahead of vehicle because driver is entering dedicated lane). • Removes turning vehicles from through-vehicle lane for improved intersection operations.	• High turning speeds are detrimental to pedestrian safety, so this design is not generally recommended in the urban environment. • Vehicles are observed to frequently stop prior to entering the cross street even with an available dedicated lane, because drivers do not know they have a dedicated lane or how long it lasts. • Dedicated downstream lane must be sufficient length for vehicles to merge. • Access needs to be managed along dedicated downstream lane to ensure proper operation.



Radius	Crossing Distance	Increase Crossing*	Percent Increase
15 ft	26 ft	+0 ft	0%
25 ft	36 ft	+10 ft	38%
50 ft	65 ft	+39 ft	150%



Radius	Crossing Distance	Increase Crossing*	Percent Increase
15 ft	37 ft	+11 ft	42%
25 ft	50 ft	+24 ft	92%
50 ft	89 ft	+53 ft	203%

* Compared to 26 ft

Figure 1. Added Crosswalk Distance with Increased Radius (Illustrated Using a 26 ft Roadway, 5 ft Sidewalk, and 6 ft Planting Strip for the Setback Sidewalk) (*2*).

Although recommended limits for vehicle turning speeds in various environments have not been established, it has been found that survival rates of pedestrians struck by motor vehicles are much higher if vehicle speeds are reduced (*3*). Eighty percent of pedestrians are killed when struck by motor vehicles traveling 35 to 45 mph; only 5 percent are killed at speeds of 18 mph.

While existing equations can provide an appreciation of the speeds of vehicles in a horizontal curve, there is a need to determine speeds in right-turn scenarios. As part of this Texas Department of Transportation project, right-turn speeds at a range of corner radii were sought.

RESEARCH OBJECTIVE

The objective of the study was to determine the speeds of free-flow turning vehicles in an exclusive right-turn lane. The sites reflected a range of curb radii and included right turns separated by a lane line or by a corner island. In addition, the crash history with respect to different right-turn lane configurations was sought.

ORGANIZATION

The research findings are presented in six chapters. A brief summary of the material in each chapter follows:

Chapter 1: Introduction contains a brief overview of right-turn lane configurations and issues associated with their design. It also explains the research objectives and provides an overview of the contents of the report.

Chapter 2: Review of Right-Turn Lane Design presents a summary of key design components, an overview of three previous research projects where prediction equations were developed for speeds on horizontal curves, and an example of a right-turn lane design.

Chapter 3: Comparison of Portable Speed Measurement Devices in Right-Turn Lane discusses a pilot study that determined the relative accuracy of four speed measurement devices and made recommendations on their use for the field study that measured speeds of vehicles in a right-turn lane.

Chapter 4: Free-Flow Vehicle Speeds in a Right Turn presents the procedure and findings from the field study that measured speeds of vehicles at the beginning and in the middle of a right turn.

Chapter 5: Evaluation of Right-Turn Lane Crashes contains the procedures and findings from an evaluation of right-turn crashes at nine intersections.

Chapter 6: Conclusions and Recommendation summarizes the conclusions and the recommendation from this project.

CHAPTER 2

REVIEW OF RIGHT-TURN LANE DESIGN

RIGHT-TURN LANE DESIGN

Right-turn lanes are used to provide space for deceleration and storage of turning vehicles. They may be used to improve safety and/or operations at intersections. Figure 2 provides an illustration of basic right-turn lanes along with key design components.

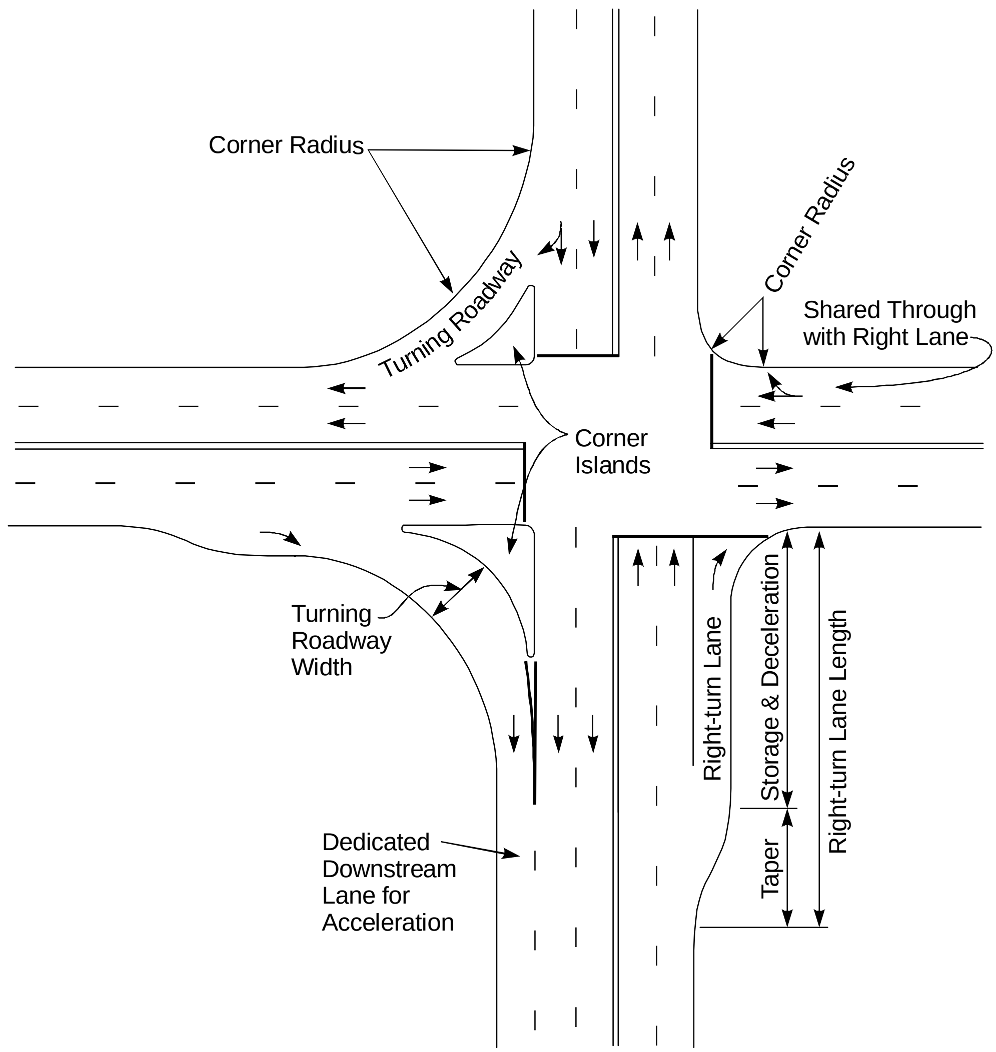


Figure 2. Right-Turn Lane and Right Turning Roadway Examples.

A number of factors enter into the decision regarding whether right-turn lanes should be used: speeds, pedestrian volumes, traffic volumes, percentage of trucks, capacity, type of highway, and the arrangement and frequency of intersections. Specific warrants, however, for when turning roadways should be considered are not available.

A synthesis of current literature and state and local highway agency policies and practices related to channelized right turns was prepared as part of the National Cooperative Highway Research Program (NCHRP) 3-72 project *(4)*. Researchers defined "channelized right turns" as turning roadways at intersections that provide for free-flow or nearly free-flow right-turn movements. The synthesis included a discussion on geometric design issues as they relate to channelized right-turn lanes for the following areas: warrants, design principles, island size and design, design speed for turning roadways, radius and superelevation for turning roadways, width of turning roadways, angle of entry to cross street, deceleration lanes, and acceleration lanes.

The American Association State Highway Transportation Officials (AASHTO) book, *A Policy on Geometric Design of Highways and Streets*, commonly known as the *Green Book*, provides guidance on the design of right-turn lanes under the topic of turning roadways *(2)*. The TxDOT *Roadway Design Manual* and the *Urban Intersection Design Guide* also provides information on the design of right-turn lanes *(5,6)*.

Following is a summary of some of the key variables considered in a design.

Design Vehicle

The choice of the motorized design vehicle greatly influences the selection of an appropriate turning radius or turning roadway width. Consideration should be given to occasional vehicles (i.e., moving vans) as well as the predominant vehicle (i.e., passenger car) in developing an intersection design.

All Users

In addition to roadway motorized vehicles, other users, such as pedestrians and bicyclists, should influence the right-turn lane design. Consideration of pedestrians can influence the selection of the radius (smaller radii are associated with slower speeds and shorter crossing distances), the presence of an island (can provide refuge or it could result in pedestrians having to cross a moving lane of uncontrolled traffic to reach the traffic signal pushbutton), and the appropriate location for the curb ramp. Pedestrians can also influence the location of the crosswalk and whether traffic signal equipment is present and where it is located. When bicycle lanes are present, the pavement markings in the area of a right-turn lane are different.

Length

The length of turn lanes depends upon three elements:

- entering taper,
- deceleration length, and
- storage length.

Per the TxDOT *Roadway Design Manual* if insufficient room is available for each of these elements, a moderate amount of deceleration in the taper section is acceptable. Deceleration lanes that include storage lanes for turning traffic are particularly advantageous, providing improved intersection performance and safety. Recommended lengths are included in the TxDOT *Roadway Design Manual* (*5*). Storage length calculations should consider that the queue from the through movement may block the entry to the right-turn lane, so both the right-turn and through-movement queues should be reviewed when establishing the length of the right-turn lane.

Radius

The design of the corner radius affects how drivers traverse the intersection, including the speeds chosen as well as the path the driver follows. The corner radius value also affects pedestrians both with respect to dealing with the speed of the turning vehicle and their path and crossing experience. The corner radius value is associated with other features such as the provision of islands. Turning templates (hardcopy or computer aided-design cells) or turning path software can be used to predict the paths of vehicles in curves.

The relationship between lane width, radius, and intersection angle affects the path vehicles take when turning at an intersection. The selection of the radius at an intersection affects turning-vehicle speeds and lane positioning. Consideration of the type of vehicle used in the design and acceptable lane positioning are made based on the types of main and cross roadways. Curb radii are selected to accommodate desired design vehicles (but not necessarily to turn into first lane on a multilane roadway). For intersections with minor roadways it is frequently judged acceptable for infrequent large trucks to occupy both lanes on the minor roadway in the course of completing the turning maneuver. This type of design would be inappropriate for a major crossroad, of course, or where trucks are frequent users of the minor roadway. Table 2 summarizes some of the effects the corner radii selection has on the operation of an intersection.

Table 2. Turning Radius Effects.

Benefits of Larger Radii	Benefits of Smaller Radii
• Accommodates larger vehicles without encroachment • Permits higher turning-vehicle speeds in free-flow situations which can produce smaller-speed differentials with following vehicles and thus less severe rear-end conflicts • May allow the presence of islands for traffic control devices and pedestrian refuge areas	• Reduced vehicle crossing time • Reduced pedestrian crossing time which leads to reduced vehicular delay at signalized intersections • Reduced turning speeds can benefit pedestrians • Reduced pavement area

Figure 3 illustrates various radii and swept paths for two design vehicles. The *Green Book* provides tabular values for the cross-street width occupied by turning vehicles in its Exhibit 9-31.

The following curb radii are generally recommended:

- 15 ft to 25 ft to accommodate passenger cars, and
- 40 ft to 50 ft to accommodate heavy volumes of trucks or buses.

Additional information is available in the TxDOT *Roadway Design Manual's* section on Minimum Designs for Truck and Bus Turns, Chapter 7 or in the AASHTO *Green Book* if combination tractor-trailer units are anticipated in significant volume (*2*,*5*).

Corner Islands

Corner islands may be used effectively to reduce conflicts where large corner radii or oblique crossings lead to large areas of pavement. Used to delineate the path of through and turning vehicles, corner islands also provide refuge areas and space for sign placement. They are typically triangular in shape with one side curved to match the alignment of the roadway and the noses rounded and offset. Figure 4 shows details of a corner island design.

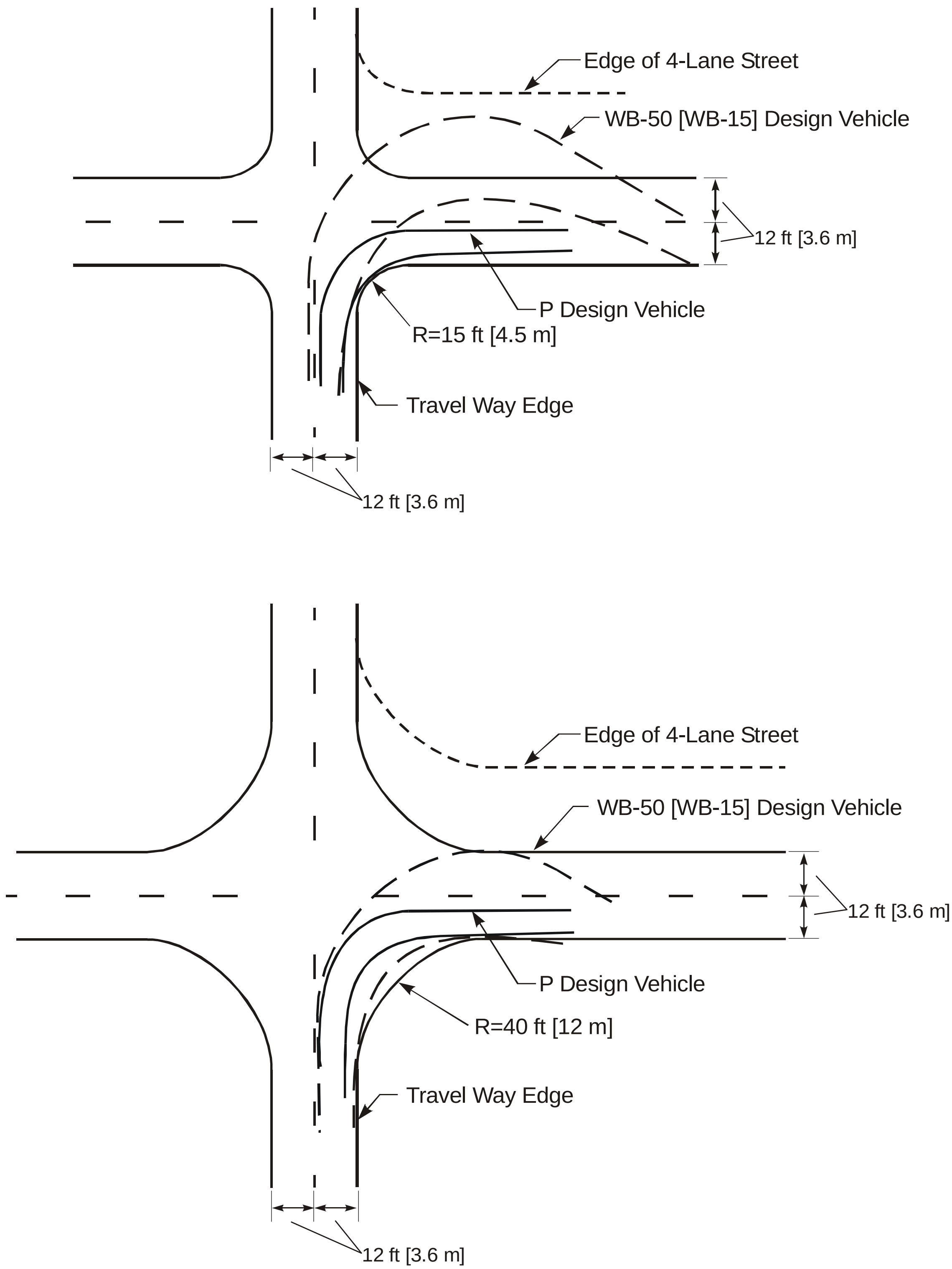


Figure 3. Effect of Curb Return Radius on Right Turning Paths (R=15 ft and R=40 ft) (*2*).

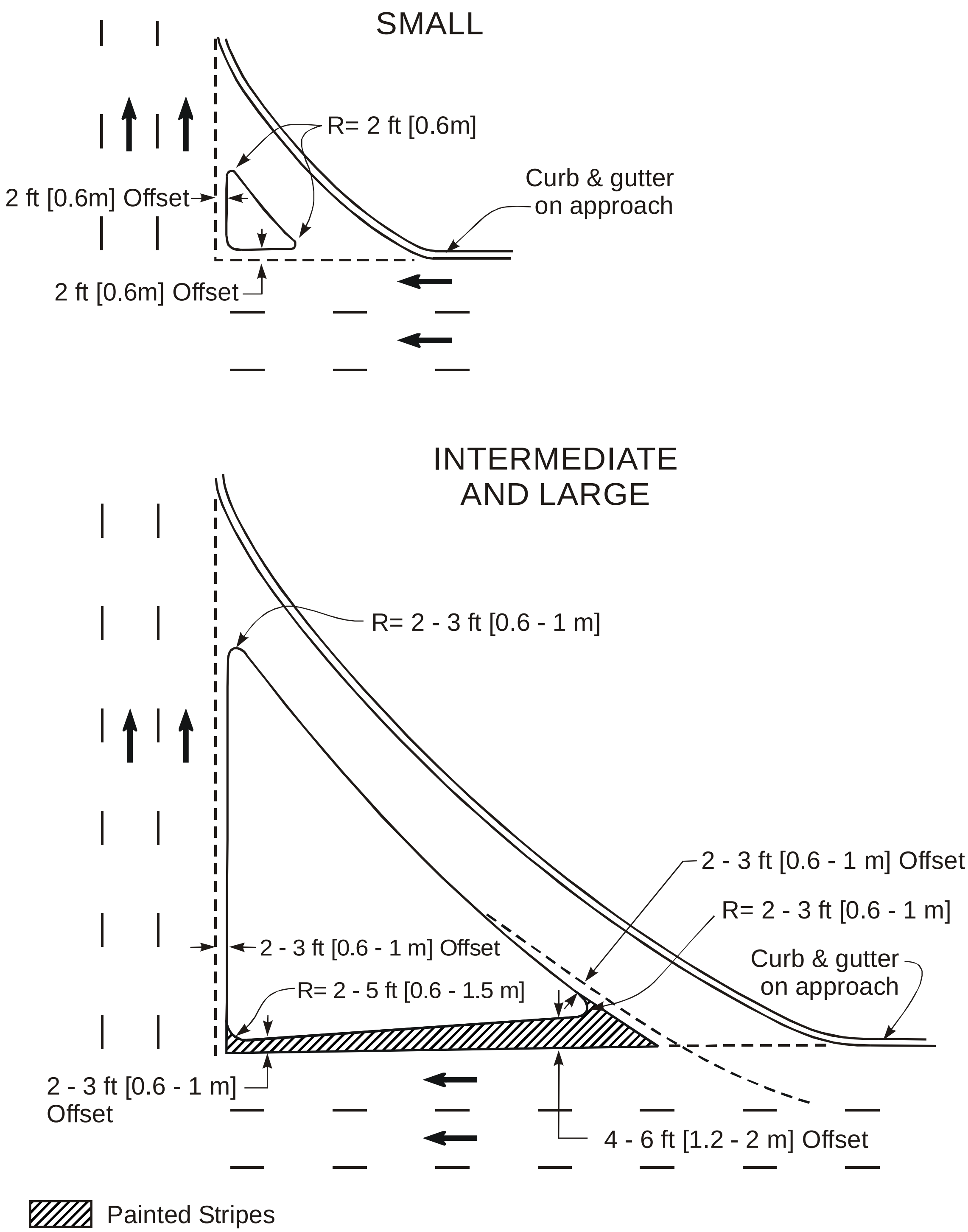


Figure 4. Details of Corner Island Designs for Turning Roadways (Urban Locations), Based on Information in *Green Book* (2).

Channelization in the form of raised islands should be designed so that it commands the driver's attention. Because small islands may be overlooked, curbed corner islands should be at least 50 ft^2 for urban intersections, although 100 ft^2 is preferred. If a cut through the island is planned to accommodate pedestrians, the cut must have a minimum 5 ft width. If curb ramps are used, there must be a minimum 5 ft × 5 ft landing provided on the island. This landing area, combined with a maximum curb ramp slope of 1:12, means that ramped islands are only feasible where the median or island width in the area of the cut is at least 17 ft.

Turning Roadway Widths

Corner islands should accommodate turning roadway widths of 14 ft and allow turning vehicles to keep their wheel tracks within the traveled way by about 2 ft on both sides. If large trucks are used as design vehicles this may result in undesirably wide lanes that may encourage passenger cars to use the facility as if it had two lanes; to discourage this behavior, paint or other flush markings may be used to delineate the desired path. For a right turn at a 90-degree intersection with a minimum-size island, a 60 ft radius on the outer edge provides a 14 ft turn lane. AASHTO's Exhibit 9-41 shows other designs using three-centered curves.

LITERATURE REVIEW ON TURN SPEED

An issue with the use of right-turn lanes, especially when a large radius is used, is the speed of the turning vehicle. Higher turning speeds could improve operations; however, pedestrians may have greater difficulties in crossing the road. Drivers, especially older drivers, may not be comfortable with the higher speed of the turn when trying to turn their head to look upstream while making the merging decision. The driver may prefer to slow or stop at the end of the lane. This behavior could result in rear-end collisions as more familiar drivers or drivers more comfortable with the higher speed do not anticipate the stopped vehicle.

The ability to predict the free-flow turning speed at a right-turn lane should permit for better informed decisions on the trade-offs between improved operations and pedestrian comfort and safety.

A review of the literature identified several studies that developed equations to predict speeds on roadways. Most of the studies focused on the rural environment, and horizontal curvature was the primary variable used to predict operating speed. For many of these studies, few of the radii included in the study are near the radii values that would be used in a right-turn lane design. However, lacking other sources of information, researchers reviewed the equations developed in three studies to identify whether they could be reasonably used to predict speeds in a right-turn lane.

Emmerson

A 1970 paper by Emmerson reported on speeds measured at the center of a horizontal curve on two-lane roads in rural areas (*7*). The radii included in the study ranged from 82 to 1500 ft. The equation based upon the data available in the study was:

$$V_{avg} = 74\,(1-\exp(-0.017R)) \qquad \text{Metric} \tag{1}$$

Where V_{avg} = time-mean speed of cars, km/h
R = curve radius, m

Converting the equation into U.S. Customary (English) units would produce the following:

$$V_{avg} = 46\,(1-\exp(-0.00518R)) \qquad \text{U.S. Customary} \tag{2}$$

Where V_{avg} = time-mean speed of cars, mph
R = curve radius, ft

Emmerson found that for curves with radii greater than 656 ft curvature has little influence on speed, whereas with radii less than 328 ft there are substantial reductions in speed. Figure 5 illustrates Emmerson's data and equation using the U.S. Customary equation.

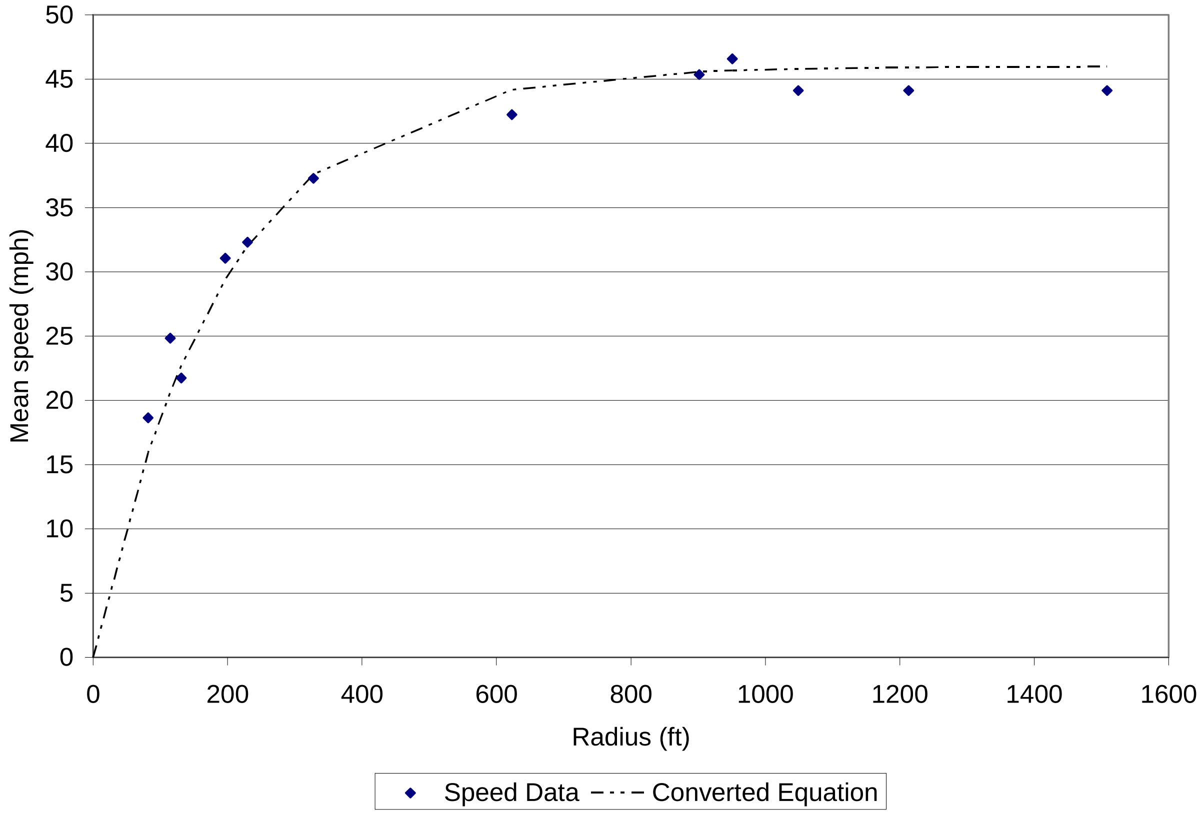


Figure 5. Emmerson's Data and Plot of Equation.

FHWA Speed Prediction

A 2000 Federal Highway Administration study by Fitzpatrick et al. collected speeds on over 200 two-lane rural highways segments (*8*). Radii included in the study ranged from 285 to 5725 ft. Regression equations were developed for passenger car speeds for most combinations of horizontal and vertical alignment. Equations that could relate to a right turn on a level grade include the following:

Horizontal curve on grade, grade between -4 and 0%

$$V_{85} = 105.98 - 3709.90/R \tag{3}$$

Horizontal curve on grade, grade between 0 and 4%

$$V_{85} = 104.82 - 3574.51/R \tag{4}$$

Where V_{85} = 85th percentile speed of passenger car, km/h
R = radius of curvature, m

The FHWA study found that operating speeds on horizontal curves drop sharply when the radius is less than 820 ft. Figure 6 shows the data and associated plots of the regression equations for the data from horizontal curves on grades between -4 and 4 percent. The figure uses U.S. Standard units.

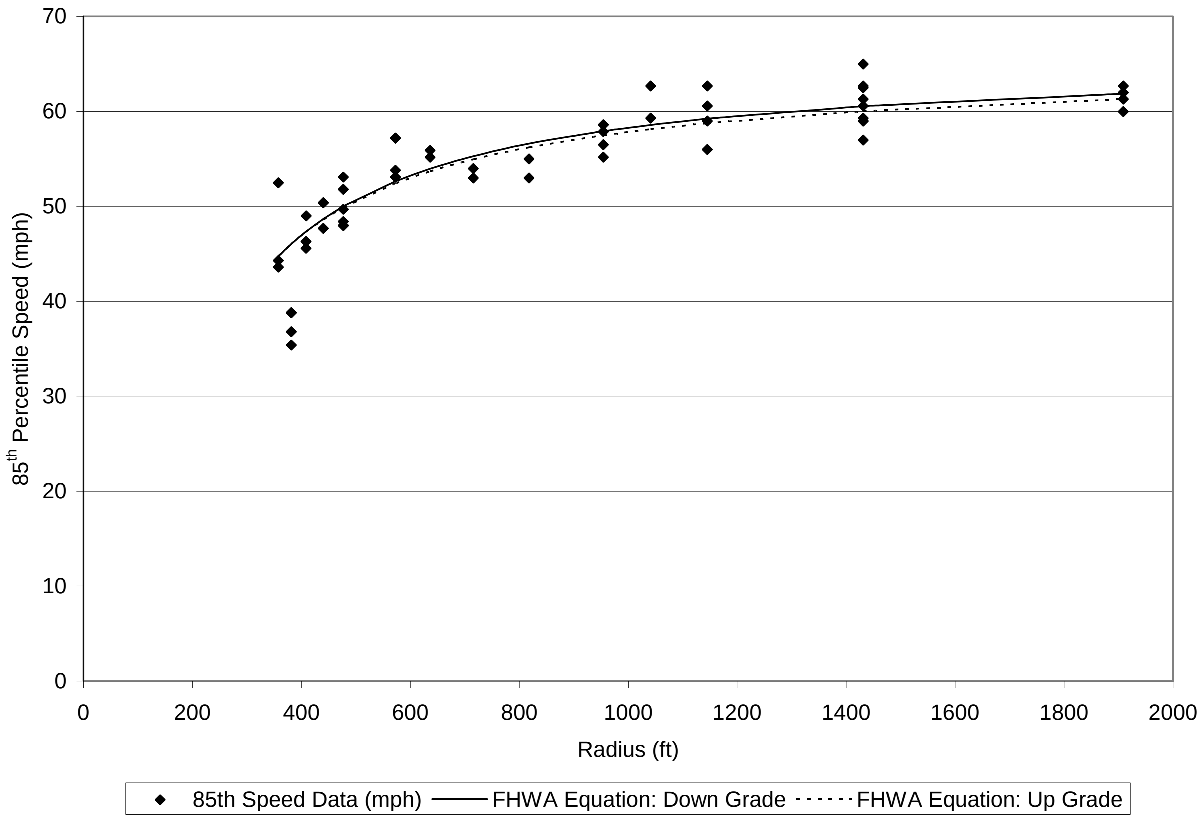


Figure 6. FHWA Study's Data and Plot of Regression Equations.

TxDOT Arterial Speed Prediction

A 1995 TxDOT study collected speeds at 14 horizontal curve sites on suburban arterials (9). Radii included in the study ranged between 511 to 3250 ft. The 85th percentile speeds on the horizontal curves studied ranged from 40 to 60 mph. Several regression equations were examined with the following being the preferred:

$$V_{85} = 54.18 + 1.061\, R^{0.5} \qquad (5)$$

Where: V_{85} = 85th percentile speed on the curve (km/h)

R = curve radius

Figure 7 shows the data and plot of regression equation from the TxDOT arterial study using U.S. Standard units.

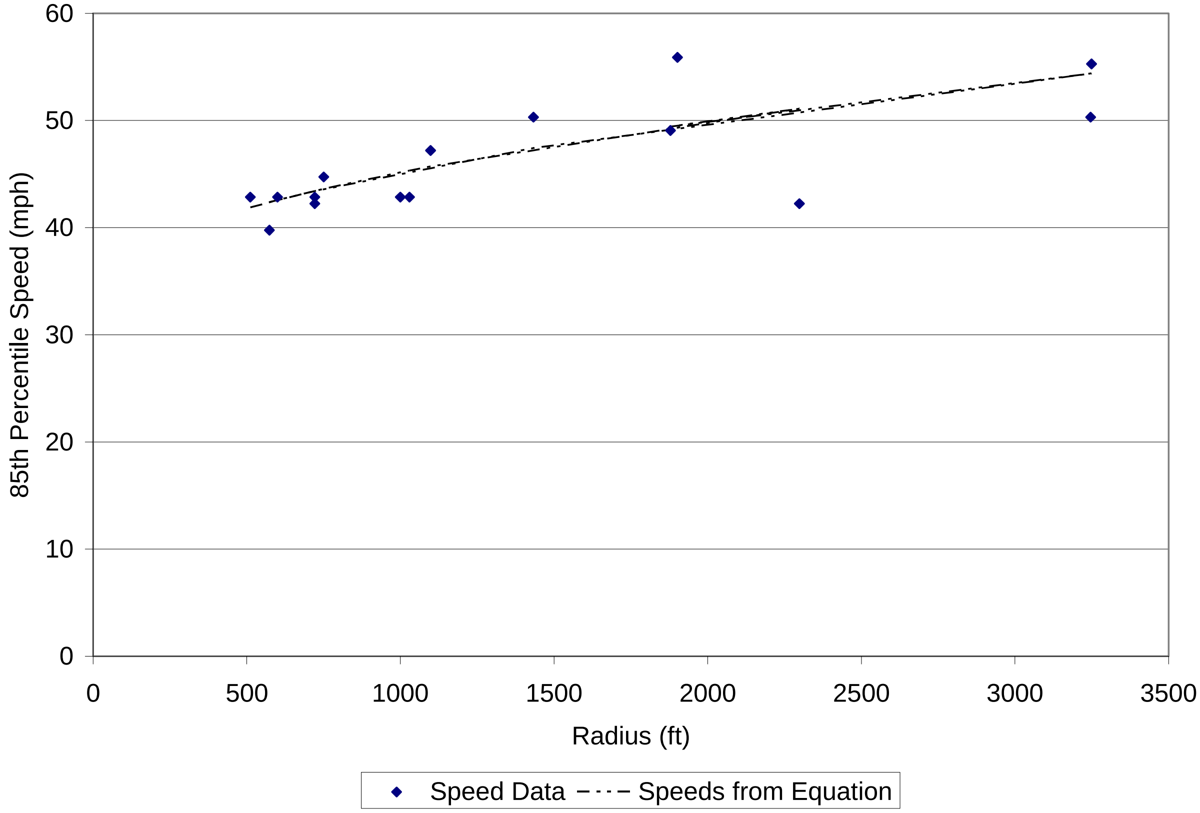


Figure 7. TxDOT Arterial Study's Data and Plot of Regression.

Comments on Literature Review

Several studies have examined the relationship between radius and curve speed on horizontal curves. In only one study was the radius of any of the horizontal curves included in the study less than 100 ft. In addition to the obvious care needed when extrapolating a regression equation into the lower radius values, the question about the angle of the turn needs to be considered. The angle of the turn is much greater in a right turn (typically 90 degrees) than within a horizontal curve. The angle of turn should have a large influence on the turning speed of vehicles. The turning speeds collected as part of the field studies and reported in Chapter 4 will be compared to the above equations.

EXAMPLE OF A RIGHT-TURN LANE DESIGN

An exploration of the impacts of selected factors was undertaken to show their influence on the design of a major intersection. Areas explored included the influence on turning vehicle speed, pedestrian facilities, and the desirability of including corner islands. The primary variables used in the evaluation are:

- 100 ft radius, and
- WB-50 design vehicle.

The design also has the following dimensions:

- outside, or curb lanes are 12 ft;
- curb offset is 2 ft; and
- inside lanes (if present) are 12 ft.

The application used turning templates to approximate the wheel paths of the vehicle. Simulation software can be used to better customize the turning path to the geometry present at an intersection.

The selection of the design vehicle for an intersection should be made after consideration of the vehicle mix that is projected to use the facility. The WB-50 truck is used in this example, although other design vehicles are appropriate in other circumstances. Passenger cars would be capable of traversing the designs created for a WB-50 truck; therefore their turning paths are not included on the figures for clarity. It is noted that the choice of a WB-50 truck as a design vehicle is not appropriate for many locations, and its use as a design vehicle may undesirably affect intersection designs with regard to pedestrian facilities (i.e., crossing distance and vehicle turning speed) and the layout of the resulting intersection design (i.e., island use may not be an option and a large, poorly defined paved area may result).

Proposed Designs

Figure 8 shows a design using a 100 ft radius with the turning template of a WB-50 truck. The truck is able to turn right without infringing on other lanes of the original or receiving roadway. It is apparent that the use of a large simple radius, while effective at allowing the truck to turn without infringing on other lanes, results in a very large, poorly defined intersection area. The turning path shown in Figure 8 shows that the radius could be reduced while still allowing the design vehicle to complete the right turn.

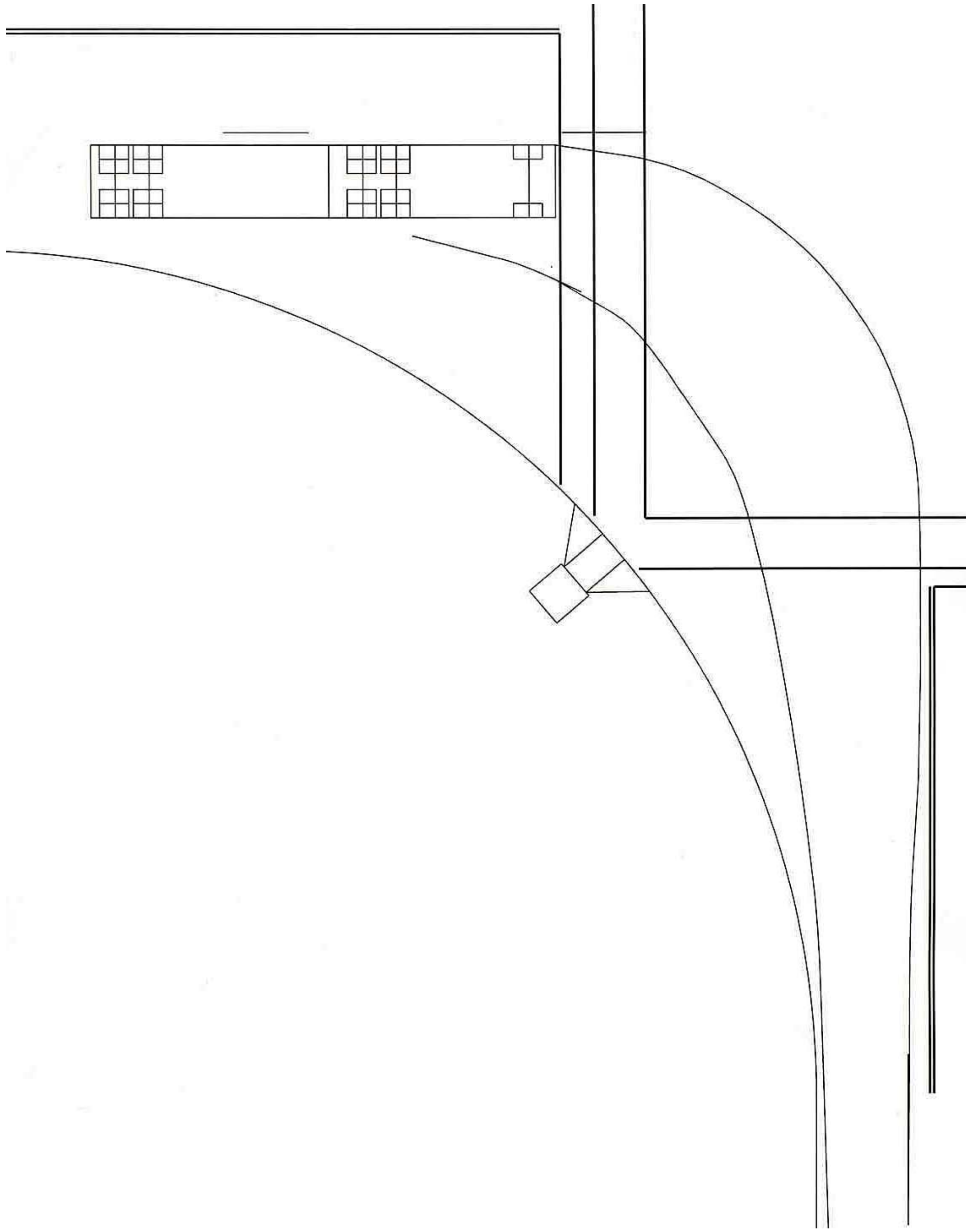


Figure 8. WB-50 Truck on 100 ft Radius Curve.

Figure 9 shows the design as modified by the inclusion of an island. The use of the island provides better definition for the intersection, by channelizing the traffic. The islands also provide refuge for pedestrians and locations for traffic control devices. The island is shown with a cut-through pedestrian path rather than curb ramps, because the island is too small to allow the necessary 5 ft by 5 ft landing area at the top of the ramps.

The use of corner islands would be desirable with respect to reducing crossing distances and providing refuge areas, although drivers of WB-50 trucks would have to exercise care to avoid over-running the curb. The turning speeds of passenger cars would remain an issue.

Passenger car turning speeds on the roadways shown in Figure 8 and Figure 9 might be predicted using the equation developed by Emmerson (*7*). However, the research presented in Chapter 4 may suggest that other methods are more appropriate. Using the equation provided and a corner radius of 100 ft, the turning speeds of passenger cars are predicted to be 20 mph. Pedestrians crossing the intersection could find the crossing to be quite difficult, given the high speeds of the turning vehicles and the long crossing distance of any crosswalk placed close to the intersection.

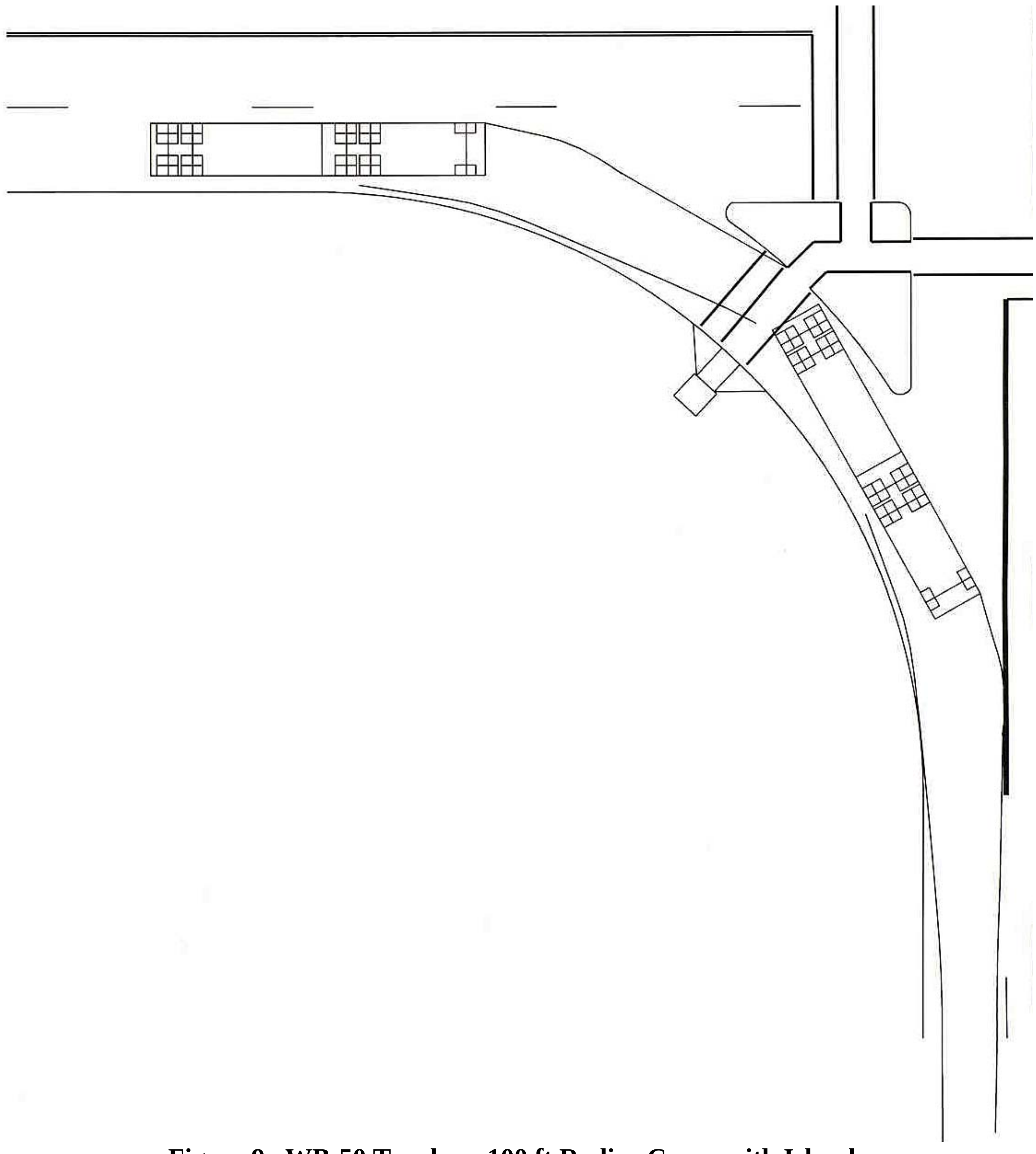


Figure 9. WB-50 Truck on 100 ft Radius Curve with Island.

CHAPTER 3

COMPARISON OF PORTABLE SPEED MEASUREMENT DEVICES IN RIGHT-TURN LANE

Accurate knowledge of right-turn lane speeds can assist with the selection of right-turn lane design elements. The objective of this effort was to determine the relative accuracy of four speed measurement devices and to make recommendations on their use in future studies that will measure the speeds of vehicles in a right-turn lane. The recommendation would be based on: accuracy, reliability, installation requirements, driver's interaction with equipment, worker effort, and worker safety. Elements of the driver's interaction with the equipment include: 1) does the driver know the equipment is present, or 2) does the driver need to be in an instrumented vehicle.

PROCEDURE

Preferred are in-field vehicle speeds (as opposed to speeds on a test track) for the research effort. Therefore, preliminary tests using several speed measurement devices were conducted at two urban intersections with exclusive right-turn lanes. The results from these tests are to provide direction on how to collect speeds at right-turn lanes for a larger study.

SITES

Two intersections were selected for the testing of the speed measurement devices. Figures 10 and 11 are photographs of the two sites focusing on the approaches to the right-turn lanes.

Site 1 had the following characteristics:

- Right-turn lane length: 178 ft
- Island: 30 ft × 22 ft × 22 ft
- Turning radius: 43 ft
- Exclusive downstream lane: no

Site 2 had the following characteristics:

- Right-turn lane length: 200 ft

- Island: 170 ft × 105 ft × 117 ft
- Turning radius: 160 ft
- Exclusive downstream lane: no

Figure 10. Photograph of Site 1.

Figure 11. Photograph of Site 2.

SPEED-MEASURING DEVICES

The speed measurement devices tested at each site included:

- distance measuring instrument (DMI) (*10*),
- pneumatic tubes connected to automated vehicle classifier (tubes) (*11*),
- lidar (laser) (*12*), and
- video.

Distance Measuring Instrument

A Ford Taurus was instrumented with a properly calibrated DMI. The laptop computer and data acquisition unit record speeds every 0.5 seconds during the test runs. The TTI technician was instructed to drive as he would normally for a goal of 12 test runs. Using this type of speed-measuring device produces high quality and detailed data continuously through the right turn (i.e., not just at the point of curvature or the midpoint). A severe limitation for this approach for collecting speed data is that it requires the subject to use the TTI vehicle which limits the number of subjects that can be used for similar projects, limits the number of sites and test runs that can be included in the study (since there is a concern with driver fatigue), creates the situation that the drivers know they are part of a roadway study, and places drivers in an unfamiliar vehicle.

Pneumatic Tube

Pairs of pneumatic tubes were placed 16 ft apart at two locations on the curve. The first location was near the point of curvature, and the second was at the midpoint of the curve. The tubes near the point of curvature were placed across the entire lane and halfway into the lane at the midpoint. The placements of the tubes at the midpoint were based on observations of vehicle paths through the curve. As the vehicle enters the curve, the axle location with the respect to the tube is perpendicular allowing for the front wheels to cross the tubes at the same time. As the vehicle travels through the curve, all four wheels are no longer perpendicular to the curve, which creates four hits instead of two. By placing the midpoint tubes halfway across, only one wheel per axle traveled over the tubes, which lowered the chance for erroneous data. The use of pneumatic tubes requires the technicians to place the devices onto the pavement either during gaps between vehicles or to use traffic control to stop vehicles for installation. The visibility of the device (both seeing the tubes on the approach and feeling the tubes when driving over them) results in drivers being aware of the tube's presence.

Laser

Using laser gun speed-measuring devices, technicians would position themselves off the roadway to record the speed of the DMI vehicle through the right turn. The laser guns were wired to laptop computers that recorded data every 0.3 seconds when the laser was activated. The collected data would then be adjusted according to the manufacturer's recommendation to adjust for the cosine error that occurs when the centerline of the laser is not the exact same as the centerline for the vehicle's path. When a vehicle is traveling straight, the angle between the laser gun and the vehicle does not change and, in most cases, the angle between the vehicle and the laser gun is less than 8 degrees, resulting in a very small correction (<1 percent). The limiting factor for vehicles traveling in a straight line is the sight distance and the range of the laser gun. When vehicles are traveling through a curve, the limiting factor on the performance of the laser gun is the effective angle between the line of sight of the laser gun and the direction of the vehicle. As a vehicle travels through a curve, the vector of the vehicle is constantly changing with respect to the curve of the road and the laser gun. The cosine error stated by the manufacturer is less than 1 percent when the laser gun is within 8 degrees of the vehicle. The cosine error increased to 3 percent when the laser gun is between 8 degrees and 14 degrees.

Advantages of using a laser gun are that it allows the technicians to be completely off the roadway prior to and during data collection. Disadvantages include the difficulty in finding a location that is not visible to passing drivers (and thus having a potential effect on their performance) and having an optimal recording location (e.g., minimal cosine error correction, minimizing the potential for other vehicles interrupting the recording of the subject vehicle, etc.). When shooting speeds in a curve, one laser gun is not sufficient for recording the speed of the vehicle through the entire curve. Several laser guns may be required to measure speeds and maintain a small correction factor throughout a tight radius.

Video

Researchers placed a video camera in the field such that it could record the area of interest. Three cones were placed at each intersection. At Site 1, cones one and two were located at the point of curvature and the point of tangent of the curve while cone three was located at the midpoint. At Site 2, cones one and two were positioned at the point of curvature and the midpoint, cone three was located equidistance from cones one and two. Once the cones were located at the intersection, the distance between each cone was measured (Site 1: 40 ft, Site 2: 59 ft). This distance was used to calculate the speeds of the DMI vehicle from the video. After several minutes of video recording that included one run by the DMI vehicle, the cones were removed from the intersection. After the field data collection and in the office, a transparency was placed directly on the monitor. Pen marks were made on the transparencies at the exact location of each cone. For the initial trial run, time was recorded from the point at which the DMI vehicle crossed the marks on the transparency. For each DMI run, times were measured at the three cones. Once the time was recorded, using the known distance of the video speed zones, the speed for the DMI vehicle was calculated to the nearest integer.

COMPARISONS

The DMI vehicle was considered to be the true speed associated with the speed detection zones. Comparisons were defined by Equation 6:

$$\text{Net Difference} = (\text{DMI Speed})_{mph} - (\text{speed-measuring device})_{mph} \tag{6}$$

When the net difference was negative, the technique overestimated the DMI vehicle speed. All results were rounded to the nearest whole number.

The three different speed measurements devices (laser, tubes, and video) were compared to the DMI vehicle. A two-dimensional Cartesian coordinate system was developed as a reference to record the location of the point of curvature, midpoint of the curve, and the point of tangent. The coordinate system was also used to reference the location of the sampling devices.

Site 1

Figure 12 is a drawing of the representative locations of the curve and the equipment for Site 1. In Figure 12, the point of curvature (PC) was located at (0, 0), the midpoint of the curve at (17, 35), and the point of tangent at (55, 49). (All locations in the coordinate system are in units of ft.) After initial observation of the intersection, two locations were selected for the laser guns. Two laser guns were used to lower the potential of a cosine error correction. The first laser gun (LG1) was located 327 ft north of the intersection (0, -327) and the second laser gun

(LG2) was located 275 ft southwest of the intersection (120, 247). LG2 was across the major road, and on some occasions it did not have a clear line of sight to the intersection due to traffic.

There were two speed zones for this intersection; speed zone one (SZ1) was located at the point of curvature, and speed zone two at the midpoint of the turn. Figure 12 shows that speed zone one is within the 8-degree range for LG1. In speed zone two (SZ2), it was more difficult for LG2 to maintain a constant angle because of the change in direction of the vehicle. Speed zone two was set to less than 16 ft and included angles that were less than 8 degrees, angles between 8 and 14 degrees, and between 14 and 20 degrees with respect to LG2.

Site 1 was densely populated with obstacles, which included fences, trees, and buildings. These obstacles limited the video camera placement. The location of the video camera was approximately 75 ft northwest of the intersection. This location was selected because it provided the best line of sight of the intersection.

There were 11 DMI vehicle runs at Site 1. Two of these runs were excluded from the overall findings due to equipment malfunction. For one of the runs, the driver had to stop the vehicle at the end of the turn due to a conflicting vehicle. Figure 13 shows the speed of the test vehicle for each drive through the right turn. The average speed for the nine runs was 19 mph at the PC, and the average speed at the midpoint for the 43 ft radius was 15 mph. The difference between the speed for the DMI vehicle and the other speed-measuring devices was calculated. Table 3 lists the findings for Site 1.

Point of Curvature

Since the location of LG1 was within 8 degrees of the DMI vehicle at the point of curvature, there was less than a 1 percent difference between the recorded laser gun speed and the true speed determined using a cosine error correction. The video at Site 1 had the lowest accuracy. This low accuracy may be explained by the limited options for the camera placement. At the point of curvature for Site 1 the tubes had the highest frequency of both 0 and 1 mph net differences. The tubes also had the lowest frequency for net differences greater than 2 mph. At Site 1, the laser gun preformed the second most accurate followed by the video measurement.

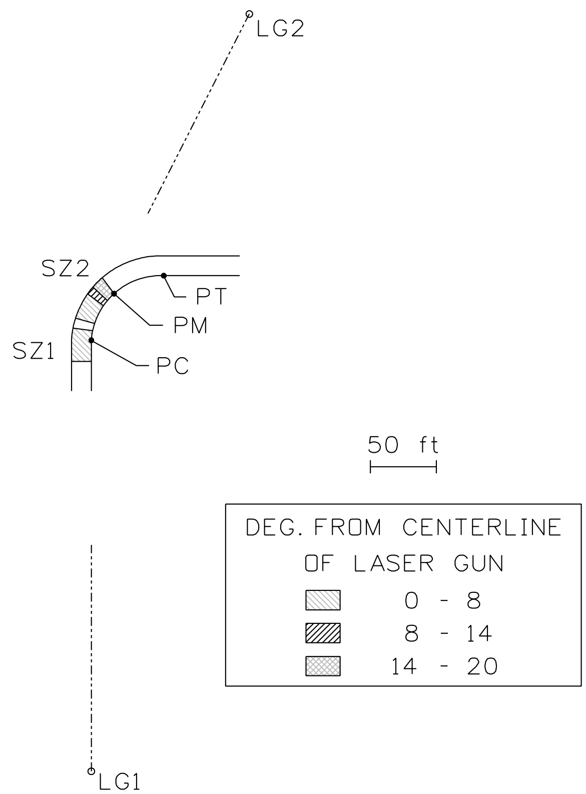


Figure 12. Drawing of Site.

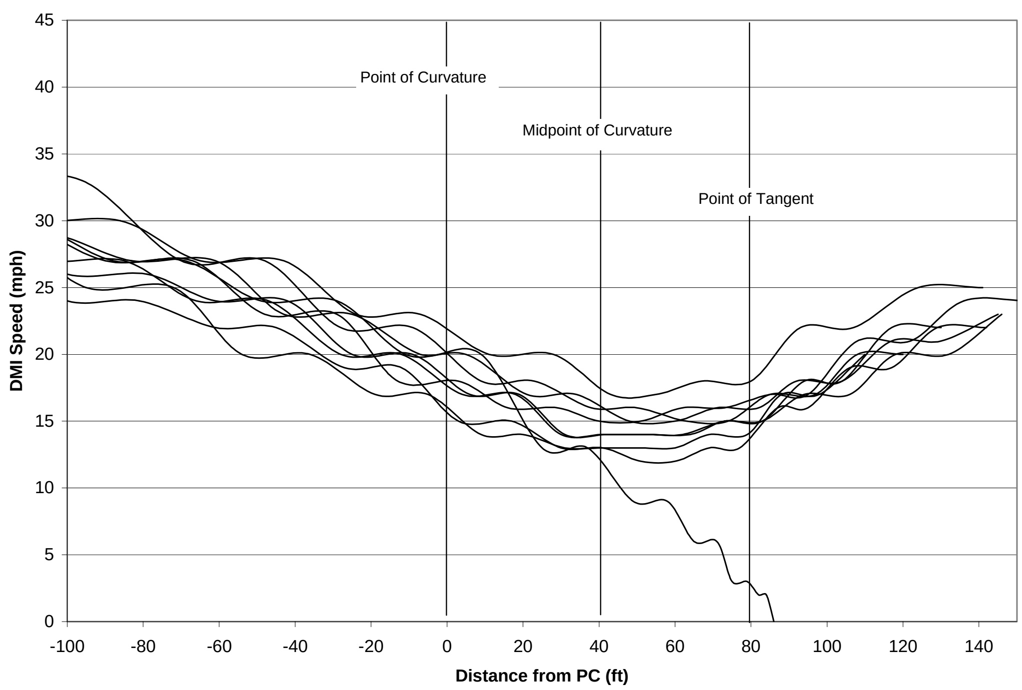


Figure 13. DMI Vehicle Speed Through Right Turn at Site 1.

Table 3. Site 1 Comparison.

With a Difference of:	Number of Runs by Speed Measurement Device:		
	Laser	**Tubes**	**Video**
Point of Curvature			
0 mph	2	3	0
1 mph	3	4	1
2 mph	2	1	4
>2 mph	2	1	4
Average	1.4 mph	1.0 mph	2.7 mph
Midpoint of the Curve			
0 mph	1	4	4
1 mph	1	3	5
2 mph	3	2	0
>2 mph	4	0	0
Average	2.2 mph	0.8 mph	0.6 mph

Midpoint of the Curve

As the vehicle travels around the midpoint of the curve, the angle between the laser gun and the vehicle increases more rapidly when directly compared to the point of curvature. Based on the two-dimensional coordinate system, SZ2 should have either a 1 percent or a 3 percent correction. Site 1 had an average DMI speed of 14 mph at the midpoint. With this speed, a 3 percent correction will not significantly change the overall difference with respect to the DMI vehicle. The laser had the lowest number of runs that were within 1 mph of the DMI vehicle speed. The pneumatic tubes improved only slightly from the midpoint location when compared to the point of curvature. The video performance improved dramatically over the first position. The location of the video camera was more perpendicular to the midpoint of the curve which made the identification of the vehicle placement easier to identify. Although the performance of the video was the best at the midpoint, the tubes still had seven of nine runs within 1 mph of the DMI vehicle.

Site 2

Figure 14 illustrates the effective coverage area associated with the two laser guns. LG1 covered the PC. A 1 percent correction factor was used for the cosine error. LG2 covered the midpoint of the curve and was between 8 to 14 degrees offset. Similar to the first intersection, laser gun two was placed 430 ft away from the PC across the major street and, on occasion, traffic blocked the line of sight. Unlike the first intersection, this intersection provided ample video camera placement. Directly to the southwest of this intersection was a large field with no obstacles therefore, there was a clear line of sight between the video camera and the entire intersection. For intersection two, the camera location was 200 ft southwest of the intersection and provided a better view.

Figure 15 shows the speed of the test vehicle for each drive through the right turn. The average speed for the nine runs was 28 mph and 24 mph at the point of curvature and the midpoint, respectively. Table 4 compares the 12 different DMI runs that were used to evaluate the laser guns, tubes, and video detection for both the point of curvature and the midpoint of the exclusive right-turn lane.

Point of Curvature

At the point of curvature, the tubes and laser devices provided slightly better results than the video. For video detection at Site 2, there was a higher percentage for both 0 and 1 mph net differences and a lower percentage of net differences greater than 2 mph when directly compared to Site 1. The improvement in video detection was due to the location of the video camera. Site 1 had trees and other viewing obstacles that limited the placement of the video camera. Site 2 had a large field that provided ample space for the ideal placement of the video camera.

Midpoint of the Curve

The laser gun was less accurate at the midpoint than the point of curvature. There were two less runs where the net difference was 0 mph. The tubes located at the midpoint of the curve performed the most accurate at Site 2. The video performance was slightly more accurate for the midpoint than the point of curvature for Site 2. In this case there were two more runs with a net difference of 0 mph and a total of eight runs with a net difference of 1 mph or less, an increase of one over the video detection used at the point of curvature. In general the equipment performed better for Site 2 than Site 1.

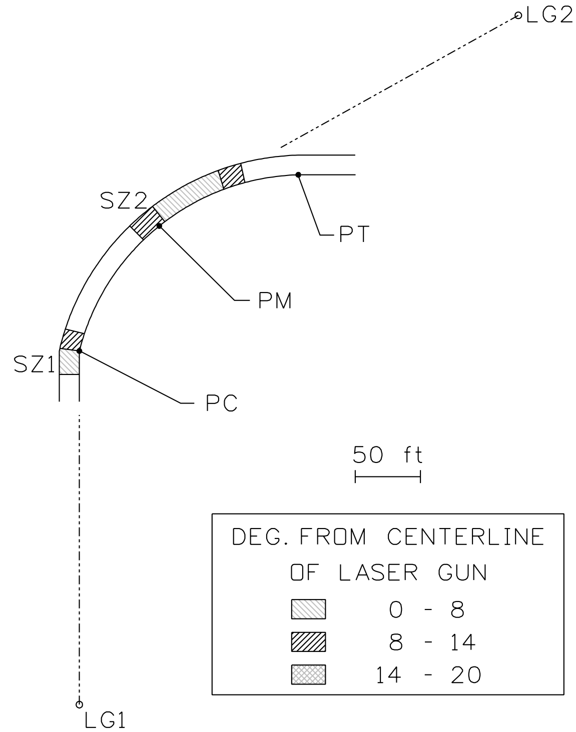


Figure 14. Drawing of Site 2.

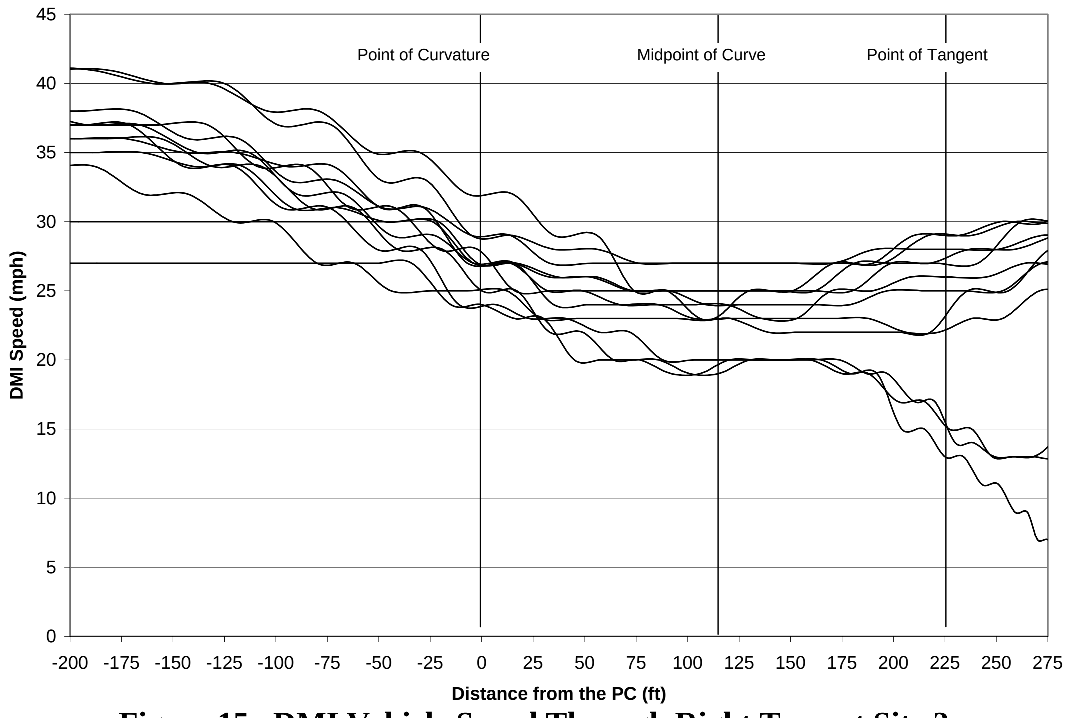


Figure 15. DMI Vehicle Speed Through Right Turn at Site 2.

Table 4. Site 2 Comparison.

With a Difference of:	Number of Runs by Speed Measurement Device:		
	Laser	**Tubes**	**Video**
Point of Curvature			
0 mph	3	5	4
1 mph	5	4	3
2 mph	2	3	2
>2 mph	0	0	3
data not available	2	0	0
Average	**0.9 mph**	**0.8 mph**	**1.5 mph**
Midpoint of the Curve			
0 mph	1	8	6
1 mph	5	2	2
2 mph	3	1	2
>2 mph	1	0	2
data not available	2	1	0
Average	**1.4 mph**	**0.4 mph**	**1.2 mph**

FINDINGS

There are many factors that are associated with the measurement of speeds through right-turn lanes. Depending on the amount and location of speed information that is required, different speed sampling techniques are adequate. If the purpose of the study is to measure speeds throughout the entire turn to locate where speeds are the lowest or highest within a segment, the best technique is a DMI equipped vehicle. The advantage of a DMI vehicle is continuous coverage through the curve. The disadvantage is the limited number of trial runs, the selection of the pool of drivers, and the driver's bias towards the study. For other methods, complete coverage of the curve will require several laser guns, pneumatic tubes, or video cameras. Additional equipment will increase the coverage area at the expense of higher probability of affecting drivers and increasing study costs.

The goal of this study was to evaluate and compare different techniques available to measure right-turn lane speeds. The speeds recorded using a DMI instrumented vehicle served as the "true" speed for the analysis. Researchers selected two sites for the comparison of the different speed-measuring devices. Each site included two different speed detection zones: the point of curvature and the midpoint of the curve.

The results of this study found that pneumatic tubes had the largest number of net 0 mph differences with the DMI vehicle for both the point of curvature as well as the midpoint of the curve. The laser gun at both sites performed better at the point of curvature than the midpoint of the curve. The increase in performance at the point of curvature compared to the midpoint of the curve was explained by the rapid change in the angle between the vehicle and the laser gun. There was also improvement in accuracy for the laser gun between the midpoint in Site 2 and the midpoint in Site 1.

The gradual turn of Site 2 allowed the vehicle's speed vector in relation to the laser gun to change less drastically compared to a curve with a smaller radius. In a tight, small radius curve, the vehicle's speed vector changes more quickly with respect to the laser gun. Therefore, the angle in a larger radius is more consistent throughout the detection zone located in the curve.

The results of the video revealed the importance of camera location to measure right-turn lane speed. Video data at Site 1 was not as accurate as Site 2. For Site 1, space was limited and there were very few places that provided a clear line of sight of the intersection. The second site was directly adjacent to a large field, which provided the opportunity for a better camera placement. In an optimal setup, all the measurement devices are accurate; however, in this study the pneumatic tubes were the most accurate with the highest number of trial runs with a net speed difference of 2 mph. Therefore, the selection of the portable measurement device should be made on other criteria such as worker safety and the scope of the study.

EQUIPMENT RECOMMENDATIONS FOR FIELD STUDY

The overall findings for this pilot study suggested that pneumatic tubes provided the closest most accurate overall results when directly compared with the DMI instrumented vehicle. The video provided accurate results when the video camera was placed in the correct location and in general the laser gun also provided decent results, but multiple laser guns would need to be used at each intersection, especially intersections with a small radius. The results of the pilot study suggest the combination of pneumatic tubes and video for the full field study.

CHAPTER 4

FREE-FLOW VEHICLE SPEEDS IN A RIGHT TURN

The selection of a large radius for a corner permits higher turning-vehicle speeds in free-flow situations. The higher speeds can result in smaller-speed differentials with following vehicles and thus less severe rear-end conflicts in the through lanes. Other benefits of a channelized right turn are the removal of the turning vehicles from the through lane and more efficient merging opportunities. Trade-offs include the increased challenge for the pedestrian crossing the roadway due to the higher operating speeds along with the drivers' expectation that they do not have to stop since a "free-flow" right-turn lane is present. The objective of this study was to determine the free-flow speeds of vehicles in an exclusive right-turn lane.

SITE SELECTION

Site selection was to identify approximately 15 sites with exclusive right-turn lanes with a range of radii and channelization treatments (raised island versus lane line). From satellite images, intersections with exclusive right-turn lanes with different radii were identified. This initial list included 30 plus different intersections. After the preliminary selection, researchers used field observations to select the final intersections. The final selection of the intersections was based on the volume of traffic, including the number of right-turning vehicles; the intersection's relative location with respect to other sites; and the potential video camera line of sight.

The research team selected the Cities of College Station and Irving for this study. There were seven approaches selected in College Station and 10 approaches in the City of Irving. All approaches had exclusive right-turn lanes, which included raised islands or pavement markings. All intersections are located in urban/suburban areas, have a traffic signal, and had sufficient traffic volumes where the research team felt they would achieve at least a sample population greater than 30 per approach. At some locations, the right-turn lane turned into a dedicated downstream lane.

Table 5 lists the characteristics of the selected sites. Figure 16 shows a photograph from the perspective of the driver traveling in the right-turn lane for each site. As shown in Table 5, the smallest radius was 27 ft and the largest radius was 86 ft. There were seven radii less than 40 ft, three radii between 40 and 50 ft, and eight radii greater than 50 ft.

Table 5. Site Characteristics.

Site	RTL* Length (ft)	RTL* Width (ft)	Turning Roadway Width (ft)	Down-stream Lane Width (ft)	Corner Radius (ft)	CH*	Island Dimensions	Island Size (ft^2)	Accel. Lane Length (ft)	TCD*
A	204	9	22.5	11	33	RI	27×21×26	255	None	Y
B	178	15	23	12	43	RI	30×22×22	242	None	Y
C	113	14	17.3	12	35	RI	15×15×19	110	None	N
D	150	11	22	13.8	82	RI	15×15×22	112	200	N
E	143	11	N/A	N/A	50	LL	N/A	N/A	None	N/A
F	150	13	13	12	50	RI	43×43.5×38	740	None	N
G	199	14	N/A	N/A	28	LL	N/A	N/A	None	N/A
H	115	13	22	10	68	RI	47×35×33	578	None	Y
I	200	11	20	17.5	86	RI	42×40×70	749	None	Y
J	200	14	20	12	79	RI	28×24×37	337	None	Y
K	164	10	20	11	65	RI	60×37×54	984	None	Y
L(1)	300	10	N/A	N/A	28	LL	N/A	N/A	None	N/A
L(2)	300	10	N/A	N/A	38	LL	N/A	N/A	None	N/A
M(1)	250	10	N/A	N/A	28	LL	N/A	N/A	None	N/A
M(2)	250	10	N/A	N/A	38	LL	N/A	N/A	None	N/A
N	195	10	N/A	N/A	27	LL	N/A	N/A	None	N/A
O	200	11	19.0	10.5	62	RI	54×42×39	813	70	Y
P	160	10.5	19	10	59	RI	42×41×60	860	60	Y
Q	167	11	19.5	12	70	RI	56×42×44	913	62	Y

Note
*RTL = Right-Turn Lane
*CH=Channelization
RI = Raised Island
LL = Lane Line
*TCD=Traffic Control Device, Is a yield sign present along turning roadway?
Y = Yes
N = No
N/A = Turning Roadway not present.

Site A

Site B

Site C

Site D

Site E

Site F

Figure 16. Photographs of the Sites.

Site G

Site H

Site I

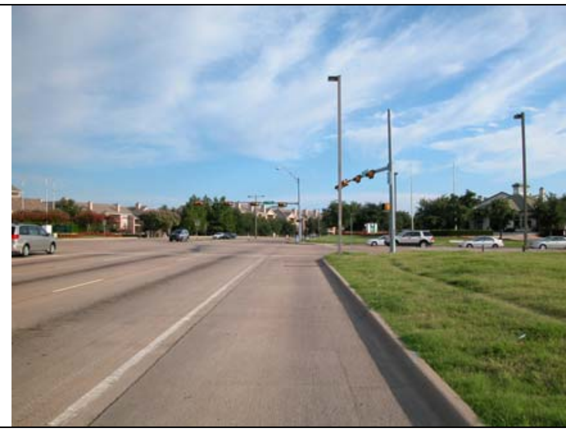
Site J

Site K

Site L

Figure 16. Photographs of the Sites (continued).

Site M



Site N

Site O

Site P

Site Q

Figure 16. Photographs of the Sites (continued).

DATA COLLECTION

Pneumatic Tubes

The configuration of the classifiers for the field studies in College Station and Irving were slightly different due to the classifier equipment being used in each city. The classifiers in College Station required the tubes be placed 16 ft apart, while the Irving classifiers required the tubes be placed 10 ft apart. The first location was near the beginning of the turn at the point of curvature (PC) for the corner radius. The second set of tubes was near the midpoint of the turn (PM). The tubes near the beginning of the turn were placed across the entire lane. The tubes placed at the midpoint of the turn were placed halfway across the lane. Figure 17 shows the setup for one location. Chapter 3 provides additional information on the placement of the tubes.

Figure 17. Driver's Traveling View in Right-Turn Lane.

Video Collection

In addition to the pneumatic tubes, video cameras were located at each intersection. The video cameras were positioned to view the vehicles entering and exiting each right-turn lane. The goal of the video camera was to provide additional information on the behavior of the vehicle traveling through the lane. From the video, the research team identified free-flow conditions, as well as potential erroneous data associated with lower speeds (< 5 mph). The video provided additional information and was used as a second check for free-flow conditions.

Duration of Sample Collection

The objective of this study was to measure the free-flow speed of vehicles traveling through a right-turn lane. The goal was to collect 100 free-flow vehicles or to record for a maximum of four hours. For most intersections, the four-hour duration was used to be conservative. At each intersection several hundred vehicles were recorded, however, generally only between 30 and 50 free-flow vehicles met the free-flow requirement and were available for use in the analysis. The requirement that the speed of the subject vehicle used in the analysis be unaffected by other vehicles resulted in several data points being eliminated.

DATA REDUCTION

After the field collection, the data stored in the classifiers were downloaded onto a computer. Once on the computer, the raw data files were then imported into a spreadsheet. At this point the files were manually inspected for errors and unnecessary data were deleted. Common errors associated with this study included vehicle speeds that were too slow for accurate detection, and misclassification of vehicles. Once the researchers removed the errors they analyzed each vehicle record to determine if the vehicle would be considered free flow. The definition of free flow for this study was that the vehicle had a minimum of a 5 second headway and that a minimum of 3 seconds separated the subject vehicle with the following vehicle. The time stamp generated by the classifier for each vehicle was used to determine if the vehicle could be considered free flow.

The video recording provided information about the behavior of each driver. For this study, seven driver behavior codes described the right turn:

- Clear – Clear, vehicle is under free-flow conditions with no obstacles

- SL-Look – Vehicle slowed to look for traffic
- SL-Traffic – Vehicle slowed as a result of traffic
- ST-Look – Vehicle stopped to look
- ST-Traffic – Vehicle stopped for oncoming traffic
- ST-Other – Vehicle stopped due to other traffic waiting to turn
- ST-Ped – Vehicle stopped for pedestrian crossing

Each error-free vehicle recorded by the classifier was assigned one of the driver-behavior codes. The final data set included only vehicles that were under free-flow conditions with a driver-behavior code of "Clear." These vehicles were considered to be traveling under normal conditions without influence by other vehicles. Vehicles with other driver-behavior codes were not used for this study because speeds could be affected by variables (such as other vehicles) not directly associated with the corner radius of the turn or the channelization treatment. Table 6 lists the number of right-turning vehicles recorded along with their distribution among the driver-behavior codes. The majority of the vehicles recorded had a clear, free-flow condition. The data collection efforts attempted to minimize recording during peak periods or near peak-period times so as to minimize the number of data points that would not be usable in the study. For about 20 percent of the vehicles recorded, the driver notably slowed to consider the behavior of other vehicles. Only 1 of the 1976 right turns involved a pedestrian crossing the right-turn lane.

Table 7 provides the summary statistics for the 17 sites. Two approaches were subdivided into two sites to account for the different radius used by turning vehicles. At Sites L and M, drivers would either turn into the near lane (following the radius of the curb return) or would turn into the 2nd lane of the cross street, therefore using a larger radius than that represented by the curb return. For this study, the final sample size per intersection varied from 4 to 174 vehicles as shown in Table 7. Intersection P with only 4 value data points was not included in the analysis of 85th percentile speed.

Table 6. Distribution of Driver Behavior.

Site	Clear*	SL-Look	SL-Traffic	ST-Look	ST-Traffic	ST-Other	ST-Ped
All Sites							
Freq	1111	375	187	28	257	17	1
%	56	19	9	1	13	1	0
Individual Sites, Percentage (%)							
A	76	14	4	3	3	0	0
B	70	20	2	2	5	0	0
C	54	32	9	0	4	0	0
D	54	22	23	0	2	0	0
E	94	0	6	0	0	0	0
F	37	19	10	6	27	1	0
G	41	12	8	4	29	5	0
H	17	32	23	1	25	1	0
I	72	19	4	0	5	0	0
J	59	20	9	2	11	0	0
K	75	11	2	1	11	0	0
L(1)	82	8	0	3	5	3	0
L(2)	78	19	0	3	0	0	0
M(1)	80	15	4	2	0	0	0
M(2)	82	11	2	2	4	0	0
N	67	21	6	3	1	0	1
O	40	15	11	0	31	2	0
Q	76	15	6	0	2	1	0

* Clear – Clear, vehicle is under free-flow conditions with no obstacles
SL – Look – Vehicle slowed to look for traffic
SL – Traffic – Vehicle slowed as a result of traffic
ST – Look – Vehicle stopped to look
ST – Traffic – Vehicle stopped for oncoming traffic
ST – Other – Vehicle stopped due to other traffic waiting to turn
ST – Ped – Vehicle stopped for pedestrian crossing

Table 7. Summary Statistics.

Site	Number of Data Points	Speed at Beginning of Turn (mph)			Speed at Middle of Turn (mph)		
		Average	85th	Standard Deviation	Average	85th	Standard Deviation
A	55	20.5	21.8	2.49	13.2	14.9	2.61
B	31	19.0	20.7	2.32	15.2	17.2	2.16
C	37	19.6	21.1	2.57	17.0	19.3	2.55
D	50	24.0	25.5	2.86	18.2	19.8	2.09
E	30	23.3	25.9	2.86	15.7	17.2	1.99
F	47	22.3	24.8	2.69	17.7	19.4	2.62
G	26	16.7	19.5	3.70	15.7	18.0	3.17
H	57	24.5	27.0	2.99	17.1	18.4	1.75
I	174	23.0	25.3	2.75	17.3	19.2	2.44
J	33	25.8	28.5	3.30	17.1	20.5	3.66
K	125	21.8	23.9	2.50	18.5	21.0	2.84
L(1)	32	16.4	23.9	3.01	11.0	13.1	2.90
L(2)	25	16.7	19.1	3.79	12.2	15.1	3.23
M(1)	44	15.6	17.4	2.63	12.7	14.6	2.33
M(2)	47	16.9	18.7	2.48	14.3	16.3	2.33
N	47	16.4	18.5	2.38	12.3	14.0	2.22
O	85	19.3	22.2	2.67	14.6	16.7	2.45
P	4	22.3	22.9	2.06	16.5	18.5	2.65
Q	161	21.8	24.3	2.87	16.5	18.5	2.62

DATA ANALYSIS

Visual Review of 85th Percentile Speed Data

Table 7 lists the speed data for the 19 sites. One of the sites (Site P) was eliminated from the 85th percentile speed analysis due to the low number of turning speeds available for the study (equipment malfunctioned during the study and most of the data were lost). Figure 18 shows the 85th percentile speed and the average speed at the middle of the turn for the 18 sites. The data shows a potential relationship between turn radius and speed. As the corner radius increases, the speeds within the turn also increase.

Figure 19 illustrates the range of the speed data for the 18 sites. In the figure, the line is centered at the average speed, and its limits represent the 90 percent confidence interval for the site’s data at the middle of the turn. The standard deviation for the 18 sites ranged between 1.75 and 3.17 mph.

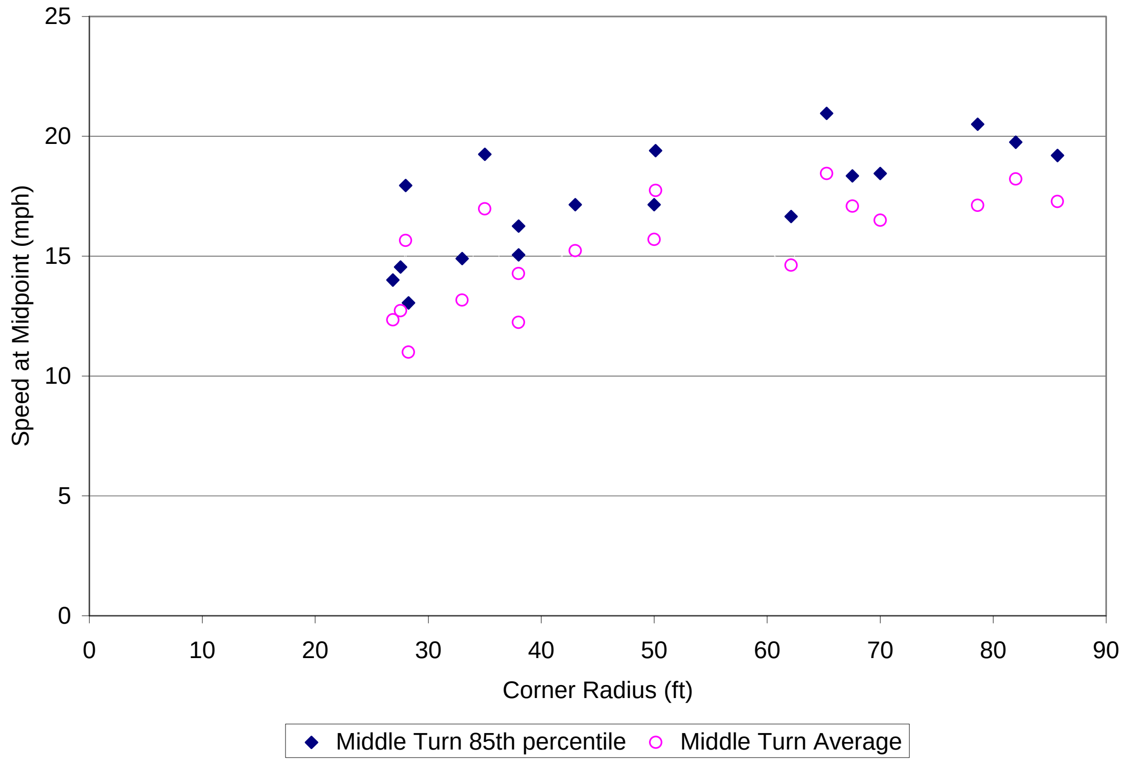


Figure 18. 85th Percentile Speed at the Midpoint of the Turn.

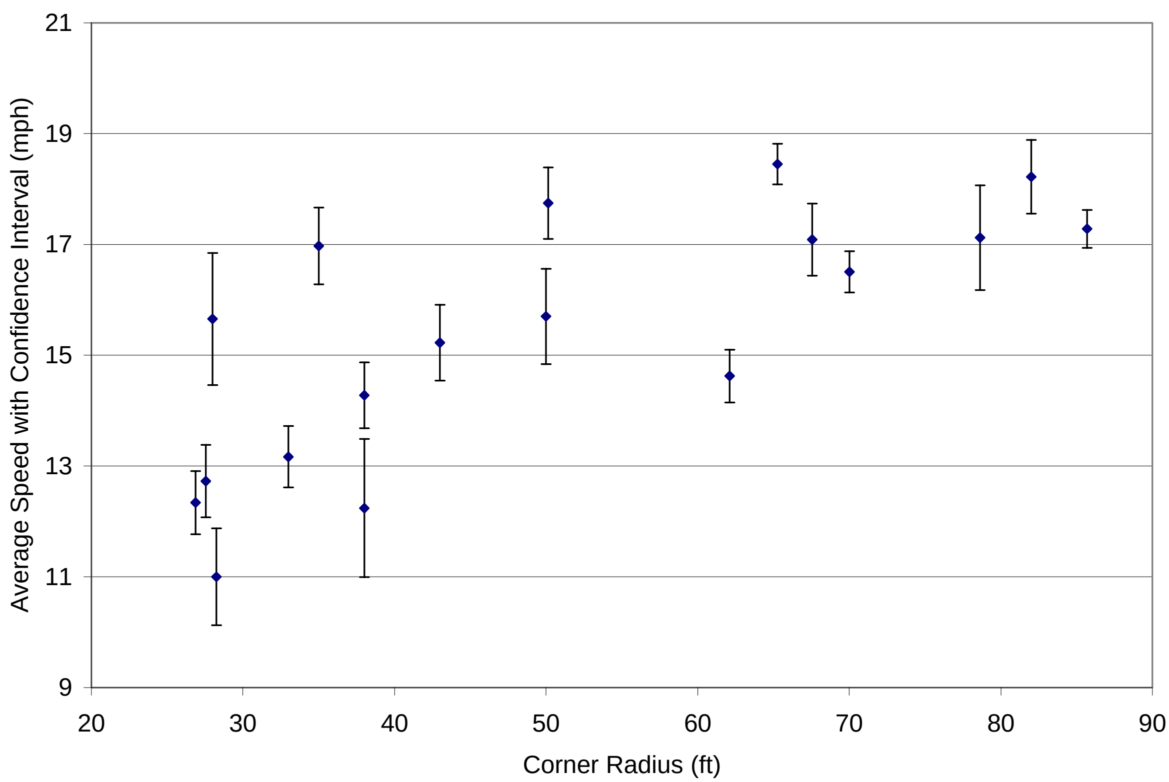


Figure 19. Plot of Average Speed with 90 Percent Confidence Interval.

Comparison of Speed Data with Literature Findings

Before this TxDOT project, an estimate of speeds within right-turn lanes was not readily available within the literature. Three studies were identified as having potential application for estimating speeds within a turn. However, they had major limitations in that all the sites were for horizontal curves rather than right turns and in most cases the horizontal curves had radii much larger than the values used for a corner radius. A simple comparison between the speeds found at the 18 right-turn lane sites in this TxDOT project and the plots using the extrapolated equations from the previous studies illustrates the difference. Figures 20, 21, and 22 show a comparison between the right-turn lane data with Emmerson, FHWA, and TxDOT project data, respectively. The comparison with Emmerson shows that in all cases, Emmerson's equation would under predict the speed in the right turn (see Figure 20). The equation developed for horizontal curves on rural highways (see Figure 21) would also underpredict speeds for curves in all cases with speeds less than 0 mph, which is not feasible. Using the equations developed within the TxDOT horizontal curves on suburban arterials project (TxDOT Project 1465) would overpredict the speed within the right turn (see Figure 22).

In summary, it is recommended that equations developed for horizontal curves not be used to estimate speeds in a right turn.

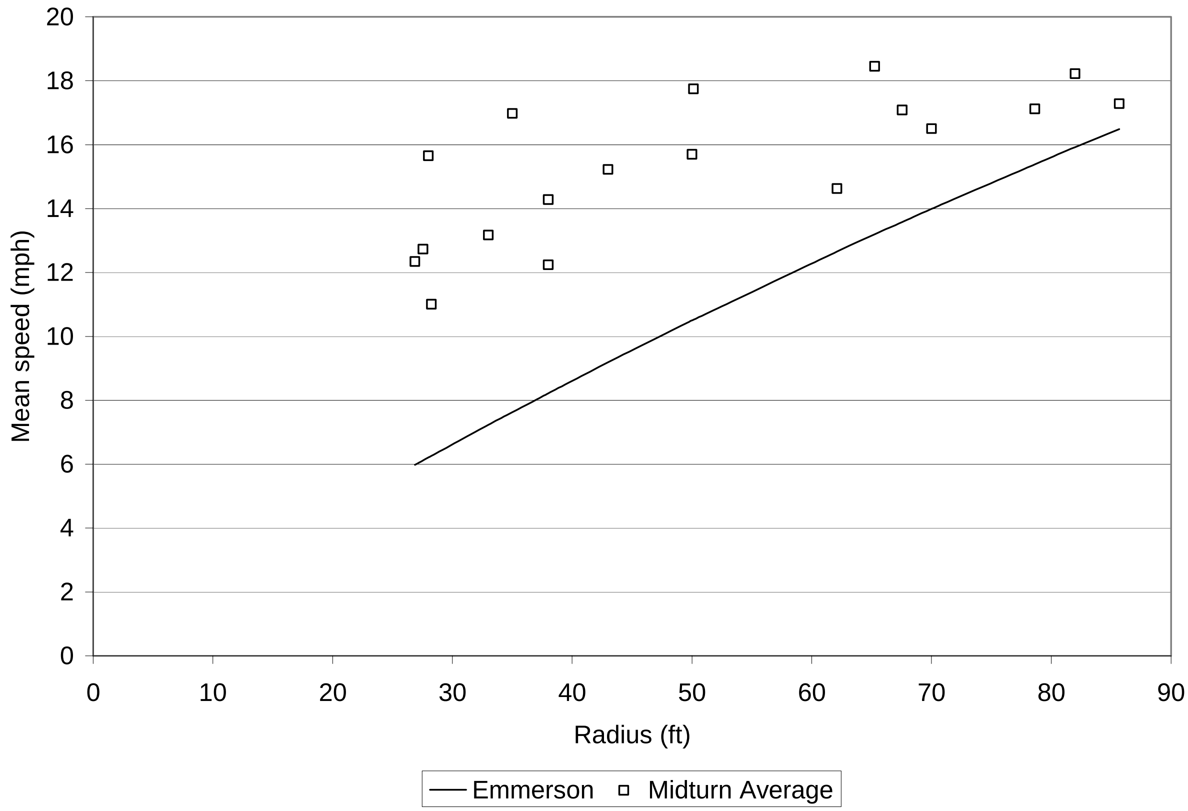


Figure 20. Comparison of Right-Turn Mean Speeds with Findings from Emmerson.

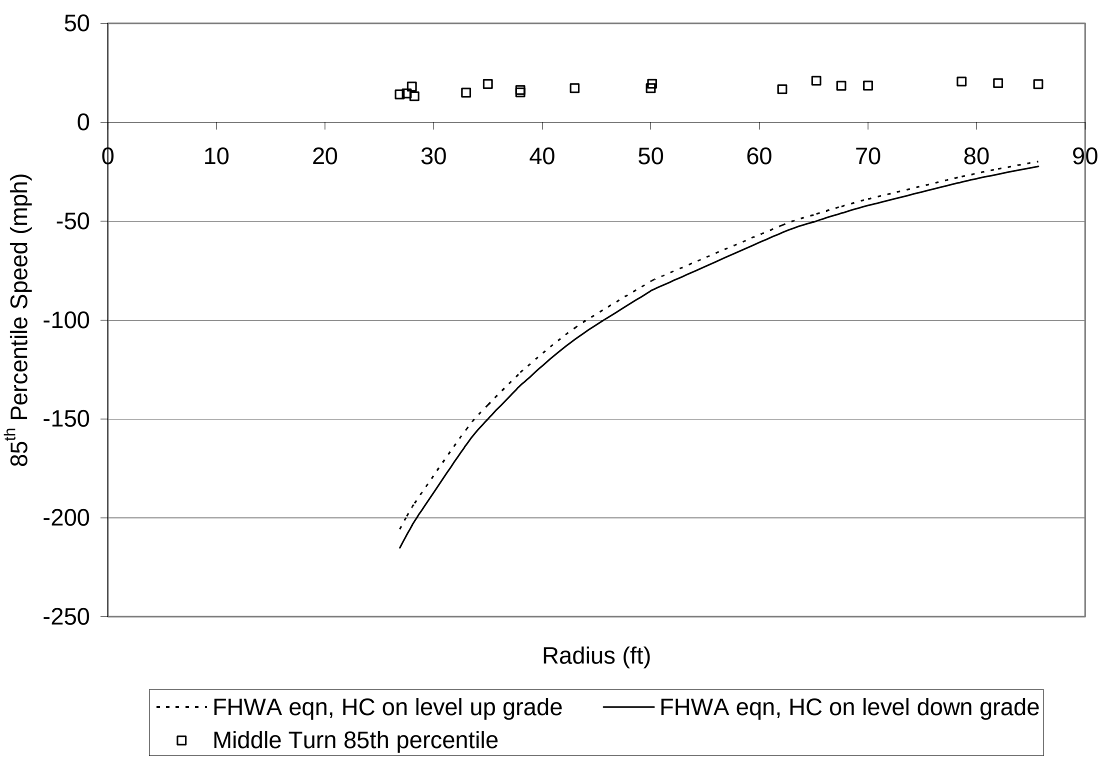


Figure 21. Comparison of Right-Turn 85th Percentile Speeds with Findings from FHWA Project.

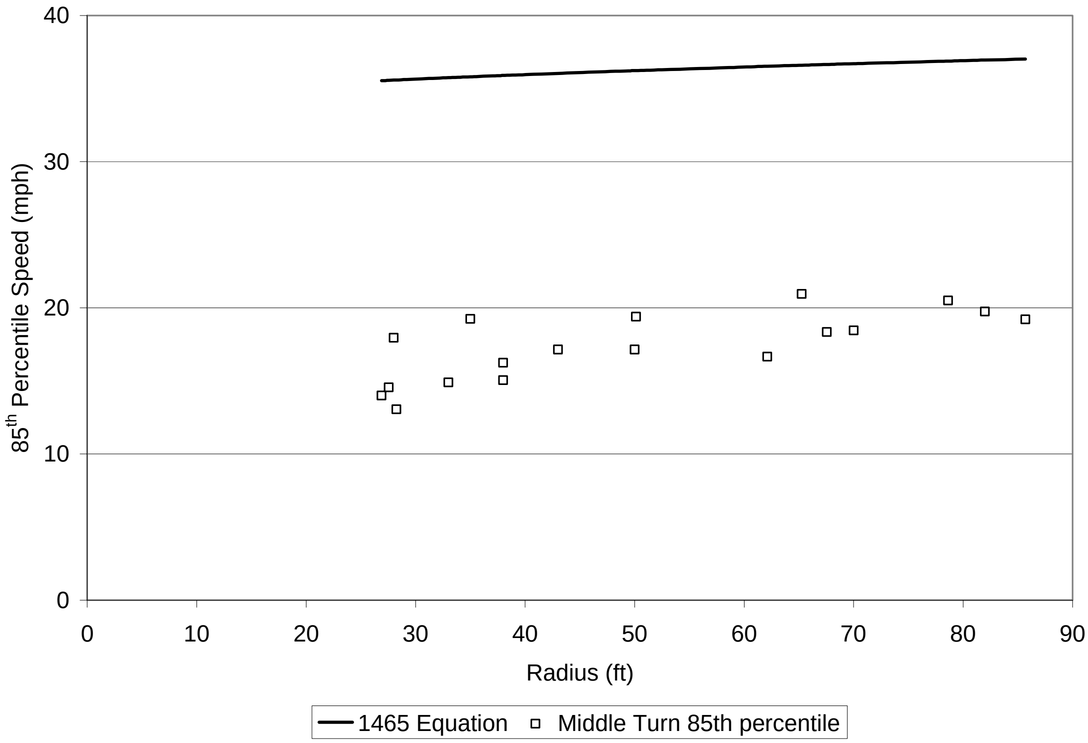


Figure 22. Comparison of Right Turn 85th Percentile Speeds with Findings from TxDOT 1465 Project.

PREDICTING 85TH PERCENTILE SPEED

The 85th percentile speed within the right turn ranged from 13.1 to 20.5 mph while on the approach it ranged from 17.4 to 28.5 mph. Figure 23 is a scatter plot of the 85th percentile speed versus corner radius for the 18 sites examined. The figure shows both the speed at the beginning of the turn and near the middle of the turn.

Beginning of Right Turn

A regression analysis was performed using the 85th percentiles of the speed measurements at each site. A regression equation will permit the ability to predict the 85th percentile speeds at the beginning of a right turn and near the middle of the right turn. An Analysis of Covariance model having channelization as a discrete factor (either island or line) and radius, right-turn lane length, and right-turn lane width as continuous factors along with all possible two-way interactions between channelization and other factors was fitted for the speed at the beginning of the turn and the speed near the middle of the turn. The analysis found that the interactions of other factors with channelization were not significant. Table 8 contains the results of fitting the model with radius, channelization, right-turn lane length, and right-turn lane width for the speed at the beginning of the turn. From the table it can be observed that only the effect of radius is significant at alpha of 0.05. Another evaluation using only radius was conducted. The results are shown in Table 9. The amount of variability in the data explained by the regression equation goes from 73 percent when radius is included to 83 percent when the other variables (channelizaton, right-turn lane length, and right-turn lane width) are included.

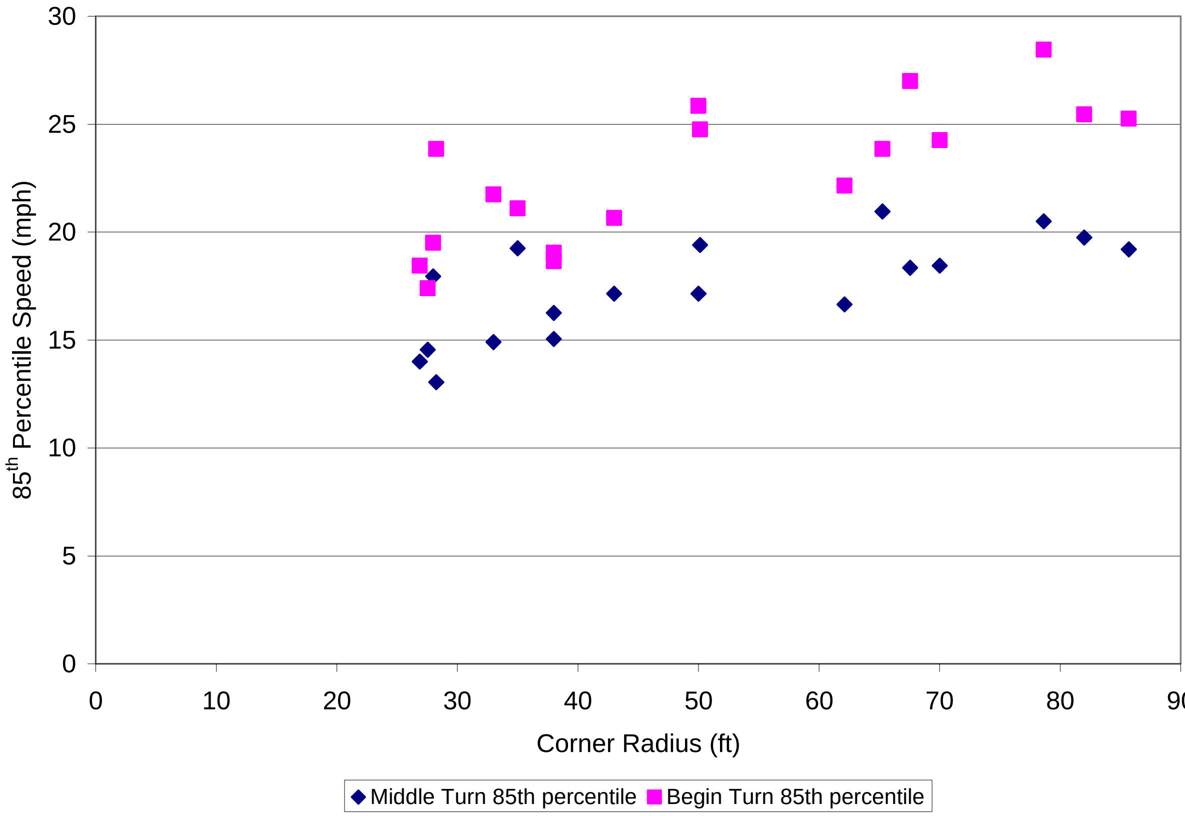


Figure 23. 85th Percentile Speed for Right Turns.

Table 8. Least Squares Fit for Speed at Beginning of Right Turn Based on the 85th Percentile Data.

R-square	Term	Parameter Estimate	Standard Error	t-ratio	Prob>t
0.833999	**Intercept**	**17.498472**	**4.021552**	**4.35**	**0.0007**
	Chan[Line]	-1.007401	0.716603	-1.41	0.1816
	Radius	**0.0959625**	**0.024969**	**3.84**	**0.0018**
	Right-Turn Lane Length	-0.006023	0.010918	-0.55	0.5899
	Right-Turn Lane Width	0.1266755	0.221829	0.57	0.5770
Bold line represents a significant variable					

Table 9. Least Squares Fit for Speed at Beginning of Right Turn Based on the 85^{th} Percentile Data When Only Radius Is Included in Model.

R-square	Term	Parameter Estimate	Standard Error	t-ratio	Prob>t
0.731849	**Intercept**	**16.03447**	**1.103573**	**14.53**	**<0.0001**
	Radius	**0.1377658**	**0.020225**	**6.81**	**<0.0001**
Bold line represents a significant variable					

Figure 24 illustrates the speed that would be predicted at each site along with the speed measured at the site. Note that Figure 24 only shows the radii values along the x-axis while the predicted value also considers the values of right-turn lane length, right-turn lane width, and channelization present. Because only radius is shown, connecting the predicted values would not result in a smooth curve.

The prediction equation for the speed at the beginning of the right turn can be written as follows:

$$V85BT = 17.50 - 1.00\ Chan + 0.10\ CR - 0.006\ Len + 0.13\ Wid \qquad (7)$$

Where:

V85BT = 85^{th} percentile free-flow speed near the beginning of the right turn (mph)
Chan = channelization present at site, Chan = 0 for raised island and 1 for lane line
CR = corner radius (ft)
Len = length of right-turn lane (ft)
Wid = width of right-turn lane at start of right turn (ft)

If the length and width of the right-turn lane is not readily available and the average values of 12 ft for lane width and 193 ft for lane length are assumed, the equation becomes:

$$V85BT = 17.80 - 1.00\ Chan + 0.10\ CR \qquad (8)$$

Limits for the above equations along with all equations developed from this dataset include:

- Corner radius range is 33 to 86 ft.
- Right-turn lane length range is 115 to 300 ft.
- Right-turn lane width range is 9 to 15 ft.

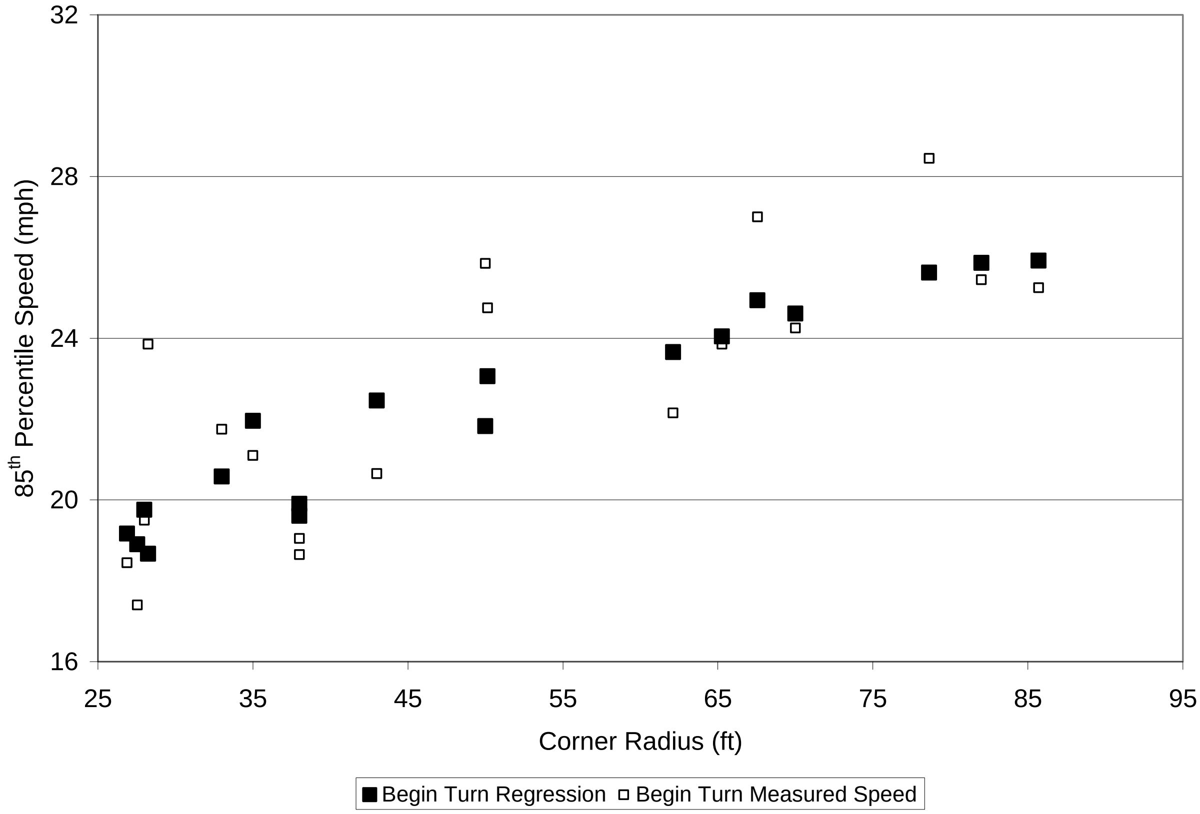


Figure 24. Predicted and Measured Speed Values at Beginning of Right Turn Using 85th Percentile Speed Data.

Middle of Right Turn

Table 10 contains the results of fitting the model with radius, channelization, right-turn lane length, and right-turn width for speeds near the middle of the turn. From the table it can be observed that there are statistically significant effects of radius and right-turn lane width on the speed at alpha of 0.05. Table 11 lists the findings when only radius and right-turn lane width are included in the model. The parameter estimates change slightly and the r-square value decreases from 77 percent to 71 percent. The r-square decreases to 50 percent when only radius is considered (see Table 11). The inclusion of right-turn lane width in the model assists with explaining the variability in the speeds at the middle of the right turn. Figure 25 illustrates the speed that would be predicted at each site using the equation presented in Table 10 along with the speed measured at the site.

Table 10. Least Squares Fit for Speed at Middle of Right Turn Based on the 85th Percentile Data.

R-square	Term	Parameter Estimate	Standard Error	t-ratio	Prob>t
0.769574	**Intercept**	**13.032479**	**3.219556**	**4.05**	**0.0012**
	Chan[Line]	0.2300127	0.573695	0.40	0.6945
	Radius	**0.0644222**	**0.019989**	**3.22**	**0.0061**
	Right-Turn Lane Length	-0.014486	0.008741	-1.66	0.1197
	Right-Turn Lane Width	**0.4034347**	**0.177591**	**2.27**	**0.0394**
Bold line represents a significant variable					

Table 11. Least Squares Fit for Speed at Middle of Right Turn Based on the 85th Percentile Data When Only Radius and Right-Turn Width Are Included in Model.

R-square	Term	Parameter Estimate	Standard Error	t-ratio	Prob>t
0.709667	**Intercept**	**8.0596531**	**1.973033**	**4.08**	**0.0009**
	Radius	**0.07144**	**0.01486**	**4.81**	**0.0002**
	Right-Turn Lane Width	**0.5568794**	**0.165754**	**3.36**	**0.0040**
0.504849	**Intercept**	**14.112623**	**1.018993**	**13.85**	**<0.0001**
	Radius	**0.0777504**	**0.018675**	**4.16**	**0.0007**
Bold line represents a significant variable					

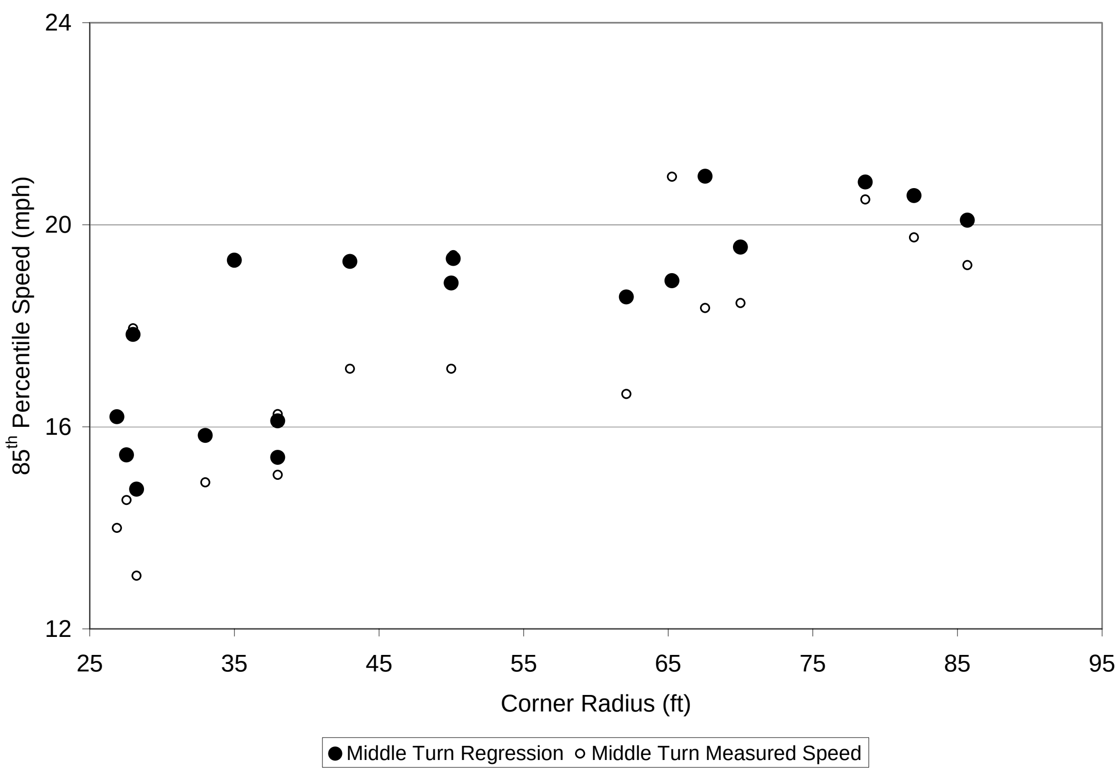


Figure 25. Predicted and Measured Speed Values at Middle of Right Turn Using 85th Percentile Speed Data.

The equation for predicting 85th percentile speed near the middle of the right turn is:

$$V85MT = 13.03 + 0.23\ Chan + 0.06\ CR - 0.01\ Len + 0.40\ Wid \tag{9}$$

Where:

V85MT = 85th percentile free-flow speed near the middle of the right turn (mph)
Chan = channelization present at site, Chan = 0 for raised island and 1 for lane line
CR = corner radius (ft)
Len = length of right-turn lane (ft)
Wid = width of right-turn lane at start of right turn (ft)

If the length and width of the right-turn lane is not readily available and the average values of 12 ft for lane width and 193 ft for lane length are assumed, the equation becomes:

$$V85BT = 14.87 + 0.23\ Chan + 0.06\ CR \tag{10}$$

Difference Between Beginning and Middle of Right Turn

Figure 23 also shows that speeds are different whether the vehicle is at the beginning of the right turn or in the middle of the right turn. As shown in Figures 13 and 15 vehicles decelerate on the approach to the right turn and within the first half of the turn. The midpoint of the right turn appears to be the location where speeds are the lowest (which is similar to the findings for horizontal curves). The test vehicle in the pilot study showed increased speeds after the right-turn midpoint when under free-flow conditions. Figure 26 shows the 85th percentile speed difference between the beginning and the middle of the right turn. The figure shows that vehicles are decelerating between the beginning and middle of the right turn. For example, at none of the sites was the 85th percentile speed at the middle of the turn higher, in fact, the 85th percentile speeds were always at least 1.5 mph slower. While vehicles are decelerating within the turn, the amount of reduction does not appear to have a strong relationship with the corner radius. A regression trend line using radius as the independent variable could only explain 9 percent of the variability of the data.

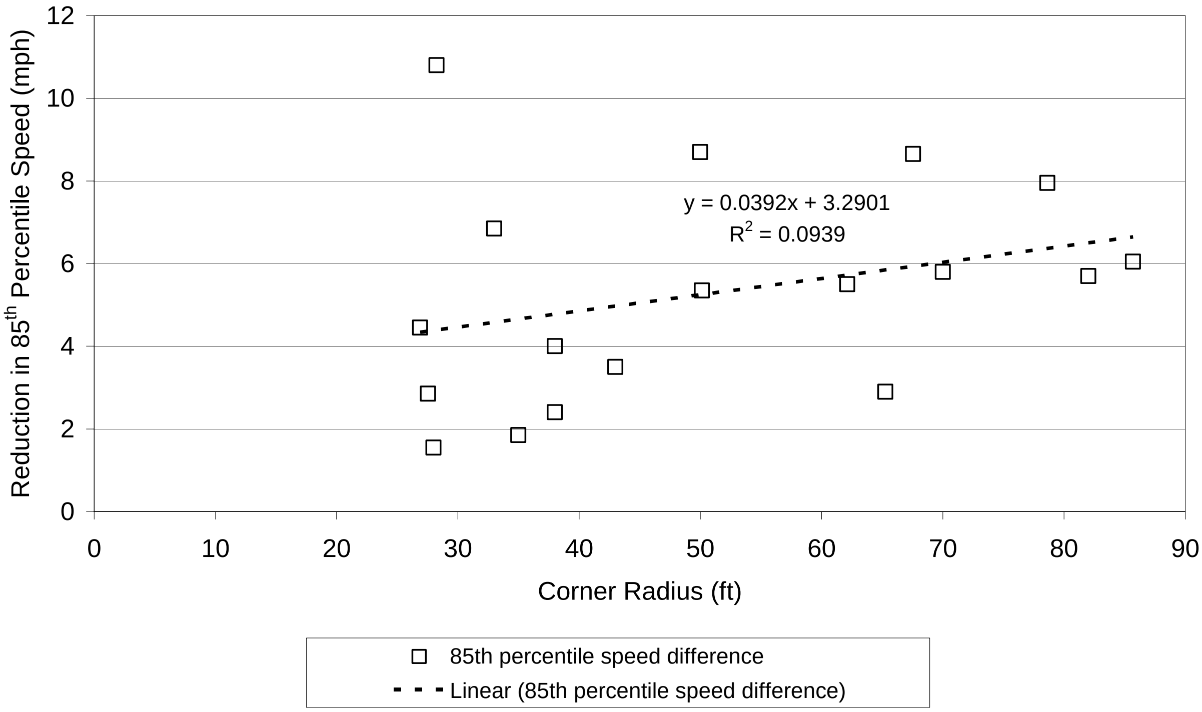


Figure 26. Speed Difference Between Beginning and Middle of Right Turn.

Influence of Channelization Treatment

Along with selecting sites with a range of corner radii, the research team also selected some sites with corner islands and some sites with only a lane line separating the through and right-turning movements. Available for analysis were seven sites with only a lane line and 11 sites with a raised island. A question explored was whether the type of channelization at the right-turn lane influenced the turning speeds of the vehicles. Figure 27 shows the 85th percentile speed of the vehicles near the middle of the turn subdivided by the channelization treatment. The speeds at sites with lane lines as the separation between the through and right-turn lane had the lower corner radii and the lower speeds. The regression analysis used an indicator variable to represent the type of treatment with the value being 1 when the channelization was a line and the value being 0 when an island was present. For the middle turn speed prediction equation, the difference in channelization treatments was only 0.23 mph, which is not practically significant.

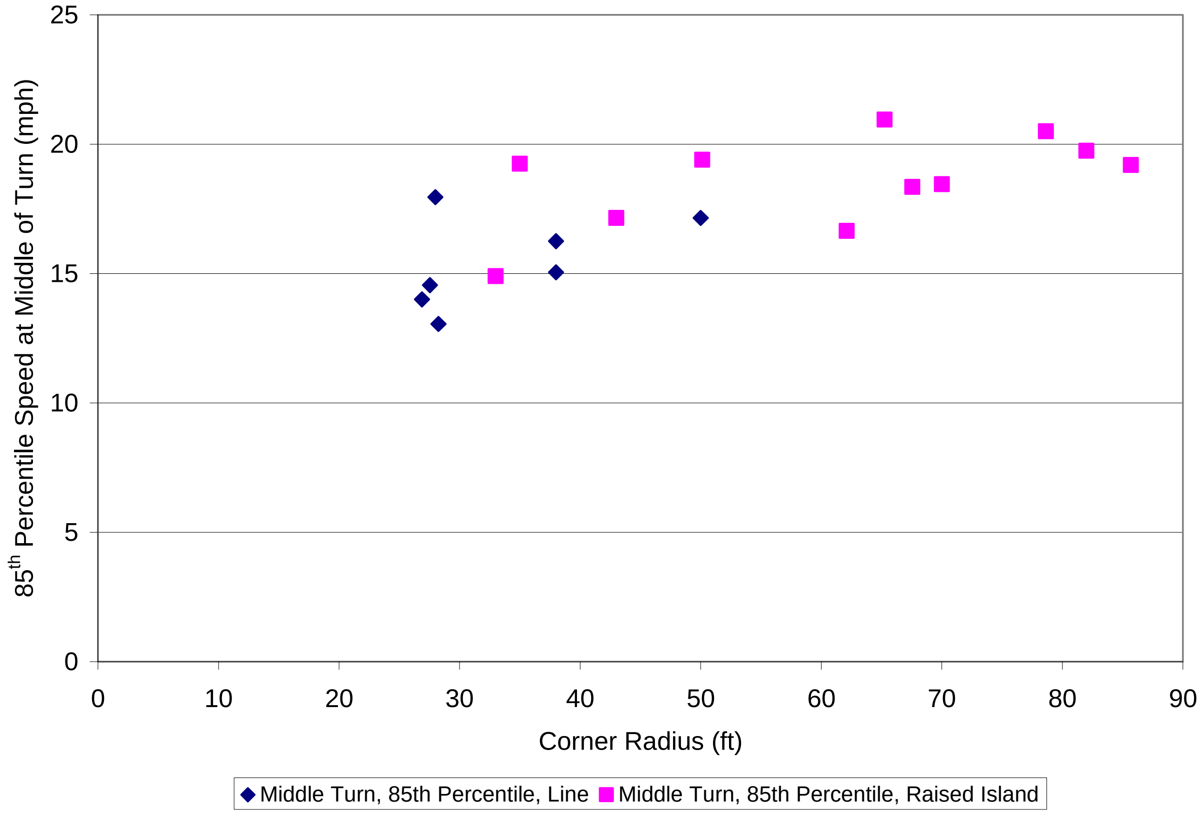
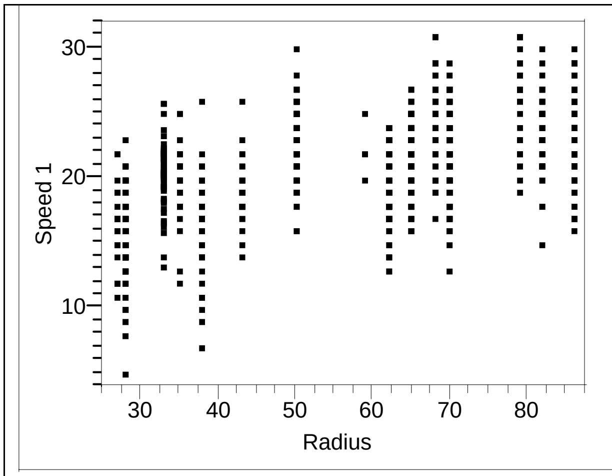


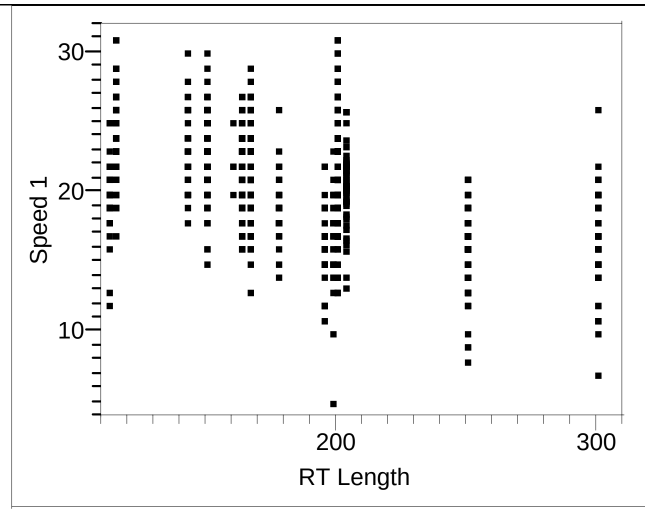
Figure 27. 85th Percentile Speed Near Middle of Turn Subdivided by Channelization Treatment at the Site.

PREDICTING FREE-FLOW SPEED OF A VEHICLE IN RIGHT-TURN LANE

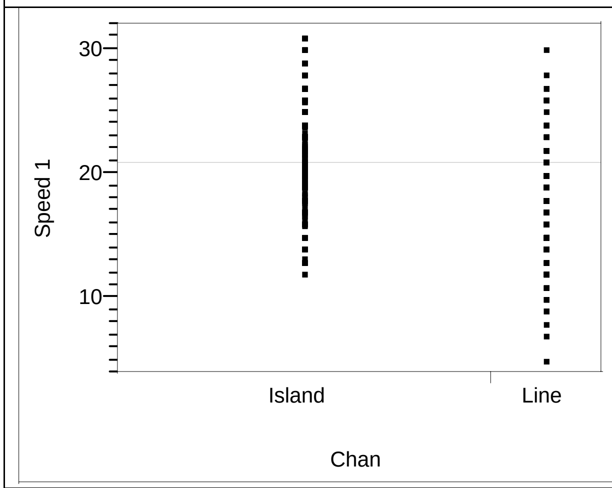
The speeds of the individual free-flow vehicles at the 19 sites were used to develop prediction equations. This approach permits the consideration of each unique vehicle rather than collapsing the variability of a site into one value – the 85th percentile value. The analysis considered site characteristics such as corner radius, channelization, right-turn lane length, and right-turn lane width. Figures 28 and 29 show the scatterplots for the variables at the beginning of the turn and near the middle of the turn, respectively. Each plot shows the range in speed measurements from each site and the overall trend between each of the predictor variables and the speed measurements.



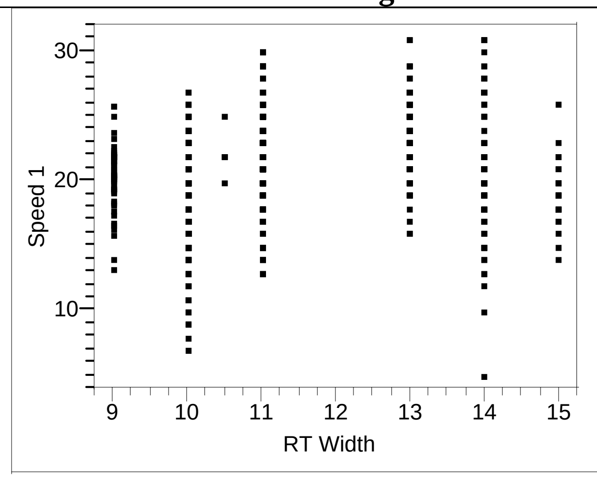
Speed at Beginning of Right Turn by Corner Radius



Speed at Beginning of Curve by Right-Turn Lane Length

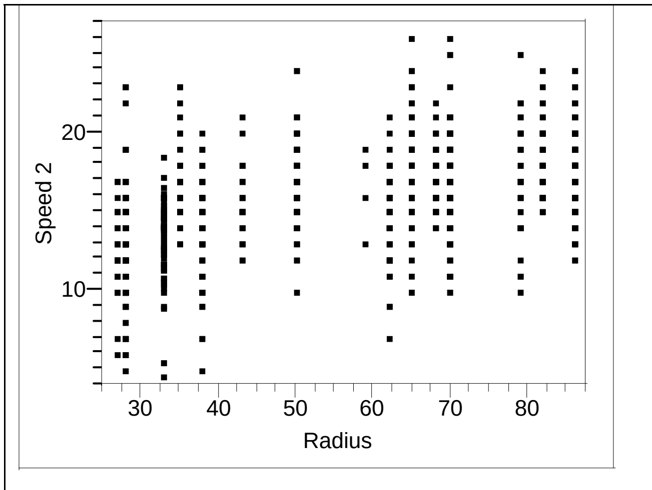


Speed at Beginning of Right-Turn by Channelization

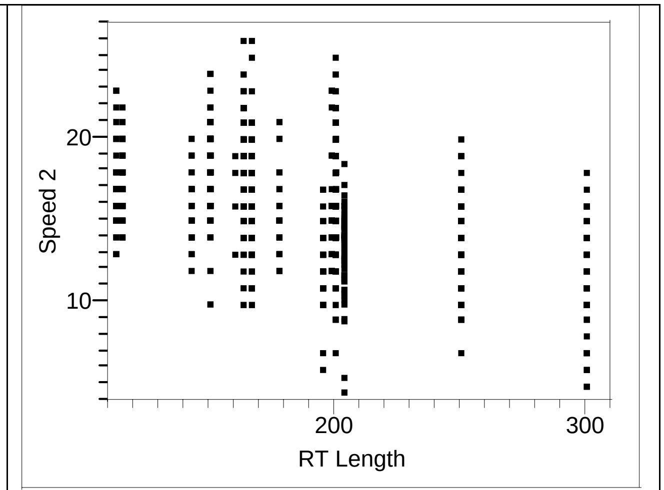


Speed at Beginning of Curve by Right-Turn Lane Width

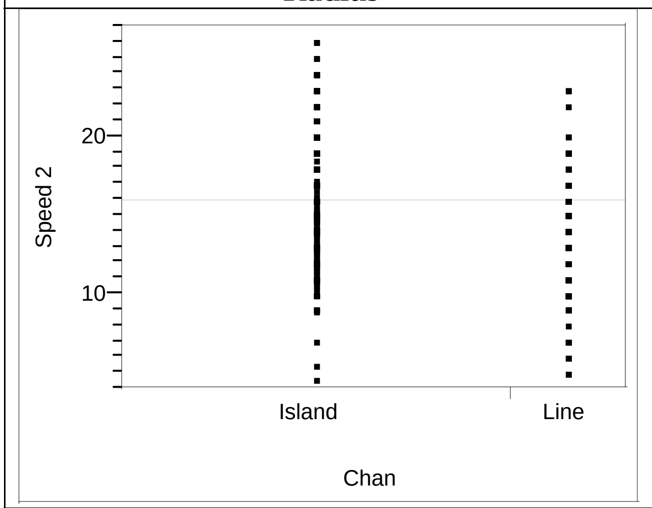
Figure 28. Distribution of Individual Speeds at Beginning of Right Turn.



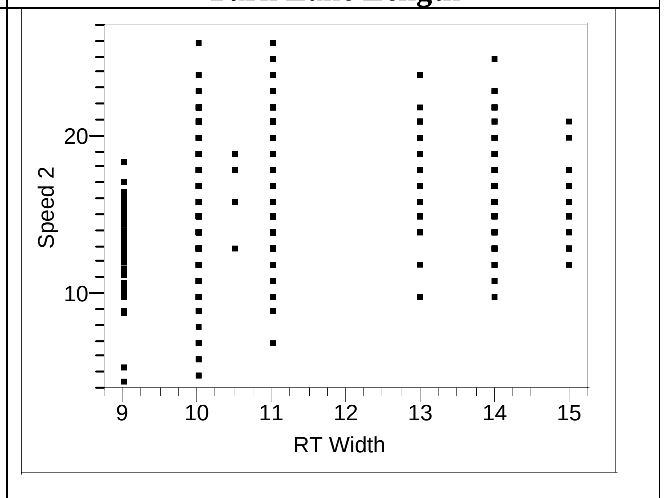
Speed Near Middle of Right Turn by Corner Radius



Speed near Middle of Right Turn by Right-Turn Lane Length



Speed Near Middle of Right Turn by Channelization



Speed near Middle of Right Turn by Right-Turn Lane Width

Figure 29. Distribution of Individual Speeds Near Middle of Right Turn.

To see which of the predictor variables have a significant effect on turning speed, an Analysis of Covariance model having channelization as a discrete factor (either island or line) and radius, right-turn lane length, and right-turn lane width as continuous factors along with all possible two-way interactions was fitted for the speed at the beginning of the turn and near the middle of the turn, respectively.

The results showed significant interaction effects between channelization and other factors suggesting that the effects of radius, right-turn lane length, and right-turn lane width are different for each type of channelization. Therefore, a separate model was fitted for island sites and lane line sites.

Limits for the equations developed from this dataset include:

Island

- Corner radius range is 33 to 86 ft.
- Right-turn lane length range is 115 to 200 ft.
- Right-turn lane width range is 9 to 15 ft.

Line

- Corner radius range is 27 to 50 ft.
- Right-turn lane length range is 143 to 300 ft.
- Right-turn lane width range is 10 to 14 ft.

Beginning of Right Turn

Table 12 contains the result of the fit by the type of channelization for the speed at the beginning of the turn. Note from the table that the parameter estimate for radius is different for each type of channelization. The low R-square values in the table were due to the variabilities in the speed measurements within each site. In this study, the variabilities of speed measurements within each site can not be explained systematically and they are simply attributed to the random variation because there is no predictor variable specific to each speed measurement at each site. Figure 30 illustrates the predicted speed value for the project sites using the regression equations. Also shown is the measured average speed at a site.

Table 12. Least Squares Fit for Speed at Beginning of Right Turn Based on the Individual Speed Measurements.

Chan	R-square	Term	Parameter Estimate	Standard Error	t-ratio	Prob>t
Island	0.147441	**Intercept**	**18.247957**	**1.362992**	**13.39**	**<0.0001**
		Radius	**0.0777979**	**0.006563**	**11.85**	**<0.0001**
		Right-Turn Lane Length	**-0.017085**	**0.004097**	**-4.17**	**<0.0001**
		Right-Turn Lane Width	0.1311404	0.077031	1.70	0.0890
Line	0.339748	**Intercept**	**13.647215**	**2.867673**	**4.76**	**<0.0001**
		Radius	**0.2136043**	**0.026722**	**7.99**	**<0.0001**
		Right-Turn Lane Length	**-0.017886**	**0.004493**	**-3.98**	**<0.0001**
		Right-Turn Lane Width	0.0592073	0.172167	0.34	0.7312
Bold line represents a significant variable						

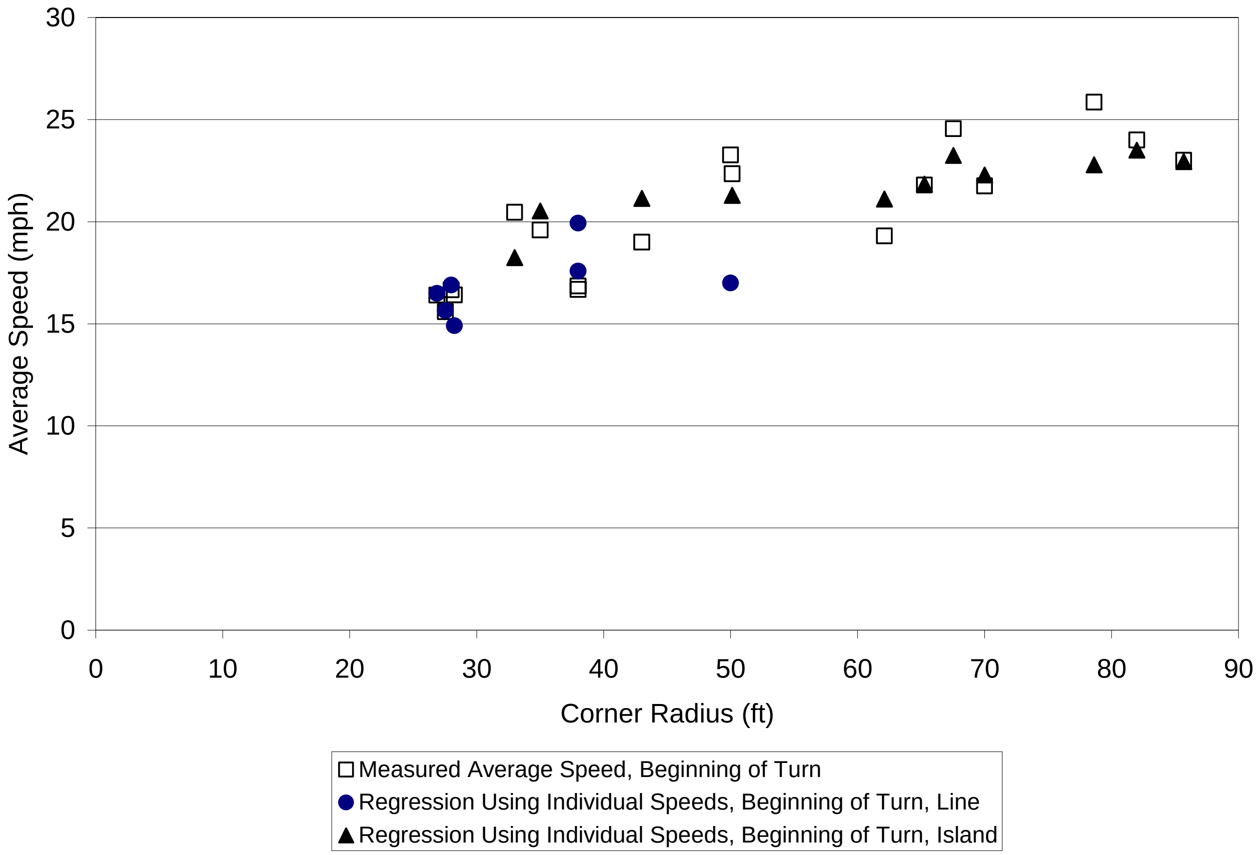


Figure 30. Predicted and Measured Speed Values at Beginning of Right Turn Using Individual Speed Data.

The prediction equations for the speed near the beginning of the right turn can be written as follows:

$$VBT_{island} = 18.25 + 0.08\ CR - 0.02\ Len + 0.13\ Wid \tag{11}$$

$$VBT_{line} = 13.65 + 0.21\ CR - 0.02\ Len + 0.06\ Wid \tag{12}$$

Where:

VBT_{island} = free-flow speed near the beginning of the right turn when an island is present (mph)
VBT_{line} = free-flow speed near the beginning of the right turn when only a line separates the right-turn lane from the through lane (mph)
CR = corner radius (ft)
Len = length of right-turn lane (ft)
Wid = width of right-turn lane at start of right turn (ft)

Middle of Right Turn

Table 13 contains the result of the fit by the type of channelization for the speed near the middle of the right turn. Note from the table that the parameter estimates for radius, right-turn lane length, and right-turn lane width are somewhat different for each type of channelization. The effect of right-turn lane width is statistically significant at 0.05 for Line, but not for Island. Figure 31 illustrates the predicted and measured speed values for the project sites.

Table 13. Least Squares Fit for Speed near Midpoint of Right Turn Based on the Individual Speed Measurements.

Chan	**R-square**	**Term**	**Parameter Estimate**	**Standard Error**	**t-ratio**	**Prob>t**
Island	0.146186	**Intercept**	**18.927851**	**1.246147**	**15.19**	**<0.0001**
		Radius	**0.0604248**	**0.006**	**10.07**	**<0.0001**
		Right-Turn Lane Length	**-0.031943**	**0.003746**	**-8.53**	**<0.0001**
		Right-Turn Lane Width	-0.060349	0.070427	-0.86	0.3917
Line	0.235686	Intercept	4.4703183	2.506303	1.78	0.0757
		Radius	**0.1040881**	**0.023354**	**4.46**	**<0.0001**
		Right-Turn Lane Length	**-0.008657**	**0.003927**	**-2.20**	**0.0284**
		Right-Turn Lane Width	**0.703839**	**0.150471**	**4.68**	**<0.0001**
Bold line represents a significant variable						

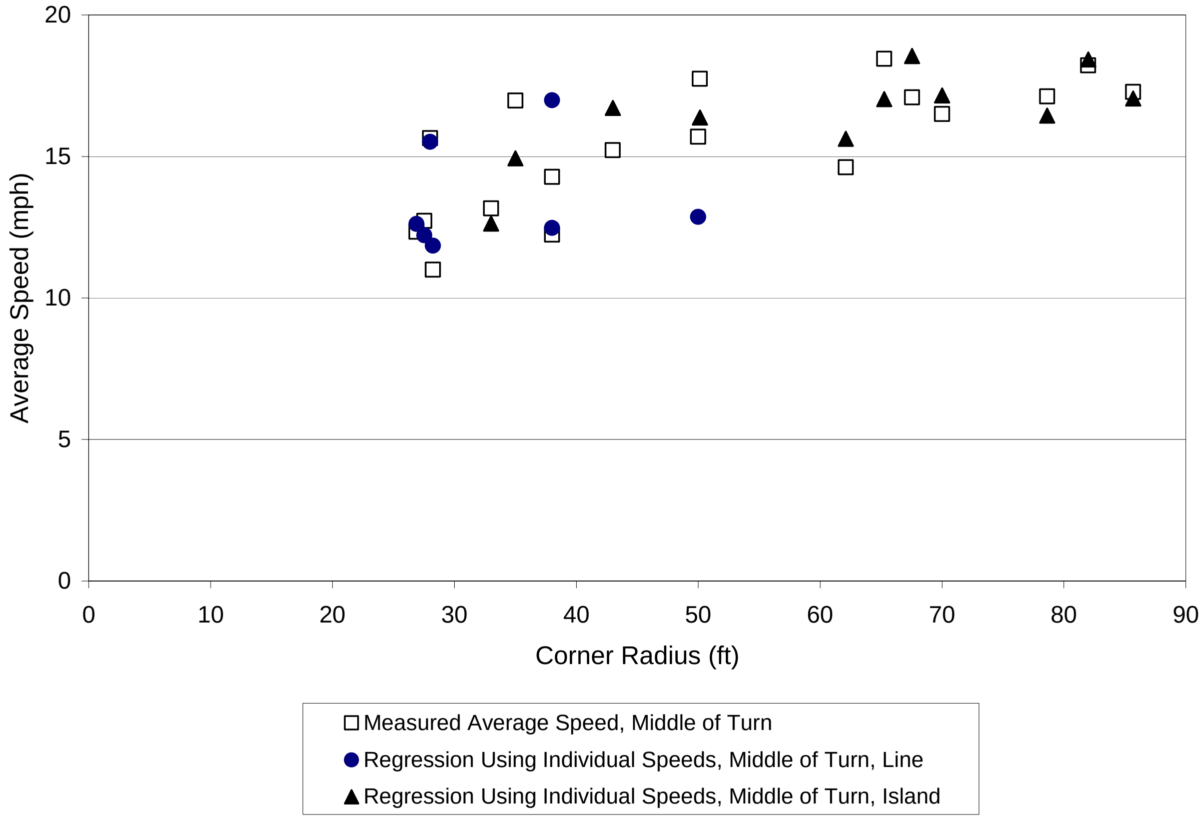


Figure 31. Predicted and Measured Speed Values at Middle of Right Turn Using Individual Speed Data.

The prediction equations for the speed near the middle of the right turn can be written as follows:

$$VMT_{island} = 18.93 + 0.06\ CR - 0.03\ Len - 0.06\ Wid \qquad (13)$$

$$VMT_{line} = 4.47 + 0.10\ CR - 0.01\ Len + 0.70\ Wid \qquad (14)$$

Where:

VMT_{island} = free-flow speed near the middle of the right turn when an island is present (mph)
VMT_{line} = free-flow speed near the middle of the right turn when only a line separates the right-turn lane from the through lane (mph)
CR = corner radius (ft)
Len = length of right-turn lane (ft)
Wid = width of right-turn lane at start of right turn (ft)

Influences on Turning Speed When Island Is Present

The data for the 13 sites with raised islands were used to identify those variables influencing the speed at the beginning and in the middle of the right turn. In addition to the variables used in the previous evaluations (radius, right-turn lane length, right-turn lane width), this evaluation also included island size and turning roadway width. Table 14 lists the results of the least squares fit. From Table 12 is can be observed that there are statistically significant effects on turning speed for the following variables:

Beginning of Turn	Middle of Turn
Radius	Radius
Right-Turn Lane Length	Right-Turn Lane Length
Island Size	Turning Roadway Width

Table 14. Least Squares Fit for Speed at Beginning and Middle of Right Turn Based on the Individual Speed Data for Sites with a Raised Island.

R-square	Term	Parameter Estimate	Standard Error	t-ratio	Prob>t
0.159497	**Intercept**	**21.038815**	**2.162282**	**9.73**	**<0.0001**
	Turning Roadway Width	-0.031569	0.058118	-0.54	0.5871
	Island Size	**-0.001535**	**0.000475**	**-3.23**	**0.0013**
	Radius	**0.0870107**	**0.007243**	**12.01**	**<0.0001**
	Right-Turn Lane Length	**-0.01831**	**0.004088**	**-4.48**	**<0.0001**
	Right-Turn Lane Width	-0.003214	0.090991	-0.04	0.9718
0.160853	**Intercept**	**22.880779**	**1.97387**	**11.59**	**<0.0001**
	Turning Roadway Width	**-0.179251**	**0.053054**	**-3.38**	**0.0008**
	Island Size	-0.000072	0.000434	-0.17	0.8673
	Radius	**0.0629563**	**0.006612**	**9.52**	**<0.0001**
	Right-Turn Lane Length	**-0.031321**	**0.003732**	**-8.39**	**<0.0001**
	Right-Turn Lane Width	-0.115563	0.083062	-1.39	0.1645
Bold line represents a significant variable					

CHAPTER 5

EVALUATION OF RIGHT-TURN LANE CRASHES

Along with operational improvements, right-turn lanes are thought to improve safety by removing the turning vehicle from the through lane. A growing concern is that right-turn lanes may not provide the safety benefit once believed. Rear-end crashes may increase due to collisions with drivers stopping at the end of the turning roadway (i.e., the following vehicle does not expect the lead vehicle to stop) or due to the driver being more focused on looking upstream in preparation for the merging task rather than scanning to the right for potential pedestrians.

SITE SELECTION

The research team requested information on crashes for the intersections used as part of the right-turn speed study (see Chapter 4). For the City of Irving sites, the research team received crash narratives for five sites. For the City of College Station sites, the research team received information from the state's crash database for four sites. The Irving sites reflected crashes for 2001, 2002, and 2003 while the College Station sites were for 1999, 2000, and 2001. All intersections included in this analysis were signalized.

CRASH TYPE

The crashes were grouped into the following categories:

- **Rear End –** vehicle one is stopped (or slowing) and vehicle two collides into the rear of vehicle one while in a through or left-turn lane. In this study, rear-end collisions in a right-turn lane were recorded in a different category (see below). In most cases, the cause of the crash was driver inattention or following too closely.
- **Rear End, Right Turn –** vehicle one is stopped (or slowing) and vehicle two strikes the rear of vehicle one while in a right-turn lane.
- **Angle, Straight –** both vehicles are traveling straight in perpendicular directions through the intersection resulting in a collision near the middle of the intersection. In most cases the cause of this type of crash was because one of the vehicles violated the red signal.

- **Angle, Left –** one of the vehicles is traveling straight and the other vehicle is turning left coming from opposing directions. In this type of crash, the most common cause was failing to yield the right-of-way while turning left on a permissive green ball.
- **Sideswipe –** vehicles are driving nearly parallel with one vehicle striking the neighboring vehicle.
- **Other –** refers to all other types of crashes that occurred, in most cases it involves a vehicle leaving the roadway and hitting an object. This category does not include any crashes associated with the right-turn lane.

Table 15 lists the number of crashes per crash type for the five Irving intersections. Table 16 provides similar information for the four College Station intersections. A total of 96 crashes occurred at the Irving intersections during the three-year period. The most prevalent crash type involved angle, left-turn crashes (42 percent) followed by rear-end crashes (30 percent). Approximately one-third of the rear-end crashes at the five Irving intersections occurred in a right-turn lane. Whether wet pavement was present at the time of the crash was also available for the Irving intersections. The intersection with the highest number of crashes also had the largest percentage of wet-pavement crashes (40 percent). That location also had the largest number of rear-end crashes.

Table 15. Crashes at Five Intersections in Irving for 2001-2003.

Intersection	Total	Rear End	Rear-End, Right Turn	Angle, Straight	Angle, Left	Sideswipe	Other	%wet
IR-1	21	2	2	3	13	1	0	5
IR-2	25	9	4	4	5	0	3	40
IR-3	13	3	3	2	2	3	0	15
IR-4	15	2	0	2	10	1	0	0
IR-5	22	4	0	3	10	5	0	18
TOTAL	**96**	**20**	**9**	**14**	**40**	**10**	**3**	**41**
Percent (%)		21	9	15	42	10	3	

Table 16. Crashes at Four Intersections in College Station for 1999-2001.

Intersection	**Total**	**Rear End**	**Rear-End, Right Turn**	**Angle, Straight**	**Angle, Right**	**Angle, Left**	**Sideswipe**	**Other**
CS-1	28	12	0	4	1	9	0	2
CS-2	27	11	0	1	1	14	0	0
CS-3	23	7	0	11	1	2	0	2
CS-4	37	13	1	7	1	14	1	0
TOTAL	**115**	**43**	**1**	**23**	**4**	**39**	**1**	**4**
Percent (%)		37	1	20	3	34	1	3

College Station also had a high proportion of the crashes at the intersections related to the left-turn movement with 34 percent of the crashes being in that category. College Station intersections had a larger proportion of crashes in the rear-end category (38 percent); however, only 1 of the 44 rear-end crashes involved a right-turning vehicle. An additional four crashes involved a right-turning vehicle; however, those crashes occurred at the end of the turning maneuver as the driver was merging with the cross-street traffic.

MOVEMENT INVOLVED IN CRASH

The narratives of the Irving crashes were used to identify the movement – left, through, or right – involved in the crash. In many cases, the crash involved two vehicles going straight (i.e., in a through lane) or two vehicles within a dual left turn. In those cases where a right-turning vehicle was involved, the crash was assigned into the "right turn" category whether the right-turning vehicle was responsible for the crash or not. In most cases where a left-turning vehicle was involved, the crash was assigned into the "left turn" category. In the rare cases when the narrative clearly stated that the responsibility for the crash was the through driver running a red signal, the crash was assigned to the "through" category. Each crash was only assigned to one category. For Irving, only 11 percent of the crashes at the five intersections involved a right-turning vehicle. The remaining crashes were about evenly split between left-turns (43 percent) and through (46 percent) movements. A total of 11 of the 96 crashes in Irving involved a right-turning vehicle.

The style of data for College Station did not permit a similar type of classification of lane involvement in the crash; however, those crashes involving a right-turning vehicle could be identified. A total of five of the 115 crashes in College Station involved a right-turning vehicle.

RIGHT-TURN CRASHES

At the nine intersections, a total of 16 of the 211 crashes involved a right-turning vehicle. These 16 crashes can be divided into the following:

- **Rear end –** involves two vehicles in the right-turn lane
- **Right angle or merge –** involves a crash between turning vehicle merging with through vehicles on the cross street
- **Sideswipe –** involves two vehicles with one of the vehicles in the right-turn lane
- **Other –** involves a single vehicle traveling at a high rate of speed through the turn

Table 17 lists the type of right-turn crash for each intersection. The majority of these crashes (75 percent) were property-damage only crashes.

Table 17. Right-Turn Crashes by Crash Type for a Three-Year Period.

Intersection	Number of Right-Turn Crashes	Type			
		Rear End	Right Angle	Sideswipe	Other (object)
IR-1	3	2		1	
IR-2	5	4			1
IR-3	3	3			
IR-4	0				
IR-5	0				
CS-1	1		1		
CS-2	1		1		
CS-3	1		1		
CS-4	2	1	1		
TOTAL	**16**	**10**	**4**	**1**	**1**
Percent (%)	100	63	25	1	1

RIGHT-TURN LANE CRASH LOCATION

For this project, the location of the right-turn lane crashes was determined with respect to the type of right-turn treatments. The 30 approaches (six intersections had four approaches and three intersections had two approaches) included four different right-turn treatments:

- right-turn lane with raised island,
- right-turn lane with white lane line,
- shared through/right lane, and
- shared through/right lane with island.

At five of the right-turn lane with raised island approaches a short acceleration lane was present. The length of the acceleration lane was less than 80 ft; therefore, those five sites were included with the other 10 approaches as a right-turn lane with raised island site. Table 18 lists the type of right-turn lane treatment at the approaches by intersection.

Table 18. Number of Approaches with a Right-Turn Treatment.

Intersection	Number of Approaches	Treatment*			
		RTL w Raised Island	RTL w Line	SL	SL w Island
IR-1	2	1	1		
IR-2	4	4			
IR-3	2	1			1
IR-4	2	2			
IR-5	4		3	1	
CS-1	4	3		1	
CS-2	4	1	1	1	1
CS-3	4	1	1	2	
CS-4	4	1		3	
TOTAL	**30**	**14**	**6**	**8**	**2**

*RTL = right-turn lane
SL = shared lane

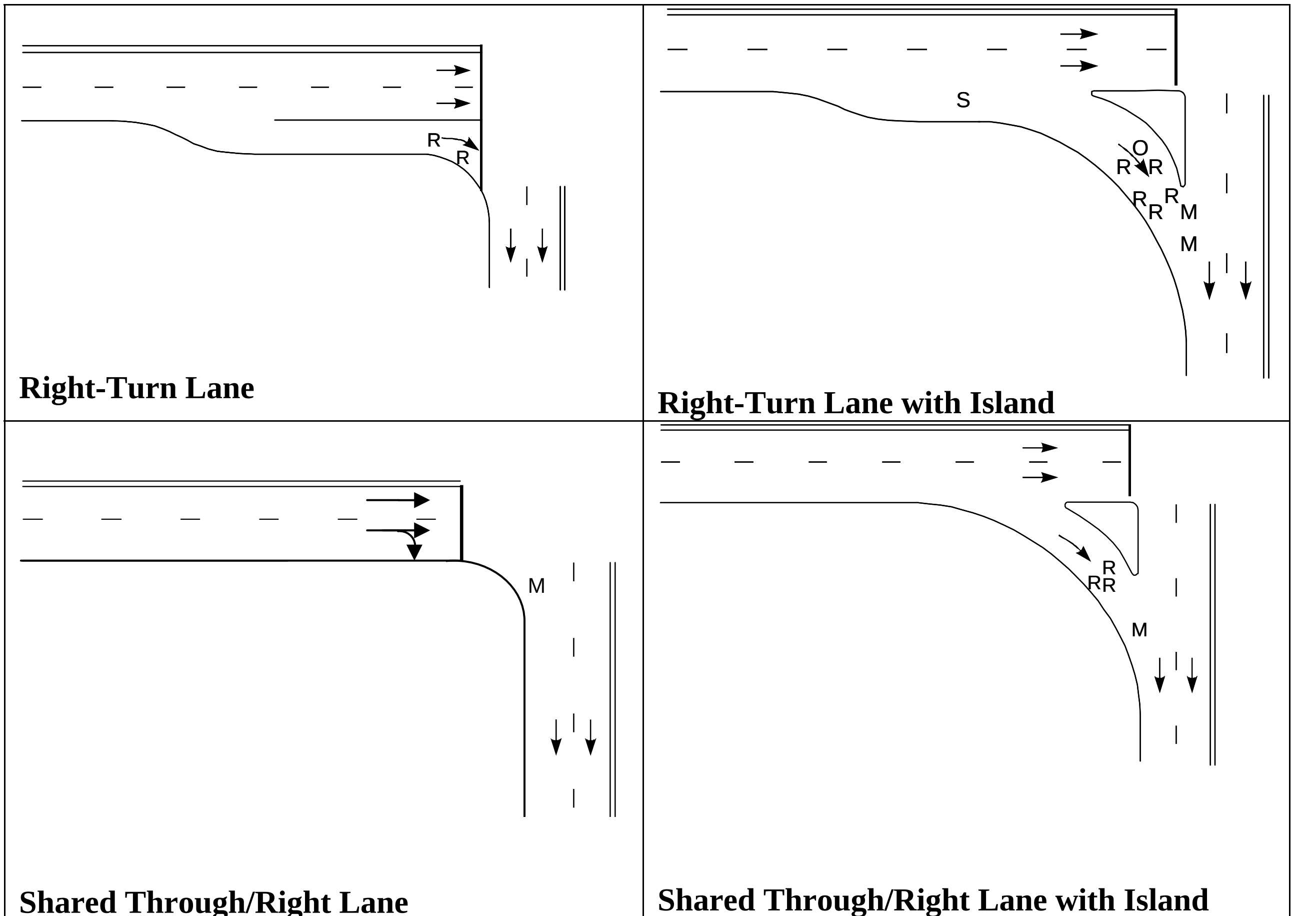
Table 19 shows the type of right-turn lane treatment associated with the 16 crashes by intersection, while Table 20 lists the data by type of crash. Most of the rear-end crashes occurred on an approach with an island (eight of the 10 crashes). Figure 32 illustrates the location of the right-turn crashes by treatment type.

Table 19. Number of Right-Turn Crashes by Right-Turn Treatment.

Intersection	Number of Right-Turn Crashes	Treatment*			
		RTL w Raised Island	RTL w Line	SL	SL w Island
IR-1	3	1	2		
IR-2	5	5			
IR-3	3				3
IR-4	0				
IR-5	0				
CS-1	1	1			
CS-2	1				1
CS-3	1	1			
CS-4	2	1		1	
TOTAL	**16**	**9**	**2**	**1**	**4**
*RTL = right-turn lane SL = shared lane					

Table 20. Right-Turn Crashes by Crash Type and Type of Right-Turn Treatment.

Crash Type	Total	Treatment*			
		RTL w Raised Island	RTL w Line	SL	SL w Island
Rear End	10	5	2		3
Right Angle or Merge	4	2		1	1
Sideswipe	1	1			
Other	1	1			
Number of Crashes (3-year period)	**16**	**9**	**2**	**1**	**4**
*RTL = right-turn lane SL = shared lane					



Key
R - Represents rear-end crashes
M - Represents right angle or merge crashes
S - Represents Sideswipe Crashes
O - Represents Other Crashes

Figure 32. Summary of Crashes by Right-Turn Treatment Type (for Three Years of Crash Data at Nine Intersections).

CRASH RATE

Table 21 provides the annual number of right-turn crashes by type of right-turn treatment. The values do not include consideration of right-turn volume; however, the values can provide an appreciation of the variability of right-turn crash rates between the different treatments. For this study, the sites with islands had higher crash rates than the sites without islands. A right-turn crash would be expected every 4.8 years for an approach with a right-turn lane and a raised island. The frequency of right-turn crashes was much higher at locations with shared lane with island, going to one right-turn lane crash every 18 months. Using the values from this study (see

Table 21), a right-turn lane separated only by a lane line would have a right-turn crash once every nine years, while a shared lane would have a right-turn lane crash once every 25 years.

Table 21. Annual Right-Turn Crashes by Type of Right-Turn Treatment.

Intersection	Total	Treatment*			
		RTL w Raised Island	RTL w Painted Line	SL	SL w Island
Number of Approaches	30	14	6	8	2
Number of Crashes (3-year period)	16	9	2	1	4
Number of Right-Turn Crashes per Approach per Year	0.18	0.21	0.11	0.04	0.67
*RTL = right-turn lane SL = shared lane					

COMPARISON WITH PREVIOUS RESEARCH

A late 1990s study in Georgia looked at two years of crashes at 17 signalized intersections (*13*). The dataset included 77 right-turn crashes for an average of 2.3 right-turn crashes per year per intersection. The Texas study found only 0.6 right-turn crashes per year per intersection. Several other differences are present between the findings of the two studies. Table 22 lists the right-turn crash rates identified in the Georgia study as compared to the findings from this TxDOT project. The Georgia study also had approaches with an exclusive right-turn lane with island and dedicated downstream lane. Those crashes are not represented in Table 22 since the Texas project did not include that treatment.

The treatment with the highest crash rate for Georgia is the right-turn lane with raised island. For Texas this type of treatment had the second highest rate of those treatments evaluated. In both projects, the shared through/right lane had the lowest crash rates.

While the data from the two projects indicate that a shared lane has a better safety record than separating the right-turning traffic with an island, a larger, more comprehensive project would be needed to provide definitive advice on the safety effects of the different right-turn treatments.

Table 22. Comparison of Annual Right-Turn Crashes by Type of Right-Turn Treatment.

Intersection	Treatment*			
	RTL w Raised Island	**RTL w Line**	**SL**	**SL w Island**
TxDOT Project Number of Right-Turn Crashes per Approach per Year	0.21	0.11	0.04	0.67
Georgia Project Number of Right-Turn Crashes per Site per Year	1.57	0.81	0.31	0.63
*RTL = right-turn lane SL = shared lane				

CHAPTER 6

CONCLUSIONS AND RECOMMENDATION

Right-turn lanes are used to provide space for the deceleration and storage of turning vehicles and to separate the turning vehicles from the through movement. They may be used to improve safety and/or vehicle operations at intersections. The path of pedestrians is affected when a large radius is selected for the right-turn lane at the intersection. Crosswalk lengths increase with larger corner radii if the crosswalk is located inside the corner radius which increases pedestrian crossing time and, subsequently, traffic signal timing. Larger radii can increase the distance pedestrians are exposed to traffic. They also result in crosswalks and curb ramps being away from the intersection. The selection of a radius is weighed in light of these effects and may result in a compromise between pedestrian needs and vehicle needs.

Another challenging issue for pedestrians is the speed of vehicles. Resources have not been available to estimate the speed of vehicles in a right turn. Equations are available for horizontal curves; however, these equations are not appropriate for the angle of turns present within a right turn. While existing equations can provide an appreciation of the speeds of vehicles in a horizontal curve, there is a need to determine speeds in right-turn scenarios. As part of this Texas Department of Transportation project, right-turn speeds at a range of corner radii were sought. The objective of the project was to determine the speeds of free-flow turning vehicles in an exclusive right-turn lane. In addition, the crash history with respect to different right-turn lane configurations was sought.

CONCLUSIONS

Specific conclusions include the following:

- Prediction equations developed in previous studies on horizontal curves should not be used to predict speeds in a right turn.
- Vehicles slow on the approach and in the initial portion of a right turn with slowest speeds near the middle of the turn. Therefore the speed predicted for a pedestrian crossing needs to consider whether that crossing is at the beginning of the right turn

or near the middle of the right turn (which is where the crossing may be placed when a corner island is present at the site).

- The 85th percentile speed within the right turn ranged from 13 to 21 mph while on the approach it ranged from 17 to 29 mph. Prediction equations were developed for free-flow speeds at the beginning and near the middle of a right turn. (Table 23 summarizes the equations developed using the 85th percentile speed, and Chapter 4 has the equations developed using the individual speeds.)
- For the nine intersections included in the project, the monthly crash rate for a shared lane with island (0.67 right-turn crashes per approach per year) was the highest of the four treatments studied. The next highest was the right-turn lane with island design with 0.21 right-turn crashes per approach per year.

Table 23. Prediction Equations for the 85th Percentile Speed of Right Turns.

Prediction equation for the **85th percentile** speed at the **beginning** of the right turn: $V85BT = 17.50 – 1.00\ Chan + 0.10\ CR – 0.006\ Len + 0.13\ Wid$ Where: V85BT = 85th percentile free-flow speed near the beginning of the right turn (mph) Chan = channelization present at site, Chan = 0 for raised island and 1 for lane line CR = corner radius (ft) Len = length of right-turn lane (ft) Wid = width of right-turn lane at start of right turn (ft)
* If the length and width of the right-turn lane is not readily available and the average values of 12 ft for lane width and 193 ft for lane length are assumed, the equation becomes: $V85BT = 17.80 – 1.00\ Chan + 0.10\ CR$
Prediction equation for the **85th percentile** speed near the **middle** of the right turn: $V85MT = 13.03 + 0.23\ Chan + 0.06\ CR – 0.01\ Len + 0.40\ Wid$ Where: V85MT = 85th percentile free-flow speed near the middle of the right turn (mph) Chan = channelization present at site, Chan = 0 for raised island and 1 for lane line CR = corner radius (ft) Len = length of right-turn lane (ft) Wid = width of right-turn lane at start of right turn (ft)
* If the length and width of the right-turn lane is not readily available and the average values of 12 ft for lane width and 193 ft for lane length are assumed, the equation becomes: $V85MT = 14.87 + 0.23\ Chan + 0.06\ CR$

RECOMMENDATION

The recommendation for the project based upon the conclusions of the study follows:

- Regression analyses were conducted using both the individual data points and the 85^{th} percentile speed for 18 sites. The analyses included only free-flow vehicles. Limits for the equations developed from this dataset are listed in Table 24. The equations for predicting **85^{th} percentile speed** near the middle and beginning of the right turn are listed in Table 23.
- The issues of efficiency, pedestrian needs, and effects of traffic and pedestrian operations on performance were not studied as part of this research effort. Rather the focus was on predicting speeds using free-flow vehicles for a given set of geometric characteristics. As available, crash data were also obtained for a subset of the sites used in the speed study. Therefore, future research in this area should focus on expanding the knowledge regarding the safety performance of right-turn lane treatments as well as the issues of efficiency, pedestrian needs, and performance of various designs.

Table 24. Data Limits for Regression Equations.

Island
• Corner radius range is 33 to 86 ft. • Right-turn lane length range is 115 to 200 ft. • Right-turn lane width range is 9 to 15 ft.
Line
• Corner radius range is 27 to 50 ft. • Right-turn lane length is range 143 to 300 ft. • Right-turn lane width range is 10 to 14 ft.

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