Discussion Paper No. 7

FUNCTIONAL INTERSECTION AREA

prepared for the

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DISCLAIMER

This discussion paper represents the viewpoints of the authors. Although prepared for the Oregon Department of Transportation (ODOT), they do not represent ODOT policies, practices nor procedures.

GENERAL OBJECTIVE

This and other discussion papers were prepared for the purpose of stimulating discussion among interested individuals representing a variety of agencies having an interest in Oregon's highways.

SPECIFIC OBJECTIVES

The specific objectives of this discussion paper are:

1. To provide technical information relative to the concept of functional intersection area and suggestions as to its physical length.

2. To serve as background information for discussions which might lead to ODOT policies, practices, and/or procedures.

ACKNOWLEDGMENTS AND CREDITS

Mr. Del Huntington is project manager for ODOT. Dr. Robert Layton, Professor of Civil Engineering at OSU is project director for the TRI. This discussion paper was prepared by Dr. Vergil G. Stover, consultant to the TRI. The content of this discussion paper is an elaboration on information which Dr. Stover has published elsewhere.

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Discussion Paper No. 7

FUNCTIONAL INTERSECTION AREA

INTRODUCTION

Overview

This discussion paper addresses the concepts involved in defining the functional area of an intersection. The elements which comprise the upstream functional area are identified; dimensions of the upstream area exclusive of queue storage, are given for various speeds. The various approaches for defining the downstream area are also presented.

Topics to be discussed based upon this paper include the following:

1. The concept of functional area and the importance of considering functional area in access management and design.

2. The physical length of the upstream functional area.

3. The physical length of the downstream functional area.

Discussion Items

The reader is encouraged to consider the following items for discussion while reading this discussion paper:

1. What is the length of the upstream functional intersection area? How is it determined?

2. What are the implications if the length of the deceleration lane is less than that needed by drivers?

3. How much queue storage is needed for left-turns and for right-turns at signalized intersection? At unsignalized intersections?

4. What are the implications if the queue storage length is inadequate?

(Continued)

Discussion Items (Continued)

5. What is the physical length of the downstream functional intersection area?

6. Can the upstream functional area of a road approach overlap with the downstream functional area of an intersection? Under what situations?

Functional Boundary

AASHTO specifically states that "Driveways should not be situated within the functional boundary of at-grade intersections. This boundary would include the longitudinal limits of auxiliary lanes" (1 p. 841, 2 p. 888). AASHTO also recognizes that vehicles leaving a major roadway disrupts traffic flow in absence of a speed change lane. While AASHTO does not present guidelines as to the size of the functional area of an intersection, logic indicates that it must be much larger than the physical area (see Figure 1). Logic also suggests that the functional area should be comprised of the maneuver distance plus any required storage length. The minimum maneuver distance assumes that the driver is in the proper lane and only needs to move laterally into a right-turn bay or a left-turn bay.

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Functional Boundary (Continued)

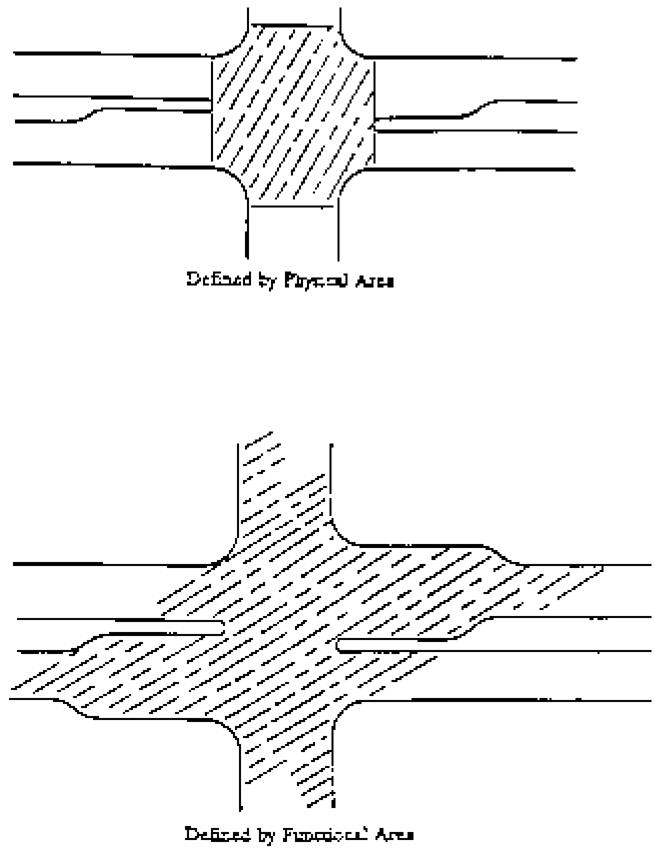

Figure 1: Boundary of Intersection

Source: Reference (3), Figure 4-16, p. 100, Stover and Koepke

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UPSTREAM FUNCTIONAL AREA

Elements of the Upstream Functional Area

The maneuver elements which must be evaluated in the determination of upstream maneuver distance are identified in Figure 2 and include the following:

d_1: The distance traveled during the perception-reaction time required by the driver. It is assumed that the driver is in the proper lane prior to reaching the beginning of the taper and only needs to initiate deceleration and lateral movement. For motorists who frequently use the street this may be as little as one second or less. However, strangers may not be in the proper lane to execute the desired maneuver and may require several seconds.

d_2: The distance traveled while braking and moving laterally. This is a more complex maneuver than braking alone -- perhaps one-half the deceleration rate utilized in d_3. Lateral movement under urban conditions is commonly assumed to be 4 feet per second (1.2 metres per second) and 3 fps (0.9 m/s) for rural conditions. At low deceleration rates the driver will have shifted laterally so that a following vehicle can pass without encroaching on the adjacent lane before a 10 mph (16 km/h) speed differential occurs. For urban conditions, the speed differential will exceed 10 mph (15 km/h) before the turning vehicle clears the through traffic lane if the average deceleration during the lateral movement exceeds approximately 1.5 m/s^2 (4.9 fps^2). And, for rural conditions if the average deceleration exceeds about 1.1 m/s^2 (3.7 fps^2).

d_3: The distance traveled during full deceleration after moving laterally into the turn bay. Figure 3 shows that most drivers (85%) will utilize a deceleration rate of 6 fps^2 (1.8 m/s^2) or more; only about 50% can be expected to accept a rate of 9 fps^2 (2.7 m/s^2) or greater.

d_4: The length required to store turning vehicles.

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UPSTREAM FUNCTIONAL AREA (Continued)

Elements of the Upstream Functional Area (Continued)

As illustrated in Figure 2 the physical length of the turn bay excludes the distance traveled during perception-reaction time. The turn bay should be designed so that a turning vehicle will develop a speed differential of 15 km/h (10 mph) or less at the point it clears the through traffic lane. The length of the bay should allow the vehicle to come to a comfortable stop prior to reaching the end of the expected queue in the turn bay.

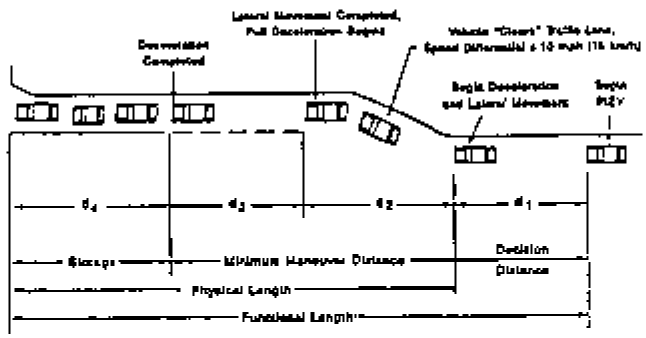

Figure 2: Elements of the Functional Area of An Intersection

Source: References (6) Stover, and (3) Stover and Koepke

Upstream Maneuver Distances

Table 1 presents maneuver distances and total distances (maneuver plus PIEV distance) for the selected conditions indicated with the table. These distances represent the minimum functional length of an approach to an intersection as they exclude storage.

As indicated in the footnotes to Table 1, 1.8 metres per second per second (6 fps^2) was used in as the desirable full deceleration rate (distance d_2 in Figure 2). This is somewhat less than the 2.1 m/s^2 (7.0 fps^2) used in

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Upstream Maneuver Distances (Continued)

previous guidelines such as in Transportation Land Development. The change is due to the research results shown in Figure 3. This figure shows that most (85% of drivers will use an average deceleration rate of at least 1.8 m/s^2 (6 fps^2). Only 50% of drivers were observed to utilize an average deceleration rate of 2.7 m/s^2 (9 fps^2) or more used in calculating the limiting maneuver distance.

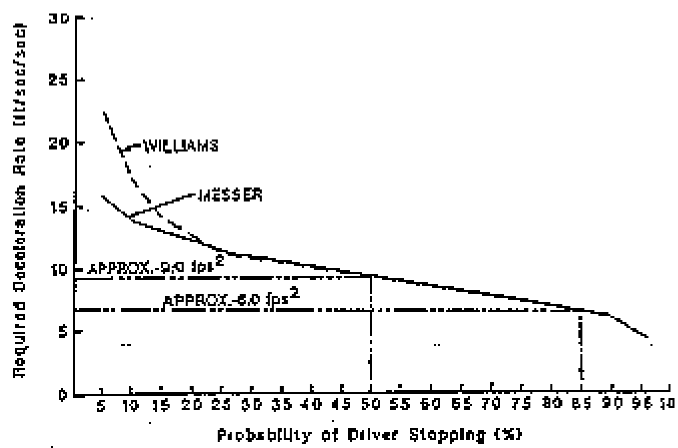

Figure 3: Observed Deceleration Rates

Source: Adapted from References (4) Williams, and (5) Chang, Messer and Santigo

Upstream Maneuver Distances (Continued)

Table I-A: Upstream Intersection Area [1], Excluding Storage, SI Units

	Desirable Conditions[(2)]		Limiting Conditions[(3)]	
Speed (km/h)	Deceleration[(4)]	PIEV Plus Deceleration[(5)]	Deceleration[(4)]	PIEV Plus Deceleration[(5)]
40	50	70	35	45
50	70	100	50	65
60	100	140	70	85
70	130	165	95	115
80	165	210	120	140
90	205	255	150	175
100	250	305	180	205
110	300	360	215	245

[(1)]all distances rounded to 5m
[(2)]2.0 second perception-reaction time; 1.1 m/s^2 through traffic lane into turn lane, 1.8 m/s average deceleration thereafter; speed differential < 15 km/h
[(3)]1.0 second perception-reaction time; 1.4 m/s^2 average deceleration while moving laterally from through traffic lane and into turn lane, 2.7 m/s^2 average deceleration thereafter
[(4)]distance to decelerate from through traffic speed to a stop while moving laterally into a left-turn or right-turn lane
[(5)]distance traveled during perception-reaction time plus deceleration distance

Source: Reference (8) Stover 1994, Adapted from (4) Stover and Koepke, 1988

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Upstream Maneuver Distances (Continued)

Table I-B: Upstream Intersection Area [1], Excluding Storage, in Feet

	Desirable Conditions[2]		Limiting Conditions[3]	
Speed (km/h)	Deceleration[4]	PIEV Plus Deceleration[5]	Deceleration[4]	PIEV Plus Deceleration[5]
30	225	315	170	215
35	295	370	220	270
40	375	490	275	335
45	465	595	340	405
50	565	710	410	485
55	675	835	485	565
60	785	960	565	605

(1)all distances rounded to 5ft
(2)2.0 second perception-reaction time; 3.5 fps^2 average deceleration while moving laterally into turn lane, 6.0 fps^2 average deceleration thereafter; speed differential < 10 mph
(3)1.0 second perception-reaction time; 4.5 fps^2 average deceleration while moving laterally into turn lane, 9.0 fps^2 average deceleration thereafter; speed differential <10 mph
(4)distance to decelerate from through traffic speed to a stop while moving laterally into a left-turn or right-turn lane
(5)distance traveled during perception-reaction time plus deceleration distance

Source: Reference (8) Stover 1994, Adapted from (4) Stover and Koepke, 1988

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Intersection Effect of Radius on Maneuver Distance

As the distances in the last column (total distance) of Table 2 indicates, the curb return radius or the inside radius of a turning roadway of a channelized intersection has very little effect on the length of an auxiliary lane measured from the beginning of the taper near the driveway edge.

Table 2: Effect of Radius and Turni ng Speed on Deceleration Distance

Radius		Turn Speed[4]		Deceleration Distance[b]		Total Distance Decel. + Radius	
metres	(feet)	km/h	(mph)	metres	(feet)	metres	(feet)
9	(30)	Stop	Stop	111	(365)	114	(375)
9	(30)	10	(6)	110	(360)	119	(390)
15[d]	(50[d])	18	(11)	104	(340)	119	(390)
23[e]	(75[e])	23	(14)	100	(330)	123	(405)
27	(90)	27	(17)	96	(315)	123	(405)
46	(150)	40	(25)	76	(250)	122	(405)

[a]Based on Emmerson's Equation, References (8, 9)
[b]Rounded to 1 km/h (5 mph)
[c]Assumes vehicle is stopped m (10 feet) from the curb line of intersecting street.
[d]Minimum radius for channelizing right-turn
[e]Minimum radius for curbed channelizing island

Source: Reference (6) Stover

Lateral Movement

Lateral movement of vehicles leaving a through lane is about 0.92 metres per second (3 feet per second) at higher speeds and 1.22 metres per second (4 feet per second) in lower speeds situations, typically in urban areas. Table 3 shows the difference a vehicle will travel in 3 seconds and 4 seconds maneuver times while the driver is executing a 3.6 metre (12-foot) lateral movement and decelerating from various speeds.

In all applications, the taper length should be less than the distance traveled during the lateral movement. In urbanized areas the taper length should be based on peak period speed; in rural areas it may be based on the design speed, posted speed, or 85th percentile speed.

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UPSTREAM FUNCTIONAL AREA (Continued)

Lateral Movement (Continued)

Table 3: Distance Traveled While Making Lateral Movement Into a Turn Bay and Decelerating

Source: Calculations by author

Entry Speed[1]		3 Second Maneuver[2]		4 Second Maneuver[3]	
km/h	(mph)	metres	(feet)	metres	(feet)
30	(20)	20	(70)		
35					
40	(25)	25	(90)		
45					
50	(30)	35	(110)		
55	(35)		(130)		
60		45			(205)
65	(40)		(155)		(235)
70	(45)	50	(175)	70	
75					(265)
80	(50)			80	
85					(295)
90	(55)			90	(305)
95	(60)				
100				100	(350)
105	(65)				

[1]Speed at the beginning of the lateral movement. Calculations assume that deceleration while making the lateral movement will be about 15 km/h (10 mph)
[2]Urban conditions
[3]Rural conditions and urban freeway

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Queue Storage

Speeds are slower during the peak periods and the maneuver distance therefore is less than during off-peak hours. Therefore, some peak period queue storage is "built into" the dimensions when a turn bay is designed with the distances given in Table 1. For example, using the desirable conditions, there is a 160-foot difference in the maneuver distances for 55 and 70 km/h and 45 mph (465-295 = 160) which is sufficient to store about 5 or 6 cars. However, is it not unusual to find left-turn queues of 20, 30 or more autos at major arterial intersections during peak hours.

The required storage for any selected probability of storing all vehicles can be determined using the queuing analysis or various tables and charts that have been developed for queue storage. In both of these methods, the length of the taper and deceleration distance must be added to the storage length.

It is essential that sufficient queue storage be provided to store all left-turn arrivals a high percentage of the time. It is recommended that turn lanes on major roadways be designed to have at least a 95% probability of storing all arrivals during the peak period.

Changing Left-Turn Demand

Changing traffic volumes and/or patterns frequently requires lengthening of the left-turn storage at major intersections. This may necessitate the elimination of left-turns at a nearby intersection of a public street or private access.

Why Is A Turn Lane Needed?

Research has shown that accident potential increases exponentially as the speed differential between a turning vehicle and through traffic increases (3). Research has also shown that all reasonable combinations of driveway throat width and curb return radii produce high speed differentials (3).

Figure 4 shows accident rates as a function of the speed differential between a vehicle and other traffic. While the actual rates changes over time and may differ by location, the relative rates can be expected to be

(Continued)

Why Is A Turn Lane Needed? (Continued)

a good indication as how speed differential affects accidents. The relative accident rates given in Table 4 were obtained by dividing the observed rates in Figure 4 by the observed rate of a speed differential of 10 mph. This indicates that a vehicle traveling 35 mph slower than other traffic is 90 times as likely to be involved in an accident, or cause an accident as one traveling only 10 mph slower than other traffic. While the variation may be considerable, the relative accident ratios clearly illustrate that there is a safety problem when a vehicle travels much slower than the traffic stream.

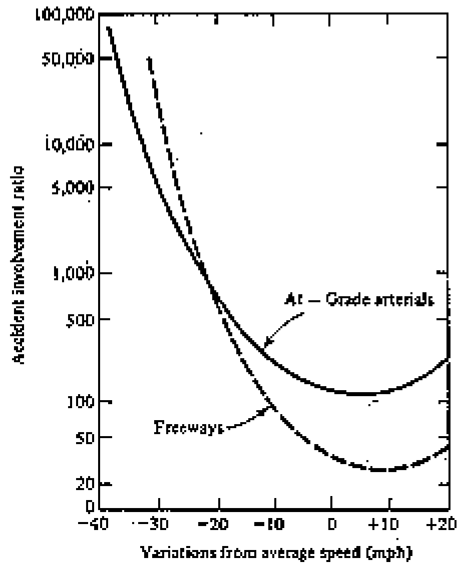

Figure 4: Observed Accident Rates as a Function of Speed Differential

Source: Reference (10) Solomon

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UPSTREAM FUNCTIONAL AREA (Continued)

Why Is A Turn Lane Needed? (Continued)

Table 4: Relative Accident Ratios

	Speed Differential				
	-0	-10	-20	-30	-35
Accident Rate	110	220	720	5000	20000
Relative Ratio: @ 0 mph differential	1	2	6.5	45	180
@ -10 mph differential		1	3.3	23	90

Source: Adapted from Reference (3) Stover and Koepke

Figure 5 shows that all reasonable combinations of driveway throat width and curb return radii result in a similar speed profile as drivers approach the driveway. As indicated on the figure, the driveway geometrics ranged from a 30 ft. throat width and a 30 ft. radius (a total curb opening of 90 ft.) to a 20 ft. throat width and a drop curb, i.e., zero curb return radius, (a total curb opening of 20 ft.). The differences is the forward speed of the right-turning vehicles were surprisingly similar. Ranging from about 9 to 14 mph (14 to 22 km/h). More importantly, the speed vector parallel to the through traffic lane ranged from only about 2 to 4 mph (3 to 6 km/h). This very slow speed vector resulted from the fact that the turning vehicle was approaching a 90^{o} angle to the through lanes. Consequently, the speed differential between a right-turning vehicle and following through traffic is approximately the speed of the through traffic.

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Why Is A Turn Lane Needed? (Continued)

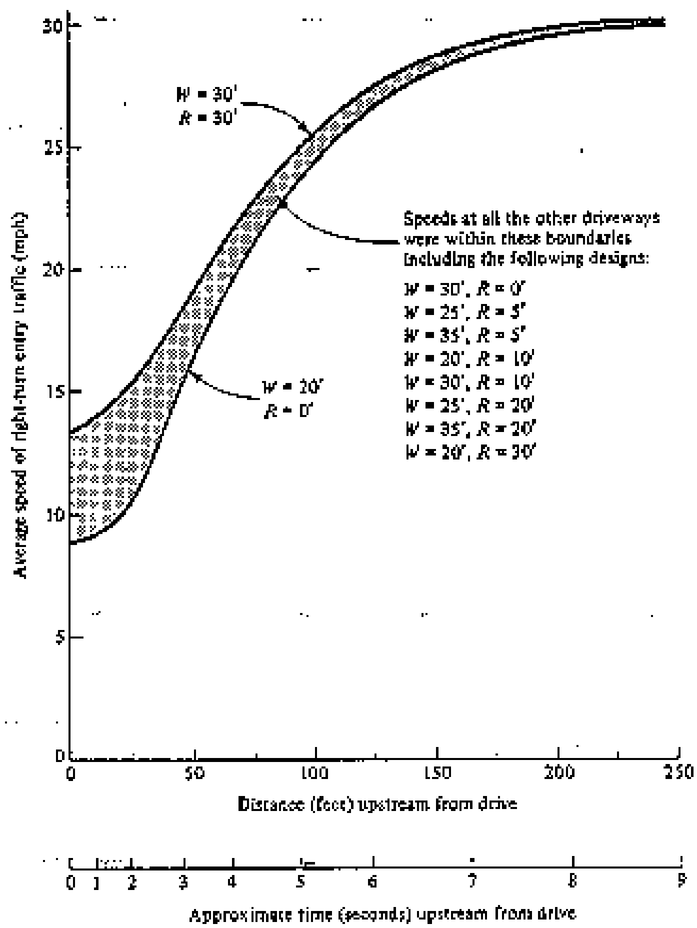

Figure 5: Speed Profile of Right-Turning Vehicles

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Why Is A Turn Lane Needed? (Continued)

These data and other observations indicate that they only way to significantly limit the speed differential between a turning vehicle and through traffic is to provide a turn lane.

DOWNSTREAM FUNCTIONAL AREA

Introduction

The functional area of an intersection extends some distance downstream from the crosswalk location because of the need to establish guidance and tracking after having passed through the area in which there are no lane lines. This is especially true following a left-turn. However, guidelines for establishing this distance are not well developed as for the upstream functional area at the present time.

Defining the Downstream Area

Various approaches can be considered in evaluating the dimension of the downstream functional area and in turn, how close a lesser intersection (driveway or approach road) can be placed downstream from a major intersection. These include the following:

- Length of an acceleration lane
- Stopping sight distance
- Conflict overlap
- The left-turn driving task

Length of an Acceleration Lane

A driveway or approach connection should not be located within the physical length of any acceleration lane. Nor, within, say 2.0 seconds downstream from the end of an acceleration lane. However, since acceleration lanes are very rarely used on at-grade arterials, this criterion will rarely be applicable.

Stopping Sight Distance

It can be argued that a vehicle should clear a major intersection before the driver is required to respond to vehicles entering, leaving or crossing the major roadway. The logic of this criterion is to simplify the driving task and thus minimize the chances of driver mistakes and collisions.

Stopping sight distance is one criterion which would allow the driver to clear the intersection before having to rapidly decelerate in response to a maneuver at a downstream intersection. AASHTO stopping sight distances are given in Table 5. When considering these stopping sight distances it should be recognized that AASHTO bases these distances on coefficient of frictions available on most wet surface pavements. In order

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Stopping Sight Distance

to utilize these coefficient of friction, drivers must accept average decelerations rates which range from 2.7 m/s^2 (9.0 fps^2) at high speeds to 3.9 m/s^2 (12.9 fps^2) at low speeds. Research has shown that about 50% of drivers utilize an average deceleration rate of 9.0 fps^2 or more (4, 5).

Table 5A: Minimum Stopping Sight Distances, SI Units

Speed (km/h)	AASHTO Stopping Distance[1] (m)	Calculated Stopping Distance (m) 2.74 m/s^2 Deceleration[2]	1.83 m/s^2 Deceleration[3]
30		35	40
40		50	70
50		70	90
60		95	120
70		120	150
80		145	190
90		175	235
100		210	280

[1]Source: 1994 AASHTO "Greenbook"

[2]2.5 second perception-reaction time; deceleration acceptable to 50% of drivers; distances rounded to 5m

[3]2.5 second perception-reaction time; deceleration acceptable to 85% of drivers; distances rounded to 5m

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Stopping Sight Distance (Continued)

Table 5B: Minimum Stopping Sight Distances

Speed (mph)	AASHTO Stopping Distance[1] (ft)	Calculated Stopping Distance (m): 9 fps^2 Deceleration[2]	Calculated Stopping Distance (m): 6 fps^2 Deceleration[3]
20	125	120	145
25	150	165	205
30	200	220	275
35	250	275	350
40	335	340	435
45	400	410	530
50	475	485	640
55	550	565	750
60	650	655	870

[1] Source: Reference (1) Table III-1, page 120, 1990 AASHTO "Green Book" (rounded to 25 ft.)
[2] average deceleration acceptable to about 50% of drivers; (see Figure 3); 2.5 second perception-reaction time; rounded to 5 ft.
[3] average deceleration acceptable to about 85% of drivers; (see Figure 3); 2.5 second perception-reaction time; rounded to 5 ft.

Right-Turn Conflict Overlap

A single conflict exists between a through vehicle and a vehicle entering the roadway at a downstream location when the drivers needs to be alert for turning vehicles at one driveway at a time. This issue is referred to as the "Right-Turn Conflict Overlap" in the literature (3).

This criterion is another way of viewing the separation of decision points. Distances from an intersection to downstream intersection are given in Table 6. As illustrated schematically in Figure 6, the distances given in Table 6 allow drivers to address one approach road or driveway at a time. Distances one-half those given in the table require that drivers monitor two access points at a time.

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DOWNSTREAM FUNCTIONAL AREA (Continued)

Right-Turn Conflict Overlap (Continued)

Table 6: Minimum Distances to Reduce Collision Potential Due to Intersection Conflict Overlap

SI Units		English Units	
Speed (mph)	Separation (ft.)	Speed (mph)	Separation(1) (ft.)
50	45	30	150
60	70	35	200
		40	250
70	95	45	300

(1)Measured from rear edge-to-rear edge of intersections as defined by curb returns. Assumes 1.0 second perception-reaction time, 6.0 fps^2 average deceleration by through vehicle, vehicle entering the roadway accelerates at an average of 2.1 fps^2 to 3.1 fps^2

Source: Adapted from Reference (3)

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Right-Turn Conflict Overlap (Continued)

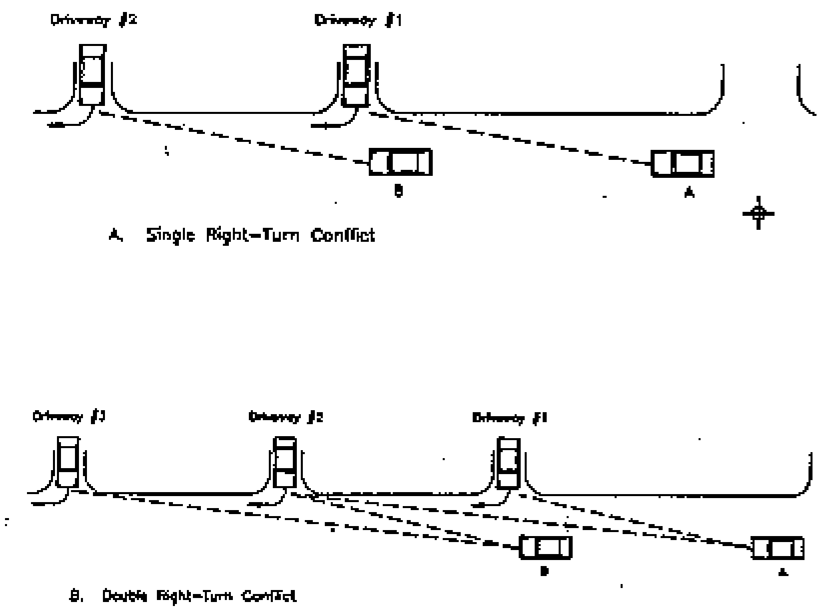

Figure 6: Schematic Illustration of the Right-Turn Conflict Overlap

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Comparison of Stopping and Conflict Overlap Distances

Comparison of stopping sight distances (Table 5) and right-turn conflict overlap distances (Table 6) shows that the latter are shorter distances than the stopping sight distances (i.e., 100 ft. -v- 200 ft. at 30 mph and 300 ft. -v- 400 ft. at 45 mph). This results from the condition that through vehicles do not come to a complete stop. However, high speed differentials will be produced in the through traffic lanes. This presents a serious potential collision problem on high volume urban arterials.

Left-Turn Driving Task

Three maneuvers are made at a major intersection. These are: right-turn, through and left-turn. Of these, the left-turn is the most critical by the following logic:

- Drivers making a right-turn have the curb lane or edge of pavement to guide them through the intersection. Moreover, they can view the roadway into which they are turning before and during the right-turn maneuver.

- Drivers proceeding straight through the intersection have a "full view" of the intersection and the downstream area on the approach to the intersection. Thus the speed may be high and the downstream distance traveled while making any maneuver is quite long. However, the drivers' ability to see a considerable distance provides good response times.

- Drivers making a left-turn are traveling some distance through a sizable undefined area while accelerating. Upon completing, or nearly completing the 90^{o} turn, they must perform the driving task so as to be properly positioned in the traffic lane which they are entering. The problem becomes more complex when dual left-turns are made. It is suggested that drivers have at least 2.0 to 3.0 seconds before they are presented with the potential of vehicles entering, or leaving the roadway. This will require a downstream distance of 60 ft. to 90 ft. (18m to 27m).

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DOWNSTREAM FUNCTIONAL AREA (Continued)

Downstream Clearance Suggested clearances to an approach road or access drive downstream from a major intersection are given in Figure 7.

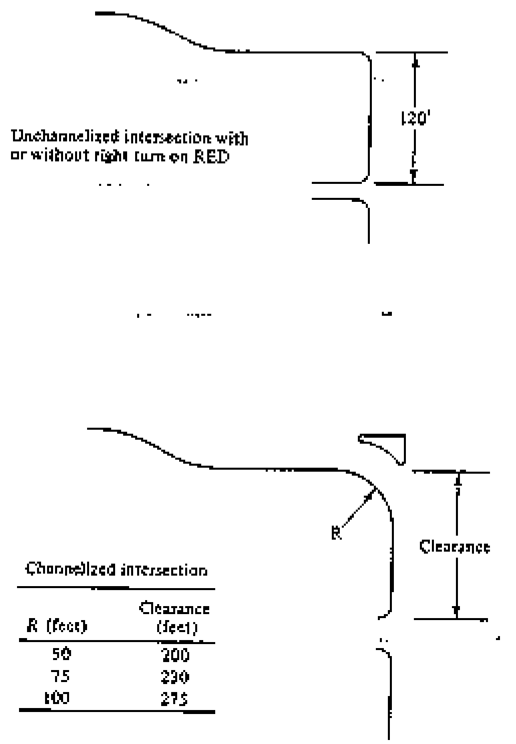

Figure 7: Downstream Corner Clearances

Source: Reference (3) Stover and Koepke

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Comparison of Downstream Dimensions

The various approaches to establishing the dimension of the downstream functional area produce different values as summarized in Table 7.

Table 7A: Comparison of Different Approaches to Defining the Downstream Functional Area, SI Units

Speed (km/h)	Stopping Sight Distance (m)	Right-Turn Conflict Overlap (m)	Left-Turn Driving Task
30	40		30
40	70		30
50	90	45	30
60	120	70	30
70	150	95	30
80	190		30
90	235		30
100	280		30

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DOWNSTREAM FUNCTIONAL AREA (Continued)

Comparison of Downstream Dimensions (Continued)

Table 7B: Comparison of Different Approaches to Defining the Downstream Functional Area, English Units

Speed (mph)	Stopping Sight Distance (ft.)	Right-Turn Conflict Overlap (ft.)	Left-Turn Driving Task[1]
20	145		90
25	205		90
30	275	100	90
35	350	150	90
40	435	200	90
45	530	300	90
50	640		90
55	750		90
60	870		90

[1] Independent of approach speed in through traffic lane

Downstream Right-Turn Lanes

Where a right-turn deceleration lane of sufficient length is provided downstream from a major intersection a distance of 35 to 40 ft. (10 to 12 m) between the end of the curb return and the beginning of the right-turn lane bay taper. The aerial photo shown in Figure 8 shows a right-turn deceleration lane which begins 35 ft. downstream from end of the curb return of the upstream intersection. Observation indicates the design works well on a 55 mph, posted speed, street.

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DOWNSTREAM FUNCTIONAL AREA (Continued)

Downstream Right-Turn Lanes (Continued)

Figure 8: Example of a Right-Turn Lane Immediately Downstream from a Major Intersection

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