1. Report No. SWUTC/12/161141-1	2. Government Accession No.	Recipient's Catalog No.	
4. Title and Subtitle Development of Warrants for Installation of Dual Right-Turn Lanes at Signalized Intersections		5. Report Date April 2012	
		6. Performing Organization Code	
7. Author(s) Qi Yi, Xiaoming Chen and Da Li		8. Performing Organization Report No. Report 161141	
9. Performing Organization Name and Address Center for Transportation Training and Research Texas Southern University 3100 Cleburne Avenue Houston, Texas 77004		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. 10727	
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplementary Notes Supported by general revenues from the State of Texas.			

16. Abstract

Right-turn lanes provide space for the deceleration and storage of right-turn vehicles, and separate turning vehicles from through movements. Dual right-turn lanes are increasingly used at urban intersections primarily for two reasons: (1) to accommodate high right-turn demands and avoid turn-pocket overflows, and/or (2) to prevent right-turn vehicles that exit from a nearby upstream freeway off-ramp (on the left of the roadway) from abruptly changing too many lanes toward the right-turn lane at the intersection.   In addition, a number of other factors may affect the decisions on the installation of dual right-turn lanes. However, warrants for dual right lane installation are almost non-existent, leaving traffic engineers to rely on engineering judgment.   This research aims to develop warrants for installation of dual right-turn lanes at signalized intersections. Both the operational and safety benefits/costs were analyzed by surveying traffic engineers and by conducting traffic simulation-based analysis. Microscopic traffic simulation model, VISSIM, was used to quantify the operation benefits and Surrogate Safety Assessment Model (SSAM) developed by Siemens was used to analyze the safety gains due to installation of dual right-turn lanes.

17. Key Words Dual Right Turn Lanes; Warrants; Microscopic Traffic Simulation; Traffic Safety		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classify (of this report) Unclassified	20. Security Classify (of this page) Unclassified	21. No. of Pages 116	22. Price

Development of Warrants for Installation of Dual Right-Turn Lanes at Signalized Intersections

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Research Report SWUTC/12/161141-1

April 2012

ABSTRACT

Right-turn lanes provide space for the deceleration and storage of right-turn vehicles, and separate turning vehicles from through movements. Dual right-turn lanes are increasingly used at urban intersections primarily for two reasons: (1) to accommodate high right-turn demands and avoid turn-pocket overflows, and/or (2) to prevent right-turn vehicles that exit from a nearby upstream freeway off-ramp (on the left of the roadway) from abruptly changing too many lanes toward the right-turn lane at the intersection. In addition, a number of other factors may affect the decisions on the installation of dual right-turn lanes. However, warrants for dual right lane installation are almost non-existent, leaving traffic engineers to rely on engineering judgment. This research aims to develop warrants for installation of dual right-turn lanes at signalized intersections. Both the operational and safety benefits/costs were analyzed by surveying traffic engineers and by conducting traffic simulation-based analysis. Microscopic traffic simulation model, VISSIM, was used to quantify the operation benefits and Surrogate Safety Assessment Model (SSAM) developed by Siemens was used to analyze the safety gains due to installation of dual right-turn lanes.

Keywords: dual right-turn lanes; warrants; capacity; microscopic traffic simulation; traffic safety

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NOTICE

ACKNOWLEDGEMENTS

EXECUTIVE SUMMARY

In recent decades, dual right-turn lanes are increasingly used as alternative design for accommodating high right-turn volume on urban signalized intersections. Traffic flows on dual right-turn lanes are generally more complex as a result of their unique friction effects between parallel turn vehicles, preference of lane utilization, and behavior of red turn on red (RTOR). However, studies on investigating the operational or safety performance of dual right-turn lanes are almost non-existent. There are also few guidelines that mention where and when to use dual right-turn lanes, leaving traffic engineers to rely on engineering judgment.

The objective of this research is to develop guidelines for installation of dual right-turn lanes at signalized intersections. Both the benefits and concerns of dual right-turn lanes were investigated from operational and safety standpoints in this study. To this end, the research team performed the following primary tasks:

- Reviewed existing literature associated with dual right-turn lanes;
- Conducted a web-based survey of traffic engineers to solicit professional opinions regarding where dual right-turn lanes should be used, how to design, and how to implement right turn on red for dual right-turn lane, etc.;
- Collected field data for dual right-turn lanes;
- Developed analytical models for capacity of dual right-turn lanes, which is a key measure of operational performance;
- Conducted simulation-based experiments to quantify effects of dual right-turn lanes on mitigating weaving traffic conflicts at frontage road intersections in proximity to freeway ramps, and quantified the relationships between the frequency of traffic conflicts and weaving distances and weaving volumes with and without dual right-turn lanes;
- Collected field data for developing, calibrating, and validating the models;
- Developed guidelines for supporting the decisions related to dual right-turn lanes.

Existing literature showed that there are very few research papers or guidelines particularly for dual right-turn lanes. The survey of traffic engineers received good responses from 44 traffic engineers throughout the nation, and showed that dual right-turn lanes are mainly used for accommodating high right-turn volume or for mitigating traffic conflicts.

The capacity study showed that the current Highway Capacity Manual (HCM) method can be used to provide reasonable estimates of saturation flow rates of dual right-turn lanes; the proposed analytical model for capacity for RTOR of dual right-turn lanes exhibited a significantly improved capability of predicting RTOR capacities for dual right-turn lanes compared to the classical Harders's model. Dual right-turn lanes can have significant operational benefits in terms of enhancing capacity, accommodating high right-turn volume, and reducing the resulting delays.

The simulation-based surrogate safety analysis is capable of predicting relative crash potentials for dual right-turn lanes at signalized intersections. In the weaving segments between a freeway off-ramp and a downstream, closely-spaced frontage road intersection, the safety benefits from dual right-turn lanes generally increase exponentially with weaving traffic volumes, and they increase exponentially as weaving distance decreases. While shared dual right-turn lanes provide a more flexible (optional) accessibility for both right-turn and through vehicles, exclusive dual right-turn lanes provide more operational and safety benefits for right-turn traffic given a more even lane utilization.

Based on the reviewed literatures, the survey of traffic engineers, the capacity study, and the simulation-based surrogate safety analysis, comprehensive guidelines are proposed to support the decision makings on the installation of dual right-turn lanes. Issues addressed in the guidelines include:

- Typical conditions when dual right-turn lanes shall be considered
- Use of dual right-turn lanes for mitigating weaving conflicts at frontage road
- Choice between exclusive dual right-turn lanes and shared dual right-turn lanes
- RTOR operations with dual right-turn lanes

Finally, future research is strongly recommended to achieve a more specific warrant for the installation of dual right-turn lanes.

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CHAPTER 1: INTRODUCTION

1.1 Background and Significance of Research

Right-turn lanes provide space for deceleration and storage of right-turn vehicles, and separate turning vehicles from through movements. During recent decades, dual right-turn lanes are increasingly used as alternative designs on urban signalized intersections.

Traffic flows on dual right-turn lanes are generally more complex as a result of their unique friction effects between parallel turn vehicles, preference of lane utilization, and behavior of RTOR. While several state Department of Transportation (DOT) highway design manuals (e.g. Texas, Ohio, and Connecticut) have presented some general guidelines for design elements of dual right-turn lanes, currently, warrants for dual right turn lane installation are almost non-existent for transportation design engineers. Since a number of traffic, environmental, and operational factors affect the decisions regarding whether dual right-turn lanes should be used, there is a critical need to develop appropriate guidelines that support decisions on when to use dual right-turn lanes at signalized intersections on urban roadways.

1.2 Research Goal and Objectives

The goal of this research is to develop guidelines for installation of dual right lanes at urban signalized intersection. The results of this project will improve safety and operational performance at urban signalized intersections. To achieve this goal, the research will:

a. Develop, calibrate, and validate analytical and micro-simulation models based on field observations, so as to characterize operational and safety performance on dual right-turn lanes;

b. Develop guidelines for installation of dual right-turn lanes at urban signalized intersections.

1.3   Organization of the Report

This report is focused on documenting all the research activities performed throughout the project. Chapter1 presents a brief overview of the research. Chapter2 summarizes existing design guidelines on dual right-turn lanes, existing warrants for single right-turn lanes, and studies on design and operation of right-turn lanes. Chapter 3 describes the results of a nationwide web-based survey of traffic engineers. Chapter 4 presents data collection efforts at five intersections with dual right-turn lanes, which will be used for calibrating and validating the models in the following Chapters 5 and 6. Chapter 5 develops the model for predicting the capacity of dual right-turn lanes. Chapter 6 develops surrogate safety assessment models to investigate the benefits of dual right-turn lanes in mitigating weaving traffic conflicts at frontage road intersections in proximity to freeway ramps. Chapter 7 develops general guidelines for dual right-turn lanes. Chapter 8 concludes with key findings and results of this research.

CHAPTER 2: LITERATURE REVIEW

To develop a full context for the project, the research team has thoroughly reviewed existing literature associated with dual right-turn lanes. As a relatively new design alternative, dual right-turn lanes have not received much attention from the transportation research community thus far. Generally, there has been very little research conducted particularly for dual right-turn lanes. In this chapter, firstly, available DOT design standards and guidelines are documented. This is followed by a synthesis of warrants for single right-turn lanes, which have been extensively discussed. Finally, the safety and operational effects of exclusive right-turn lanes are reviewed. In general, the existing literature provides a very insightful basis to accomplish the research objectives of this project.

2.1   Method for Literature Review

The literature review began with a search for any resources that had the potential for further review. An online search was conducted using transportation resource websites and search engines to gather available electronic resources. This was followed by searching 50 state DOTs' design manuals available at DOT online libraries and by exploring existing resources at Texas Southern University's (TSU) library. The literature review focused primarily on U.S. practices and experiences.

Relevant publications, reports, presentations, and manuals were located by various search methods including, but not limited to the following sources of information:

- TxDOT and 49 peer DOT online libraries;

- EBSCO/MetaPress Scholarly Content Host (with Books and Full-Text Journals available through TSU);

- Online Transportation Research Information Service (TRIS);

- Research and Innovative Technology Administration (RITA) National Transportation Library.

2.2   Existing DOT Design Guidelines on Dual Right-Turn Lanes

2.2.1   General Principles and Concerns

1)   Where to Use Dual Right-Turn Lanes

Illinois, Connecticut, Indiana, and Maine

Dual right-turn lanes should be considered when:

- There is not sufficient space to provide the necessary length of a single turn lane because of restrictive site conditions (e.g., closely spaced intersections);

- The necessary length of a single turn lane becomes prohibitive (e.g., with high turning traffic volumes, or high speed limits); or

- A single right-turn lane becomes unattainable to meet the level-of-service criteria (average delay per vehicle).

Virginia

Exclusive dual right-turn lanes may be provided when capacity analysis warrants. Safety implications associated with pedestrians and bicyclists should always be considered.

Illinois

Dual turn lanes should only be used with signalization providing a separate turning phase.

Signalized Intersection: Informational Guide (FHWA, 2004)

Approaches with right-turn volumes that cannot be accommodated in a single turn lane without excessively long green times (and delays for other approaches) may be appropriate locations for double turn lanes. Also, locations where right-of-way is not available to provide a long turn lane but there is space for two shorter turn lanes may be ideal for double turn lanes. Clearly, multiple turn lanes are not appropriate where only one receiving lane is available; however, consideration may be given to providing a departing auxiliary lane to allow for double right turns with a downstream merge.

Oregon

At some intersections, right-turn demands might be so high that dual right-turn lanes may be necessary. The approval of the state traffic engineer should be obtained, and the Transportation Planning Analysis Unit and Traffic Management Section must be consulted prior to installation of dual right-turn lanes.

2)   Concerns on Dual Right-Turn Lanes

Signalized Intersection: Informational Guide (FHWA, 2004)

Regarding dual right-turn lanes, some traffic safety concerns may exist, such as (1) higher sideswipe possibility, (2) impaired sight distance for drivers on the rightmost turn lane due to blockage of vehicles on the outer lane, and (3) longer distance and time for pedestrians to be exposed to conflicting right-turning vehicles. On the other hand, based on the subjective assessment provided in the Informational Guide, the safety experience of double right-turn lanes may be similar to that of single right-turn lanes. Rear-end collisions of decelerating right-turn vehicles and following through vehicles may be reduced after construction of the additional turn lane because the turn lanes have a higher storage capacity for the slower vehicles.

Acquisition of right-of-way to provide an additional turn lane may be expensive. If a departure auxiliary lane is to be constructed to allow for a downstream merge, this may also increase right-of-way costs. Access to adjacent properties may need to be restricted to provide a merge area. Owners of adjacent property should be involved in early discussions regarding the plans.

Connecticut, Indiana, and Maine

Dual right-turn lanes do not work as well as dual left-turn lanes because of the more restrictive space available for two abreast right-turn lanes. If practical, a designer should find an alternative to accommodate the high number of right-turning vehicles. For example, a (free-flow) turning roadway may accomplish this purpose.

2.2.2   Design Elements

Dual turn lanes (both lanes exclusive) can potentially discharge approximately 1.9 times the number of cars that will discharge from a single exclusive turn lane. However, to work properly, several design elements must be carefully considered (Connecticut DOT, Highway Design Manual, 2003).

1) *Turn Lane Length*

Figure 2-1 defines the design elements associated with a right-turn lane, including corner radius, turning roadway width, corner islands, and right-turn lane length consisting of taper, storage, and deceleration. Taper rate represents the ratio of bay taper length to lane(s) width.
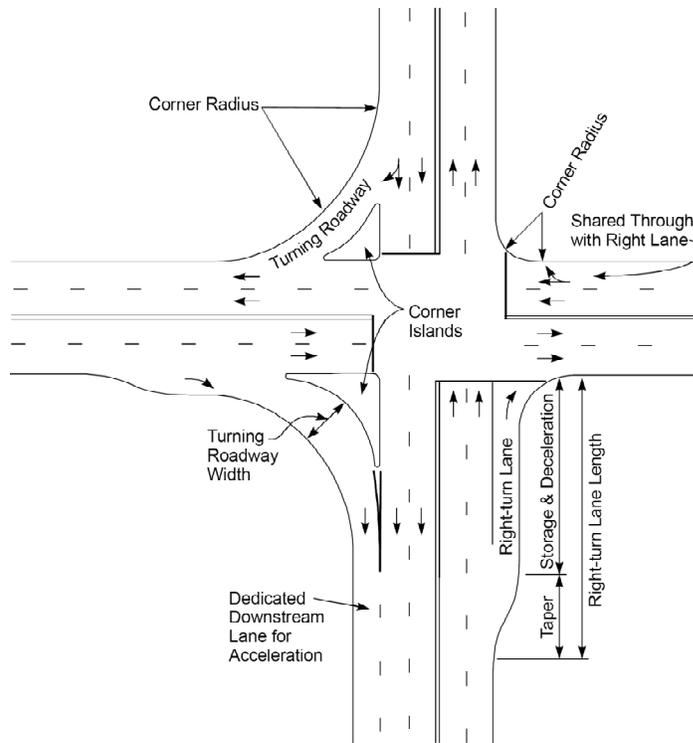
Source: Fitzpatrick et al. Urban Intersection Design Guide, 2005

Figure 2-1: Several Design Elements for Right-Turn Lanes

<u>Mississippi</u>

Generally, dual right-turn lanes, approximately 50 percent as long as a single-turn lane, will operate comparably. However, the intersecting road must have two receiving lanes for the turning vehicles.

<u>Texas</u>

The length for a dual right-turn lane is the same as for a dual left-turn lane (see Table 2-1).

Table 2-1: Lengths of Dual Right-/Left-Turn Lanes on Urban Streets (TxDOT Roadway Design Manual)

Speed (mph)	Deceleration (ft)	Taper (ft)	Storage Length (ft)
30	160	100	
35	215	100	
40	275	100	As calculated or with a minimum of 100
45	345	100	
50	425	100	
55	510	100	

Oregon

Where dual right- turn lanes are required, the taper rate is supposed to be 1.5 times the taper rate for a single right-turn lane (see Figure 2-2).
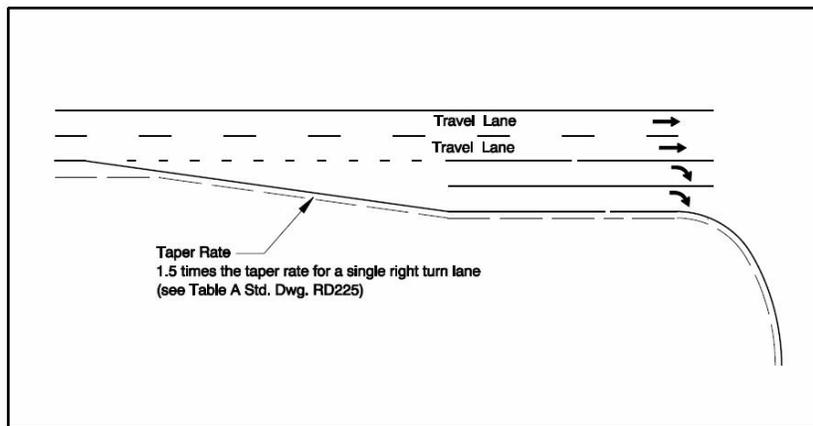
Figure 2-2: Oregon DOT Standards for Dual Right-Turn Lane Channelization

Indiana

For tangent approaches, the Indiana DOT's practice is to 45-m (148 ft) straight-line taper at the beginning of dual turn lanes for an urban street.

2)   *Throat Width and Turning Roadway Width*

A throat width, sometimes referred to as receiving lane width, is illustrated in Figure 2-3, which is denoted as W.

Connecticut, Indiana, and Maine

Because of the off-tracking characteristics of turning vehicles, the normal width of two travel lanes may be inadequate to properly receive two vehicles turning abreast. Therefore, the receiving throat width may need to be widened. For 90° intersections, the designer can expect that the throat width for dual turn lanes will be approximately 30 to 36 ft. If the angle of turn is less than 90°, it may be acceptable to provide a narrower width. When determining the available throat width, the designer can assume that the paved shoulder, if present, will be used to accommodate two-abreast turns.

If a 30-ft. or 36-ft. throat width is provided to receive dual-turn lanes, the designer should also consider how this would affect the traffic approaching from the other side. The designer should also ensure that the through lanes line up relatively well to ensure a smooth flow of traffic through the intersection.

Ohio

Double right-turn lanes are rarely used. When justified, it is generally used at an intersection involving either an off-ramp or a one-way street. Double right-turn lanes require a larger intersection radius (usually 75 ft. [22.5 m] or more) and a throat width comparable to a double left-turn (See the table in Figure 2-3 for throat width as a function of intersection radius). Note that Ohio DOT specified that double right-turn lane design shares the same criteria as the double left-turn lane for expanded throat widths.

INSIDE RADIUS -R-	EXPANDED THROAT WIDTH -W- DESIGN TRAFFIC CONDITION ▼		
	A	B	C
50 ft.	31 ft.	36 ft.	45 ft.
75 ft.	29 ft.	33 ft.	38 ft.
100 ft.	28 ft.	31 ft.	35 ft.
150 ft.	26 ft.	29 ft.	32 ft.
200 ft.	26 ft.	28 ft.	30 ft.

▼ A= mostly 'P' vehicles, some 'SU' trucks
B= sufficient 'SU' trucks to govern design, some semitrailers
C= sufficient bus and combination types to govern design

Generally, A is when T < 5%
B is when T = 5-10%
C is when T > 10%
T= percentage of type B and C trucks in Design ADT

Figure 2-3: Design of double left- and right-turn lane (Ohio DOT, 2003)

Illinois and Indiana

Multiple turn lanes may cause problems with right-of-way, lane alignment, for crossing pedestrians, and erratic movements for turning drivers. In place of dual right-turn lanes, the designer should consider providing a turning roadway with a design speed of 15 mph (25 km/h) or more and a free-flow, right-turn acceleration lane.

3) *Pavement Markings*

Connecticut, Maine, and Indiana

As illustrated in Figure 2-4, the pavement markings can effectively guide two lines of vehicles turning abreast. The Division of Traffic Engineering will help determine the selection and placement of any special pavement markings.
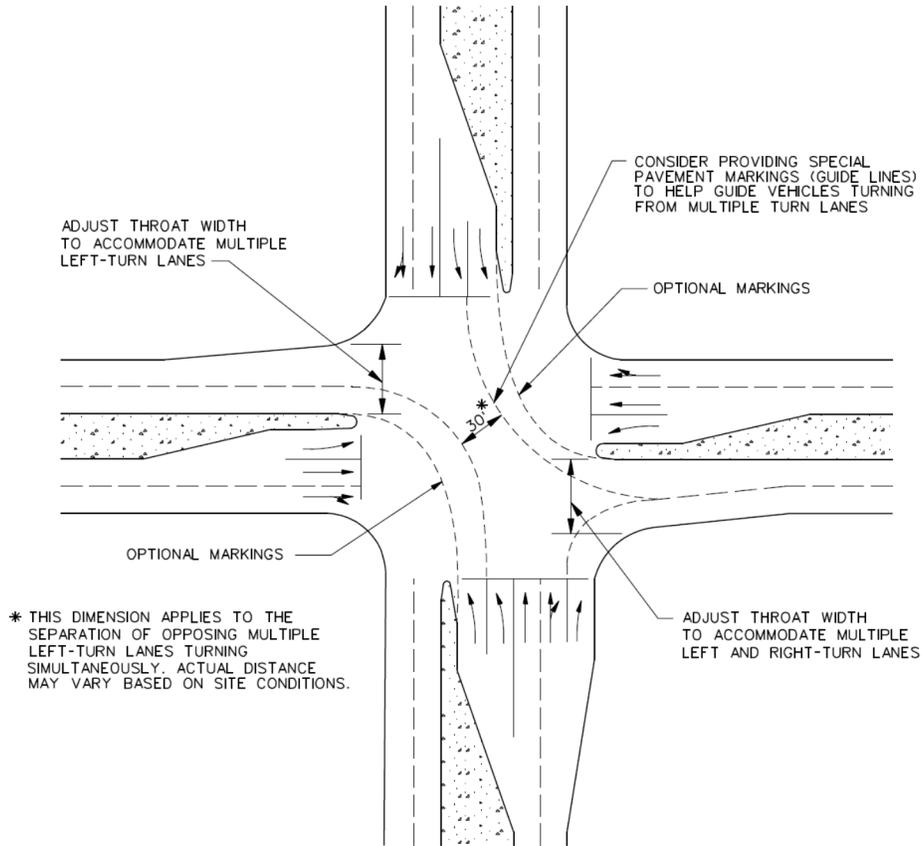
Source: Connecticut Department of Transportation. Highway Design Manual, 2003

Figure 2-4: Optional and Special Pavement Markings

Tennessee

Dotted white line shall be used for vehicle double turn path delineation, which requires an eight-inch stripe per linear foot (see Figure 2-5).
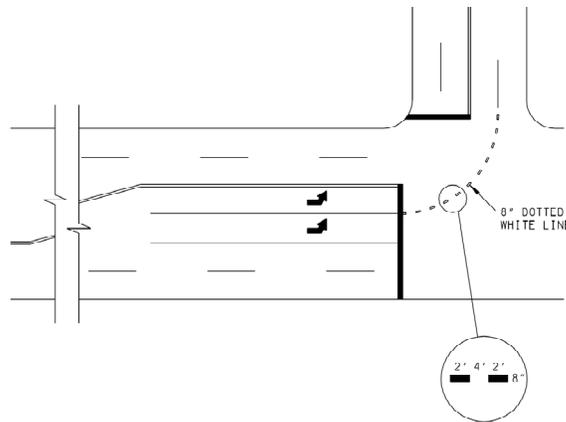
Figure 2-5: Illustrative Pavement Marking for Double Left- and Right-Turn Lane (Tennessee DOT Standard)

Signalized Intersection: Informational Guide (FHWA, 2004)

Delineation of the turn path will guide drivers through the maneuver and help reduce crossing over into adjacent lanes while turning. Sideswipes between turning vehicles are a possibility at double turn lanes. This is especially an issue if the turn radius is tight and large vehicles are likely to be using the turn lanes. Delineation of turn paths should help address this issue.

4) *Turning Templates*

Connecticut, Maine, and Indiana

It is recommended to use applicable turning templates to check all intersection design elements for dual turn lanes. The design vehicle will be assumed to be in each lane turning side by side.

New York

Vehicle encroachments occur when any portion of a vehicle extends beyond the vehicle's lane. With the exception of some low-speed local streets and roads, designs that cause frequent encroachments are undesirable as they may increase the likelihood of delays and collisions. However, designs that eliminate encroachments may also reduce safety since large turning radii allow higher turning speeds and wide turning paths create longer walking distances for pedestrians and may increase confusion for motorists confronted with large paved areas. In order to provide a balanced design, encroachments are generally acceptable for double left- or right-

turns that cannot accommodate side by side operation of the design vehicles. Designs should accommodate a passenger car alongside the design vehicle.

5) *Operations and Other Issues*

Right-Turn as Critical Movement (Signalized Intersection: Informational Guide)

Construction of an additional right-turn lane can be reasonably expected to improve the operations of intersections, provided that the affected right-turn movement is a critical movement. The additional deceleration and storage space should help prevent spillover into adjacent through lanes. Less green time should be needed for right-turn traffic, and this time thus can be allocated to other movements.

Opposing Left-Turn Traffic Issue (Connecticut, Maine, and Indiana)

If simultaneous, opposing left turns will be allowed; the designer should ensure that there is sufficient space for all turning movements. If space is unavailable, it may be necessary to alter the signal phasing to allow the two directions of traffic to move through the intersection on separate phases.

Bicycle Facility Design at Dual Right-Turn Lane (Arizona)

Based on ITE Traffic Control Devices Handbook, Arizona DOT has proposed a rule of bicycle facility design: when there are dual right-turn lanes, i.e., the bicycle lane should not be continued between right/through shared lane and the exclusive right-turn lane (See Figure 2-6).
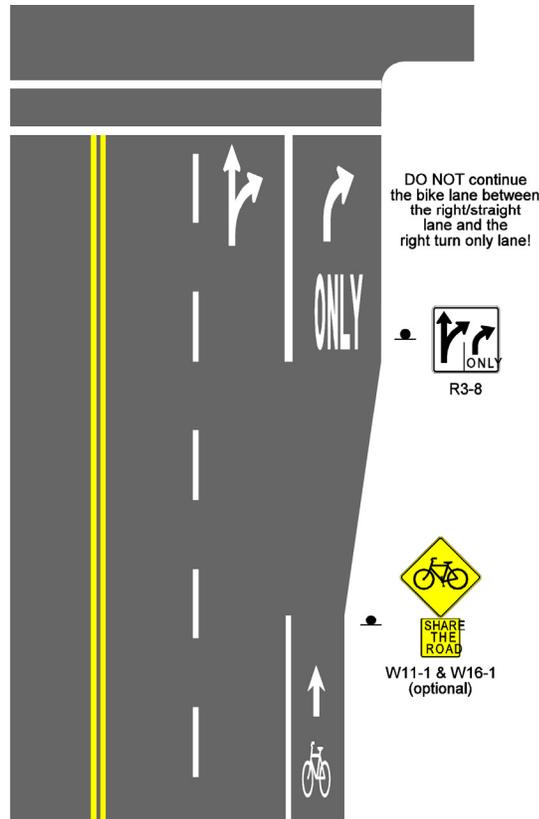
(Source: ITE Traffic Control Devices Handbook)

Figure 2-6: Optional Bike Lane Treatment at Multiple Right Turn Lanes

Yield Sign Control (New York)

Yield signs can be used at the dual right-turn stop lines to further enhance the turning capacity compared to requiring complete stop before a red-turn-on-red maneuver.

Red-Turn-on-Red Operation (Signalized Intersection: Informational Guide)

Typically, right turns on red are only permitted on the outside right-turn lane, if at all. "No turn on red" signing with appropriate lane-specific legends should be placed in a location visible to drivers (such as overhead), especially those in the inside turn lane. Lane-use signs and signs prohibiting right-turn-on-red from the inside turn lane should convey all the information that drivers would need. Periodic enforcement may be needed to ensure drivers obey any right-turn-on-red prohibitions.

Lane Utilization Factor (Highway Capacity Manual 2000 Edition, Chapter 10)

HCM (2000 Edition) has provided default lane utilization adjustment factors for exclusive dual right-turn lane. The default percentage for "traffic in most heavily traveled lane" is 56.5 percent, while the corresponding lane utilization adjustment factor is 0.885.

2.2.3 Summary for Existing DOT Design Standards

Out of the search among existing guidelines and manuals, only a total of 10 state DOTHighway/Roadway Design Manuals provide guidelines associated with dual right-turn lanes. None of these guidelines provide quantitative warrants or a complete set of tools as provided for single right-turn lanes. The review results indicate that the designs of dual right-turn lanes have not received enough attention, although it is increasingly becoming a common practice. Nevertheless, these existing guidelines provide valuable and useful information for revealing the concerns and issues to be addressed by this research project.

2.3 Existing Warrants for Single Exclusive Right-Turn Lanes

Regarding when a dual right-turn lane should be used, some general principles have been recommended and presented in the previous section (see Section 2.2.1). However, warrants for dual right-turn lanes are almost non-existent. This section will review the existing warrants for single exclusive right-turn lanes at intersections, which can be useful to this research project in two ways:

- Warrants for single right-turn lanes provide lower bounds for the conditions when a dual right-turn lane should be warranted. For example, a volume-based warrant for a dual right-turn lane should represent a right-turning traffic demand much higher than 300 vph. Recall that 300 vph is typically considered a threshold for the use of a single exclusive right-turn lane;

- Existing research on warrants for single right-turn lanes present useful methodologies on developing warrants for dual right-turn lanes.

As an upgrade to a shared through/right-turn lane, an exclusive right-turn lane is commonly recommended for high-speed and/or high-volume highways where a change in speed

is necessary for vehicles entering or leaving travel lanes. The following studies provided warrants for the installation of a single exclusive right-turn lane.

HCM (2000)

The manual states that, in general, an exclusive right-turn lane should be considered if the right-turn volume exceeds 300 vph and the adjacent mainline volume exceeds 300 vphpl.

Cottrell (1981)

Cottrell developed guidelines for right-turn treatments by using two approaches: (a) conducting field studies, and (b) conducting a survey to 48 state DOTs to collect the information about the standards used for various types of right-turn treatments. Combining the results from the field studies and the surveys, Cottrell developed guidelines for two-lane and four-lane roadways respectively. The following two figures show the developed guidelines.
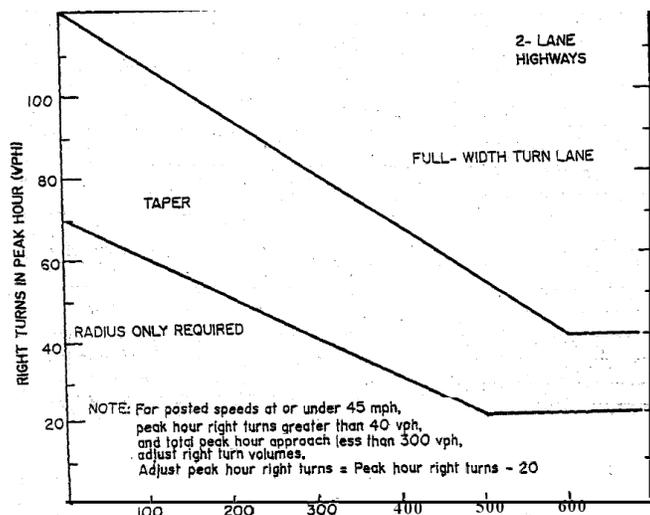
Figure 2-7: Warrants for Right-Turn Treatments on Two-Lane Highways
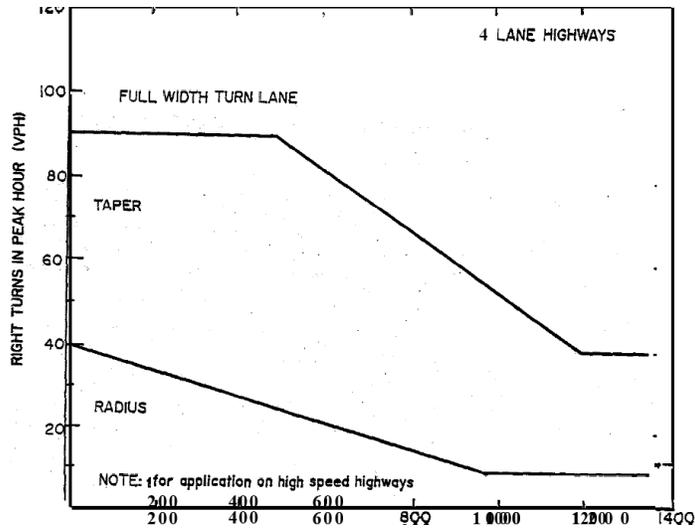
Figure 2-8: Warrants for Right-Turn Treatments on Four-Lane Highways

In these two figures, the area labeled "full width lane" indicates the combinations of peak hour right-turn volume and total peak hour traffic volume conditions that are suitable for a single exclusive right-turn lane at an un-signalized intersection.

Among the surveyed 48 contiguous state DOTs, 41 states responded and about 39 percent of the surveyed state DOTs use specific criteria to assess the need for right-turn treatments. The detail warrants for right-turn lanes were listed in Table 2-2.

Table 2-2: Warrants for Right-Turn Lane Used by State DOTs

Category	Warrants for right-turn lanes	state
Volume based	Right-turn volume>200 vpd	CO
	2-lane road if right-turn volume>60 vph	IL
	Right-turn volume>50 vph	IN
	Right-turn volume>600 vpd	MI
	Right-turn volume=30 to 60 vph	NB
	Right-turn DHV>50 vph	VT
	Right-turn DHV>250 vph and through DHV>500 vph	WV
Roadway type based	For all high speed 2-lane roads	CA
	For FAS roads, except those with very low volumes	KS
	Based on traffic and roadway types	ND
	For all 4 lane highways where sign route turn	OH
Capacity based	Based on capacity analysis	NY
	Through volume>600 vph	OR
Use various rules of thumb	Right-turn vehicle %>20%	CT
	Based on conflict tables and total DHV	ID
	Exposure index	IA

DHV: design hour volumes

DeBaie (2004)

This paper reviewed the concepts, standards, and applications of turn lanes at un-signalized intersections. For right-turn lanes,

(1) Both AASHTO and HCM suggested when the hourly right-turn volume exceeds 300 vph, a single exclusive right-turn lane should be considered.

(2) Most states incorporated volume-based graphic warrants in their design manuals for right-turn lanes (see Figure 2-9 as an example).
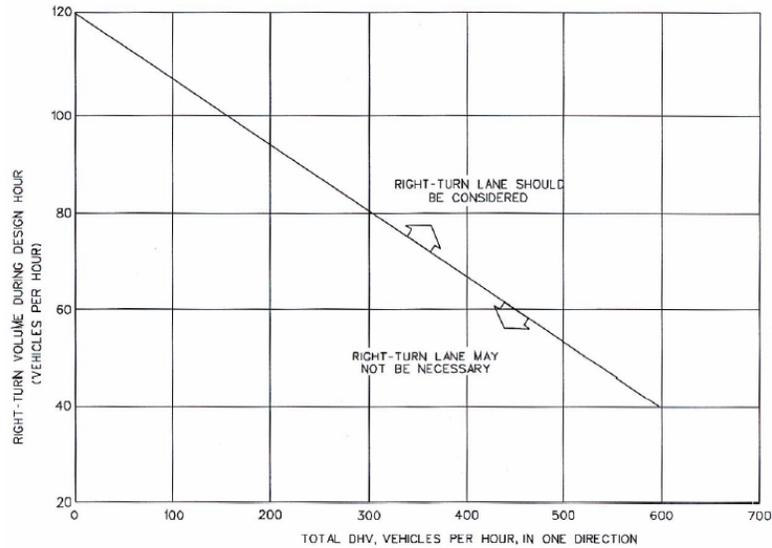
Figure 2-9: Typical State Design Manual Guideline for Right-Turn Lanes at Unsignalized Intersections on Two-Lane Highways

2.4 Studies on Right-Turn Lane Design and Operations

As a relatively new design alternative, dual right-turn lanes have so far received very little attention from the transportation research community. There is little research that has been found. Nevertheless, the existing studies on single right-turn lanes, which have been extensively discussed, can provide a very insightful basis on examining how to represent the traffic flow and operations on dual right-turn lanes. This subsection will present a technical report on dual right-turn lanes, and a few representative research and findings on single exclusive right turn lanes.

2.4.1 Studies on Dual Right Turn Lanes

Cooner et al. (2011)

In this study, Cooner et al. conducted safety performance evaluation and developed general guidelines on the use of dual right-turn lanes. The research team investigated the safety experience of 20 dual right-turn lanes in Texas and conducted a field traffic conflict study to supplement the crash history analysis. It was concluded that a well-designed dual right-turn lane does not cause significantly higher crash frequency or severity compared to a single right-turn lane. Major findings by the evaluation of safety performance were summarized:

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- Clear turning guide lines are highly recommended for both sides of the left side right-turn lane when the intersection has a turning angle greater than 90 degrees.
- Narrow dual right-turn lanes (turning roadway width is less than or equal to 30 ft) with channelization should not be used.
- RTOR is not recommended for the left side right-turn lane when there are more than two receiving lanes.
- If an auxiliary receiving/acceleration lane is provided for the curb right-turn lane at channelized dual turn lanes, its length should not be less than 150 ft.
- Design engineers should avoid installing dual right-turn lanes near access points (e.g., from gas stations, parking lots, or other traffic generators).
- For closely spaced intersections, if a downstream intersection uses dual right-turn lanes, the curb right-turn lane should not be aligned with any through lane at the upstream intersection.
- Turning radii should be not less than 25 ft. at dual right-turn lanes.
- The use of channelization should be carefully studied for dual right-turn lanes.

The design guidelines are summarized:

- Traffic signal-controlled intersection approaches with forecasted right-turn volumes approaching 300 vehicles per hour (vph) should receive consideration for use of a dual right-turn configuration.
- Dual right-turn lanes are particularly difficult for bicyclists and pedestrians and should be provided only if absolutely necessary.
- The minimum lengths for various dual right-turn lane geometrics should be determined based on the speed (in mph) as shown in the following table:

Table 2-3: The minimum lengths for dual right-turn lanes based on the speed

Speed (mph)	Deceleration Length (ft)	Taper Length (ft)	Storage Length (ft)
30	160	100	100
35	215	100	100
40	275	100	100
45	345	150	100
50	425	150	100
55	510	150	100

- Dual right-turn lanes require a larger intersection radius (usually 75 ft or more) and a throat width comparable to a dual left-turn configuration.

- Dual right-turn lane consideration should take into account an adjacent upstream intersection that is in close proximity.

2.4.2   Studies on single exclusive right turn lanes

1)   Operational Studies

Fitzpatrick and Schneider (2004)

This study focused on the following two aspects: (1) free-flow speed on single exclusive right-turn lanes and (2) the contributing factors that affect pedestrian's paths. The major conclusions of this report are summarized as Table 2-4.

The free-flow condition was defined as the right-turn vehicle having a minimum of five seconds headway and a minimum three seconds to separate with the following vehicle. The data was collected by pneumatic tubes and video camera. The authors investigated the impacts of the variables, including corner radius, channelization, right-turn lane length, and right-turn lane width on the turning speeds. Analysis of co-variance methods was used for developing models for the speed at the beginning of the turn and near the middle of the turn, respectively. The results showed that:

- Variables that affect the turning speed at an exclusive right-turn lane include: type of channelization present (either lane line or raised island), right-turn lane length, and corner radius.

- Variables that affect the turning speed at an exclusive right-turn with island design include: corner radius, right-turn lane length, and island size at the beginning of the turn and corner radius, right-turn lane length, and turning roadway width near the middle of the turn.

Pedestrian path (see Figure 2-10 adapted from AASHTO) can be affected by curb radius. That is, if the crosswalk is located inside the corner, pedestrian path increases as the curb radius increases; this could lead to longer crossing time for pedestrians and increase the clearance interval for the traffic signal timing subsequently.
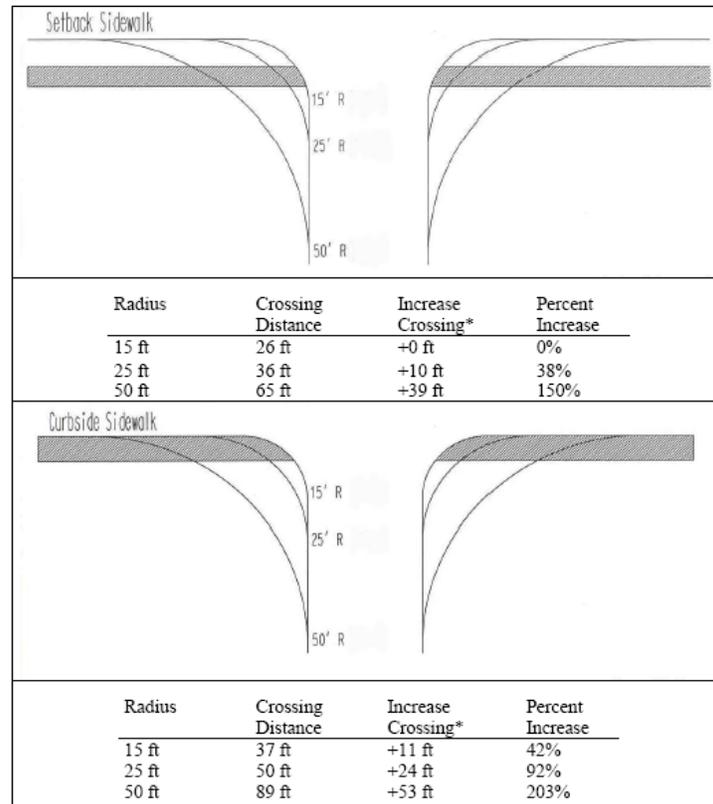
Figure 2-10: Pedestrian Path Can Be Affected by Curb Radius

Table 2-4: Summary of Operational Studies on Right-Turn Lanes

85th percentile free-flow speed		Significant contributing factors on free-flow speed		Impacts of geometric design on pedestrian's path
At the beginning point of right-turn lane	In the middle point of right-turn lane	At an exclusive right-turn lane without island design	At an exclusive right-turn lane with island design	
Range from 13.1 to 20.5 mph	Range from 17.4 to 28.5 mph	• Type of channelization present (lane line or raised island) • Right-turn lane length corner radius.	At the beginning of the turn • Right-turn lane length • Island size • Corner radius In the middle of the turn: • Corner radius, • Right-turn lane length • Turning roadway width	The increase of curb radius will result in the increase of the length of the pedestrian path

Kikuchi and Kronprasert (2008)

Focusing on the right-turn lane at a signalized intersection, the study examined the factors affecting the required right-turn lane length, derived the recommended length analytically, and

developed a set of tables of the recommended lane lengths as a function of approach volumes (right-turn, through-traffic, and cross-traffic volumes) and signal timing.

The authors concluded that the vehicle arrival rates, sequence of arrivals, signal timing, and with or without RTOR are the most relevant factors for determining lane length from the standpoint of vehicle storage. These factors were used as independent variables for determining the length of the right-turn lane. The recommended length of the right-turn lane is computed based on the premise: the probability that neither block between movements nor overflow will occur must be greater than a threshold value. Accordingly, the possible patterns of arrival at end of red phase were emulated, and the probabilities for each pattern were formulated. Based on the arrival vehicles probabilities, the recommended length of right-turn lane is shown in Table 2-5.

Table 2-5: Recommended Right-Turn Lane Lengths in Numbers of Vehicles Based on 95% Probability

Total Approach Volume (vphpl)	Green-to-Cycle Time Ratio (g/C) = 0.3									Green-to-Cycle Time Ratio (g/C) = 0.5								
	%Right Turn = 30%			%Right Turn = 50%			%Right Turn = 70%			%Right Turn = 30%			%Right Turn = 50%			%Right Turn = 70%		
	RTOR Cross Traffic		No RTOR	RTOR Cross Traffic		No RTOR	RTOR Cross Traffic		No RTOR	RTOR Cross Traffic		No RTOR	RTOR Cross Traffic		No RTOR	RTOR Cross Traffic		No RTOR
	400	800		400	800		400	800		400	800		400	800		400	800	
Cycle Length = 90 s																		
200	4	4	4	3	3	4	2	2	4	3	3	3	2	2	3	2	2	3
400	7	7	7	6	6	7	4	4	7	5	5	5	4	4	5	3	3	5
600	10	10	10	8	8	9	6	6	10	8	8	8	6	6	7	4	5	8
800	13	13	13	11	11	12	7	8	13	10	10	10	8	8	9	6	6	10
Cycle Length = 120 s																		
200	5	5	5	4	4	5	3	3	5	3	3	4	3	3	4	2	2	4
400	9	9	9	7	7	8	5	5	9	7	7	7	6	6	6	4	4	7
600	13	13	13	11	11	12	7	8	13	10	10	10	8	8	9	6	6	10
800	17	17	17	14	14	15	9	10	17	13	13	13	10	10	11	7	8	13
Cycle Length = 150 s																		
200	6	6	6	5	5	6	4	4	6	4	4	4	4	4	4	3	3	4
400	11	11	11	9	9	10	6	6	11	8	8	8	7	7	8	5	5	8
600	16	16	16	13	13	14	9	9	16	12	12	12	10	10	11	7	7	12
800	21	21	21	17	17	18	11	12	21	16	16	16	12	12	13	8	10	16

Potts et al. (2007)

The operational benefits of right-turn deceleration lanes on through-traffic movements at un-signalized intersections and driveways were evaluated. The purpose of this study was to assess the delay savings for through traffic due to installation of an exclusive right-turn lane. A micro simulation model (VISSIM) was used to measure the impact of decelerating right-turn vehicles on through traffic. The runs consisted of a range of through and right-turn volumes for two types of intersection approaches: (a) single-lane shared approach and (b) two-lane approach

with one through lane and one exclusive right-turn lane. To evaluate delay, each volume scenario was modeled without a right-turn lane and again with a right-turn lane. The difference between the average delays with and without a right-turn lane represents the operational benefit of having a right-turn lane.

According to the simulation results, typical delay reduction for through vehicles that right-turn lanes provide on two-lane arterials ranges from 0 to 6 s/veh; while 0 to 1s/veh on four-lane arterials. The effects of pedestrians were also studied in this paper, because pedestrian activity at un-signalized intersections and driveways can have a substantial impact on delay to through vehicles because of right-turning vehicles having to yield to pedestrians. The results demonstrated that the provision of a right-turn lane at such locations can provide substantial benefits in delay reduction. At pedestrian volumes of 50 ped/h, benefits in delay reduction for through vehicles range from 0.4 to 2.1 s/veh. At pedestrian volumes of 100 ped/h, benefits in delay reduction for through vehicles range from 0.6 to 3.1 s/veh. Benefits in delay reduction for through vehicles can be as high as 6 s/veh for pedestrian volumes of 200 ped/h.

Summary of Operational Studies

The reviewed operational studies have covered the many aspects including turning speed, required lane length, and delay reduction effects (for through vehicles) of installing single exclusive right-turn lanes.

2)   Safety Studies

Safety studies on exclusive right-turn lanes have focused on analyzing the frequency and location of the crashes occurred on right-turn lanes.

Dixon et al. (1999)

The study was conducted at seventeen signalized intersections located in Cobb County, Georgia, to evaluate the safety impact of different right-turn treatments. In this study, a total of 70 right-turn movements at different intersections were selected. The treatments of these right-turn movements can be grouped into five common types as follows:

- Shared right, no island, merge, no additional control
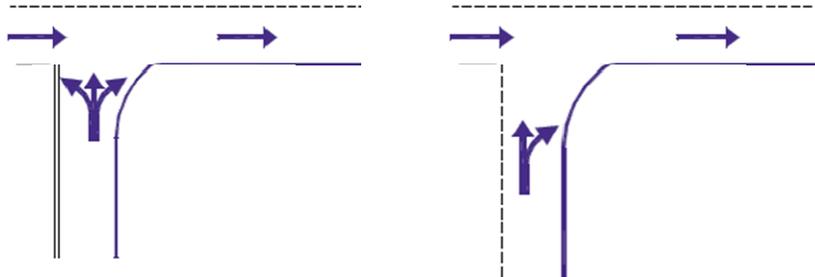
Figure 2-10: Shared Right-Turn Lane with No Island, Merge, and No Additional Control

- Exclusive right, no island, merge, no additional control
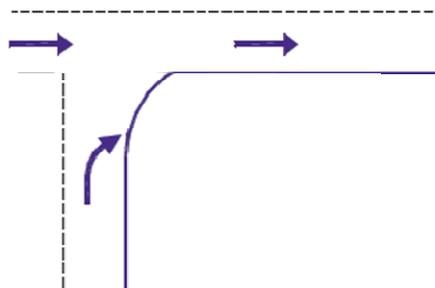
Figure 2-11: Exclusive Right-Turn Lane with No Island, Merge, and No Additional Control

- Exclusive right, raised island, added lane, no additional control
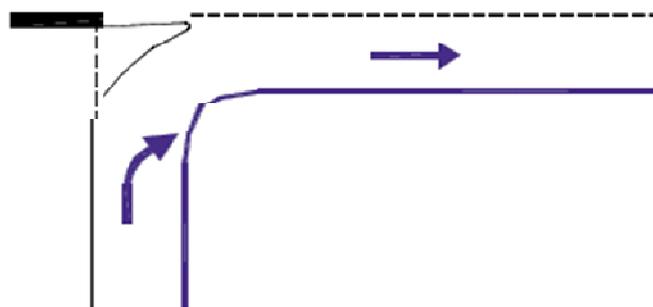
Figure 2-12: Exclusive Right-Turn Lane with Raised Island; Added Lane, and No Additional Control

- Exclusive right, raised island, merge, yield control
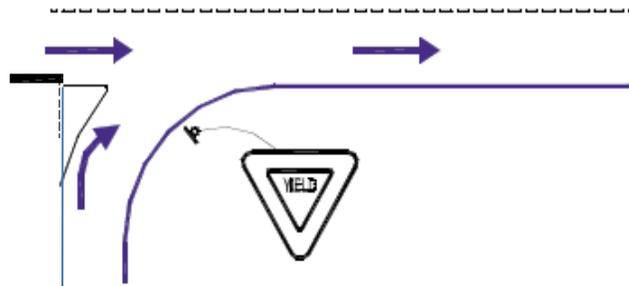
Figure 2-13: Exclusive Right-Turn Lane with Raised Island, Merge, and Yield Control

- Shared right, raised island, large turning radius, merge, yield control
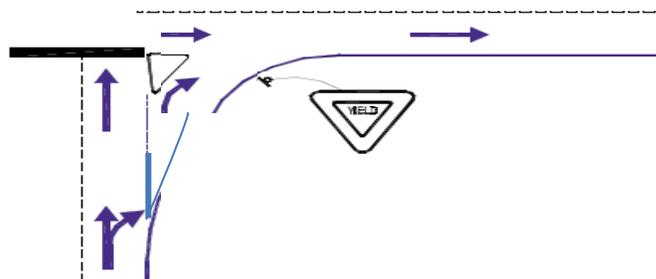
Figure 2-14: Shared Right-Turn Lane with Raised Island, Large Turning Radius, Merge, and Yield Control

For each of these types, the frequency of crashes over a two-year period is calculated directly without considering the impacts of traffic exposure (the traffic volume). By comparing the frequency of different types of crashes, this paper concluded that:

- The use of a traffic island appears to reduce the number of right-turn angle crashes.
- The addition of an exclusive right-turn lane appears to correspond to elevated sideswipe accidents.
- When no additional control is implemented, the addition of an exclusive right-turn lane on the cross street for right-turn vehicles does not appear to reduce the number of rear-end crashes.

This paper also presented some interesting findings extracted from other related research:

- The addition of an exclusive right-turn lane appears to increase the average number of right-turn involved crashes per site per year. Note that, this result may result from the fact that the intersections with exclusive right-turn lane have relative higher turning volume, which increases the risk of sideswipe accidents.
- The use of a traffic island appears to increase the average number of right-turn crashes per site, per year.

Fitzpatrick and Schneider (2004)

Crash frequency and safety effects of right-turn treatments were studied to evaluate the right-turn lane crashes based on the crash data collected at five intersections in Irving. TX and four in College Station, Texas.

The authors grouped the crashes into six categories, including rear-end type I (in through or left-turn lane), rear-end type II (in right-turn lane), angle type I (in straight lane), angle type II (in left-turn lane), sideswipe, and others. Analysis was focused on the percentage of different types of crashes involved a right-turn vehicle. These results showed that only a small proportion (16 out of 211) of the crashes involved right-turn vehicles.

The authors identified the locations of right-turn lane crashes with respect to the types of right-turn treatments; they are commonly located at right-turn lane with lane line, right-turn lane with island, shared through/right lane, and shared through/right lane with island (see Figure 2-11).
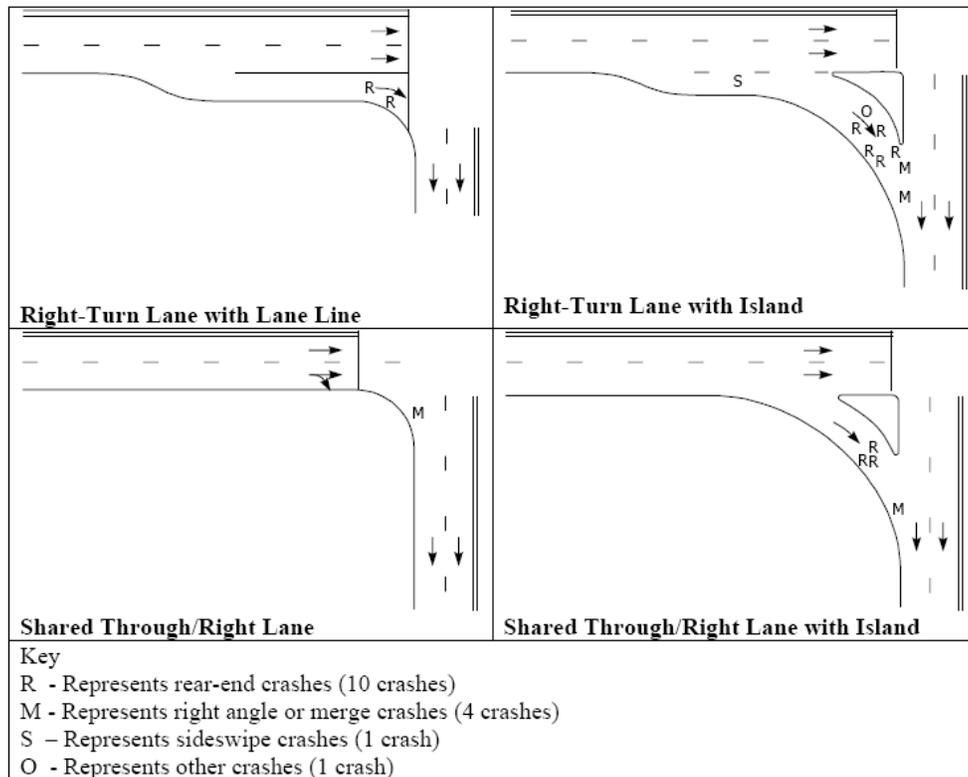
Figure 2-11: Summary of Crash Hotspots with Various Right-Turn Treatments

The results showed that:

- Sites with islands have higher number of crashes than sites without islands. This result is consistent with the findings in Dixon et.al (1999), i.e. the use of a traffic island appears to increase the average number of right-turn crashes per site, per year.
- The shared through/right-turn lane had the lowest number of crashes. This result is consistent with the findings in Dixon et.al (1999), i.e. the addition of an exclusive right-turn lane appears to correspond to elevated average number of right-turn crashes per site, per year.

Harwood et al. (2003)

A before-after evaluation was performed to investigate the safety effects of providing right-turn lanes for at-grade intersections. Three contrasting approaches to before-after evaluations were used; they were the yoked-comparison (matched-pair approach), the comparison group approach, and the empirical Bayes approach.

It was concluded that right-turn lanes are effective in improving safety at signalized and un-signalized intersections in both rural and urban areas. Table 2-6 presents comparable effectiveness estimates for right-turn lanes that are applicable to both rural and urban intersections.

Table 2-6: Expected Percent Accident Reduction in Total Accidents from Installation of Right-Turn Lanes on Major Road Approaches to Rural and Urban Intersections

Intersection traffic control	Number of major-road approaches on which right-turn lanes are installed	
	One approach	Both approaches
STOP sign[a]	14[b]	26[b]
Traffic signal	4[c]	8[c]

a: STOP signs on minor-road approach(es).
b: Based on EB evaluation for rural intersections
c: Based on EB evaluation for urban intersections

Summary of Safety Studies

In general, the existing safety research findings of right-turn lanes are mixed, since various right-turn treatments may significantly affect the safety experience.

- Positive comments on exclusive right-turn lanes

Right-turn lanes are effective in improving safety at signalized and un-signalized intersections in both rural and urban areas. The accident reduction effect for un-signalized intersections is more significant than for signalized intersections (Harwood et al., 2003).

- Negative comments on exclusive right-turn lanes

The addition of an exclusive right-turn lane appears to increase the average number of right-turn crashes per site, per year (Dixon et al., 1999). Note that this conclusion may be limited in scope and applicability since the analysis did not consider the impacts of traffic exposure. The intersections with exclusive right-turn lanes have relatively higher turning volume.

The use of a traffic island appears to increase the average number of right-turn crashes

(Fitzpatrick and Schneider, 2004).

The addition of an exclusive right-turn lane appears to increase the number of sideswipe accidents, and when no additional traffic control is implemented, it does not appear to reduce the number of rear-end crashes either (Dixon et al., 1999).

References

Connecticut Department of Transportation. Highway Design Manual, 2003.

Cooner A. S. et al., Development of Guidelines for Triple Left and Dual Right-Turn Lanes: Technical Report. Publication FHWA/TX-11/0-6112-1. FHWA, U.S. Department of transportation, 2011.

Douglas W. Harwood, Karin M. Bauer, Ingrid B. Potts, Darren J. Torbic, Karen R. Richard, Emilia R. Kohlman, Rabbani, Ezra Hauer, Lily Elefteriadou, and Michael S. Griffith. Safety Effectiveness of Intersection Left- and Right-Turn Lanes. Transportation Research Record, No. 1840, Washington, D.C., pp. 131–139, 2003.

Fitzpatrick, F., W. H. Schneider, and E. S. Park. Operation and Safety of Right-Turn Lane Designs, Transportation Research Board, Washington, D.C., 2006

Fitzpatrick, F., W. H. Schneider. Turn Speeds and Crashes within Right-Turn Lanes. Publication Technical Report FHWA/TX-05/0-4365-4: September 2001-August 2004, Texas Transportation Institute, the Texas A&M University System

Illinois Department of Transportation. Bureau of Design and Environment Manual, 2001.

Indiana Department of Transportation. Indiana Design Manual, Part 5, "Road Design" Chapter 46: Intersections At-Grade. Available at www.in.gov/dot/div/contracts/standards/dm/Part5/Ch46/DCh46.pdf

Ingrid B. Potts, John F. Ringert, Douglas W. Harwood, Karin M. Bauer. Operational and Safety Effects of Right-Turn Deceleration Lanes on Urban and Suburban Arterials. Transportation Research Record, No. 2023, Washington, D.C., 2007, pp. 52–62.

MaineDOT Highway Design Guide. Maine Department of Transportation, 2007.

Maintenance Guidelines for Consideration: Arizona Statewide Bicycle and Pedestrian Plan, 2003. Available at http://www.azbikeped.org/appendix%20c/08_DG.pdf

New York Department of Transportation. Highway Design Manual, Chapter 5 - Basic Design, Revision 59, 2010.

Ohio Department of Transportation. Highway Design Manual, 2003.

Ohio Department of Transportation. Highway Design Manual, Chapter 9, 2003. Available at
    ftp://ftp.odot.state.or.us/techserv/roadway/web_drawings/HDM/Rev_E_2003Chp09.pdf

Rodegerdts, L. A., B. Nevers, B. Robinson, J. Ringert, P. Koonce, J. Bansen, T. Nguyen, J.
    McGill, D. Stewart, J. Suggett, T. Neuman, N. Antonucci, K. Hardy, and K. Courage.
    Signalized Intersections: Informational Guide. Publication FHWA-HRT-04-091. Federal
    Highway Administration, U.S. Department of Transportation, 2004.

Shinya Kikuchi. Nopadon Kronprasert. Determining the Length of the Right-Turn Lane at a
    Signalized Intersection. Transportation Research Record, No. 2060, Washington, D.C.,
    2008, pp. 19–28.

Special Report 209: Highway Capacity Manual. TRB, National Research Council, Washington,
    D.C., 2000.

Tennessee Department of Transportation, Design Division. Roadway Design Guidelines, 2008.

Texas Department of Transportation. Highway Design Manual, 2010.

Virginia Department of Transportation. Access Management Regulations and Design Standards
    for Entrance/Intersection Access Management, 2007. Available at
    http://www.virginiadot.org/projects/accessmgt/ResponseAccessMgtPublicComments11.
    0.07.pdf

To collect more information regarding the use of dual right-turn lane in current practice, the research team conducted a nationwide, web-based survey of traffic engineers in March 2011. The survey was sent to traffic engineers through the ITE Traffic Engineering Council. A total of seven questions were included in this survey, and 44 responses were received. The questions and corresponding answers are presented and summarized below:

3.1   Survey Questions and Results

Question 1: Have you used the types of dual right turn lanes shown in the illustration?

Comment on the reason(s) you used these types of dual right-turn lanes.

The Curb Right-Turn Lane

The Second Right-Turn Lane

(A) Exclusive curb right-turn lane + Optional second right-turn lane

(B) Exclusive curb right-turn lane + Exclusive second right-turn lane
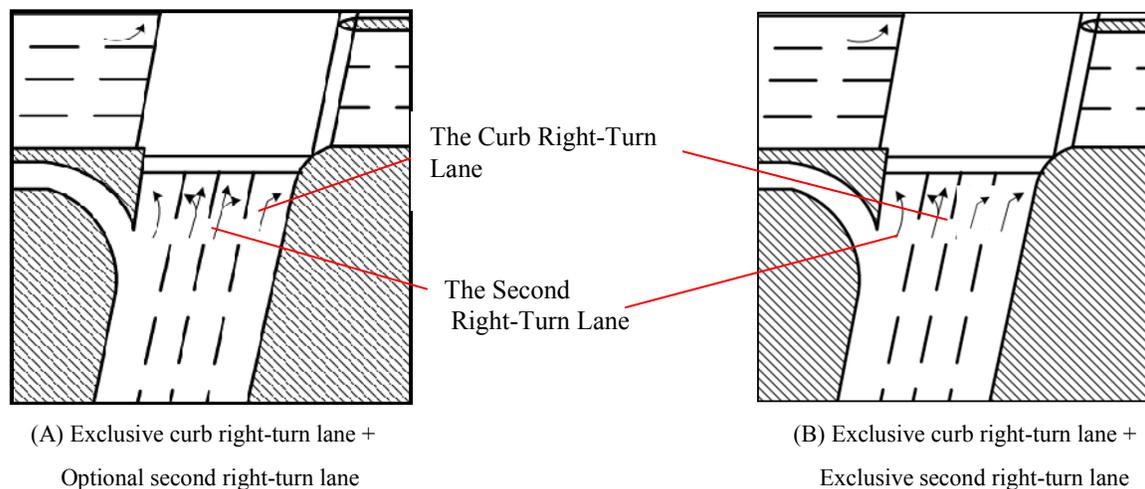
Figure 3-1 shows that 33 out of the 44 engineers indicated that they have used Type A, and 39 engineers have used Type B. From the results, Type B is more widely used than Type A in practice.
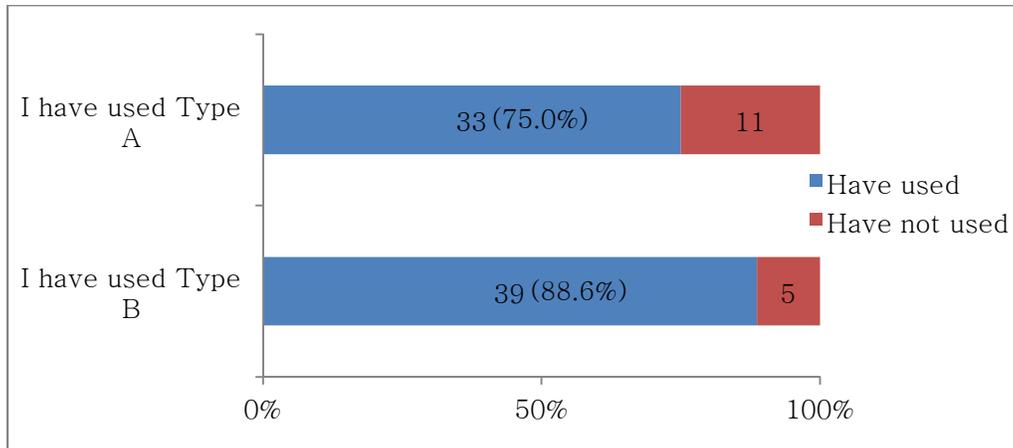
Figure 3-1: Percentage of Respondents That Have Used Dual Right-Turn Lanes

The second part of Question 1 focuses on the reasons for the use of dual right-turn lanes. A total of 42 respondents answered this question. According to their responses, dual right-turn lanes are generally used on intersections that have high right-turn volumes, so as to provide additional capacity and reduce delays for all users of the intersection. Dual right-turn lanes can be considered as an alternative especially when free-flow right turn lanes are not advisable. Note that free-flow right turn lanes may provide higher capacity than dual signalized right turns according to one traffic engineer's experience. Sometimes, safety concerns are also the reasons why dual right-turn lanes are used, e.g. the second right-turn lane may prevent right-turning vehicles that exit through a nearby upstream freeway off-ramp from abruptly changing too many lanes toward the curbside lane, or mitigate the difficulty for the right-turning vehicles to turn left on the downstream roads (see Figures 3-2 and 3-3 for examples).
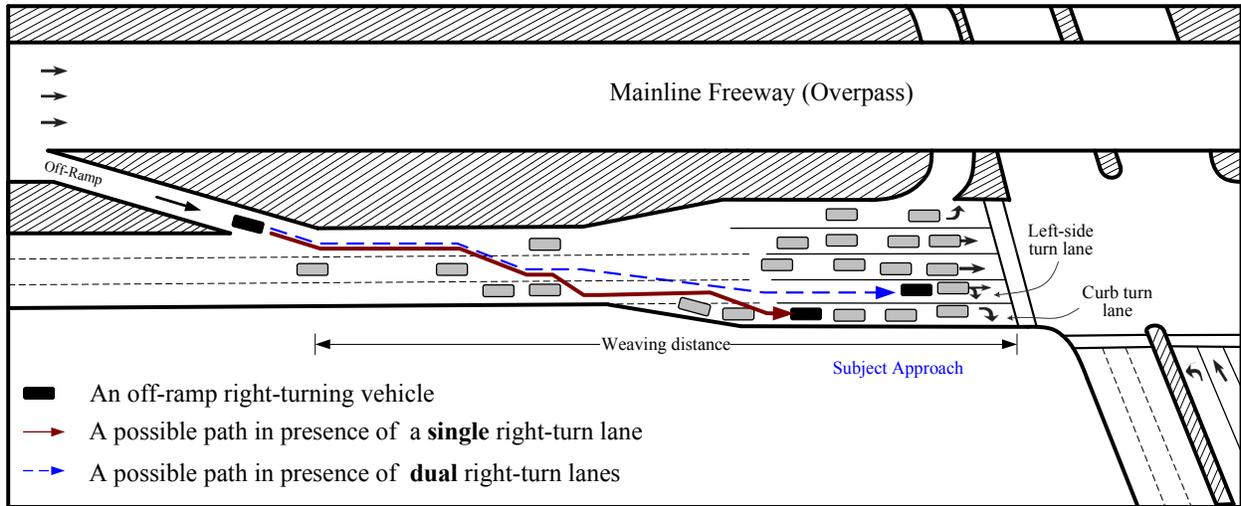
Figure 12-2: Illustration of How Dual Right-Turn Lanes Mitigate Upstream Lane Change Conflicts
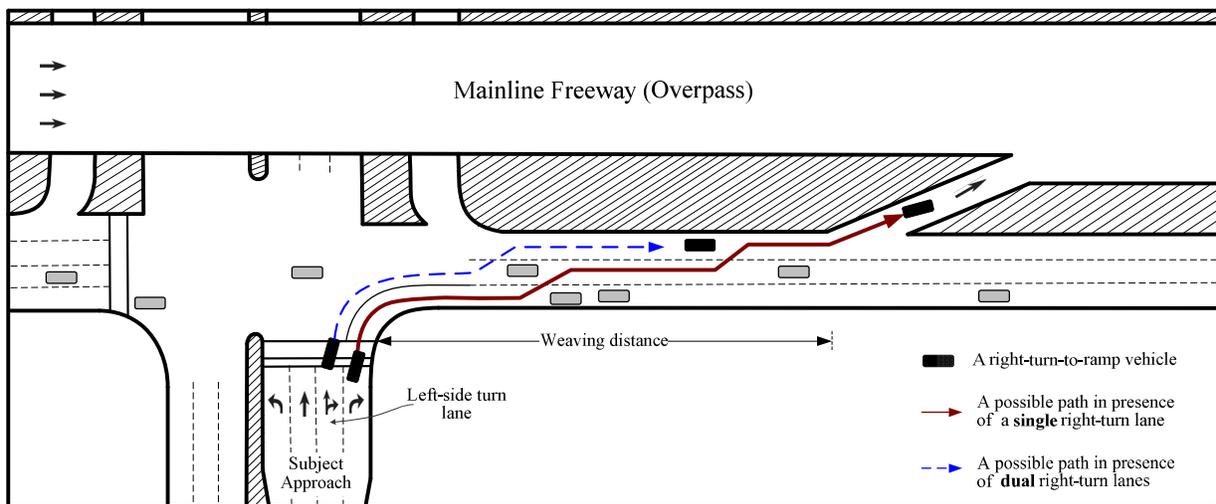
Figure 3-3: Illustration of How Dual Right-Turn Lanes Mitigate Downstream Lane Change Conflicts

According to the results, the types of dual right-turn lanes are generally chosen based on the traffic volume and peak hour volume. The geometric conditions of the receiving lanes downstream also influence the selected option. Type B is more widely used than Type A in practice. Some engineers indicate that most of time they don't use shared lanes if it can be avoided. According to one engineer, Type B can typically be used at a diamond interchange. Some comments on selection between these two types of design are summarized as follows:

Type A is used for the following reasons:

- To consider the restricted right-of-way, but not to reduce the through capacity dramatically as required by certain times of day.

- It is more economical to implement the striping changes than to construct a new lane.

Type A is not preferred for the following reasons:

- Type A has adverse impacts on bicyclists and pedestrians.

- Type A precludes using the right turn overlap phase.

- Type A does not accommodate a through bicycle lane. (It is difficult to insert a bicycle lane)

- A shared through/right-turn lane has lower lane utilization than an exclusive right-turn lane since a single through vehicle may block right turns on red; the lower lane utilization may result in the need for longer storage in the curb right-turn lane.

- Drivers may not realize that the curb lane is an exclusive lane and may attempt to go straight, causing a large number of side-swipe collisions.

Type B is used for the following reasons:

- Type B can accommodate higher right-turn volume as opposed to Type A.

- Type B can be used when right-of-way is available to add the second exclusive right-turn lane.

- Type B has the ability to overlap the movement, which will lead to more efficient signal operations.

- Type B is more flexible for changes in signal operations.

- Type B allows for bicycle lanes between the through and right-turn lanes (see Figure 3-4).
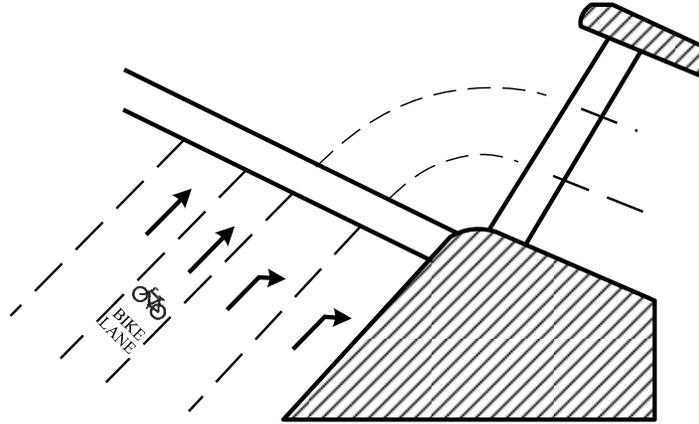
Figure 3-4: Illustration of Bike Lane at Exclusive Dual Right-Turn Intersection

Question 2: If you have not used the dual right-turn lanes shown in the illustration above, would you use any in the future?

A total of 20 people answered this question. Fifteen (75%) of the engineers expressed that they would use Type A, while 20 of (100%) the engineers preferred to use Type B in the future. Generally, Type B is more preferable than Type A from a design standpoint.

Question 3: Typically, where are dual right-turn lanes installed? (Please give the approximate percentage according to your estimation.)

☐ **Freeway Frontage/Service Roads (Approximate % _____)**

☐ **Arterial (Approximate % _____)**

☐ **Collector (Approximate %_____)**

☐ **Local Street (Approximate %_____)**

A total of 42 out of the 44 participating engineers answered this question. As shown in Figure 3-5, averagely, 47.37 percent of dual right-turn lanes are installed on freeway frontage or service roads; 43.2 percent are installed on arterials; 7.66 percent are installed on collectors; and dual right-turn lanes are seldom installed on local streets.
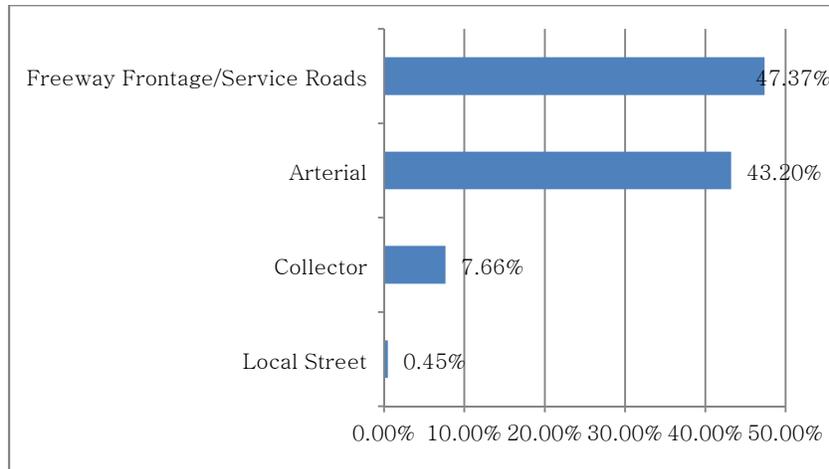
Figure 3-5: Location Distribution for Dual Right-Turn Lanes in Practice

Question 4: To your knowledge, how are the decisions made to install dual right-turn lanes? (Please give specified criteria for each item that applies.)

☐ **Based on engineering judgment**

☐ **Based on right-turn volume**

☐ **Limited right-turn capacity as a result of traffic conditions and signal timing**

☐ **Due to safety concerns, e.g. to prevent right-turn vehicles that exit from a nearby upstream freeway off-ramp from abruptly changing too many lanes toward the curb right-turn lane at the intersection.**

☐ **Others**

☐ **I don't know related practices**

A total of 43 out of 44 participating engineers answered this question. From their answers, we got to know that there are no established criteria for engineers to follow when dual right-turn lanes are installed. However, the engineers provided us some general guidelines in practice. A total of 79percent of engineers thought that dual right-turn lanes should be provided where the right-turn demand volume is high. Fifty eight percent of engineers installed dual right-turn lanes based on their own judgment. Fifty-eight percent of engineers believed that dual right-

turn lanes are installed because of the limited right-turn capacity. Figure 3-6 shows the results of this question.
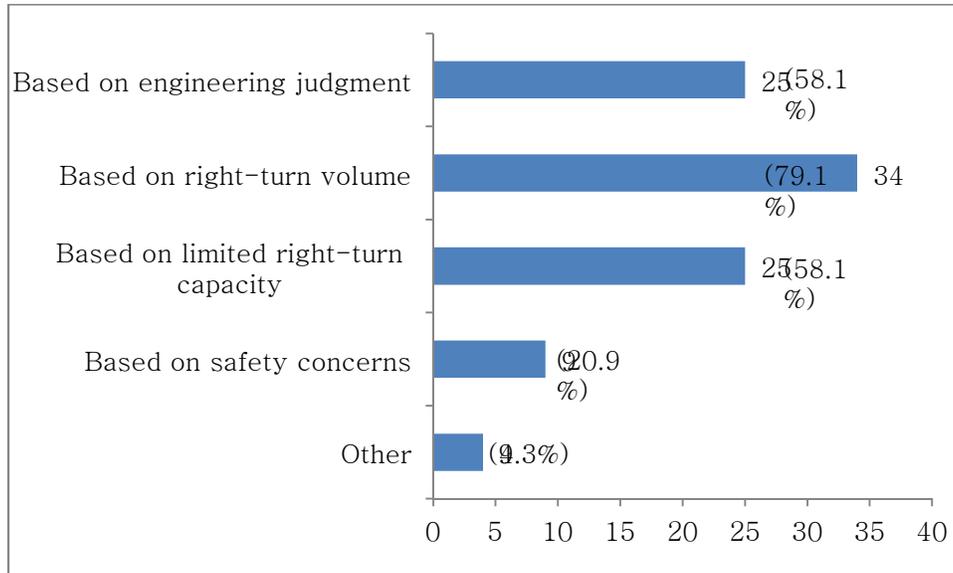
Figure 3-7: Criteria for When to Use Dual Right-Turn Lanes in Practice

According to the participating engineers, right-turn volume, right-of-way, intersection capacity, LOS, safety, and delay are defined as the parameters for the consideration of installing a dual right-turn lane. The detailed comments are summarized as follows:

- High peak-hour right-turn volume is the primary reason for installing dual right-turn lanes:

  o There are some suggested volume thresholds for warranting dual right-turn lanes, include 300 vph (1 response), 400 vph (2 responses), 500 vph (4 responses), 600 vph (2 responses), and 800 vph (2 responses).

  o If right-turn green time and green time from an overlap are not sufficient to handle the right-turn volume, consideration can be given to signalized dual right-turn lanes.

  o If converting the right-turn lane to a free-flow right-turn lane, channelized island, with or without acceleration lane is insufficient to handle the right turn volume, consider signalized dual right-turn lanes.

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- Dual right-turn lanes are installed based on following operational purposes:

  o Minimizing average intersection delay (focus on whether or not the vehicles are served each signal cycle).

  o Clearing queues (to avoid the queue extend beyond available storage, past adjacent intersections, or onto the freeway).

  o Allowing drivers to turn into the desired path (where the driver is traveling and if the second lane can facilitates that travel path).

- Dual right-turn lanes may be installed at the intersections where right-turn capacity is limited because of traffic conditions and signal timing.

- Level-of-service analysis is also needed for installing dual right-turn lanes. Dual right-turn lanes are warranted when the LOS of peak hours is lower than a certain lever, level D or E as responded.

- There is a safety benefit if there is an upstream intersection that would be detrimentally impacted by traffic queuing in only one right-turn lane (e.g. an upstream railroad crossing or busy intersection).

Question 5: In your opinion, should Right-Turns-on-Red (RTOR) be allowed for dual right-turn approach?

☐ **For both right-turn lanes**

☐ **For curb right-turn lane only**

☐ **For the second right-turn lane only**

☐ **Not allowed for either right-turn lane**

☐ **Others (for example, timing-varying or case specific)**

A total of 41 out of the 44 respondents answered this question. Figure 3-7 shows that almost half of the engineers (46.3%) stated that RTOR should be allowed for both lanes. On the other hand, 24.4% respondents recommended RTOR be prohibited for both right-turn lanes, and 36.6% respondents suggested RTOR be allowed for the curb right-turn lane only. However, the option "RTOR allowed for the second right-turn lane" is generally not acceptable for any the respondents.
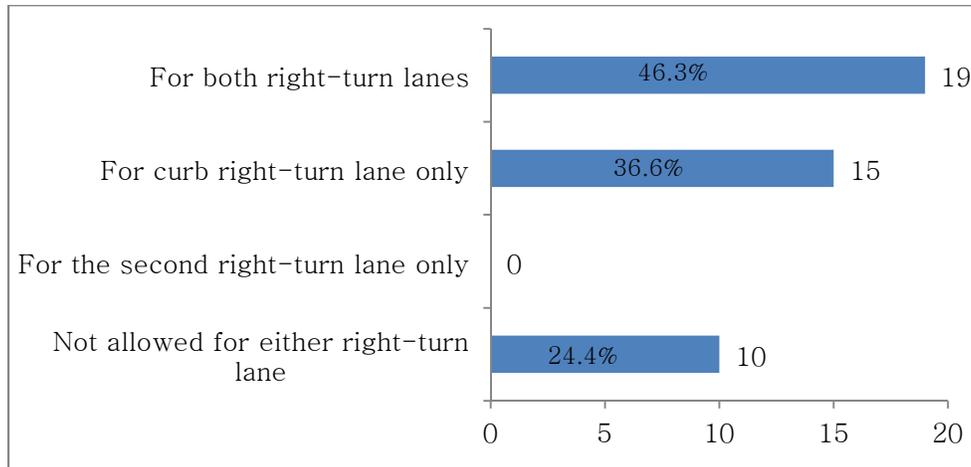
Figure 3-8: Lane-Specific Preferences on RTORs

Generally, the decision on whether and how RTOR should be implemented is dependent upon several factors, e.g. sight distance, approach speed, conflicting pedestrian movements, and conflicting cross-street through and U-turn movements. From the survey results, most respondents have no issues with allowing RTOR for both right-turn lanes or for curb right-turn lane only. As an engineer stated, motorists do not like being restricted from making a RTOR but if an overlap is used, their waiting time is usually very tolerable. For intersections with presence of pedestrians, variable message signs can be used to restrict the RTOR during pedestrian phases and to allow RTOR when no pedestrians are present. The survey results also indicated that curb-lane-only RTOR is of acceptance by the public, and if it is allowed, the curb lane is better to be pulled out beyond the second turn lane so vehicles on the curb lane have a clear unobstructed view of the approaching traffic. A sign with a legend, "RTOR FROM RIGHT LANE ONLY" should be used. However, RTOR should be restricted for the Type A dual right turns, so that both right-turn lanes can move together rather than encourage frequent lane changes pending the lane that is moving. RTOR is not recommended for the following circumstances:

- Where sight distance is not good.

- Where there is a crash history against the use of RTOR.

- When there is frequent presence of pedestrians.

- When the opposing left-turn movement is allocated a protected indication.

- When there is a significant number of U-turns during the protected left-turn phase from the right-hand cross street.

- When vehicles turn right onto a high-speed road.

- When the receiving lanes receive a large number of traffic from the left-hand cross-street movement.

Question 6: When should a protected right-turn phasing (or right-turn overlap) be used for dual right-turn approach?

Dual right-turn lanes with protected phasing can function more safely and add significant capacity. It is suggested by traffic engineers that dual right-turn lanes be operated as an overlap, with the traffic signal operating as a minus pedestrian overlap (if the adjacent pedestrian is in WALK or Flashing DON'T WALK, the vehicle display is a red arrow). It should be noted that a dedicated load switch in the controller is needed for setting up the overlap, instead of simply wiring with the left-turn phase, so that the conflict monitor can watch out the lens.

According to the results, protected right-turn phasing or right-turn overlap can be used under the following conditions:

- Only when both right-turn lanes are exclusive turn lanes.

- When there is a parallel (overlap) left-turn phase. Overlaps should always be used if there is a cross-street protected left-turn phase, unless that left-turn also has a significant U-turn movement that cannot be prohibited.

- When additional capacity is needed.

- When there are heavy right-turn volumes.

- When geometry allows it. To avoid the waste of green time, the protected movement should not be considered where the turn geometry is so tight that traffic turns slowly.

The use of right-turn overlap may be limited:

- When there are pedestrian movements with adjacent through movements, or pedestrians are accommodated by a dedicated pedestrian phase.

- When there is potential for conflicting turning paths, such as opposing left-turn movements due to an inadequate number of receiving lanes.

- When the U-turn volumes from the right-hand cross street is not significant.

Question 7: Your general comments on the use of dual right-turn lanes and major design issues such as overlap/separate right-turn phasing.

General comments:

a. Positive

- Dual right-turn lanes can be very effective in shortening the green time required for an approach, thus increasing the capacity of a congested intersection.

- Dual right-turn lanes can be geometrically difficult, but have the advantage for a high volume of traffic.

- Dual right-turn lanes can aid capacity under appropriate circumstances.

- Dual right-turn lanes should work well with right-turn overlaps. Dual right turns with protected red arrows (no RTOR) are effective with overlap phasing. The overlap often allows the protected right phasing which then is a safer design by minimizing pedestrian and auto conflicts.

b. Negative:

- Dual right-turn lanes should be kept to a minimum use due to longer crossing distances and multiple threat situations when they are permissive.

- Dual right-turn lanes may create safety and operation problems; while some of these problems can be handled with a free-flow right-turn lane.

Design Issues:

a. Problems with dual right-turn lanes

- Dual right-turn lanes make crosswalks longer, which can affect minimum cycle time, increase pedestrian exposure, and precipitate long pedestrian clearance intervals that may or may not work with coordination timing plans.

- Dual right-turn movements across a concurrent pedestrian movement may be unsafe because sight lines for vehicles in the second turn lane can be blocked by a vehicle in the curb lane who is yielding to a pedestrian

- Bicycles have a more difficult time traversing both right turn lanes on a green signal.

- Truck traffic utilization is an issue when designing dual right-turn lanes. Similar to a roundabout, if designed too wide to accommodate truck traffic, then traffic may create a "third turn lane", especially during snowy conditions.

b. *Suggestions to operation and design of dual right-turn lanes*

- Capacity analyses should be performed to determine if right turn overlap will be the best solution, but only in case of exclusive dual right turn lanes.

- Upstream lane signing is important for good lane utilization.

- Variable message signs should be used to restrict the RTOR during pedestrian phases and to allow them when no pedestrians are present.

- The turn radius needs to be sufficient to allow a smooth turn from both turn lanes. Also, consider narrowing median near intersection, with a transition taper to allow the second lane to have an easier turn.

- A good design will likely require some type of modification of the typical signal display location as you will want drivers to be able to see the signal status at all times.

3.2 Major Findings

The findings obtained in the nationwide survey of traffic engineers are summarized as follows:

- Dual right-turn lanes are primarily used for two reasons: 1) to accommodate high right-turn volumes and provide enhanced capacity at intersections, and 2) to mitigate weaving traffic conflicts at frontage road intersections in proximity to freeway ramps.

- Exclusive dual right-turn lanes are generally more preferable than shared dual right-turn lanes for traffic engineers.

- Dual right-turn lanes are mostly installed on freeway frontage or service roads, followed by arterials, are seldom used on collectors; no one reported the use of dual right-turn lanes on local streets.

- In current practice, dual right-turn lanes are installed based on engineering judgment, right-turn volume, and the need for capacity enhancement. However, there are no established criteria for traffic engineers to follow when they consider dual right-turn lanes.

- Nearly half of the participating engineers thought that RTOR should be allowed for both right-turn lanes, except when the location has some problems to preclude it, for example, poor sight distance, frequent presence of pedestrians, presence of crash history that supports no RTOR, etc.

- Protected right-turn phasing (or right-turn overlap) should be used: (a) when there is a heavy right-turn volume; (b) for two exclusive right-turn lanes only; (c) when there is parallel left-turn phase; (d) when there is a heavy opposing left movement; (e) where the sight distance is not good; (f) where vehicles turn right onto a high-speed road.

CHAPTER 4: DATA COLLECTION

Field data was collected to provide real-world data for developing, calibrating, and validating the models in this study. Videos of field traffic were recorded at five intersections with dual right-turn lanes located in Houston, Texas. The detailed characteristics of the study locations are summarized in Table 4-1. The observation periods spanned from 6:00 A.M. to 9:00 A.M. and from 4:00 P.M. to 7:00 P.M. for each of the locations. The data collected included traffic volume, traffic composition, and signal timing at the intersections, as well as lane utilization, critical gaps for RTOR vehicles, saturation flow rates, and delays in the dual right-turn lanes.

In Chapter 5, data from the five studied locations were used for calibrating and validating the analytical model proposed in this study for predicting capacity of dual right-turn lanes.

In Chapter 6, field observation of the first three locations (frontage road intersections in proximity to freeway ramps) was used in developing and calibrating micro-simulation models, which is part of the process of simulation-based surrogate safety assessment.

According to the field study, lane utilization of the exclusive dual right-turn lanes is significantly different from that of shared dual right-turn lanes. A total of 285 minutes of lane-specific traffic counts (57 samples in 5-minute intervals) were observed for the exclusive dual right-turn lanes on US 59 at Highway 6 NB. As traffic volumes approached the capacity of the dual turn-lane group, uniform lane utilization developed (nearly 50% of right-turning vehicles distributed on each right-turn lane), as shown in Figure 4-1(a). A total of 620 minutes of traffic counts (124 samples in 5-minute intervals) were collected from the shared dual right-turn lanes on Kirby Drive at I-610 WB and on Shepherd Drive at I-10 WB. It was observed that the proportion of right-turning drivers who used a shared left-side turn lane was around 10percent regardless of saturation degrees of the lane groups, as shown in Figure 4-1(b). The unbalanced lane utilization may result from right-turning drivers being concerned about the possibility of being blocked by through vehicles that utilize the shared through/right-turn lane during RTOR periods.
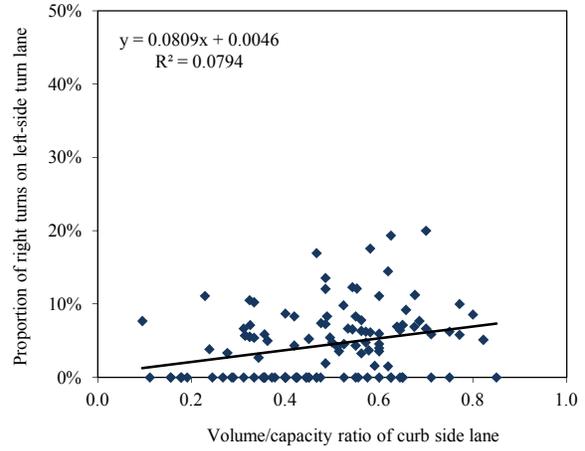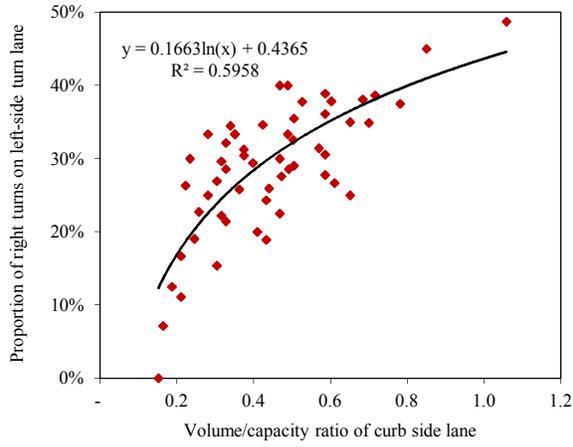
(a) Utilization ratio of an exclusive left-side right-turn lane   (b) Utilization ratio of a shared left-side right-turn lane

Figure 4-1: Lane Utilization Ratios as a Function of Volume/Capacity Ratio

Table 7: Characteristics of the Dual Right-Turn Lanes Studied

Intersection	Road type	Lane allocation	Speed limit, mph (kmph)	Curb pocket lane length, ft (m)	Presence of island	Corner angle	RT volume, vph	% of heavy vehicles	Approach lane width, ft (m)	Distance to upstream ramp junction
US 59 & Highway 6	Frontage Road	↱↱	50 (80.5)	340 (104 m)	No	110°	752	3.70%	12 (3.6 m)	3,314 ft (1,010 m)
Kirby Drive & I-610_WB	Frontage Road	↱↱	45 (72.4)	330 (101 m)	Yes	90°	676	4.48%	11 (3.4 m)	1,837 ft (560 m)
Shepherd Drive & I-10 WBFR_WB	Frontage Road	↱↱	45 (72.4)	300 (91 m)	No	90°	327	4.48%	12 (3.6 m)	1,624 ft (495 m)
West Bay Area Blvd. & I-45 FR_NB	Interchange Ramp	↱↱	50 (80.5)	800 (245 m)	Yes	70°	700	2.57%	12 (3.6 m)	N/A
Saturn Lake & NASA Parkway	Arterial Road	↱↱	45 (72.4)	N/A	No	90°	415	1.04%	12 (3.6 m)	N/A

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CHAPTER 5: CAPACITY OF DUAL RIGHT-TURN LANES

According to the survey of traffic engineers, a primary reason for the use of dual right-turn lanes is to accommodate high right-turn traffic demand and the installation of dual right-turn lanes typically needs to be justified by a before-and-after evaluation before the decision is made. As a key performance measure of dual right-turn lanes, an accurate estimation of capacity can enable analysts to evaluate whether dual right-turn lanes provide the desired capacity enhancements for the subject right-turn movement. Additionally, the estimates of capacity will allow analysts to estimate delays and level-of-service (LOS) after dual right-turn lanes are installed.

This chapter aims to develop a method for estimating the capacity of dual right-turn lanes. The capacity can be divided into capacities for right turns on green (RTOG) and for right-turns-on-red (RTOR). The results will be validated by the field data collected at five studied intersections with dual right-turn lanes.

5. 1 Capacity of Right Turn on Green

5.1.1 Determining Saturation Flow Rate

The calculation for RTOG capacity for dual right-turn lanes is generally based on the method provided in the HCM, 2000. First, saturation flow rates are calculated and then they are multiplied with the corresponding signal split.

Saturation flow rate defines equivalent hourly rate at which queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all times. Saturation flow rate for each lane group can be computed according to Equation 5-1.

$$s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \tag{5-1}$$

s = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (veh/h);

s_0 = base saturation flow rate per lane (pc/h/ln);

N = number of lanes in lane group;

f_w = adjustment factor for lane width;

f_{HV} = adjustment factor for heavy vehicles in traffic stream;

f_g = adjustment factor for approach grade;

f_p = adjustment factor for existence of a parking lane and parking activity adjacent to lane group;

f_{bb} = adjustment factor for blocking effect of local buses that stop within intersection area;

f_a = adjustment factor for area type;

f_{LU} = adjustment factor for lane utilization;

f_{LT} = adjustment factor for left turns in lane group;

f_{RT} = adjustment factor for right turns in lane group;

f_{Lpb} = pedestrian adjustment factor for left-turn movements; and

f_{Rpb} = pedestrian-bicycle adjustment factor for right-turn movements.

The HCM provides 11 adjustment factors covering a wide variety of possible conditions. Each adjustment factor involves a separate model. The adjustment factors are calculated later by using the field data one by one.

5.1.2   Determining RTOG Capacity

Capacity at signalized intersections is based on the concept of saturation flow and defined saturation flow rate. The flow ratio for a given lane group is defined as the ratio of the actual or projected demand flow rate for the lane group (vi) and the saturation flow rate (si). The flow ratio is given the symbol (v/s)i for lane group i. The capacity of a given lane group may be stated as shown in Equation 5-2:

$$c_i = s_i \frac{g_i}{C} \tag{5-2}$$

c_i = capacity of lane group i (vph),

s_i = saturation flow rate for lane group i (veh/h), and Green ratio defined

g_i/C = effective green ratio for lane group i.

5.1.3   Validation of HCM Method

It is intuitively expected that the friction between the two right-turn lanes may make the traffic flow mechanism more complex than single right-turn lanes. To verify whether the HCM method is applicable for estimating saturation flow rates of dual right-turn lanes, field data was used for comparing with the results of HCM calculations.

In the field, saturation flow rate is typically achieved after 10 to 14 s of green, or from the front axle of the fourth to sixth passenger car crossing the stop line after the beginning of green. Prevailing saturation flow rates were directly measured through the field traffic videos. Table 5-2 shows a comparison of dual right-turn saturation flow rates between field measurements and HCM estimates. The HCM calculation incorporates adjustments for lane width, heavy vehicles, grade, lane utilization, and proportion of right turns in the lane groups, as listed in Table 4-1 in Chapter 4. To allow a comparison of lane group saturation flow rates, lane utilization adjustment factors have also been applied to the field measurements. In general, HCM method yields very reasonable estimates which are consistent with the field measurements.

Table 8: Observed Saturation Flow Rates vs. HCM Based Estimates

Intersections	Lane group total (vph)			Rightmost lane (vph)		
	Observed	HCM	Errors	Observed	HCM	Errors
Exclusive dual right-turn lanes						
US 59 @ Highway 6	2254	2293	1.75%	1598	1592	-0.38%
West Bay Area Blvd. @ I-45 FR_NB	2606	2517	-3.41%	1439	1577	9.61%
Saturn Lake @ NASA Parkway	2640	2555	-3.21%	1603	1634	1.93%
Shared dual right-turn lanes						
Kirby Drive @ I-610_WB	1885	1713	-9.17%	1781	1408	-20.92%
Shepherd Drive @ I-10 WBFR_WB	2018	2157	6.92%	1573	1548	-1.56%

5. 2   Capacity of Right Turn on Red

The current HCM method does not provide any procedure for estimating RTOR capacity. On the other hand, the calculation of RTOR capacity can provide a more accurate estimate of the capacity for intersections, so as to better evaluate the effectiveness of the dual right-turn lanes.

For the analysis of RTOR capacities, three typical arrangements of dual right-turn lanes were considered in this study, and they are shown in Figure 5-1.

(a) Exclusive lanes, no channelization island

(b) Shared and exclusive lanes, no channelization island

(c) Shared and exclusive lanes, channelized
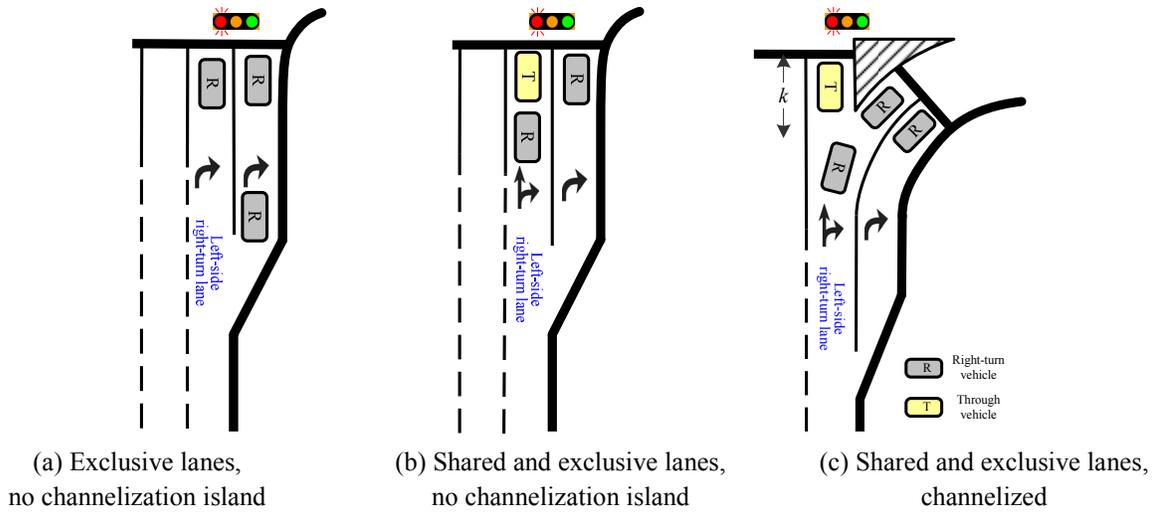
Figure 5-1: Typical Lane Arrangements of Dual Right-Turn Lanes

In these lane arrangements, the curb lane is an exclusive right-turn lane, and the left-side turn lane can be either an exclusive right-turn or a shared through/right-turn lane. As illustrated in Figure 5-1(b), without a channelization island, a single through vehicle in the shared through/right-turn lane can block all the following RTOR vehicles in this lane. When a channelization island has been installed, as shown in Figure 5-1(c), storage space may be available for through vehicles, thereby allowing RTOR maneuvers from the shared lane even in presence of several through vehicles.

Similar to single right-turn lanes, dual right-turn lanes can accommodate RTORs in the following two regimes:

RTOR Regime A: RTOR vehicles find acceptable gaps when the conflicting traffic streams (from a left-hand cross street and/or an opposing left-turn movement) are unsaturated, as illustrated in Figure 5-2(a). In the literature related to single right-turn lanes, the RTOR capacity that can be realized during Regime A is often modeled using a "stop-sign analogy" treatment, e.g., Luh and Lu (1990), Tarko (2001), and Creasey et al. (2011). A capacity equation, which was derived based on gap-acceptance theory by Harders (1968) and later presented in this chapter for Un-signalized Intersections in Highway Capacity Manual (2000), is used extensively to estimate capacities in this regime:

$$c_{p,x} = q_{c,x} \cdot \frac{e^{-q_{c,x} \cdot t_{c,x}/3600}}{1 - e^{-q_{c,x} \cdot t_{f,x}/3600}} \tag{5-3}$$

where

$c_{p,x}$ = potential capacity of minor movement x (vph), i.e., RTOR capacity of a specific right-turn lane in the context of this paper.

$q_{c,x}$ = conflicting flow rates for minor movement x (vph), i.e., conflicting flow rates for RTOR vehicles, which is comprised of traffic streams from the left-hand cross street and/or the opposing left-turn movements.

$t_{c,x}$ = critical gap in the major movement for minor movement x (s), i.e., critical gap for RTOR vehicles, which defines the minimum gap in the conflicting traffic streams that allows one vehicle to turn right on red.

$t_{f,x}$ = follow-up time for minor movement x (s), i.e., follow-up time for RTOR vehicles, which defines the time between the departure of one RTOR vehicle from the right-turn lane and the departure of the next such vehicle that takes the same gap, given continuously queued RTOR vehicles.

Harders's model was developed based on the assumption that n minor-movement vehicles can enter a major movement, given a gap of h that meets the condition of

$$t_{c,x} + (n-1) \cdot t_{f,x} \leq h < t_{c,x} + n \cdot t_{f,x}$$

RTOR Regime B: Vehicles can turn right on red without conflicting traffic streams when a protected left-turn phase is allocated to the left-turn movement from the right-hand cross street, as illustrated in Figure 5-2(b). This regime is often referred to as "shadowing" or "overlapping" left-turn phases. While RTOR vehicles can cross the stop lines continuously, they are required to come to a complete stop before finishing the RTOR maneuver.

Therefore, the total RTOR capacity of a specific right-turn lane is equal to the sum of the RTOR capacities under Regime A and Regime B, i.e. $c = c_A + c_B$.

(a) RTOR Regime A   (b) RTOR Regime B
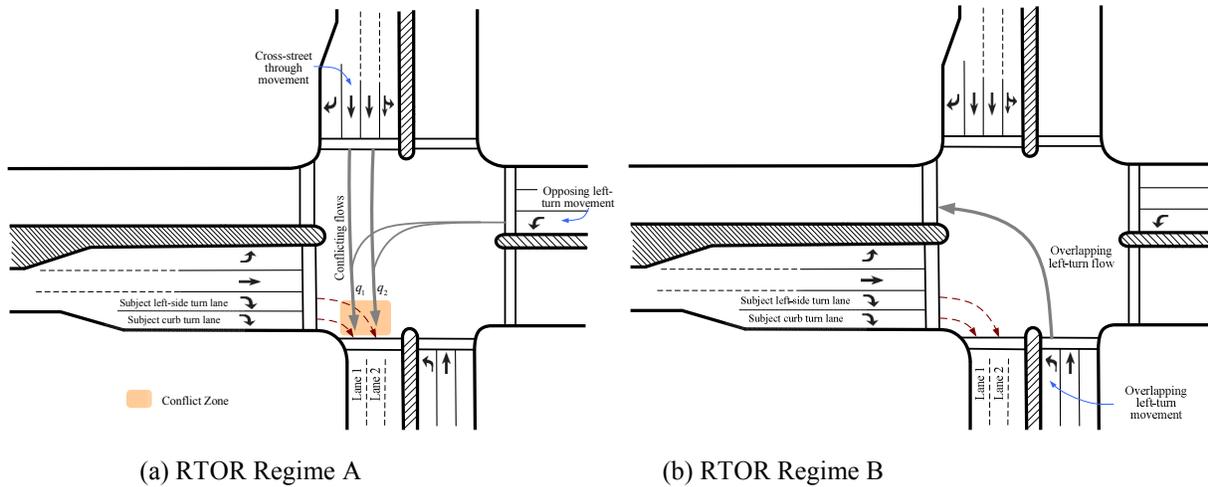
Figure 5-2: RTOR Regimes in the Analysis of Capacity for Dual Right-Turn Lanes

So far, research associated with RTOR capacity for dual right-turn lanes is almost non-existent. The existing methods based on Harders's model for single right-turn lanes potentially may be adapted to dual right-turn lanes. But, note that, for the Harders's model, conflicting volume is a critical input that influences the accuracy of the model. Luh and Lu (1990) explicitly emphasized that only the flow rate in the *outside* lane on the cross street (Lane 1 shown in Figure 5-2) is the conflicting flow of interest. However, field observations conducted in this study showed that an RTOR vehicle departing from the curb right-turn lane is also subject to the impedance of the traffic stream in Lane 2 as well as Lane 1. An RTOR driver may be worried about a sideswipe collision and may decide not to turn on red until both Lane 1 and Lane 2 are "clear". Additionally, for a dual right-turn lane approach, an RTOR vehicle departing from the left-side right-turn lane must cross the conflicting traffic stream in Lane 1 and merge into Lane 2 (the target lane), as shown in Figure 5-2(a). Thus, traffic streams in both Lane 1 and Lane 2 also affect the RTOR capacity of the left-side right-turn lane. Furthermore, according to the field observations, the traffic streams from Lane 1 and Lane 2 have unequal levels of impeding effects upon the RTOR vehicles. In estimating the RTOR capacity for dual right-turn lanes, the different impacts of conflicting traffic streams on different lanes should be considered.

For predicting lane-specific RTOR capacities for dual right-turn lanes, a gap acceptance-based model was developed to represent the unequal impacts of conflicting flows from different cross-street lanes on RTOR capacities. Then, existing probabilistic methods were adapted to adjust the estimated RTOR capacity for the shared through/right-turn lanes by accounting for the

possible presence of through vehicles. Subsequently, micro-simulation models were developed and calibrated based on field-collected data, and the models were used to provide benchmarks for validating the proposed model. Finally, numerical experiments were conducted to show the performance of the proposed model by comparing it to Harders's model.

5.2.1 Reviews on the Estimation of RTOR Capacity

The existing literature on RTOR capacity of single right-turn lanes provides deep insights and excellent resources for predicting the RTOR capacities of dual right-turn lanes. In their pioneering research, Luh and Lu (1990) identified the major factors that contribute to RTOR capacity, including lane arrangement, conflicting volume, and the proportion of right turns using a shared through/right-turn lane. The authors based their calculation of RTOR capacity on Harders's model and emphasized that only the conflicting flow rate in the *outside* lane of the cross street (Lane 1 in Figure 5-2) is of interest. Virkler and Maddela (1995) explicitly determined that RTOR can occur during two regimes, i.e., when the gaps in the conflicting flows are sufficient for RTOR to occur, as shown in Figure 5-2(a) and when the RTOR movement is overlapped by the left-turn phase from the right-hand cross street, as shown in Figure 5-2(b). Tarko (2001) extended the prior research by recognizing that the presence of through vehicles from the same approach may affect RTOR capacity. For example, with a shared through/right-turn lane, a single vehicle other than RTOR vehicles may block all the other drivers from making an RTOR maneuver; with an exclusive right-turn lane, an excessively long queue on the adjacent through lanes that spills back to the taper area may block RTOR vehicles from accessing the right-turn bay. Accounting for the probabilistic nature of these impedances, Tarko (2001) derived predictive equations for the number of unblocked RTORs. Recently, Creasey et al. (2011) formulated an incremental RTOR capacity model for shared through/right-turn lanes. They proposed a probabilistic adjustment factor and demonstrated that the current HCM method (2000) yields an underestimated capacity and an overestimated delay for approaches that contain a shared lane.

5.2.2   Model Development

1)   *Gap-Acceptance Characteristics of RTORs Departing from Dual Right-Turn Lanes*

Gap-acceptance theory is based on the concept of defining the extent to which drivers will be able to utilize a gap of a particular size or duration. The concept is generally applicable for the analysis of RTOR capacities in Regime A. In this study, the first vehicle defining the presence of a gap is termed as the opening-gap vehicle. Likewise, the vehicle defining the end of the gap is termed as the closing-gap vehicle. Field observations of critical gaps were performed at five existing dual right-turn lanes located in Houston, Texas, as listed in Table 4-1in Chapter 4.

The method proposed by Siegloch, in 1973, was used to estimate critical gaps from the observed traffic flow patterns. In this approach, the linear regression technique was used to establish the relationship between the size of a given gap and the corresponding number of RTORs that can occur, given that there is a continuous queue of RTOR vehicles. Then, the coefficients of the linear regression equation can be used to calculate mean critical gap and follow-up time.

We observed a total of 299 gaps accepted by continuous RTOR vehicles that departed from the left-side right-turn lanes. The sizes of these gaps ranged from 2.3 s to 40.3 s with one to 12 RTOR vehicles able to turn. The resulting critical gap was 4.8 s. The 299 observations were grouped based on whether the closing-gap vehicle was traveling in Lane 1 or Lane 2. For each of the two subsets, Siegloch's method was used. Vehicles in Lane 2 closed 133 accepted gaps, and the estimated critical gap was 5.2 s; vehicles in Lane 1 closed 166 accepted gaps, and the estimated critical gap was 4.4 s. The results indicated that the conflicting flows in Lanes 1 and 2 may have different levels of impedance to the RTOR vehicles departing from the left-side right-turn lane.

Field observations also revealed that an RTOR vehicle departing from the curb right-turn lane was also subject to the impedance of traffic flow in Lane 2 as well as Lane 1. On the other hand, the impedance levels of Lanes 1 and 2 are significantly different. To support this point, we observed a total of 704 gaps accepted by continuous RTOR vehicles from the curb turn lanes. These gaps ranged from 1.4 s to 37.8 s. The entire set of data led to a critical gap estimate of 4.2s. Vehicles in Lane 1 closed a subset of 406 accepted gaps, and the estimated critical gap was

5.2 s. By contrast, vehicles in Lane 2 closed a subset of 298 accepted gaps, and the estimated critical gap was 3.1 s.

These results are summarized in Table 5-2. The squared Pearson correlation coefficients indicate the goodness of fit for the regression analysis in Siegloch's method.

Table 9: Critical Gaps and Follow-Up Times for Dual Right-Turn Lanes

Departure lane	Left-Side Right-Turn Lane			Curb Right-Turn Lane		
Minimum conditions under which one (1) RTOR can occur						
Closing-gap vehicles on	**Lane 1**	**Lane 2**	**Aggregated**	**Lane 1**	**Lane 2**	**Aggregated**
Mean critical gap	$t_C^1 = 4.4$ s	$t_C^2 = 5.2$ s	$t_C = 4.8$ s	$t_C^1 = 5.2$ s	$t_C^2 = 3.1$ s	$t_C = 4.2$ s
Mean follow-up time	$t_F^1 = 3.3$ s	$t_F^2 = 3.2$ s	$t_F = 3.2$ s	$t_F^1 = 3.7$ s	$t_F^2 = 3.6$ s	$t_F = 3.7$ s
Sample size	166	133	299	406	298	704
Pearson correlation R^2	0.82	0.86	0.85	0.81	0.74	0.78
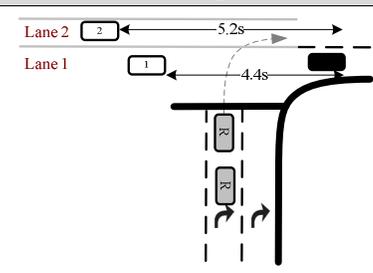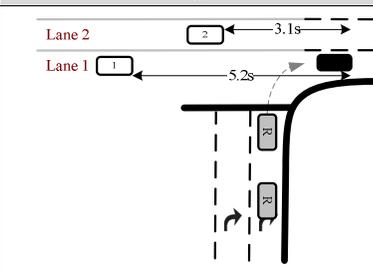
The above field observation implies that, for quantifying the effects of conflicting traffic streams on RTOR capacities of dual right-turn lanes, the conflicting traffic streams in both Lane 1 and Lane 2 should be considered, but not treated equally. In this manner, modeling improvement may possibly be achieved over the classical Harders's model.

2)   Modeling RTOR Capacity during Regime A

To account for the aforementioned gap-acceptance characteristics, different critical gaps and follow-up times are assumed for the situations when closing-gap vehicles travel in Lane 1 and Lane 2. In addition, we assume that a saturated traffic condition is present on the subject dual right-turn lane; an RTOR vehicle departing from the curb lane turns into Lane 1, while an RTOR vehicle from the left-side right-turn lane turns into Lane 2. Following these assumptions, we formulated a gap acceptance-based model.

The notations in the proposed model are introduced as follows:

q_1 = conflicting volume in Lane 1 (vph)

q_2 = conflicting volume in Lane 2 (vph)

q = conflicting flow volume of interest (vph); in the proposed model, $q = q_1 + q_2$

h = time headway between vehicles in the conflicting flows of interest, as a random variable (s)

t_C^1 = critical gap for RTOR vehicles when the gap is closed by vehicles traveling in Lane 1 (s)

t_C^2 = critical gap for RTOR vehicles when the gap is closed by vehicles traveling in Lane 2 (s). Based on the field observations shown in TABLE 1, we assumed that $t_C^1 > t_C^2$ for RTOR vehicles departing from a curb lane and $t_C^1 < t_C^2$ for RTOR vehicles departing from a left-side right-turn lane

t_F^1 = follow-up headway of RTOR vehicles on a subject turn lane when the gap is closed by conflicting vehicles in Lane 1 (s)

t_F^2 = follow-up headway of RTOR vehicles on a subject turn lane when the gap is closed by conflicting vehicles in Lane 2 (s)

C = signal cycle length (s)

t_G = time length of effective green phase of the subject approach per cycle (s)

t_{OL} = time length of protected phase for the overlapping left-turn movement per cycle (s)

t_{SF} = total time length when the conflicting zone is occupied by platoons that are discharged at the beginning of the green phase of cross-street through and opposing left-turn movements (s)

λ = cycle split for Regime A (%), which equals $(1-(t_G + t_{OL} + t_{SF})/C) \times 100\%$

Since h denotes time headway between vehicles in the conflicting flows of interest (traffic streams in Lanes 1 and 2 as a whole), h has a minimum headway of zero. Then, we assume that h is distributed exponentially, which can be mathematically written as $\Pr(h \le t) = 1 - e^{-q \cdot t}$, where t is a given gap size.

To illustrate the proposed method, the RTOR capacity for a left-side exclusive right-turn lane is taken as an example. Table 5-3 shows three possible patterns of gap acceptance during Regime A.

Table 10: Table 11: Possible Patterns of Gap Acceptance and Capacity of the Left-Side Right-Turn Lane

Case	Patterns of Gap Acceptance (assuming $t_C^1 < t_C^2$)	Possibility of Case	Possibility that n RTORs can cross within gap h, $\Pr(n)$	Average number of RTORs that can occur per hour (vph)
A	Lane 2 / Lane 1	The gap is closed by a vehicle in Lane 2.	$\dfrac{q_2}{q}$	$\Pr(t_C^2 + (n-1)\cdot t_F^2 \le h < t_C^2 + n\cdot t_F^2)$	$\alpha = \lambda \cdot q_2 \cdot \dfrac{e^{-q\cdot t_C^2/3600}}{1 - e^{-q\cdot t_F^2/3600}}$
B	Lane 2 / Lane 1	The gap is closed by a vehicle in Lane 1 followed by a vehicle traveling in Lane 2.	$\dfrac{q_1}{q}\cdot\dfrac{q_2}{q-1}$ $\approx \dfrac{q_1\cdot q_2}{q^2}$	$\Pr(t_C^1 + (n-1)\cdot t_F^1 \le h < t_C^1 + n\cdot t_F^1)$ $\cdot \Pr(h + h' \ge t_C^2 + (n-1)\cdot t_F^2)$	$\beta = \lambda \cdot \dfrac{q_1\cdot q_2}{q}\cdot e^{-q\cdot(t_C^2 + t_F^2)/3600}$ $\cdot \dfrac{1 - e^{-q\cdot t_F^1/3600}}{(1 - e^{-q\cdot t_F^2/3600})^2}$
C	Lane 2 / Lane 1	The gap is closed by a vehicle in Lane 1 followed by a vehicle traveling in Lane 1.	$\dfrac{q_1}{q}\cdot\dfrac{q_1}{q-1}$ $\approx \left(\dfrac{q_1}{q}\right)^2$	$\Pr(t_C^1 + (n-1)\cdot t_F^1 \le h < t_C^1 + n\cdot t_F^1)$	$\gamma = \lambda \cdot \dfrac{(q_1)^2}{q}\cdot \dfrac{e^{-q\cdot t_C^1/3600}}{1 - e^{-q\cdot t_F^1/3600}}$

The sum of the possibility of the three cases is equal to 1. Case A represents the situation in which a gap in the conflicting traffic stream is closed by a vehicle in Lane 2. For a gap closed by a vehicle in Lane 1, there are two different cases. First, when the closing-gap vehicle is

followed by a vehicle in Lane 2 (Case B), even if this gap h is greater than the critical gap t_C^1, the driver of the RTOR vehicle may still not make the turn due to concerns about potential conflict with the cross-street vehicle in Lane 2 (since $t_C^1 < t_C^2$, it is possible that $h + h' < t_C^2$). On the other hand, when the closing-gap vehicle is followed by a vehicle in Lane 1 (Case C), if this gap h is greater than the critical gap t_C^1, the driver of the right-turning vehicle will make a turn on red without worry about conflict with the crossing vehicles in Lane 2. Therefore, Case B and Case C should be considered separately. The RTOR capacity for a left-side right-turn lane, c_A^{left}, should be the sum of the number of RTORs under each of the three cases:

$$c_A^{\text{left}} = \alpha + \beta + \gamma \tag{5-4}$$

Potential Capacity for Case A

Case A represents the situation in which a gap in the conflicting traffic stream is closed by a vehicle in Lane 2, as illustrated in TABLE 2. In these cases, the probability that n RTORs can depart from the left-side right-turn lane during a gap of h is:

$$
\begin{aligned}
\Pr(n | \text{Case A}) &= \Pr(t_C^2 + (n-1) \cdot t_F^2 \le h < t_C^2 + n \cdot t_F^2) \\
&= e^{-q \cdot \left(t_C^2 + (n-1) \cdot t_F^2\right)/3600} - e^{-q \cdot \left(t_C^2 + n \cdot t_F^2\right)/3600}
\end{aligned}
$$

On a per hour basis, a total of q gaps appears in the conflicting traffic stream (Lane 1 and Lane 2 as a whole), and $\lambda \cdot q$ of them appear during the period of RTOR Regime A. The probability of occurrence of Case A is equal to q_2 / q. Then, the average number of RTORs that can occur in the Cases A per hour can be written as:

$$
\begin{aligned}
\alpha &= (\lambda \cdot q) \cdot \sum_{n=1}^{\infty} n \cdot \Pr(\text{Case A}) \cdot \Pr(n | \text{Case A}) \\
&= (\lambda \cdot q) \cdot \sum_{n=1}^{\infty} n \cdot \left(\frac{q_2}{q}\right) \cdot \Pr(n | \text{Case A}) \\
&= \lambda \cdot q_2 \cdot \frac{e^{-q \cdot t_C^2/3600}}{1 - e^{-q \cdot t_F^2/3600}}
\end{aligned}
\tag{5-5}
$$

Notice that the reduced equation is similar to Harders's model.

Potential Capacity for Case B

Case B represents the situation in which a gap is closed by a vehicle in Lane 1 that is followed by a vehicle traveling in Lane 2. As illustrated in Table 5-3, h' denotes a random time headway between the closing-gap vehicle and the following vehicle, and h' is an identically distributed variable to h. In Case B, n RTORs can occur during a gap of h only when

$$t_C^1 + (n-1) \cdot t_F^1 \le h < t_C^1 + n \cdot t_F^1 \text{ and } h + h' \ge t_C^2 + (n-1) \cdot t_F^2$$

The probability can be written as:

$$\Pr(n|\text{Case B}) = \Pr(t_C^1 + (n-1) \cdot t_F^1 \le h < t_C^1 + n \cdot t_F^1) \cdot \Pr(h + h' \ge t_C^2 + (n-1) \cdot t_F^2)$$

$$\approx \Pr(t_C^1 + (n-1) \cdot t_F^1 \le h < t_C^1 + n \cdot t_F^1) \cdot \Pr(h \ge (t_C^2 - t_C^1) + (n-1) \cdot (t_F^2 - t_F^1))$$

$$\approx [e^{-q \cdot (t_C^1 + (n-1) \cdot t_F^1)/3600} - e^{-q \cdot (t_C^1 + n \cdot t_F^1)/3600}] \cdot e^{-q \cdot ((t_C^2 - t_C^1) + n \cdot (t_F^2 - t_F^1))/3600}$$

The possibility of Case B (i.e., a gap is closed by a vehicle in Lane 1 that is followed by a vehicle traveling in Lane 2) is equal to $(q_1/q) \cdot (q_2/q)$. Then, the average number of RTOR vehicles that can occur in the Cases B per hour can be formulated as:

$$\beta = (\lambda \cdot q) \cdot \sum_{n=1}^{\infty} n \cdot \Pr(\text{Case B}) \cdot \Pr(n|\text{Case B})$$

$$= (\lambda \cdot q) \cdot \sum_{n=1}^{\infty} n \cdot \frac{q_1 \cdot q_2}{q^2} \cdot \Pr(n|\text{Case B})$$

$$= \lambda \cdot \frac{q_1 \cdot q_2}{q} \cdot e^{-q \cdot (t_C^2 + t_F^2)/3600} \cdot \frac{1 - e^{-q \cdot t_F^1/3600}}{(1 - e^{-q \cdot t_F^2/3600})^2} \tag{5-6}$$

Potential Capacity for Case C

Case C represents the situation in which a gap is closed by a vehicle in Lane 1 that is followed by a vehicle traveling in Lane 1. The probability of Case C can be written as $(q_2/q)^2$. For a gap of h, the probability that n RTORs can occur is:

$$\Pr(n|\text{Case C}) = \Pr(t_C^1 + (n-1) \cdot t_F^1 \le h < t_C^1 + n \cdot t_F^1)$$

The average number of RTOR vehicles in the Cases C per hour can be expressed as:

$$\gamma = (\lambda \cdot q) \cdot \sum_{n=1}^{\infty} n \cdot \Pr(\text{Case C}) \cdot \Pr(n|\text{Case C})$$

$$= (\lambda \cdot q) \cdot \sum_{n=1}^{\infty} n \cdot \left(\frac{(q_1)^2}{q^2} \right) \cdot \Pr(n|\text{Case C})$$

$$= \lambda \cdot \frac{(q_1)^2}{q} \cdot \frac{e^{-q \cdot t_C^1 / 3600}}{1 - e^{-q \cdot t_F^1 / 3600}} \tag{5-7}$$

Then, the capacity of the left-side right-turn lane during Regime A can be expressed as:

$$c_A^{\text{left}} = \alpha + \beta + \gamma$$

$$= \lambda \cdot \left(q_2 \cdot \frac{e^{-q \cdot t_C^2 / 3600}}{1 - e^{-q \cdot t_F^2 / 3600}} + \frac{q_1 \cdot q_2}{q} \cdot e^{-q \cdot (t_C^2 + t_F^2)/3600} \cdot \frac{1 - e^{-q \cdot t_F^1 / 3600}}{(1 - e^{-q \cdot t_F^2 / 3600})^2} + \frac{(q_1)^2}{q} \cdot \frac{e^{-q \cdot t_C^1 / 3600}}{1 - e^{-q \cdot t_F^1 / 3600}} \right)$$

$$\tag{5-8}$$

Likewise, the capacity of a curb lane during Regime A can be expressed by interchanging q_1 and q_2, t_C^1 and t_C^2, as well as t_F^1 and t_F^2 because the subject vehicles departing from the curb lane commonly turn into the target lanes of Lane 1 (other than Lane 2):

$$c_A^{\text{curb}} = \alpha + \beta + \gamma$$

$$= \lambda \cdot \left(q_1 \cdot \frac{e^{-q \cdot t_C^1 / 3600}}{1 - e^{-q \cdot t_F^1 / 3600}} + \frac{q_1 \cdot q_2}{q} \cdot e^{-q \cdot (t_C^1 + t_F^1)/3600} \cdot \frac{1 - e^{-q \cdot t_F^2 / 3600}}{(1 - e^{-q \cdot t_F^1 / 3600})^2} + \frac{(q_2)^2}{q} \cdot \frac{e^{-q \cdot t_C^2 / 3600}}{1 - e^{-q \cdot t_F^2 / 3600}} \right)$$

$$\tag{5-9}$$

The proposed gap-acceptance model is analytically tractable and can easily be implemented in an Excel spreadsheet.

3) ***RTOR Capacity during Overlapping Left-Turn Phase (Regime B)***

As shown in Figure 5-2(b), a parallel RTOR movement can take place because there is no conflicting traffic during a protected left-turn phase from the northbound approach (RTOR Regime B). During this regime, the RTOR capacity equals the product of the time for the overlapping left-turn phase t_{OL} and the corresponding flow rate s_{OL}, at which "stop-and-go" RTORs can cross the stop line without conflicting traffic.

$$c_B = s_{OL} \cdot t_{OL} \tag{5-10}$$

In the absence of field data, s_{OL} can be estimated by the reciprocal of mean follow-up time, i.e. $s_{OL} = 3600/t_F$. (Refer to Table 5-3 for values of t_F). The time occupied by U-turns from the overlapping left-turn movement should be deducted from t_{OL}.

5.2.3   Adjustment for Left-Side Shared Through/Right-Turn Lane

For a left-side shared through/right-turn lane, RTOR capacity may also be affected by the presence of through vehicles sharing the lane, and the capacity can be mathematically expressed by:

$$c_{Shared} = \min(\frac{3600 \cdot \omega}{C}, c_A^{left} + c_B^{left}) \tag{5-11}$$

where ω = average number of unblocked RTOR vehicles per cycle;

c_B^{left} = RTOR capacity for the left-side shared lane during Regime B.

1) ***ω for Shared Lanes without Islands***

As shown in Figure 5-1(b), without a channelization island, the presence of a single vehicle other than a right-turn vehicle can block the shared lane. The probability that n RTOR vehicles can depart from the shared lane is equal to that n right-turning vehicles arrive first, followed by one through vehicle during a red interval, i.e.,

$$\Pr(x = 1) = p^n \cdot (1 - p)$$

where p = the proportion of right-turn vehicles in the shared lane.

On a per cycle basis, the average number of unblocked right-turn vehicles can be approximated by the same equation derived by Tarko (2001) and Creasey et al. (2011):

$$\omega = \sum_{n=1}^{\infty} n \cdot p^n \cdot (1-p) = \frac{p}{1-p} \tag{5-12}$$

2)   *ω for Shared Lanes with Islands*

With a channelization island (Figure 5-1(c)), a left-side shared through/right-turn lane may not be blocked before available storage spaces (k measured in number of vehicles) are fully occupied by through vehicles sharing the lane. A model was developed by Tarko (2001) to estimate how many right-turning vehicles can utilize the single-lane right-turn bay before the queue of the adjacent through movement spills back to block the taper area. Recognizing its great similarity to our problem, we adapted Tarko's model (2001) to represent the RTOR capacities for left-side shared lane with a channelization island. On a per cycle basis, the average number of unblocked right-turn vehicles can be approximated as:

$$\omega = \frac{p \cdot k}{1-p} \tag{5-13}$$

5.2.4 Model Validation

Generally, capacities of intersections are observable only when queued vehicles are continuously present. The required saturated traffic condition makes it difficult to directly observe sufficient data samples for RTOR capacity in the field. Instead, micro-simulation models, which are calibrated to replicate real-world traffic conditions, can be used to provide benchmarks for testing the proposed model.

1)   *Data Collection*

Field data collection was conducted to provide real-world data for developing, calibrating, and validating the micro-simulation models. Videos of field traffic were recorded at five intersections with dual right-turn lanes located in Houston, Texas. The detailed characteristics of the study locations are summarized in Table 5-4.

The observation periods spanned from 6:00 AM to 9:00 AM and from 4:00 PM to 7:00 PM for each of the locations. The videos were replayed to observe lane-specific parameters. The data collected included traffic volume, traffic composition, and signal timing at all of the

intersections, as well as critical gaps for RTOR vehicles, lane utilization, saturation flow rates, and delays at the dual right-turn lanes.

Table 12: Characteristics of Field Study Sites

Intersection	Road type	Lane allocation	Speed limit, mph (kmph)	Curb pocket lane length, ft (m)	Presence of island	Corner angle	RT volume, vph	% of heavy vehicles	Approach lane width, ft (m)
US 59 & Highway 6	Frontage Road	↱↱	50 (80.5)	340 (104 m)	No	110°	752	3.70%	12 (3.6 m)
West Bay Area Blvd. & I-45 FR_NB	Interchange Ramp	↱↱	50 (80.5)	800 (245 m)	Yes	70°	700	2.57%	12 (3.6 m)
Saturn Lake & NASA Parkway	Arterial Road	↱↱	45 (72.4)	N/A	No	90°	415	1.04%	12 (3.6 m)
Kirby Drive & I-610_WB	Frontage Road	↱↱	45 (72.4)	330 (101 m)	Yes	90°	676	4.48%	11 (3.4 m)
Shepherd Drive & I-10 WBFR_WB	Frontage Road	↱↱	45 (72.4)	300 (91 m)	No	90°	327	4.48%	12 (3.6 m)

2) *Micro-Simulation Models for Benchmarking RTOR Capacity*

Micro-simulation models were developed using VISSIM for each of the five locations. The models were calibrated and then validated by comparing simulated delays and saturation flow rates against field observations.

Table 13: Effectiveness of Calibrated Micro-Simulation Models

Intersection	Measure of effectiveness	Curb turn lane			Additional turn lane		
		Observed	Simulated	Error	Observed	Simulated	Error
US 59 & Highway 6 NB	Delay, s	17.3	16.8	-2.9%	15.8	15.3	-3.4%
	Saturation flow, vph	1,598	1,614	1.0%	1,531	1,506	-1.7%
Kirby Dr. & I-610 WB	Delay, s	5.2	5.3	1.9%	6.7	6.6	-1.7%
	Saturation flow, vph	1,781	1,783	0.1%	1,373	1,381	0.6%
Shepherd Dr. & I-10 WB	Delay, s	38.4	38.5	0.4%	26.1	27.8	6.7%
	Saturation flow, vph	1,573	1,577	0.3%	1,440	1,445	0.3%
West Bay Area Blvd. & I-45 NB	Delay, s	21.6	20.7	-4.0%	15.1	16.1	6.0%
	Saturation flow, vph	1,439	1,453	1.0%	1,827	1,842	0.8%
West Bay Area Blvd. & I-45 NB	Delay, s	9.1	10.1	11.2%	11.5	11.8	2.8%
	Saturation flow, vph	1,603	1,597	-0.4%	1,773	1,785	0.7%

The relative errors of the model predictions are shown in Table 5-5. The results indicated that the calibrated simulation models replicate a realistic traffic flow condition as observed in the field. To further simulate RTOR capacities, oversaturated traffic conditions were assumed and input to the VISSIM models, while the other parameters remained as calibrated.

3) Harders's Model for Comparison

Comparison Model (a): Harders's Model with Unweighted Conflicting Volume

Conflicting volume is a key parameter for Harders's model, as formulated in Equation (5-3). For the curb-side right-turn lane, the conflicting traffic volume for Comparison Model (a) can be either q_1 only (volume of Lane 1) or the sum of q_1 and q_2 (total volume of Lane 1 and Lane 2). For the left-side right-turn lane, the conflicting volume was assumed to be the sum of q_1 and q_2, since RTOR vehicles departing from this lane must cross Lane 1 and merge into Lane 2 .

Comparison Model (b): Harders's Model with Weighted Conflicting Volume

To account for the unequal effects of traffic streams from Lane 1 and Lane 2 on RTOR capacity during Regime A, an alternative way is to assign different weights to the volumes of Lane 1 and Lane 2 (q_1 and q_2) to be input to Harders's model, while identical critical gaps and follow-up times are assumed for Lane 1 and Lane 2. As an example, Liu et al. (2009) adapted Harders's model to estimate capacity of U-Turns at un-signalized median openings on six-lane streets.

In this model validation, we assumed a form of weighted conflicting volume as $(q_1 + \tau \cdot q_2)$ for estimating capacities for curb right-turn lane, and $(\tau \cdot q_1 + q_2)$ for a left-side right-turn lane. Then, the weighted conflicting volume was substituted for the conflicting volume items in Harders's model. The weight τ is to be calibrated by solving the following program with a single decision variable, which aims to minimize the mean absolute percent error (MAPE) relative to the micro-simulation benchmarks.

$$\min_{\tau} \text{MAPE} = \min_{\tau} \left(\frac{1}{n} \sum_{i=1}^{n} \left| \frac{c_w^i - c_s^i}{c_s^i} \right| \right) \tag{5-14}$$

where

n =   training sample size

c_w^i =   estimated RTOR capacity by Harders's model with a weighted conflicting volume (vph)

c_s^i =   simulated RTOR capacity (vph)

4)   *Validation of Estimated Capacity for Exclusive Dual Right-Turn Lanes*

Estimated Capacity for Curb Right-Turn Lane

Given a set of 38 combinations of q_1 and q_2, the proposed model was used for the curb lanes of the three exclusive dual right-turn lanes listed in Table 5-5. Other parameters were input as observed values. Given the same inputs, the RTOR capacities were also estimated using Comparison Model (a). Two kinds of un-weighted conflicting volumes for Harders's model were tested in this numerical experiment; in the first approach, only q_1 was input as the conflicting flow, while, in the second approach, the sum of q_1 and q_2 were input as the conflicting flow. Figure 5-3 shows that the proposed model yielded an MAPE of 9.11%, presenting a good performance in predicting RTOR capacities for the curb right-turn lane. In comparison, Harders's model yielded an MAPE of 17.41% with the sum of q_1 and q_2 input as conflicting volumes. It can be noted that the predicted values tended to be lower than simulated capacities. With only q_1 (outside lane) as the conflicting volume, the MAPE was 30.76 percent relative to simulated capacities, showing an overestimation bias.
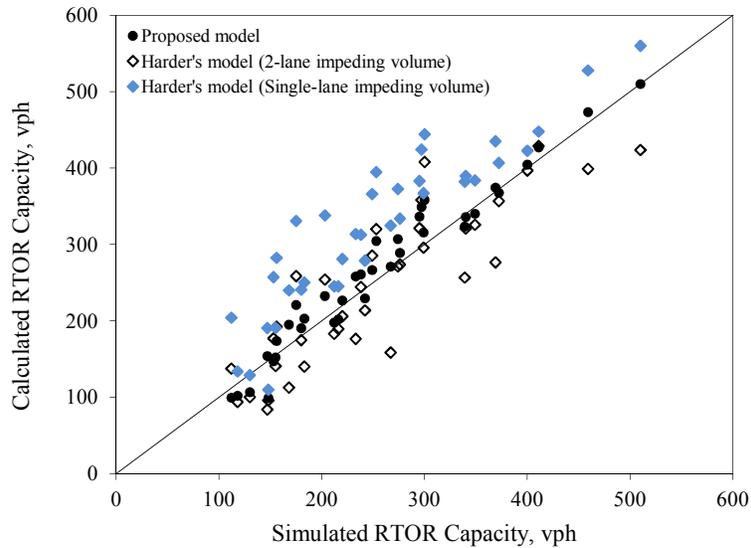
Figure 5-3: Validation of the Proposed Model for Curb Right-Turn Lane

The proposed model was also compared with Comparison Model (b) - Harders's model with weighted conflicting volumes. Comparison Model (b) must be trained before it can yield reasonable estimates of RTOR capacities. Out of the 38 data samples, a subset that consisted of 19 samples was used for calibrating the weight, and the other 19 samples were used for testing. The proposed model had an MAPE of 9.12 percent over the set of 19 testing data samples. Comparatively, Comparison Model (b) with an optimal weight led to an MAPE of 10.38 percent if the weighted conflicting volume was equal to $(q_1 + 0.57 \cdot q_2)$. The optimal weight implied that one vehicle from Lane 2 should be considered as 0.57 vehicle when we estimate capacity for the curb right-turn lane. The results are essentially consistent with our field observation, i.e., the traffic streams in Lane 1 and Lane 2 have unequal effects on RTOR capacity. The underlying reason may be that right-turning vehicles from the curb right-turn lane are supposed to merge into Lane 1 instead of Lane 2, but they are affected by Lane 2 in a way to avoid sideswiping vehicles from Lane 2.

While Comparison Model (b) yielded reasonable estimates, it should be noted that this model requires training data to calibrate the weight before it can be used. RTOR capacity is not easy to observe in the field, which may compound the difficulty of using Comparison Model (b).

Similarly, the proposed model was applied to the left-side right-turn lanes at the three exclusive dual right-turn lanes (Table 5-3), given a set of 29 combinations of q_1 and q_2. Figure 5-4 shows that the proposed model can make reasonable predictions of RTOR capacities for left-side exclusive right-turn lanes, showing an MAPE of 11.32 percent. Comparison Model (a) was used with $q_1 + q_2$ input as the conflicting volume to Harders's model. The resulting MAPE was 25.52 percent.
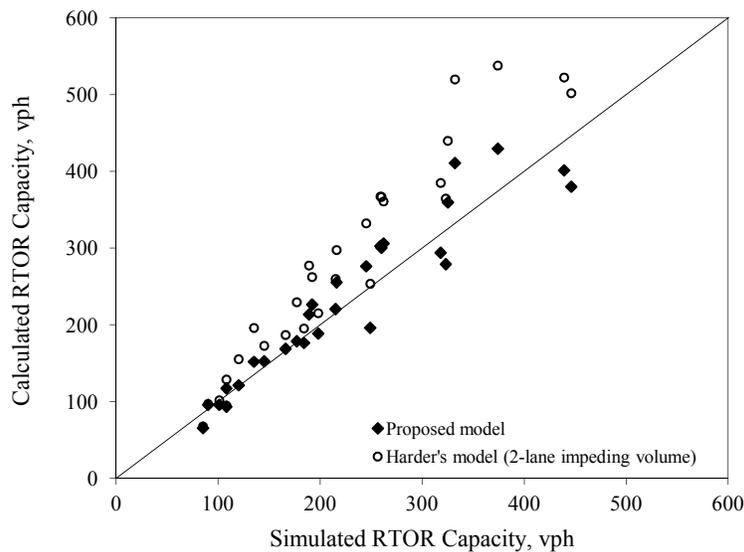
Figure 5-4: Validation of Estimated RTOR Capacity for Exclusive Left-Side Right-Turn Lanes

Using 15 of the 29 samples to train Comparison Model (b), the optimal MAPE was 15.80 percent when the weighted conflicting volume was input as $1.45 \cdot q_1 + q_2$. Comparatively, the proposed model exhibited an MAPE of 10.48 percent over the same set of 14 testing samples. The weight of 1.45 demonstrated that the traffic flow in Lane 1 has a greater effect on the RTOR capacity of left-side right-turn lane than the traffic flow in Lane 2.

With respect to the comparison models, the proposed model exhibited an improved performance for predicting RTOR capacity for exclusive dual right-turn lane, particularly compared to the classical Harders's model, as summarized in Table 5-6.

Table 14: Comparison of MAPEs between the Proposed Model and Harders's Model

MAPE values	Proposed model	Comparison model (*a*) – classical Harders's model	Testing sample size	Proposed model	Comparison model (*b*) – weighted Harders's model	Testing sample size
Curb lane	9.11%	30.76% (or 17.41%)	38	9.12%	10.38%	19
Left-side lane	11.32%	25.52%	29	10.48%	15.80%	14

5)   *Validation of Estimated Capacity for Shared Dual Right-Turn Lane*

Based on the shared dual right-turn lane at Shepherd Dr. & I-10 WB, 25 scenarios were designed to test the proposed model. The scenarios involved different conflicting volumes (q_1 and q_2) and different proportions of right-turn vehicles in the shared lane (p). Figure 5-5(a) shows that the proposed model yielded a reasonable prediction for left-side shared lanes without channelization islands. The MAPE was 17.94 percent compared to the simulated RTOR capacities. Likewise, based on the shared dual right-turn lane at Kirby Dr. & I-610 WB, 26 scenarios were designed to test the performance of the model for left-side shared lanes with a channelization island. As shown in Figure 5-5(b), the MAPE of the proposed model was 10.92 percent for those cases in which there were channelization islands (as shown in Figure 5-1(c)).

The results indicated that Equations (5-11) - (5-13), adapted from Tarko's and Creasey's models, can be used to make reasonable adjustments to RTOR capacities for shared right-turn lanes within a dual right-turn lane group.
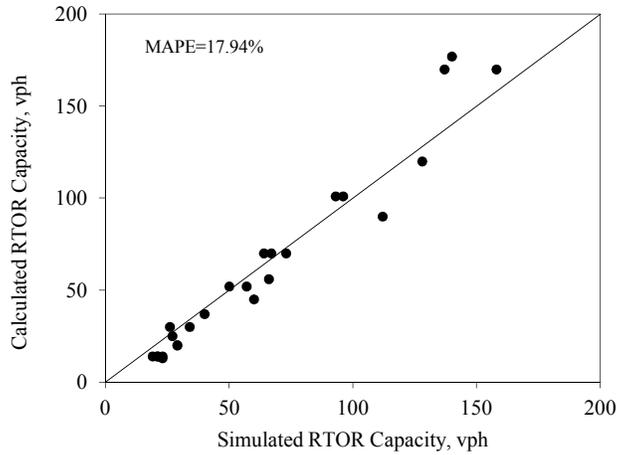
(a) Left-side shared turn lane without channelization islands
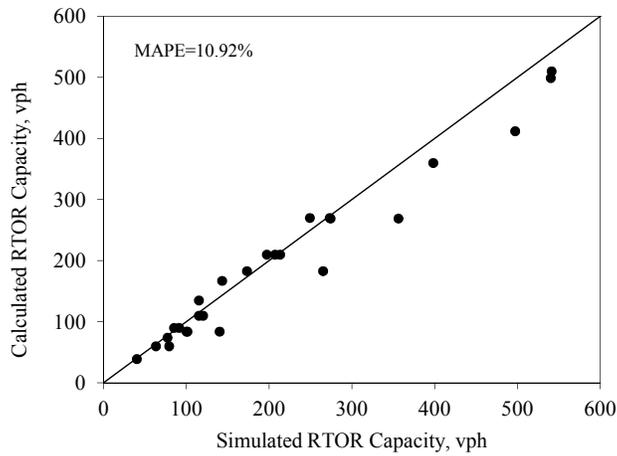
(b) Left-side shared turn lane with channelization islands

Figure 13: Estimation of RTOR Capacity for Shared Right-Turn Lane

Collectively, for most experimental scenarios, Harders's model provided reasonable estimates of RTOR capacities for dual right-turn lanes with an MAPE typically less than 30percent . On the other hand, by considering different levels of impedance from different cross-street lanes, the proposed model generally exhibited an improved performance for predicting RTOR capacities for dual right-turn lanes.

5.3   Summary

In this chapter, the models for predicting the capacity of dual right-turn lanes were developed. These models were generally divided into two categories, i.e. models for predicting the capacity of RTOG and the capacity of RTOR.

The calculation of capacity of RTOG followed the HCM method. The comparison of field observed data and the results HCM method proved that the HCM method provide excellent estimates of saturation flow rate for the dual right-turn lane, so as to provide accurate estimates of capacity of RTOG.

An analytical model for predicting RTOR capacities of dual right-turn lanes was developed in this chapter. The model calculates capacities of dual right-turn lanes with three typical lane arrangements. In the proposed model, both the stop-sign analogy and overlapping left-turn phases were considered. Probabilistic methods were adapted to adjust the results for the left-side shared through/right-turn lane. Micro-simulation models were developed, calibrated based on field data, and used as benchmarks to validate the proposed model.

References

Brilon, W., R. Koenig, R.J. Troutbeck. Useful Estimation Procedures for Critical Gaps. Transportation Research, Part A: Policy and Practice, Vol. 33, 1999, pp.161–186.

Creasey, T.F., N. Stamatiadis, K. Viele. Right-Turn-on-Red (RTOR) Volume Estimation and Incremental Capacity Models for Shared Lanes at Signalized Intersections. Presented at the 90th Annual Meeting of the Transportation Research Board; National Research Council; Washington, D.C.; January 2011.

Liu, P., J. Lu, and B. Cao. Capacity of U-Turns at Unsignalized Median Openings on Six-Lane Streets. In Transportation Research Record: Journal of the Transportation Research Board, No. 2130, 2009, pp. 59–65.

Luh, J.Z. and Y. Lu. Capacity Computations of Right-Turn-On-Red Using the Highway Capacity Manual. ITE Journal; Institute of Transportation Engineers; Washington, D.C., April 1990, pp. 34–38.

Tarko, A.P. Predicting Right Turns on Red. In Transportation Research Record: Journal of the Transportation Research Board, No. 1776, 2001, pp. 138–142.

Special Report 209: Highway Capacity Manual. TRB, National Research Council, Washington, D.C., 2000.

Virkler, M.R. and R.R. Maddela. Capacity for Right Turn on Red. In Transportation Research Record: Journal of the Transportation Research Board, No. 1484, 1995, pp. 66–72.

Revised Monograph on Traffic Flow Theory. Federal Highway Administration, U.S. Department of Transportation, 2005.

CHAPTER 6: DUAL RIGHT-TURN LANES IN MITIGATING WEAVING TRAFFIC CONFLICTS

In terms of safety impacts of installing dual right-turn lanes, well-designed dual right-turn lanes generally do not cause significantly higher crash frequency or severity than a single right-turn lane, according to a study conducted by the research team in collaboration with Texas Transportation Institute (Cooner et al., 2011).

The survey showed that an important reason for the use of dual right-turn lanes is to improve weaving traffic safety at freeway frontage roads. As reported by traffic engineers, the use of dual right-turn lanes may provide an improved weaving environment for right-turning vehicles by reducing forced merges. Moreover, it was showed that approximately 47 percent of dual right-turn lanes in the participants' jurisdictions are installed on urban freeway frontage roads or service roads, which are characterized by high turning volumes and high frequency of traffic conflicts.

As illustrated in Figure 3-2 in Chapter 3, a right-turn lane (either exclusive or shared) on the left of the curb right-turn lane may reduce forced lane-changes toward the curb lane for off-ramp right-turning vehicles. The left-side right-turn lane provides easier access while requiring less lane-change maneuvers. The benefits derived from dual right-turn lanes may be especially significant when geometric conditions do not present an adequate weaving distance.

Another similar hypothesis proposed by the participating traffic engineers is depicted in Figure 3-3 in Chapter 3. It was hypothesized that the use of dual right-turn lanes may mitigate weaving conflicts where a number of right-turning vehicles turn from a frontage road intersection into a closely-spaced, downstream on-ramp.

While the traffic engineers suggested that dual right-turn lanes could bring safety benefits by mitigating traffic conflicts, the degree to which weaving conflicts can be reduced is still unknown, leaving transportation engineers to rely on their judgments.

The objective of this chapter is to investigate the impacts of installing dual right-turn lanes on weaving traffic safety. The safety performances were measured in terms of traffic conflict frequency, which is an established crash surrogate (Zegeer 1978, Parker 1989, Tarko 2011, Laureshyn 2010, Ozbay 2008). In the chapter, the following research questions are addressed:

- How does weaving distance affect the frequency of weaving traffic conflicts in single and dual right-turn lane operations?

- How do weaving traffic volumes (i.e., volume of frontage road and volume of right-turning volume from/to freeway ramps) affect the frequency of weaving traffic conflicts in single and dual right-turn lane operations?

- How differently do an exclusive and a shared left-side right-turn lane contribute to the reduction of weaving conflicts?

Since dual right-turn lanes are an emerging design alternative, statistical analysis based on crash data is generally not applicable for assessing these research questions due to the limited amount of data available. In this study, a two-stage, simulation-based method was used for safety analysis. In the first stage, micro-simulation models which were well calibrated were used to generate vehicle trajectories at frontage road intersections with dual right-turn lanes. In the second stage, the simulated trajectories were used as input to surrogate safety assessment models to derive surrogate safety measures and estimate the frequency of weaving conflicts. By comparing historical crash rates with predicted frequency of weaving conflicts, the simulation-based surrogate safety analysis was validated. The validated method was used to estimate the reduction of weaving conflicts due to installation of dual right-turn lanes at frontage intersections in proximity to freeway ramps.

6. 1   Review of Simulation-Based Surrogate Safety Assessment

To overcome the limitations of conventional safety analysis based on crash data, surrogate safety assessments have been proposed with the development of traffic conflict techniques (Tarko 2011, Laureshyn 2010, Ozbay 2008). As an emerging branch of surrogate safety assessments, simulation-based surrogate safety analysis was initially proposed by Darzentas et al. (1980), and it has been receiving increasing attention in recent years. Along this line, Minderhoud and Bovy (2001) demonstrated that time-to-collision (TTC) is a useful safety measure in micro-simulation studies that focus on safety impacts. The TTC concept considers two vehicles with eventually crossing trajectories and computes the time at which the two vehicles would collide if they maintained their current vectors at each time step of the micro-simulation. Also, Ozbay et al. (2008) proposed surrogate safety indicators based on TTC, and the

results indicated a strong relationship between the proposed safety measures and actual crash data collected on the New Jersey Turnpike. Eisele and Frawley (2004) investigated the safety performance of median-divided roadways by applying TTC to identify conflicts that occur in the VISSIM simulation. Proof of concept for this test was illustrated. To study the safety impact of different truck-restriction strategies, Garber and Liu (2007) also used a similar concept and extracted TTC from Paramics models as a safety measure.

As a representative effort to advance this promising methodology, the Federal Highway Administration sponsored a research project (FHWA-RD-03-050) to investigate the potential for deriving surrogate safety measures from existing traffic simulation models (Gettman 2008, Gettman 2003). The research was based on identifying, classifying, and evaluating traffic conflicts by processing TTC as well as other surrogate safety measures, such as post-encroachment time, speed differential, and maximum deceleration. The method was validated based on a set of 83 intersections in British Columbia, Canada. It was reported that the predicted traffic conflict results had a significant correlation with crash data collected in the field (Gettman 2008). A computational tool, referred to as the Surrogate Safety Assessment Model (SSAM) was developed along with the method for facilitating the surrogate safety analysis.

Generally, existing studies have provided deep insights into simulation-based surrogate safety assessment and indicated that such assessment holds great promise for a wide range of applications.

6. 2   Historical Crash Data Collection

Angle and sideswipe crashes, which are highly associated with weaving traffic, were used as benchmarks to validate the simulation-based surrogate safety assessment. Police-reported crash records of these two types were collected during a six-year period from 2003 to 2008 at the three dual right-turn lanes being studied. In the police reports, angle crashes were defined as situations in which one vehicle collides with another vehicle in a crossing direction or in which two vehicles collide while traveling in the same direction during lane change. Sideswipes were defined as crashes in which one vehicle impacts another vehicle that is traveling in the same direction by "swiping" along the surface with the direction of travel.

6. 3   Micro-Simulation Models for Dual Right-Turn Lanes

As the first stage of the simulation-based surrogate safety analysis, micro-simulation models were developed using VISSIM. The models were calibrated to replicate a realistic traffic flow condition as observed in the field. Then, the calibrated models were validated by comparing simulated delays and saturation flow rates to field observations. In this study, delay was defined as the additional travel times required, compared to ideal conditions (free flow and no signal), from the time a vehicle enters the approach until it leaves the stop lines with regained speed. Saturation flow was observed and simulated as the flow rates at which queued vehicles traverse the stop lines under given conditions, assuming that the green signal is available at all times.

The relative errors of model predictions are shown in Table 6-1. The results indicated that the calibrated simulation models provide a sound basis for characterizing traffic flows on the dual right-turn lanes, thereby reasonably predicting the trajectories of vehicles traveling through the right-turn lanes. The simulated vehicle trajectories can then be processed by the SSAM model to derive the surrogate safety measures.

Table 15: Effectiveness of Calibrated Micro-Simulation Models

Intersection	Measure of effectiveness	Curb right-turn lane			Left-side right-turn lane		
		Observed	Simulated	Error	Observed	Simulated	Error
US 59 at Highway 6 NB	Delay (s)	17.3	16.8	-2.9%	15.8	15.3	-3.4%
	Saturation flow (vph)	1,598	1,614	1.0%	1,531	1,506	-1.7%
Kirby Dr. at I-610 WB	Delay (s)	5.2	5.3	1.9%	6.7	6.6	-1.7%
	Saturation flow (vph)	1,781	1,783	0.1%	1,373	1,381	0.6%
Shepherd Dr. at I-10 WB	Delay (s)	38.4	38.5	0.4%	26.1	27.8	6.7%
	Saturation flow (vph)	1,573	1,577	0.3%	1,440	1,445	0.3%

6. 4   Validation of Surrogate Safety Assessment

For the second stage of the simulation-based surrogate safety analysis, the SSAM model (Gettman 2008, Gettman 2003) was used to conduct surrogate safety assessment. SSAM can enable analysts to automatically process the simulated vehicle trajectories to identify traffic conflicts. The software uses two surrogate measures of safety to delineate which vehicle-to-vehicle interactions are classified as conflicts. These surrogate measures include TTC and post-

encroachment time (PET), thresholds for which are predetermined by analysts. In this study, a TTC threshold of 1.5 s (Sayed 1994, Hayward 1972) and a PET threshold of 5.0 s (Hyden 1987) were used to identify traffic conflicts that occurred during the VISSIM micro-simulations. If the TTC and PET of two simulated vehicles during a micro-simulation are less than the predetermined thresholds, the interaction between them is identified as a traffic conflict. After that, according to the conflict angle and the intersection turning paths, the identified traffic conflicts were further categorized into three types, i.e., lane-change, crossing, and rear-end conflicts.

To validate this approach for safety assessment, the estimated total rates of lane-change and crossing conflicts, which are most associated with weaving traffic safety, were compared with the total rates of angle and sideswipe crashes at the three study locations. To check the reasonableness of the predicted weaving conflict frequencies, Spearman's rank analyses and Pearson correlation analyses were performed. The Spearman's rank correlation coefficient was calculated as:

$$R_{\mathrm{S}} = 1 - 6 \cdot \sum \frac{d^2}{N(N^2 - 1)}$$

(6-1)

where d = the difference between ranks, and N = the number of paired ranks.

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Table 16: Comparison between Historical Crash Data and Predicted Frequency of Weaving Conflicts

Intersection	Weaving Crashes [1] (Angle plus sideswipe crash data)	Weaving Conflicts [2] (Lane-change plus crossing conflicts)	Spearman's rank correlation [3]	Pearson correlation [3]
US 59 at Highway 6 NB	2.00	7.2		
Shepherd Dr. at I-10 WB	0.17	0.4	$R_S^2 = 1.000$	$R_P^2 = 0.999$
Kirby Dr. at I-610 WB	0.50	1.5		

Note: [1] Units are crashes per year; [2] units are traffic conflicts per hour; [3] at 95% confidence level.

The results of Spearman's rank correlation coefficient showed that the predicted frequencies of weaving conflicts can reasonably reflect relative rankings of safety performance between the dual right-turn lanes. The Pearson correlation coefficient also exhibited a statistically significant linear association between predicted frequency of weaving conflicts and historical crash rates. Then, the validated approach was used in the following sections to predict the impacts of the installation of dual right-turn lanes on weaving traffic safety.

6.5 Dual Right-Turn Lanes in Mitigating Weaving Conflicts for off-Ramp Right Turns

As illustrated in Figure 6-1, the use of dual right-turn lanes may potentially alleviate weaving conflicts associated with forced merges for off-ramp right-turning vehicles. The following factors may affect the extent to which weaving traffic conflicts can be reduced:

- Weaving distance (between ramp-street junction and right-turn stop line): The effective weaving distance may be reduced further as a result of queues developed at the stop line

- Off-ramp right-turn volume: volume of vehicles exiting from the upstream off-ramp and then turning right at the frontage intersection

- Frontage road volume: volume of conflicting traffic on the frontage roads

- Turn lane arrangement (exclusive vs. shared turn lane on the left of the curb lane)

Using the calibrated micro-simulation models and SSAM, experiments were conducted and sensitivity analyses were performed to show the safety benefits (weaving conflict reduction) from installing dual right-turn lanes under various combinations of the factors.

6.5.1   Design of Experimental Scenarios

Scenarios for Exclusive Dual Right-Turn Lanes

According to the base conditions on US 59 at Highway 6 NB, a set of experimental scenarios was designed for exclusive dual right-turn lanes. The scenarios covered 108 different combinations of assumed traffic conditions and weaving distances, including five different levels of off-ramp right-turn volume (ranging from 20-140 vph), four levels of frontage road volume (ranging from 400-1,000 vph, i.e., 133-333 vphpl), and eight weaving distances (ranging from 100 m to 600 m). For comparison, each scenario includes one sub-scenario with a single exclusive right-turn lane and one sub-scenario with dual right-turn lanes. According to field observations, a lane utilization ratio of about 30% (left-side) vs. 70% (curb) was used as input for the sub-scenarios with exclusive dual right-turn lanes.

Scenarios for Shared Dual Right-Turn Lanes

Similarly, experimental scenarios for shared dual right-turn lanes were designed. According to the base case of Shepherd Dr. at I-10 WB, a set of 36 scenarios with two-lane frontage roads was developed. As shown in Table 4-1 in Chapter 4, a lane utilization ratio of about 3% (left-side) vs. 97% (curb) was input as observed for the sub-scenarios with shared dual right-turn lanes. The scenarios covered four levels of off-ramp right-turn volume (ranging from 70 to 200 vph), two levels of frontage road volume (i.e., 283 and 333 vphpl), and six weaving distances (ranging from 150 m to 500 m). Note that the experiments were not performed based on the conditions on Kirby Dr. at I-610 WB, because there were some deficiencies in the design of the dual right-turn lanes at that location (e.g., narrow turn lanes with a channelization island), which resulted in some safety issues. Thus, it does not represent a typical geometric design for dual right-turn lanes.

In the simulation experiments, the simulation of each sub-scenario covered 30 simulation minutes after a warm-up period of 15 minutes, and the simulation was conducted with 10 different random number seeds. Each run generated one trajectory file, which was input to SSAM for processing.

6.5.2 Results for Exclusive Dual Right-Turn Lanes

Effects of Weaving Distance on the Reduction of Weaving Conflicts

To illustrate the effects of weaving distance on the frequency of weaving conflicts, two examples are presented using two different levels of off-ramp right-turn volume and a frontage road traffic volume of 1,000 vph (i.e., 333 vphpl on the three travel lanes). Figure 6-1(a) shows the predicted frequencies of weaving conflicts, given a relatively low off-ramp right-turn volume (70 vph). As the weaving distance decreases, the frequency of weaving conflicts increases exponentially for single and dual right-turn lanes, and conflict reduction also increases progressively. Figure 6-1(b) exhibits the frequencies of weaving conflicts for a higher off-ramp right-turn volume level (140 vph), and the safety benefits are much more significant, as is shown by comparing Figure 6-1(a) and 4(b). In Figure 6-1(a), a paired *t*-test at a 95 percent confidence level showed that the frequencies of weaving conflicts are significantly different between single and dual right-turn lanes when the weaving distance is less than 200 m; in Figure 6-1(b), the frequencies are statistically significantly different when the weaving distance is less than 400 m.

(a) Relatively low off-ramp right-turning volume   (b) Relatively high off-ramp right-turning volume
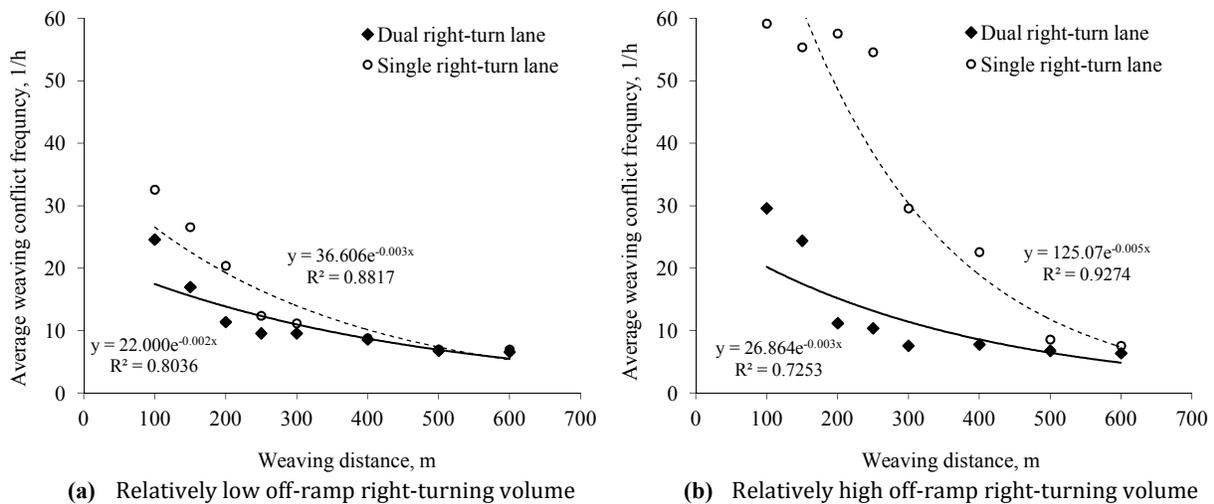
Figure 6-1: Effects of Weaving Distance on Weaving Conflict Frequency

Reduction of Traffic Conflicts due to Exclusive Dual Right-Turn Lanes

Based on the simulation results of the 108 scenarios, a given amount of conflict reduction can be mapped to specific combinations of weaving distance, off-ramp right-turning volume, and frontage road volume. Then, contour lines of weaving conflict reduction due to dual right-turn lanes can be plotted, as shown in Figures 6-2.

The points on the curves represent the same amount of reduction in weaving conflicts on a per hour basis. For example, the solid red line means those conditions under which an average of one weaving conflict can be reduced per hour by installing dual right-turn lanes. Likewise, an average of five weaving conflicts can be eliminated for the conditions depicted by the dotted blue lines. An average of eight weaving conflicts can be eliminated per hour for the conditions depicted by the solid black lines. Then, points in Area A indicate that less than one conflict can be eliminated per hour by converting a single right-turn lane to a dual right-turn lane. Points in Area B indicate that the conditions under which weaving conflicts can be reduced by one to five conflicts per hour. Area C indicates the conditions under which conflicts can be reduced by five to eight per hour, and Area D indicates the conditions under which conflicts can be reduced by eight or more per hour. For example, a weaving distance of 250 m, an off-ramp right-turn volume of 120 vph, and a frontage road volume of 1,000 vph will fall into Area D, as shown in Figure 6-2 (a), which means that conflicts can be reduced by more than eight per hour by installing dual right-turn lanes as opposed to using single right-turn lane operations.

By comparing Figures 6-2(a), (b), and (c), we can see that the potential of dual right-turn lanes for reducing weaving traffic conflicts decreases as the frontage road volume decreases. For example, for a weaving distance of 250 m and an off-ramp right-turn volume of 80 vph, the conflict reduction is greater than five conflicts per hour given a frontage road volume of 1,000 vph, while the reduction is less than one conflict per hour given a frontage road volume of 400 vph.
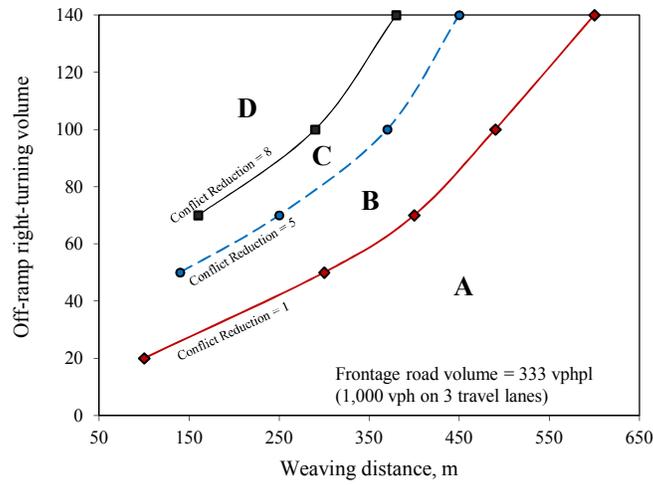
(a) Relatively high conflicting volume of frontage road
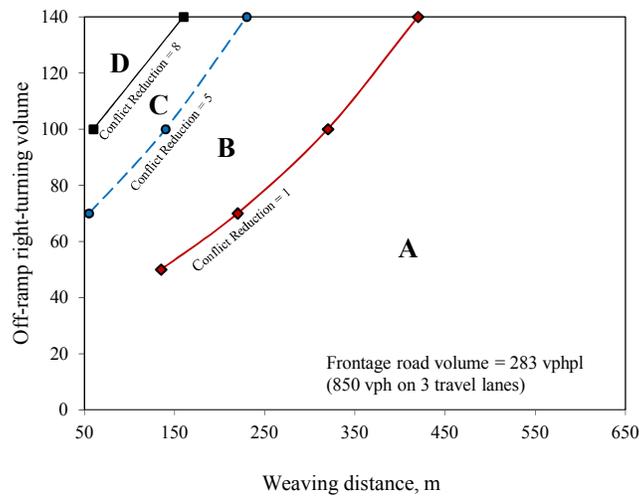
(b) Moderate conflicting volume of frontage road
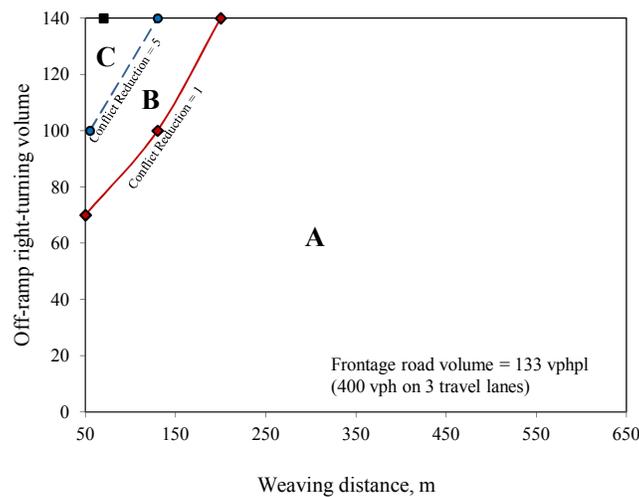
(c) Relatively low conflicting volume of frontage road

Figure 6-2: Contour Lines of Weaving Conflict Reduction Due to Installing Exclusive Dual Right-Turn Lanes

6.5.3 Results for Shared Dual Right-Turn Lanes

1) *Effects of Weaving Distance on the Reduction of Weaving Conflicts*

Two additional examples are presented, given two levels of off-ramp right-turn volume (140 vph and 200 vph) and the same frontage road traffic volume (333 vphpl) as was used in the examples shown in Figure 6-1. Figure 6-3 shows the predicted frequencies of weaving conflicts. By comparing Figure 6-3(a) with Figure 6-3(b) which had the same traffic volume conditions, we can see that a significantly less reduction of weaving conflicts was achieved due to shared dual right-turn lanes as opposed to exclusive dual right-turn lanes.

(a) Relatively low off-ramp right-turning volume   (b) Relatively high off-ramp right-turning volume
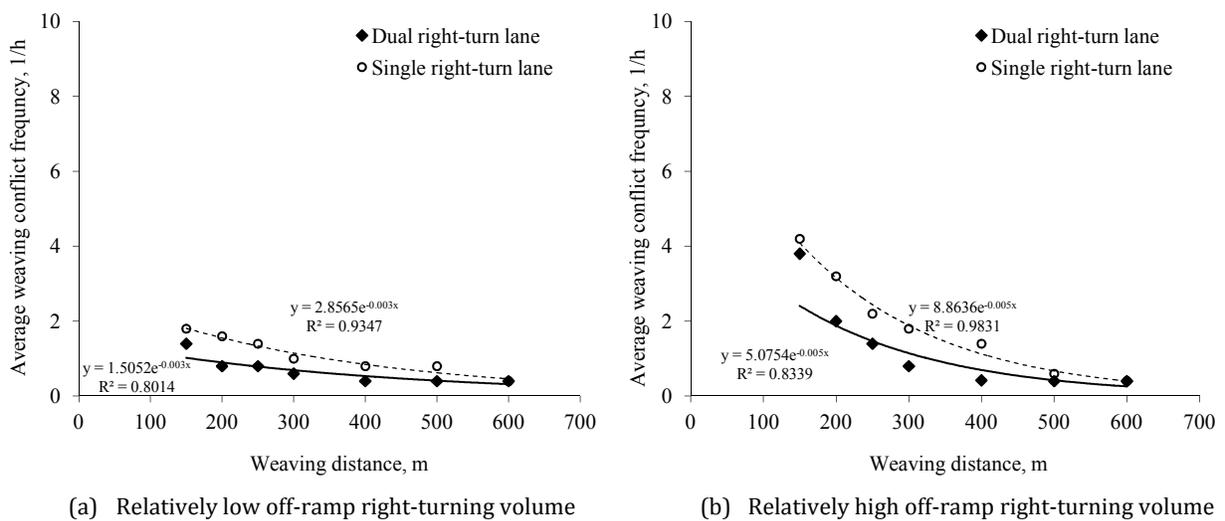
Figure 6-3: Effects of Shared Dual Right-Turn Lanes on the Frequencies of Weaving Conflicts

2) *Reduction of Traffic Conflicts due to Shared Dual Right-Turn Lanes*

Figure 6-4 shows the contour lines of reduction in traffic conflicts due to installing shared dual right-turn lanes. Compared to exclusive dual right-turn lanes, the reduction of weaving traffic conflicts is significantly less, given the same weaving traffic volumes and weaving distance. We hereby take the previously mentioned example to show this point. With shared dual right-turn lanes, a combination of a weaving distance of 250 m, an off-ramp right-turn volume of 120 vph, and a frontage road volume of 333 vphpl resulted in a conflict reduction that falls into Area A in Figure 6-4(a). This indicated that conflicts can be reduced by less than one per hour. Recall that a reduction of more than eight conflicts per hour resulted from installing exclusive dual right-turn lanes given the same conditions. The underlying reason is the relatively low

utilization ratio of the left-side, shared right-turn lane (Table 6-1). Fewer off-ramp right-turning drivers may take advantage of the left-side turn lane to avoid forced merges.

(a) Relatively high conflicting volume of frontage road

(b) Relatively low conflicting volume of frontage road
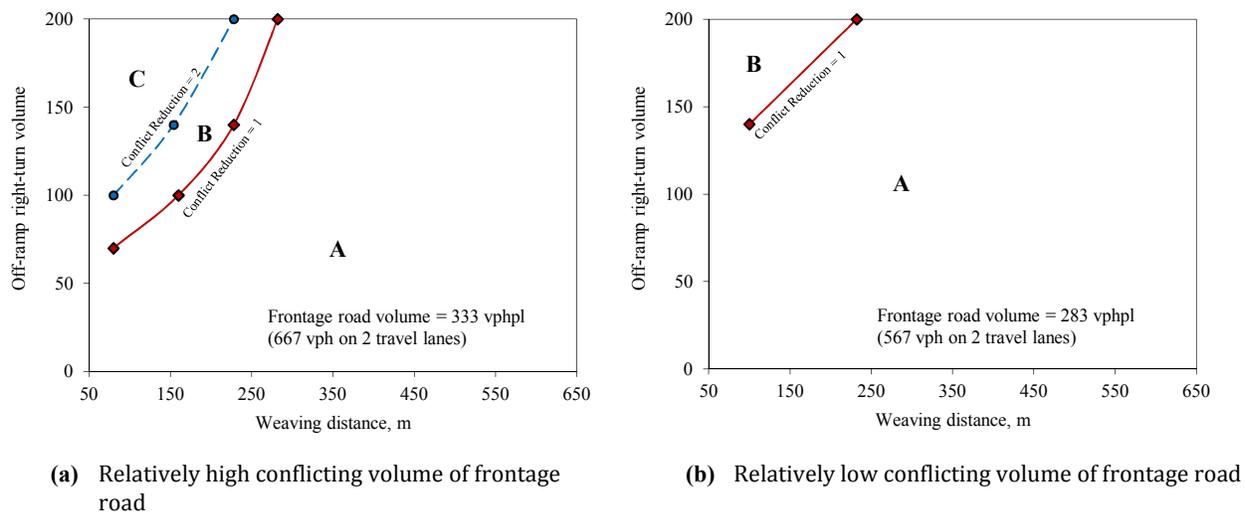
Figure 6-4: Contour Lines of Reduction in Traffic Conflicts Due to Installing Shared Dual Right-Turn Lanes

6. 6   Impacts of Dual Right-Turn Lanes Upstream of and Close to on-Ramps

As shown in Figure 3-3, the use of dual right-turn lanes may mitigate weaving traffic conflicts when a large number of right-turning vehicles turn from a frontage road intersection to a closely-spaced, downstream on-ramp. Simulation experiments were performed to test this hypothesis. Each experimental scenario included a sub-scenario with a single right-turn lane and a sub-scenario with exclusive dual right-turn lanes. Three different levels of right-turn-to-ramp volumes (70, 150, and 200 vph) were used in the tests. The numerical results indicated that the weaving traffic streams generally do not present major safety concerns, even with a short weaving distance of 75 m and a high right-turn-to-ramp volume of 200 vph. Therefore, the contribution of dual right-turn lanes is negligible.

The predicted results can be explained and justified by our field observations: the signal control separated right-turn-to-ramp traffic from the cross-street traffic stream (or opposing left-turns that are typically controlled by a protected phase) when the right-turning vehicles received a green signal indication. The interactions between right-turn-to-ramp traffic and frontage road traffic only occurred during RTOR periods. During RTOR periods, it was observed that only a very small portion of drivers took risky gaps to turn right on red, which might lead to weaving

conflicts. Most right-turning drivers were cautious and did not turn unless a sufficiently large gap was available in the cross-street traffic stream.
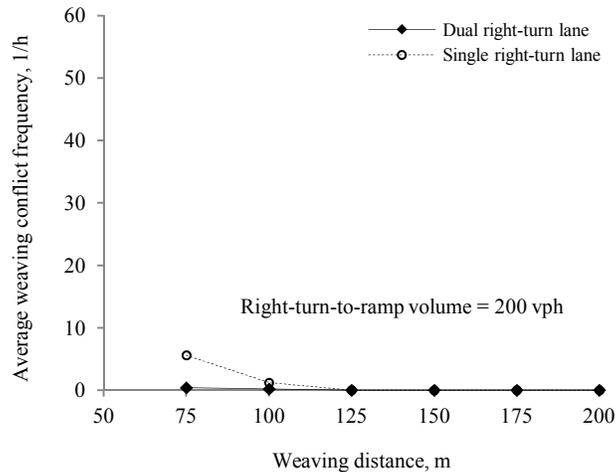
Figure 6-5: Effects of Weaving Distance on Weaving Conflicts with High Right-Turn-To-Ramp Volume

6. 7   Summary

In this study, we investigated the impacts of installing dual right-turn lanes on weaving traffic safety at frontage road intersections in proximity to freeway ramps. Instead of actual crash rates, traffic conflicts were used as a crash surrogate. Micro-simulation models were developed and calibrated based on field data. The results of the simulation-based surrogate safety analysis were validated by comparison with historical crash rate data, and the method was used to predict safety benefits from dual right-turn lanes compared to single right-turn lane operation. The following conclusions can be drawn:

(1)   Experimental results showed that the simulation-based surrogate safety analysis is capable of predicting relative crash potentials for dual right-turn lanes at signalized intersections.

(2)   In the weaving segments between a freeway off-ramp and a downstream, closely-spaced frontage road intersection, the safety benefits from dual right-turn lanes generally increase exponentially with weaving traffic volumes, and they increase exponentially as weaving distance decreases. Due to lower lane utilization ratios, the safety benefits from shared dual right-turn lanes are significantly less than exclusive dual right-turn lanes.

(3)   Dual right-turn lanes located close upstream of an on-ramp typically do not lead to significant reductions of weaving conflicts.

The results of this chapter can help transportation engineers and designers better understand the safety benefits of dual right-turn lanes and make better decisions in designing right-turn lanes at frontage road intersections in proximity to freeway ramps.

References

Cooner A. S. et al., <u>Development of Guidelines FOR Triple Left and Dual Right-Turn Lanes: Technical Report</u>. Publication FHWA/TX-11/0-6112-1. FHWA, U.S. Department of transportation, 2011.

Darzentas, J., D.F. Cooper, P.A. Storr, and M.R.C. McDowell. Simulation of Road Traffic Conflicts at T-Junctions. <u>Simulation, 1980</u>, 34 (5), pp. 155–164.

Eisele, W.L., and W.E. Frawley. Estimating the Impacts of Access Management with Micro Simulation: Lessons Learned. Presented at <u>6th National Conference on Access Management</u>, Kansas City, Mo., 2004.

Garber, N.J., and Q. Liu. Identifying Impact of Truck-Lane Restriction Strategies on Safety by Using Simulation. Presented at <u>86th Annual Meeting of the Transportation Research Board</u>, Washington, D.C., 2007.

Gettman, D., L. Pu, T. Sayed, and S. Shelby. <u>Surrogate Safety Assessment Model and Validation</u>. Publication FHWA-HRT-08-051. FHWA, U.S. Department of Transportation, 2008.

Gettman, D., and L. Head. Surrogate Safety Measures from Traffic Simulation Models. In <u>Transportation Research Record</u> 1840, TRB, National Research Council, Washington, D.C., 2003, pp. 104–115.

Hayward, J.C., Near-Miss Determination through Use of a Scale of Danger. <u>Report No. HRR 384. Highway Research Board</u>, pp. 24–35, 1972.

Hyden, C., <u>The Development of a Method for Traffic Safety Evaluation: The Swedish Conflicts Technique</u>. Department of Traffic Planning and Engineering, Lund University: Sweden, 1987.

Laureshyn, A., A. Svensson, and C. Hydén. Evaluation of Traffic Safety, Based on Micro-Level Behavioural Data: Theoretical framework and first implementation. <u>Accident Analysis</u>

and Prevention, 2010, 42 (6), pp. 1637–1646.

Minderhoud, M., and P. Bovy. Extended Time to Collision Measures for Road Traffic Safety Assessment. Accident Analysis and Prevention, 2001, 33 (1), pp. 89–97.

Ozbay, K., H. Yang, B. Bartin, and S. Mudigonda. Derivation and Validation of New Simulation-Based Surrogate Safety Measure. In Transportation Research Record 2083, TRB, National Research Council, Washington, D.C., 2008, pp. 105–113.

Parker, M.R., and C.V. Zegeer. Traffic Conflict Techniques for Safety and Operations: Observers Manual. Publication FHWA-IP-88-027. Federal Highway Administration, U.S. Department of Transportation, 1989.

Sayed, T., Brown, G., and Navis, F., Simulation of Traffic Conflicts at Unsignalized Intersections with TSC-Sim. Accident Analysis and Prevention, Vol.26, No. 5, pp. 593 607, 1994.

Tarko, A.P. Surrogate Events in Modeling Traffic Safety: A Road Departure Case. Presented at 90th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.

Zegeer, C.V., and R.C. Deen. Traffic Conflicts as a Diagnostic Tool in Highway Safety. In Transportation Research Record 667, TRB, National Research Council, Washington, D.C., 1978, pp. 48–55.

CHAPTER 7: DEVELOPMENT OF WARRANTS FOR DUAL RIGHT-TURN LANES

The purpose of this chapter is to develop warrant and comprehensive guidelines to support the decision making process related to dual right-turn lanes. The warrants and guidelines were developed in light to the results of previous chapters:

- Reviewed literature including existing DOT design guidelines on dual right-turn lanes, existing warrants for single right-turn lanes, and studies on right-turn lanes design and operations (Chapter 2);
- Results of survey of traffic engineers (Chapter 3);
- Conflict reduction due to dual right-turn lanes when the subject intersection is a frontage road intersection in proximity to freeway ramps (Chapter 6).

Warrant 1: Typical conditions when dual right-turn lanes shall be considered as an alternative

The use of dual right-turn lanes should be considered if one of the following criteria is met for the intersections with single right-turn lane:
  A. When the right-turn volume of the subject right-turn movements is higher than 500 vph;
  B. The calculated length of a single turn lane becomes prohibitive;
  C. The volume to capacity ratio for the single right-turn lane is greater than or equal to 0.90, or LOS is worse than D.

This warrant was developed based on the results of literature review and survey of traffic engineers. Warrant 1-A was proposed based on the results of traffic engineer survey. The right-turn volume thresholds proposed by the surveyed traffic engineers includes 300 vph (1 response), 400 vph (2 responses), 500 vph (4 responses), 600 vph (2 responses), and 800 vph (2 responses). The threshold of 500 vph was suggested because it received the highest response rates. Additionally, according to HCM recommendations, an exclusive right-turn lane should be considered if the right-turn volume exceeds 300 vph and the adjacent mainline volume exceeds 300 vphpl, which implies the typical upper-limit volume that a shared through/right-turn lane can accommodate. Generally, the maximum volume that an exclusive signal right-turn lane can accommodate is around 500-600 vph. When the right-turn volume reaches this level, dual right-turn lanes may be considered for improved operational performance.

Warrant 1-B is proposed based on the reviewed literatures. Several states (Illinois, Connecticut, Indiana, and Maine) have proposed that, when 1) there is not sufficient space to provide the calculated length of a single turn lane; or 2) when the 95-percentile queue length exceeds the storage length of a single exclusive right-turn lane, dual right-turn lanes should be considered. We concluded these two conditions as "The calculated length of a single turn lane becomes prohibitive".

Warrant 1-C is based on both the literature review and survey. The v/c ratio or LOS is another threshold for determining whether single right-turn lane is enough for accommodating relatively large right-turn volume.

Note that these suggested thresholds (e.g. regarding right-turn volume, queue length, and LOS) are only general guidance, which can suggest to traffic engineers the use of dual right-turn lanes as an alternative design. When a specific intersection is under analysis, an engineering study should be conducted for evaluating the intersection operational performance under, before, and after conditions. The final decisions regarding the use of dual right-turn lanes should be based on the results of engineering study.

Warrant 2: Use of exclusive dual right-turn lanes for mitigating weaving conflicts at the intersections on frontage roads

For a frontage road intersection at the downstream of a off ramp location , as shown in Figure 7-1, when the point of weaving distance (the distance between the freeway off-ramp and the intersection) plotted against off-ramp right-turning volume is in the areas of C or D, exclusive dual right-turn lanes should be considered.
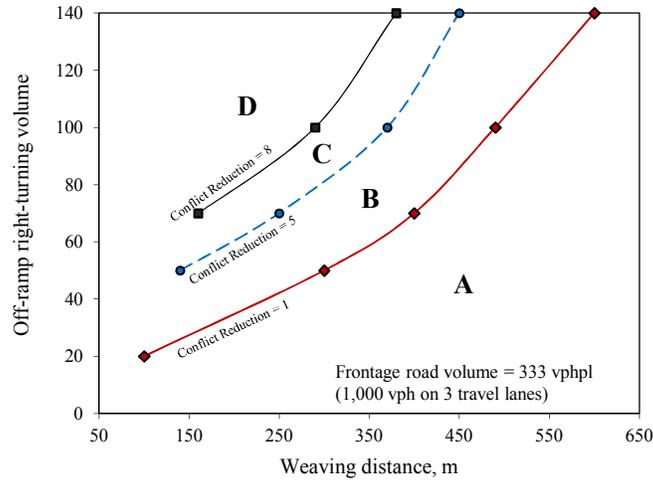
(a) Relatively high conflicting volume of frontage road
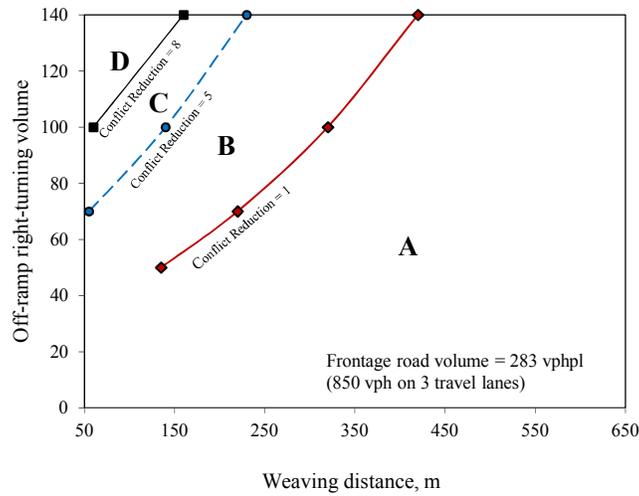
(b) Moderate conflicting volume of frontage road
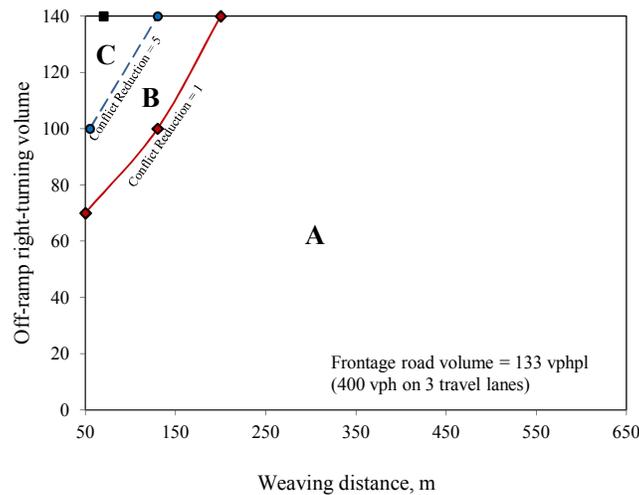
(c) Relatively low conflicting volume of frontage road

Figure 7-1: Weaving Conflict Reduction Due to the use of Exclusive Dual Right-Turn Lanes

The warrant is based on the findings in Chapter 6 (safety analysis associated with weaving conflicts). In the weaving segments between a freeway off-ramp and a downstream frontage road intersection, the safety benefits from dual right-turn lanes generally increase exponentially with weaving traffic volumes, and they increase exponentially as weaving distance decreases. Figures 7-1 (same as Figures 6-2) can be used for estimating how much traffic conflicts can be reduced as the results of use of dual right-turn lanes. Note that, due to lower lane utilization ratios, the safety benefits from shared dual right-turn lanes are significantly less than exclusive dual right-turn lanes.

In addition, guidelines associated with the choice of exclusive or shared dual right-turn lanes, and the RTOR operation of dual right-turn lanes, were concluded in the following paragraphs.

Guideline 1: Exclusive dual right-turn lanes vs. shared dual right-turn lanes

The use of exclusive dual right-turn lanes is preferred when
- More capacity enhancement is desired
- Right-turn overlap phasing is in use

The use of shared dual right-turn lanes is preferred when
- More flexibility is needed to use an optional lane
- Less impacts on the adjacent through movement is desired
- Right-of-way for providing an additional turn lane is restricted

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The guideline is based on the findings in Chapter 2 (literature review), Chapter 3 (survey of traffic engineers), and Chapter 6 (safety analysis associated with weaving conflicts). Generally, shared dual right-turn lanes are characterized by a low utilization ratio of the shared through/right-turn lane.

Guideline 2: RTOR operations with dual right-turn lanes

RTOR should typically be allowed for both of the right-turn lanes in a dual right-turn lane group. Traffic engineers should consider prohibiting RTOR on both turn lanes, when the following conditions are present at the subject intersection:

- Insufficient sight distance
- Frequent presence of pedestrians
- Use of split phase
- Significant U-turns from right-hand cross-street
- High crash history
- High-speed road, onto which subject RTOR vehicles turns
- Inadequate capacity of receiving lanes

The guideline is based on the findings in Chapter 3 (survey of traffic engineers).

CHAPTER 8: KEY FINDINGS AND RECOMMENDATIONS

This research project achieved its primary goals: to develop guidelines on the installation of dual right-turn lanes at signalized intersections. The research team performed the following primary tasks to fulfill the project goal:

- Reviewed and synthesized existing guidelines and research on dual right-turn lanes.

- Conducted survey of traffic engineers to solicit professional opinions regarding the use of dual right-turn lanes.

- Conducted field study and collected field data for analyzing operations and safety of dual right-turn lanes.

- Developed analytical model for predicting capacity of dual right-turn lanes, including capacity for RTOG and RTOR.

- Conducted micro-simulation experiments to quantify effects of dual right-turn lanes on mitigating weaving traffic conflicts at frontage road intersections in proximity to freeway ramps;

- Developed warrants and comprehensive guidelines for the installation of dual right-turn lanes.

8. 1   Summary of Key Findings

The researchers reviewed the existing states guidelines and research on dual right-turn lanes, and found that among 50 states, only a total of 10 state DOTs' Highway/Roadway Design Manuals provide relevant guidelines on dual right-turn lanes. None of these guidelines provide quantitative warrants or a complete set of standards as provided for single right-turn lanes. The review results indicated that the use of dual right-turn lanes have not received enough attention yet although they are in wide use. Published studies regarding the operation and safety of dual right-turn lanes are almost non-existent.

The nationwide survey of traffic engineers revealed that:

- Dual right-turn lanes are mainly used to accommodate high right-turn volume, and to mitigate frequency of traffic conflicts.

- Exclusive dual right-turn lane is more preferable than shared dual right-turn lane to traffic engineers.

- A significant number of dual right-turn lanes are installed on freeway frontage or service roads, followed by arterials, seldom used on collectors, no one reports the use of dual right-turn lanes on local streets.

- In practice, dual right-turn lanes are installed based on engineering judgment, right-turn volume, and limited right-turn capacity as a result of traffic conditions and signal timing. However, there are no set criteria for engineers to follow at present when they install dual right-turn lanes.

- Nearly half of the engineers think RTOR should be allowed for both right-turn lanes, except the location has some problem to preclude it, for example, insufficient sight distance, frequent presence of pedestrians, presence of RTOR-related crash history, etc.

- Protected right-turn phasing (or right-turn overlap) should be used when (a) there is heavy right-turn volume; (b) for two exclusive right-turn lanes only; (c) there is parallel left-turn phase; (d) there is a heavy opposing left movement; (e) the sight distance is not good; (f) vehicles turn right onto a high speed road, etc.

To predict the capacity of dual right-turn lanes, an analytical model for predicting lane-specific RTOR capacities of dual right-turn lanes with three typical lane arrangements was developed. In the proposed model, both the stop-sign analogy and overlapping left-turn phases were considered. Probabilistic methods were adapted to adjust the results for the left-side shared through/right-turn lane. Micro-simulation models were developed, calibrated based on field data, and used as benchmarks to validate the proposed model. Based on the experimental results, the following conclusions can be drawn:

- Compared to Harders's model, the proposed model generally shows an improved capability of predicting RTOR capacities for dual right-turn lanes by capturing different levels of impedance of traffic streams on different cross-street lanes. The improvement is particularly significant compared to the classical Harders's model.

- It is critically important to the performance of Harders's model to determine the conflicting flow volume appropriately. By using a weighted conflicting traffic volume, the capacity estimates yielded by Harders's model can be improved. To estimate

capacities for the curb right-turn lanes, a weight of 0.57 assigned to the volume of Lane 2 can lead to a minimized MAPE. For capacities of the left-side exclusive right-turn lane, a weight of 1.45 assigned to the volume of Lane 1 can minimize the MAPE. These results are limited in scope of application due to the small training sample size. The Harders's model with weighted conflicting volumes may be limited in application as a result of the difficulty in obtaining an adequate number of training data samples of RTOR capacities.

- Existing probabilistic methods developed by Tarko (*3*) and Creasey et al. (*4*) can be adapted to make reasonable adjustments to the estimated RTOR capacity for left-side shared through/right-turn lanes with and without a channelization island.

The researchers investigated the impacts of installing dual right-turn lanes on weaving traffic safety at frontage road intersections in proximity to freeway ramps. Instead of actual crash rates, traffic conflicts were used as a crash surrogate. Micro-simulation models were developed and calibrated based on field data. The results of the simulation-based surrogate safety analysis were validated by comparison with historical crash rate data, and the method was used to predict safety benefits from dual right-turn lanes compared to single right-turn lane operation. The following conclusions can be drawn:

- Experimental results showed that the simulation-based surrogate safety analysis is capable of predicting relative crash potentials for dual right-turn lanes at signalized intersections.

- In the weaving segments between a freeway off-ramp and a downstream, closely-spaced frontage road intersection, the safety benefits from dual right-turn lanes generally increase exponentially with weaving traffic volumes, and they increase exponentially as weaving distance decreases. Due to lower lane utilization ratios, the safety benefits from shared dual right-turn lanes are significantly less than exclusive dual right-turn lanes.

- Dual right-turn lanes located close upstream of an on-ramp typically do not lead to significant reductions of weaving conflicts.

- The results of this research can help transportation engineers and designers better understand the safety benefits of dual right-turn lanes and make better decisions in designing right-turn lanes at frontage road intersections in proximity to freeway ramps.

8. 2   Recommendations of the Project

Based on this research, well-designed dual right-turn lanes can provide enhanced right-turn capacity and reduce the resulting delays at intersections with high right-turn volume. They can also mitigate frequency of traffic conflicts at frontage road intersections in proximity to freeway ramps. It is recommended to install dual right-turn lanes at intersections with high right-turn volume or intersections at frontage road intersections in proximity to freeway ramps which with frequent traffic conflicts. When implementing dual right-turn lanes, the choice between the two exclusive right-turn lanes and one exclusive right-turn lane plus one shared right-turn lane should be considered carefully. RTOR and right-turn overlap are also needed to be evaluated for implementation for dual right-turn lanes. Engineering studies are recommended to be conducted for specific intersections on the installation of dual right-turn lanes.