1. Report No. SWUTC/12/161242-1	2. Government Accession No.	Recipient's Catalog No.	
4. Title and Subtitle Evaluating Safety Performance and Developing Guidelines for the Use of Right Turn on Red (RTOR)		5. Report Date December 2012	
		6. Performing Organization Code	
7. Author(s) Qi Yi, Xiaoming Chen and Da Li		8. Performing Organization Report No. Report 161242	
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 A&M 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

This research project investigates the safety performance of Right Turn on Red (RTOR) at intersections. Also, new design alternatives, such as dual right-turn lanes and guidelines incorporating the use of RTOR at intersections are evaluated. To this end, the following tasks were performed: (1) review literature on safety performance of RTOR, (2) review literature on driver behavior under RTOR operation, (3) synthesize best practices and existing guidelines on RTOR, (4) conduct field study to investigate driver behavior under RTOR operation at dual right-turn lanes, and (5) develop guidelines for the use of RTOR.

The results of this study showed that RTOR operations contributed to only a small portion of the total crashes at the intersections, and RTOR operations did not increase the crash rates after the implementation at the intersections. In this study, according to the existing guidelines and the field observation, a set of comprehensive guidelines were developed to support decision-making on the use of RTOR

17. Key Words Right Turn On Red, Guidelines, 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 59	22. Price

Evaluating Safety Performance and Developing Guidelines for the Use of Right Turn on Red (RTOR)

By

Yi Qi, Ph.D.

Xiaoming Chen, Ph.D.

Da Li, E.I.T.

Texas Southern University

3100 Cleburne Avenue

Houston, TX 77004

December 2012

ABSTRACT

This research project investigates the safety performance of Right Turn on Red (RTOR) at intersections. Also, new design alternatives, such as dual right-turn lanes and guidelines incorporating the use of RTOR at intersections are evaluated. To this end, the following tasks were performed: (1) review literature on safety performance of RTOR, (2) review literature on driver behavior under RTOR operation, (3) synthesize best practices and existing guidelines on RTOR, (4) conduct field study to investigate driver behavior under RTOR operations at dual right-turn lanes, and (5) develop guidelines for the use of RTOR.

The results of this study showed that RTOR operations contributed to only a small portion of the total crashes at the intersections, and RTOR operations did not increase the crash rates after the implementation at the intersections. In this study, according to the existing guidelines and the field observation, a set of comprehensive guidelines were developed to support decision-making on the use of RTOR.

Keywords: right turn on red; guidelines; traffic safety

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

NOTICE

Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Trade and manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGEMENTS

EXECUTIVE SUMMARY

The first use of RTOR in the United States occurred in California in 1937. The policy permitted vehicles at a traffic light showing a red signal to turn right (after a complete stop) when the way is clear. RTOR was implemented extensively in other states during the 1970s. Since then, RTOR has been a standard practice and accepted enthusiastically by a majority of drivers. Even though the use of RTOR is very common at today's signalized intersections, current versions of AASHTO Policy on Geometric Design, AASHTO Highway Safety Manual, or Manual of Uniform Traffic Control Devices do not provide detailed guidelines for the use of RTOR, leaving traffic engineers to rely on engineering judgment for their decision-making.

The objective of this research is to develop guidelines on the implementation of RTOR to enable the safety movement of right-turn related vehicles. The benefits and concerns were considered from operational and safety standpoints in this study. To this end, the research team performed the following primary tasks:

- Review Literature on Safety Performance of RTOR
- Review Literature on Driver Behavior under RTOR Operation
- Synthesize Best Practice and Existing Guidelines on RTOR
- Conduct Field Study to Investigate Driver Behavior under RTOR Operations at Dual Right-Turn Lanes
- Develop Guidelines for the Use of RTOR

Existing literatures show that RTOR do not increase crash rates at intersections and most RTOR-related crashes are not serious and commonly involve minor property damage. The previous studies also indicate that a significant number of the drivers do not come to a complete stop before making an RTOR.

In existing guidelines, there are two types on the use of RTOR: I) mandatory criteria for prohibiting RTOR (RTOR shall be prohibited) and, II) optional criteria for prohibiting RTOR (RTOR may be prohibited). In these guidelines, influencing factors related to intersection traffic conditions, geometry features, operational characteristics, environmental conditions and crash experience have been considered. Overall, five mandatory criteria in Group I and eight optional criteria in Group II were summarized in a Table.

To investigate driver behavior under RTOR operations at dual right-turn lanes, field studies were conducted at six intersections with dual right-turn lanes in Houston, Texas. Based on the collected field data, a lane-specific gap-acceptance model was developed capable of representing the unequal effects of conflicting traffic streams from different cross-street lanes on the gap-acceptance decisions of individual RTOR drivers from dual right-turn lanes. These findings can be used to enhance the modeling of the RTOR capacities of dual right-turn lanes.

Finally, according to the existing guidelines and the field observation, a set of comprehensive guidelines were developed to support decision-making on the use of RTOR.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background and Significance of Research

The first use of RTOR in the United States can be traced back to 1937 in California. The policy permitted vehicles at a traffic light showing a red signal to turn right after a complete stop when the way was clear. RTOR was implemented extensively in other states in the1970s. Since then, RTOR has been a standard practice and accepted enthusiastically by the majority of drivers. In the United States, RTOR is allowed at over 80% of the nation's intersections. RTOR operations can provide additional capacity for right-turn lanes, reduce delays for right-turning vehicles, and improve the efficiency of the entire intersection (*1, 2, 3, 4*). However, since RTOR has been in use, there has been ongoing debate about its safety performance. Many studies have been conducted to investigate the safety issues associated with RTOR. The major safety concern about the use of RTOR is that it may increase the risk of right-turn related crashes, especially crashes that involve pedestrians and bicyclists. Permitting RTOR increases the potential for conflicts between RTOR vehicles and the following four types of movements (Figure 1).

a) Cross-street through movement
b) Opposing left-turn movement
c) Cross-street U-turns
d) Cross-street pedestrians
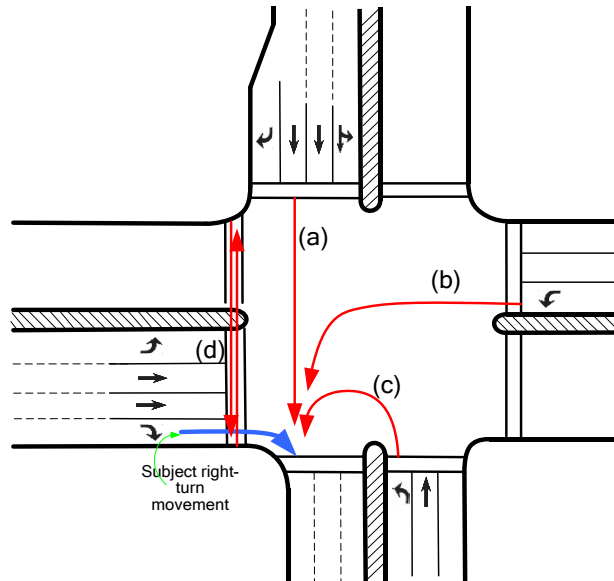
Figure 1   **Illustration of movements potentially conflicting with RTOR vehicles**

The decision of whether RTOR should be allowed at an intersection is based mainly on the safety evaluation of these four types of potential conflicts. However, the current versions of AASHTO Policy on Geometric Design, Highway Safety Manual, or Manual of Uniform Traffic Control Devices do not provide detailed guidelines for the use of RTOR, leaving traffic engineers to rely on engineering judgment for their decision-making. Therefore, there is a critical need to develop appropriate guidelines on the implementation of RTOR to warrant the safety movement of right-turn related vehicles.

1.2   Research Goal and Objectives

The goal of this research is to explore and synthesize the safety performance of RTOR and to provide recommended guidelines. The results of this project will help practitioners improve safety and operational efficiency at urban signalized intersections. To achieve this goal, the research will:

     a.   Review literature on safety performance of RTOR

     b.   Review literature on driver behavior under RTOR operation

     c.   Synthesize best practice and existing guidelines on RTOR

d. Conduct field study to investigate driver behavior under RTOR operations at dual right-turn lanes intersections

e. Develop guidelines for the use of RTOR

1.3   Organization of the Report

In this report, all the research activities performed throughout the project were documented. Chapter 1 presents a brief overview of the research. Chapter 2 summarizes the findings of existing studies on safety performance of RTOR. Chapter 3 describes the results of reviewed literatures on driver behavior under RTOR operation. Chapter 4 presents the efforts of a field study to investigate driver behavior under RTOR operations at dual right-turn lanes intersections. Chapter 5 synthesizes best practice and existing guidelines on RTOR. Chapter 6 develops a set of comprehensive guidelines for the use of RTOR. Chapter 7 concludes with key findings and results of this research.

CHAPTER 2: SAFETY PERFORMANCE OF RTOR

Since the first use of RTOR, studies have been conducted to investigate its safety performance. Most of these studies were conducted from the 1970s to the 1990s — shortly after RTOR operation was widely used in the United States — in order to verify the safety of this new principle. In general, the safety performance studies can be categorized into two groups: 1) historical crash data-based studies and 2) traffic conflict data-based studies.

2.1   Historical Crash Data-Based Studies

There are several studies in which the historical data were analyzed to investigate whether the application of RTOR increases the risk of crashes at intersections. Typically, the data were collected from intersections with and without RTOR or from intersections before and after implementation of RTOR. These reviewed studies include the analysis of RTOR-related crash rates and crash severity levels at different intersections in different cities. The analysis of crash rates reveals that RTOR contributed to only a small portion of the total crashes and did not result in more crashes than right turn on green (RTOG) (5, 6, 7). Comparison of crash rates before and after implementation of RTOR indicates that RTOR did not increase the crash rates at the intersections. The analysis of crash severity levels shows that most RTOR-related crashes were not serious and commonly involved minor property damage (8). Also, several studies (7, 9, 10) found that only a small portion of the crashes involved pedestrians and bicyclists when vehicles were turning right on red. Even though some studies (5, 8) show that RTOR increased the frequency of right-turning crashes at signalized intersections, especially crashes involving pedestrians and bicyclists, the percentage of these increased crashes were not significant. The literature sources reviewed and the major findings of those sources are summarized in Table 1.

Table 1   Summary of historical crash data-based studies of RTOR

Year	References	Study Locations	RTOR-Related Crash Rates	Pedestrian and Bicyclists Involved Crashes	RTOR-Related Crash Severity Levels	Conclusions
1956	Ray (*6*)	San Francisco	• 0.3% of total crashes at intersections • 12% of right turn-related crashes			• The percentage of RTOR crashes is small. • RTOR is no more hazardous than RTOG.
1976	Love (*7*)	Colorado, Virginia, Denver, Dallas, Chicago, and Los Angeles	• 0.61% of total crashes at intersections • A smaller percentage than for RTOG	• Small portion of RTOR-pedestrian/bicyclist crashes		• The percentage of RTOR crashes is small. • The number of pedestrians involved in RTOR crashes is small. • RTOR crashes occur less frequently than RTOG crashes.
1975	Parker (*11*)	Virginia	• No significant difference between before (NTOR) and after (RTOR) crash rates		• No significant difference between before (NTOR) and after (RTOR) crash rates for personal injury and property damage only crashes	• There is no significant difference between crash rates before and after the implementation of RTOR.
1978	Parker (*8*)	Virginia	• 0.05% (75 out of 142270) increase in crashes after permitting RTOR at all intersections • 21% decrease in the number of crashes after RTOR for 18 intersections studied	• 4 persons, including 2 pedestrians, were injured as a result of the 75 crashes.	• Most of the crashes were not serious and involved minor property damage. • No fatalities or injuries occurred as a result of the RTOR crashes for the 18 intersections studied.	• Crashes did not increase significantly as a result of RTOR. • RTOR crashes involved few pedestrians. • Most RTOR crashes were not serious.
1994	Compton (*12*)	Illinois, Indiana, Maryland, and Missouri	• 0.4% of crashes at signalized intersections • 0.05% of total traffic crashes	• 22% of RTOR crashes involved pedestrians and/or bicyclists • 93% of RTOR-pedestrian/bicyclist crashes resulted in injury, 1% resulted in fatalities.	• 0.2% of all fatal and injury crashes involved RTOR (including 44% pedestrians, 10% bicyclists, 33% between vehicles)	• RTOR accounts for a small portion of all crashes. • RTOR accounts for a small portion of fatal crashes. • Most RTOR-pedestrian crashes result in injury.

6

Table 1 Summary of historical crash data-based studies of RTOR (continued)

Year	References	Study Locations	RTOR Related Crash Rates	Pedestrian and Bicyclists Involved Crashes	RTOR Related Crash Severity Levels	Conclusions
2002	Lord (*9*)	United States and Canada	• 0.5% of all reported crashes	• 5%-15% of pedestrian crashes implicate a RTOR. • Pedestrian crashes involving RTOR account for less than 1% of all crashes. • The proportion of RTOR-related crashes involving a bicycle is slightly higher than the proportion of pedestrian crashes.	• Fatal RTOR accounts for 0.05% of all reported crashes.	• RTOR accounts for a small portion of all crashes. • Fatal RTOR accounts for a small portion of reported crashes. • There are more RTOR-bicycle crashes than RTOR-pedestrian crashes.
2002	Flerk (*10*)	San Francisco	• 0.45% of all crashes	• RTOR results in 0.8% pedestrian crashes • Pedestrian safety is not improved with NTOR.	• Collisions of RTOG are more severe than RTOR.	• Prohibiting RTOR leads to increasing the number of RTOG, which results in collisions that are more severe than RTOR.
2005	No Turn on Red Implementation Guideline (*5*)	Minneapolis	• 0.6% of crashes at intersections	• Pedestrian crashes increased from 1.47% to 2.28% after RTOR was adopted. • 0.1% of fatal pedestrian crashes result from RTOR. • The probability of vehicle-pedestrian conflict or crash is greater with RTOG than RTOR.		• Pedestrian crashes increased slightly after RTOR was implemented. • The probability of vehicle-pedestrian conflict or crash is greater with RTOG than RTOR.

2.2   Traffic Conflict-Based Studies

As a common perception, major conflicts with RTOR are the cross-street through vehicles and pedestrians, because RTOR vehicles are turning when these two movements have the right-of-way. Several previous studies have analyzed traffic conflicts related to RTOR. Parker et al. (8) found that, 52 of 594 traffic conflicts observed (8.75%) involved RTOR maneuvers. Of these RTOR conflicts, 14 (27%) were opposing left-turn conflicts; 22 (42%) were cross-street traffic conflicts, 12 (23%) were rear-end collisions; and 4 (8%) involved pedestrians. This indicates that most crashes involving a RTOR vehicle are expected to be angle-type crashes (including conflicts with cross-street traffic and opposing left-turn traffic). Additionally, after RTOR was permitted at 17 intersection approaches, the total traffic conflicts decreased by 13.5%, including a decrease in rear-end conflicts and an increase in cross-street traffic conflicts; however, these changes were not statistically significant.

The ITE Technical Council Committee 4M-20 (*13*) analyzed the traffic conflicts between RTOR vehicles and pedestrians, showing that a majority (66.3%) of right-turning vehicles had no conflicts with pedestrians and cross-street traffic, and the percentage of vehicle-pedestrian conflicts was small (about 4.6%).

CHAPTER 3: DRIVER BEHAVIOR UNDER RTOR OPERATION SYNTHESIZED

FROM EXISTING RESEARCH

In 1992, the ITE Technical Council Committee 4M-20 (*13*) observed driver behaviors at 50 intersections with RTOR. The major findings are presented below:

- Although the majority (59.6%) of drivers executing RTOR stopped completely before turning, a significant number (40.4%) of the drivers did not come to a complete stop.
- More than 95% of drivers turned right on red when provided with the opportunity to make such turns.
- Among all vehicles at an RTOR intersection, 39.2% turned right on red, and 60.8% turned right on green.
- For drivers of vehicles who did not make turns on red, about 58.1% of the drivers' vehicles were blocked by vehicles ahead; 21.5% of them were blocked by cross-street traffic; 7.8% were blocked by pedestrians; and 12.6% chose not to make a RTOR.

Yan and Richard (*14*) investigated whether restricted right-turn sight distances have a significant impact on right-turn drivers' behaviors when they are turning right on red. The research compared RTOR behaviors at intersections with and without sight-distance issues and found that restricted sight distance can cause drivers to seriously encroach into pedestrian crossings in order to maximize available sight distances at the intersections, which led to higher non-stop RTOR violation rates and more conflicts with pedestrians/bicycles.

A study conducted by the Federal Highway Administration (FHWA) (*15*) maintains that RTOR is more problematic for older drivers. The results show that older drivers attempt to make an RTOR only 16% of the time, compared to 83% of young/middle-aged drivers.

The other two studies investigated driver abidance of RTOR. The No Turn on Red Implementation Guideline by the City of Minneapolis (*5*) indicates that allowing RTOR results in an increase of vehicles not coming to a complete stop prior to proceeding. Approximately 35% to 56% of vehicles with the opportunity to turn right on red did not come to a complete stop. This was compared to 68% of vehicles that did not come to a complete stop at intersections controlled by stop signs.

Parker et al. (*8*) found that out of 1,091 RTOR maneuvers, 11% of motorists did not come to a

complete stop. However, no serious vehicle or pedestrian conflicts were observed as a result of motorists not stopping completely.

Note that the results of all of these previous studies indicate that a significant number of the drivers did not come to a complete stop before making an RTOR, which may explain the recent experiences with red-light-running camera enforcement that has resulted in a large proportion of tickets being issued to people who fail to completely stop before making right turns.

CHAPTER 4: DRIVER BEHAVIOR UNDER RTOR OPERATION AT DUAL RIGHT-TURN LANES

In recent decades, dual right-turn lanes have been used increasingly at signalized intersections in the United States in response to the high volumes of turning traffic on urban roadways. Existing literature shows that there are few studies on RTOR operations on dual right-turn lanes. At dual right-turn lanes, field observation showed behavioral patterns that are more complicated as opposed to single right-turn lanes. The objective of this chapter is to characterize RTOR drivers' behaviors at dual right-turn lanes, so as to provide more understanding of RTOR operations and to fill the existing research gap.

Operational performance of RTOR at signalized intersections is a function of drivers' gap-acceptance behavior. The concept of gap-acceptance is based on defining the extent to which drivers in a minor movement will be able to utilize a gap of a particular duration in a major movement (*16*). In conventional, deterministic gap-acceptance method, it is commonly assumed that drivers of a minor movement have a "critical gap (or critical headway)" for a specific maneuver, and they will accept a gap (or headway) if its duration is longer than the critical gap (or critical headway); otherwise, they will reject it. Based on this assumption, a large number of analytical and simulation models have been developed for assessing operational performances of minor movements, e.g., capacity and delay. On the other hand, prior research has shown that the critical gap for a certain maneuver typically varies between drivers and over time (*17*). Discrete-choice modeling of individual gap-acceptance decisions holds great promise for better representing gap-acceptance behavior and for straightforward integration with traffic simulation models (*18,19*), which can potentially enable analysts to better evaluate the operational performances of minor movements.

4.1   Existing Discrete Choice Models for Gap-Acceptance

As an emerging branch of gap-acceptance theory, the use of discrete choice models to represent gap-acceptance behavior has received increasing attention since Daganzo (*18*) used a multinomial probit model to estimate the distribution of the mean and variance of the gap-acceptance function for a population of individuals. The discrete-choice modeling approach allows estimation of individual gap-acceptance function parameters while overcoming two

potential limitations of the traditional, deterministic methods as pointed out by Miller (*17*), i.e., (1) only the mean critical gap across the population is estimated and (2) cautious drivers may be over-represented as a result of information loss.

Several gap-acceptance models have been developed that have great similarities to the classical discrete-choice models of transportation planning (*20, 21*). For example, using a probit-based modeling framework, Mahmassani and Sheffi (*19*) concluded that, on average, the critical gap of individual drivers is decreasing as they are waiting for an acceptable gap. The authors stated that the integration of the probit model with traffic simulation models can be implemented straightforwardly while capturing a high level of detail concerning individual driver behavior. Following a similar approach, Taylor and Mahmassani (*22*) explored a variety of factors that may impact the gap-acceptance behavior of bicyclists and drivers in mixed traffic. Gap-acceptance decisions were modeled using probit models from observations of cyclist and driver behavior when crossing and merging at two-way stop-controlled intersections. Statistically significant attributes were identified, including e.g., the types of turn maneuvers and the types of conflicting vehicles that define the end of gaps. Huang and Wu (*23*) focused on the gap-acceptance behavior of cyclists that cross the conflicting traffic flow at signalized intersections. Significant attributes to the proposed probit function included whether the subject vehicle comes to a complete stop before crossing and the types of conflicting vehicles that define the end of gaps. Liu et al. (*24*) developed a binary logit model to identify the gap-acceptance characteristics of U-turning drivers at median openings. The results indicated that the width of the median at a median opening has a significant effect on the gap-acceptance decisions of U-turning drivers. Generally, the existing research has provided deep insights and excellent resources for this study, showing discrete choice models very promising for use in predicting drivers' gap-acceptance decisions.

So far, the gap-acceptance characteristics of RTOR drivers turning from dual right-turn lanes are not clearly known and have received little attention from the transportation research community. Thus, the discrete-choice modeling approach has the potential to better represent the behavioral patterns and help identify the attributes that significantly affect how gap-acceptance decisions are made on dual right-turn lanes.

4.2   Modeling Gap-Acceptance Behavior on Dual Right-Turn Lanes

Attributes Considered

Typically, dual right-turn lanes are comprised of an exclusive right-turn lane as the curb lane and, to the left of the curb lane, a second right-turn lane that is referred to as the "inside right-turn lane" in this study. The inside right-turn lane can be either an exclusive right-turn or a shared through/right-turn lane. As shown in Figure 2, RTOR vehicles departing from the curb lane commonly merge onto Receiving Lane 1 when an acceptable gap appears in the conflicting flows, and vehicles departing from the inside right-turn lane typically turn onto Receiving Lane 2. The potential conflict zone is shown in Figure 2.
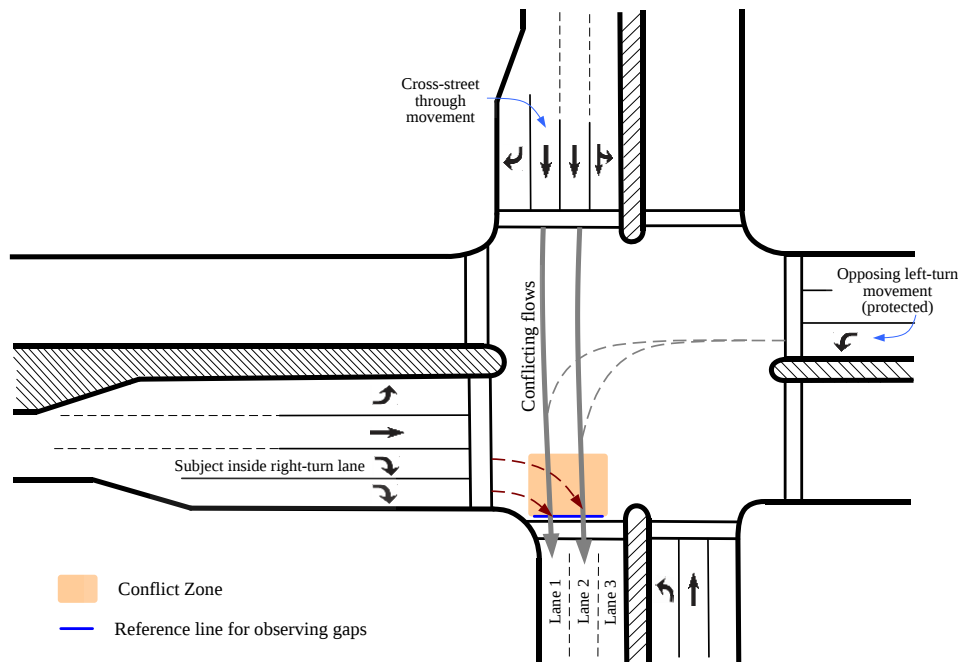
Figure 2   RTOR maneuvers from dual right-turn lanes

The following principles were used in the selection of the attributes: 1) the selected attributes have been proven by prior research to have significant effects on gap-acceptance maneuvers, and/or 2) the selected attributes can be either directly observed or easily estimated from field observation, which will allow the seamless integration of the results in this study into traffic simulation models in the future. The attributes considered and observed in this study are shown as Table 2.

Table 2   Attributes considered in the study

Attributes considered	Description	Denotation	Note
Sequential number of headways	The sequential number of headways that are present for a specific RTOR vehicle v.	i	The sequential number can be an indicator of waiting time experienced by RTOR vehicle v
Headway size	The duration of the i th headway present for a certain RTOR vehicle v	$h_{v,i}$	The time measured in seconds (s) between the front bumpers of two successive conflicting vehicles passing the observational line in Figure 2
Gap-acceptance decision (accepted or rejected)	Whether a specific headway $h_{v,i}$ is accepted or rejected	$A_{v,i}$	1 = accepted 0 = rejected
Type of subject RTOR vehicle	The vehicle type of a subject RTOR vehicle v	T_v	1 = passenger car 0 = heavy vehicle
Type of closing-gap vehicle [1]	The vehicle type of a closing-gap vehicle for the i th headway when subject RTOR vehicle v is waiting at the stop line	$T_{v,i}$	1 = passenger car 0 = heavy vehicle
Lane positioning of closing-gap vehicle	The position of lane on which a closing-gap vehicle is traveling	$P_{v,i}^1$	$P_{v,i}^1 = 1$ if closing-gap vehicle is from Lane 1 of the cross street; $P_{v,i}^1 = 0$ otherwise
		$P_{v,i}^2$	$P_{v,i}^2 = 1$ if closing-gap vehicle is from Lane 2 of the cross street; $P_{v,i}^2 = 0$ otherwise
Subject RTOR vehicle stopped or not	Rolling stopped or completely stopped	S_v	1 = complete stop 0 = rolling stop

Note: [1] The closing-gap vehicle for a specific headway is the vehicle defining the end of the headway.

Proposed Model Formulation

The proposed discrete choice model is based on the assumption that all gap-acceptance decisions are made independently. After a subject RTOR vehicle v arrives at the stop line and begins to wait for an acceptable gap to merge, a chronological sequence of headways typically includes rejected headways $h_0, h_1, h_2, \ldots, h_n$, which is followed by headway h_{n+1} that is finally accepted. We assume that the individual driver's critical headway at the time when the ith headway is present, $t_{v,i}$, can be formulated as a function of the linear combination of the predictors and a stochastic disturbance term. For curb right-turn lanes, only the conflicting traffic flows on Lanes 1 and 2 may possibly affect the gap-acceptance decisions; thus, $t_{v,i}$ can be written as

$$t_{v,i} = \left(\alpha_0 \cdot t_c + \alpha_1 \cdot T_v + \alpha_2 \cdot T_{v,i} + \alpha_3 \cdot i + \alpha_4 \cdot S_v + \alpha_5 \cdot P_{v,i}^1 \right) + \varepsilon_{v,i} \tag{1}$$

where

14

α_k =   coefficients to be estimated, in which k is the index

t_c =   mean critical headway across drivers merging from a subject right-turn lane onto the target receiving lane (s). Refer to the field-observed values based on maximum likelihood method in the following section entitled "Validation of the Proposed Logit Models"

$\varepsilon_{v,i}$ =   stochastic disturbance term that characterizes the variance between drivers and over time (s)

The other indices and variables in the equation are listed in Table 2.

For driver v turning from curb right-turn lanes, the present headway $h_{v,i}$ will be accepted if it is greater than the individual critical headway $t_{v,i}$ under the given condition of the attributes:

$$\Pr(A_{v,i} = 1) = \Pr(h_{v,i} \geq t_{v,i}) = \Pr\left(\varepsilon_{v,i} \leq h_{v,i} - \left(\alpha_0 \cdot t_c + \alpha_1 \cdot T_v + \alpha_2 \cdot T_{v,i} + \alpha_3 \cdot i + \alpha_4 \cdot S_v + \alpha_5 \cdot P_{v,i}^1\right)\right) \tag{2}$$

In a preliminary analysis of the data acquired in this study, Kolmogorov-Smirnov tests indicated that logistic distributions can fit the critical headways reliably with a p-value of 0.003 for the curb right-turn lanes and a p-value of 0.006 for the inside right-turn lanes. Thus, we assumed that follows logistic distributions across headways and drivers, and the cumulative distribution function can be formulated as:

$$F(\varepsilon_{v,i}) = \frac{1}{1 + e^{-(\varepsilon_{v,i} - \mu)/\sigma}} \tag{3}$$

where μ is the mean, and σ is a scale parameter. The distribution resembles a normal distribution in shape, but it has heavier tails (higher kurtosis).

Then, a logit model can be derived from Equations (2) and (3) and tentatively formulated as:

$$\Pr(A_{v,i} = 1) = \frac{1}{1 + e^{-\left(\beta_0 + \beta_1 \cdot T_v + \beta_2 \cdot T_{v,i} + \beta_3 \cdot i + \beta_4 \cdot S_v + \beta_5 \cdot P_{v,i}^1 + \beta_6 \cdot h_{v,i}\right)}} \tag{4}$$

$$\Pr(A_{v,i} = 0) = 1 - \Pr(A_{v,i} = 1) \tag{5}$$

where β_k is the coefficients to be estimated, $k = 0, 1, 2, ..., 6$. The final formulation depends on the statistical significance of the attributes based on the field-observed data.

For inside right-turn lanes, the conflicting traffic flows on Lanes 1, 2, and 3 may all possibly affect the gap-acceptance decisions; thus, $t_{v,i}$ can be written as:

$$t_{v,i} = \left(\alpha_0 \cdot t_c + \alpha_1 \cdot T_v + \alpha_2 \cdot T_{v,i} + \alpha_3 \cdot i + \alpha_4 \cdot S_v + (\alpha_5 \cdot P_{v,i}^1 + \alpha_6 \cdot P_{v,i}^2) \right) + \varepsilon_{v,i} \tag{6}$$

Likewise, for RTOR drivers from inside right-turn lanes, a logit model can be tentatively written as:

$$\Pr(A_{v,i} = 1) = \frac{1}{1 + e^{-\left(\beta_0 + \beta_1 \cdot T_v + \beta_2 \cdot T_{v,i} + \beta_3 \cdot i + \beta_4 \cdot S_v + (\beta_5 \cdot P_{v,i}^1 + \beta_6 \cdot P_{v,i}^2) + \beta_7 \cdot h_{v,i} \right)}} \tag{7}$$

4.3 Data Collection

To conduct this empirical study, field observations were conducted in Houston, Texas, at six typical intersections with dual right-turn lanes. Videos of field traffic were recorded with observation periods spanning from 6:00 AM to 9:00 AM and from 4:00 PM to 7:00 PM for each of the locations. The characteristics of the study locations are summarized in Table 3.

Table 3   Characteristics of field study sites

Intersection	Type of roadway	Lane allocation [1]	Speed limit, mph (kmph)	Curb pocket lane length, ft (m)	Presence of island	Corner angle	Right-turn volume, vph	% of heavy vehicles	Lane width, ft (m)
US 59 & Highway 6 FR_NB	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)
West Bay Area Blvd. & I-45 FR_EB	Interchange Ramp	↱↱	40 (64.4)	210 (64 m)	No	110°	134	0.58%	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 FR_WB	Frontage Road	↳↱	45 (72.4)	330 (101 m)	Yes	90°	676	4.48%	11 (3.4 m)
Shepherd Drive & I-10 FR_WB	Frontage Road	↳↱	45 (72.4)	300 (91 m)	No	90°	327	4.48%	12 (3.6 m)

Note: [1] RTOR maneuvers are allowed for both curb and inside right-turn lanes at all of the study sites.

By replaying the videos of field traffic on a frame-by-frame basis, the data needed were collected for 346 drivers turning right on red from the curb right-turn lanes and for 198 drivers turning right on red from the inside right-turn lanes. As shown in Table 4, the data associated with each individual driver includes a sequence of headways (one headway in each row) in the conflicting flow, typically beginning with the first headway, which is normally termed as "lag" (*25*), and ending in a finally-accepted headway, if any. The size of a lag was measured from the time when the RTOR driver arrives at the stop line until the next conflicting vehicle arrives at the observational reference line. The sizes of normal headways were calculated by subtracting the time stamp when the front bumper of a leading conflicting vehicle arrives at the reference line from the time stamp when the front bumper of the follow-up conflicting vehicle arrives. For further discussion in this study, lags are treated the same as headways. For a specific headway, the first vehicle defining the presence of the headway is termed as the opening-gap vehicle. Likewise, the vehicle defining the end of the headway is termed as the closing-gap vehicle. Note that different RTOR drivers may wait for a different number of headways before finishing their RTOR maneuvers.

Table 4   Sample data observed in the field

Vehicle ID [1]	Accepted or rejected	Sequential number of headways	Headway size, s	Type of subject RTOR vehicles	Type of closing-gap vehicles	Lane position of closing-gap vehicles	Subject RTOR stopped or not
…				…			…
35	0	0	5.8	passenger car	passenger car	Lane 2	complete stop
	0	1	0.6		passenger car	Lane 1	
	0	2	3.9		passenger car	Lane 1	
	0	3	2.5		passenger car	Lane 1	
	0	4	4.4		heavy vehicle	Lane 1	
	0	5	2.4		passenger car	Lane 2	
	0	6	3.5		passenger car	Lane 2	
	1	7	8.0		passenger car	Lane 2	
36	0	0	2.6	passenger car	heavy vehicle	Lane 1	complete stop
	0	1	2.9		passenger car	Lane 1	
	0	2	1.9		passenger car	Lane 2	
	0	3	1.5		passenger car	Lane 1	
	1	4	9.5		passenger car	Lane 1	
…				…			…

Note: [1] Two sample RTOR vehicles that departed from the curb right-turn lanes on West Bay Area Blvd. & I-45 EB

17

For the curb lanes studied, the headway sequences of the 346 RTOR drivers who tried to turn right on red were observed, including 3,123 headways. These headways consisted of 2,844 rejected headways and 279 accepted headways. Some drivers, who tried to turn right on red, were unable to find an acceptable gap during the red interval and waited until the next green interval. For these cases, there was no accepted headway but only rejected headways observed. This is in part a result of the high conflicting volumes at the study locations, because dual right-turn lanes are normally installed at busy intersections on frontage roads and major arterials. Heavy vehicles accounted for 3.6% of the subject RTOR vehicles and for 7.2% of the closing-gap vehicles. The conflicting traffic flows on Lanes 1 and 2 (Figure 2) may possibly affect the gap-acceptance decisions made by drivers from curb right-turn lanes. Of the 3,123 headways, 51.3% were closed by vehicles travelling on Lane 1, and 48.7% of the headways were closed by vehicles travelling on Lane 2. The lengths of the headway sequences that were experienced by different drivers varied from one to 32 headways.

For the inside right-turn lanes studied, the 198 headway-sequence samples were observed for RTOR drivers who tried to turn right on red, including 3,015 headways. For the 3,015 headways we observed, RTOR drivers rejected 2,933 headways and accepted 82 headways. Heavy vehicles accounted for 18.7% of the subject RTOR vehicles and 2.1% of the closing-gap vehicles. The conflicting traffic flows on Lanes 1, 2, and 3 (Figure 2) may possibly affect the gap-acceptance decisions made by drivers from inside right-turn lanes. Of the 3,015 headways, 42.2% were closed by vehicles travelling on Lane 1; 39.0% of the headways were closed by vehicles travelling on Lane 2; and 18.8% of the headways were closed by vehicles travelling on Lane 3. The lengths of the headway sequences that were experienced by the drivers varied from one to 50 headways.

Among drivers who turned right on red from the curb right-turn lanes, 9.7% had a rolling stop rather than a complete stop, compared to a rolling-stop percentage of 8.1% of the drivers turning from the inside right-turn lanes.

While waiting at the stop line, the subject RTOR drivers showed evidence of impatience, which was recognized by observing drivers who accepted headways that were shorter than the headways that they had rejected earlier. Among the 346 observed RTOR drivers who departed from the curb right-turn lanes, 51 drivers (14.7%) accepted a headway that was shorter than the

headways that they had rejected earlier. Among the 198 RTOR drivers who departed from the inside right-turn lanes, 14 drivers (7.1%) accepted a headway that was shorter than the headways that they had rejected earlier. The percentages indicated that RTOR drivers from the curb right-turn lanes may be less patient as opposed to those turning from the inside right-turn lanes, and further statistical analysis will be presented in the following section.

4.4 Model Calibration and Discussion

Calibrated Model for Curb Right-Turn Lanes

Of the 346 observed RTOR vehicles that turned from the curb right-turn lanes, the headway sequences of 309 vehicles were used for calibration, and the other 37 headway sequences were used for validation. The calibrated coefficients are presented in Table 5.

Table 5   Calibrated coefficients for the model for curb right-turn lanes

Parameter	Coefficient Estimate, β_k	Standard Error	Wald Statistics	Degree of Freedom	p-value
Intercept	-4.421	0.207	454.324	1	0.000
Headway size, $h_{v,i}$	0.695	0.038	331.677	1	0.000
Headway closed by a vehicle on Lane 1, $P_{v,i}^1$	-1.522	0.221	47.220	1	0.000
Sequential number of headway, i	0.034	0.014	5.480	1	0.019

Note: $\chi^2 \approx -2 \cdot \left(L(0) - L(\beta') \right) = 816.471$; Number of headway sequences = 309; Number of headways = 2,649

The large value of chi-square statistic (i.e., 816.471) rejected the null hypothesis that assumes all-zero coefficients. The final model that yielded the best fit with calibration data included the following significant predictors: headway size, whether the headway is closed by a vehicle on Lane 1 (referenced to those by a vehicle on Lane 2), and the sequential number of headways (an indicator of waiting time). Given the same conditions, the possibility that a RTOR driver accepts a headway is smaller if the headway is closed by a conflicting vehicle traveling on Lane 1 than on Lane 2. The results are essentially consistent with our field observation, i.e., the conflicting traffic streams, in Lane 1 and Lane 2, have unequal effects on RTOR vehicles. The underlying reason is that right-turning vehicles from the curb right-turn lane are supposed to merge onto Lane 1 instead of Lane 2, but they are affected by Lane 2 in a way to avoid sideswipe incidents with conflicting vehicles from Lane 2. Additionally, the results showed evidence that the critical

19

headway of the RTOR drivers decreased as they waited for an acceptable gap. This is the result of increasing impatience of the drivers, and this finding is also supported by the field observation mentioned before, i.e., 14.7% of the subject drivers finally accepted a headway that was shorter than the headways that they had rejected earlier.

The variables reflecting the hypothesis that the drivers of heavy vehicles tend to turn right on red more conservatively were not significant. Likewise, the hypothesis that heavy closing-gap vehicles may create a more stressful gap-acceptance environment was not statistically supported. Thus, the corresponding predictors, T_v and $T_{v,i}$, were excluded from the final model. The relatively rare presence of heavy-vehicle samples may have prevented us from obtaining statistically significant results.

Calibrated Model for Inside Right-Turn Lanes

For the inside right-turn lanes, 171 of the 198 observed RTOR vehicles were used for calibration and the other 27 samples were used for validation. The calibrated coefficients are presented in Table 6.

Table 6   Calibrated coefficients for the model for inside right-turn lanes

Parameter	Coefficient Estimate, β_k	Standard Error	Wald Statistics	Degree of Freedom	p-value
Intercept	-8.344	0.947	77.648	1	0.000
Headway size, $h_{v,i}$	0.868	0.089	94.061	1	0.000
Headway closed by a vehicle on Lane 1, $P_{v,i}^1$	-1.508	0.727	4.300	1	0.038
Headway closed by a vehicle on Lane 2, $P_{v,i}^2$	-0.593	0.691	0.735	1	0.391

Note: $\chi^2 \approx -2 \cdot \left(L(0) - L(\beta') \right) = 124.494$; Number of headway sequences = 171; Number of headways = 2,465

The chi-square statistic (i.e., 124.494) provides evidence against the restricted model that assumes all-zero coefficients. The final model included the following predictors: headway size, whether the headway is closed by a vehicle on Lane 1 (referenced to by a vehicle on Lane 3), whether the headway is closed by a vehicle on Lane 2 (referenced to by a vehicle on Lane 3). When the closing-gap vehicle is present on Lane 1, the possibility that a RTOR driver will accept a given headway is smaller than when the closing-gap vehicle is present on Lanes 2 or 3. Likewise, when the closing-gap vehicle is present on Lane 2, the possibility of accepting a given headway is smaller than when it is present on Lane 3. The underlying reason is that right-turning

vehicles from the inside right-turn lane are supposed to cross Lane 1 and then merge onto Lane 2, and they are affected by Lane 3 in order to avoid sideswipes. The results failed to provide statistical evidence of increased impatience as drivers are waiting for acceptable gaps. Since the inside right-turn lanes are relatively new to drivers, they may lead to more conservative gap-acceptance behavioral patterns as opposed to the curb lanes. In addition, a driver from an inside right-turn lane must make sure the conflicting traffic from the left hand is clear and has to avoid a possible sideswipe with the parallel RTOR movement on the right (the curb lane), which makes the maneuver more complex than that from curb lanes. By contrast, RTOR drivers from curb lanes need to focus primarily on the traffic flows from their left (i.e., parallel RTOR movement and conflicting traffic).

The samples did not show statistically significant impacts of the types of closing-gap vehicles; this may be due, in part, to the very low percentage (2.1%) of heavy vehicles observed. Although heavy vehicles accounted for 18.7% of the subject RTORs observed, no significant results were statistically supported for the candidate variable T_v. This result may indicate that from the inside lanes, even the drivers of passenger cars turned right on red as conservatively and cautiously as the heavy-vehicle drivers.

Goodness of Fit

Overall, the calibrated models were in good agreement with the calibration data sets, as summarized in Table 7. Using the calibrated models, Kolmogorov-Smirnov tests revealed that the standardized residuals ($\varepsilon_{v,i}$) for the calibration data sets can be modeled statistically as logistic distributions. This result justified the premise for the use of logit models.

Due to the sample size of the observations, the calibrated logit models may be limited in scope and applicability.

Table 7　　　　　**Summary for model calibration**

	Curb Right-Turn Lane		Inside Right-Turn Lane	
Number of RTOR vehicle samples for calibration	309		171	
Number of gap-acceptance decisions for calibration	2,649		2,465	
	Observed	Percentage Correct	Observed	Percentage Correct
Goodness of Fit	0 (rejected)	98.7%	0 (rejected)	99.5%
	1 (accepted)	53.0%	1 (accepted)	73.1%
	Overall	94.7%	Overall	98.8%
p-value ($\varepsilon_{v,i}$ fitting into a logistic distribution)	0.000		0.000	

4.5　　Validation of the Proposed Logit Models

For the curb right-turn lanes, 37 samples of the 346 observed RTOR vehicles were selected randomly and used for validating the model, including 474 gap-acceptance decisions. For the inside right-turn lanes, 27 randomly-selected samples were used for validation, including 550 gap-acceptance decisions.

Discriminatory Capability

Figure 3 shows the receiver operating characteristic (ROC) curves for model performance in terms of classifying and predicting gap-acceptance decisions. As a widely recognized measure of a diagnostic model's discriminatory power, the area under the curve (AUC) is a useful indicator of discriminatory power. A value of 0.5 means that the model is useless for discrimination (equivalent to tossing a coin), and values near one mean that higher probabilities will be assigned to cases with the outcome of interest compared to cases without the outcome. The logit models yielded an AUC of 0.94 for the curb right-turn lanes and 0.92 for the inside right-turn lanes, demonstrating a great discriminatory capability.
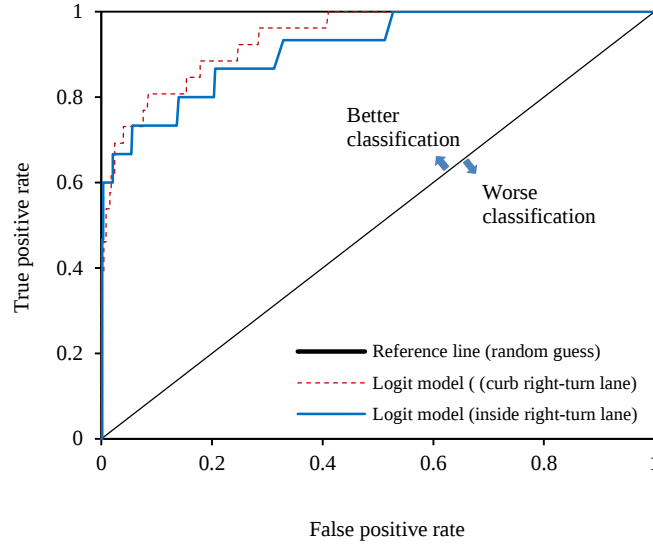
Figure 3   ROC curves for model performance in predicting gap-acceptance decisions

Comparison with Conventional, Deterministic Methods

In conventional, deterministic gap-acceptance methods, the mean critical headway across drivers is a key cut-point parameter. It is assumed that drivers will accept a present headway if its duration is longer than the mean critical headway; otherwise, they will reject the headway. From the field data, the maximum likelihood method was used for estimating mean critical headways for RTOR vehicles from dual right-turn lanes. The results provided a basis for comparing the deterministic gap-acceptance methods with the proposed logit models that were calibrated using the same set of data.

The maximum likelihood method is based on the assumption that the j th driver's critical headway is greater than her/his largest rejected headway (r_j) and less than her/his accepted headway (a_j). A probabilistic distribution for the critical headways needs to be assumed. As summarized by Mahmassani and Sheffi (*19*), Tian et al. (*26*), and Brilon et al. (*25*), a number of probability distributions have been used to describe critical gaps, e.g., log-normal distribution, normal distribution, gamma distribution, exponential distribution, and hyper-Erlang distribution. In this study, a two-parameter logistic distribution was used, which is written similar to Equation (3). To fit the observed patterns of accepted headways and largest rejected headways, the

23

maximum likelihood technique was used to estimate the parameters of the logistic distribution that maximize the log-likelihood function:

$$L = \sum_{j=1}^{n} \ln\left(F(a_j) - F(r_j)\right) \tag{8}$$

The problem was coded and solved numerically using a non-linear program solver, MINOS, in the General Algebraic Modeling System (GAMS), a modeling system for mathematical programming and optimization (27). The non-linear program has two variables μ and σ, which were optimized iteratively for maximizing the objective function (Eq. (8)). The mean critical headway is equal to the value of μ that produces the maximized objective function.

For the curb right-turn lanes, the estimated mean critical headway t_c was 5.6 s; for the inside right-turn lanes, the estimated mean critical headway t_c was 6.7 s. The results showed that RTOR drivers turning right on red from the curb lane commonly have a smaller critical headway than those from the inside right-turn lanes. This finding is consistent with another field study based on the Siegloch method for dual right-turn lanes (28). The Siegloch method is based on a linear regression relationship between the size of accepted headways and the number of RTOR vehicles able to turn during the headways, given that a continuous queue is present on the subject right-turn lanes (25).

The current version of Highway Capacity Manual (HCM, 2010) (29) does not suggest critical headway values for RTOR or other permissive maneuvers at signalized intersections. Rather, it includes only equations for estimating critical headways for minor movements (including right-turn maneuvers) at STOP-controlled, un-signalized intersections. The critical headway values presented in this study can be useful for future applications and can complement the HCM in providing suggested values for dual right-turn lanes at signalized intersections.

The classification tests for the validation are presented in Table 8, comparing the proposed logit models and the deterministic method. Relatively, the deterministic method that relies simply on the cut-point value of critical headways over-represented aggressive drivers as a possible result of the loss of information. The proposed logit models showed improved performance in predicting the gap-acceptance decisions.

24

Table 8   Classification table for model validation

Curb right-turn lanes							
Proposed logit model				Deterministic method (cut-point t_c =5.62 s)			
	Predicted		Percentage Correct		Predicted		Percentage Correct
Observed	0	1		Observed	0	1	
0	442	**6**	98.7%	0	432	**16**	96.4%
1	12	14	53.8%	1	11	15	57.7%
Overall			**96.2%**	**Overall**			**94.3%**
Inside right-turn lanes							
Proposed logit model				Deterministic method (cut-point t_c =6.69 s)			
	Predicted		Percentage Correct		Predicted		Percentage Correct
Observed	0	1		Observed	0	1	
0	531	**4**	99.3%	0	518	**17**	96.8%
1	6	9	60.0%	1	6	9	60.0%
Overall			**98.2%**	**Overall**			**95.8%**

To test whether the improvement in prediction accuracy is statistically significant, we used an inferential approach (*30*) for comparing the paired "Bernoulli trial" predictions by the two methods. The Z-statistic used is calculated as

$$Z = \frac{\left(n_{SF} - n_{FS}\right)}{\sqrt{n_{SF} + n_{FS}}} \qquad (9)$$

where

n_{SF} = number of samples that were successfully predicted by the proposed logit model but incorrectly predicted by the deterministic method

n_{FS} = number of samples that were incorrectly predicted by the proposed logit model but successfully predicted by the deterministic method

A *p*-value of 0.006 provided evidence that a statistically significant difference in prediction accuracy existed between the proposed logit model and the deterministic method for the curb lanes. Similarly, a *p*-value of 0.001 indicated that there was a statistically significant difference between the two methods for the inside lanes. On the other hand, it was also noted that the

deterministic method represented a reasonable trade-off between accuracy and ease of application for dual right-turn lanes.

4.6   Summary

In this task, the gap-acceptance decisions of individual RTOR drivers from dual right-turn lanes were characterized based on direct field observations. Binary logit models were developed and compared with the deterministic method. The study also identified the significant attributes of the gap-acceptance decisions. Evidence showed that:

(1)   Compared to the deterministic gap-acceptance methods, the proposed logit models showed a statistically significant improvement in the capability of predicting gap-acceptance decisions from dual right-turn lanes, while the deterministic method represented a reasonable trade-off between accuracy and ease of application for dual right-turn lanes. The numerical results showed that deterministic methods that rely simply on the cut-point values of critical headways may over-represent aggressive drivers due to loss of information.

(2)   Based on the maximum likelihood method, the mean critical headway was 5.6 s for RTOR drivers turning from curb right-turn lanes and 6.7 s for RTOR drivers turning from inside right-turn lanes. The values can be useful for future modeling efforts and may complement the Highway Capacity Manual (2010) in providing suggested values for dual right-turn lanes.

(3)   For drivers turning right on red from curb right-turn lanes, the critical headway decreases as they are waiting for an acceptable gap. RTOR drivers turning from the inside right-turn lanes did not show statistically significant evidence of increased impatience, which was assumed to be the result of their lack of familiarity with the RTOR maneuver from that lane relative to from curb right-turn lanes.

(4)   The lane positioning of closing-gap vehicles significantly affected the possibility that a RTOR driver from dual right-turn lanes would accept a given headway. For example, when a closing-gap vehicle was present on Lane 1, the possibility that a RTOR driver would accept a given headway was smaller than when the closing-gap vehicle was present on Lanes 2 or 3 under the same conditions.

While the proposed logit models cannot be used directly in capacity equations, these models hold great promise for immediate application in simulation studies for estimating capacities and delays. Since these models have shown improved capability to predict whether an individual RTOR vehicle will accept or reject each specific gap, through micro-simulation, it is expected that they will lead to better capacity and delay estimates than those the deterministic methods can provide.

Equally useful for researchers and practitioners is the understanding and insights on what factors affect the gap-acceptance decisions made on dual right-turn lanes. For example, the findings can be used to enhance the modeling of the RTOR capacities of dual right-turn lanes. For instance, this study showed that conflicting traffic streams from different cross-street lanes have unequal effects on RTOR behavior. Accordingly, a reformulated Harders's model incorporating this finding was proposed, and it exhibited a significantly improved capability of predicting RTOR capacities for dual right-turn lanes compared to the classical Harders's model (*28*). In addition, since increased impatience among RTOR drivers from the curb lanes was proven statistically, the discrete-choice models can be integrated straightforwardly with traffic simulation to represent drivers' impatience over various waiting times, which will provide another validated source for capturing the inherent stochasticity in traffic simulations.

CHAPTER 5: EXISTING GUIDELINES ON RTOR

Various guidelines on the use of RTOR have been developed in past studies (*5, 7, 31, 32, 33*). Generally, there are two types of guidelines: I) mandatory criteria for prohibiting RTOR (RTOR shall be prohibited), which means RTOR must be prohibited at an intersection if one or more of criteria are met, and II) optional criteria for prohibiting RTOR (RTOR may be prohibited), which means RTOR may be prohibited at an intersection if one or more of the criteria are met. In these guidelines, the following factors influencing the safety of RTOR are considered:

- Traffic conditions: significant pedestrian conflicts, a significant number of conflicts with other movements (i.e., opposing left turns)
- Geometry features: limited sight distance, intersections with more than four approaches, presence of skewed intersections, presence of dual right-turn or left-turn lanes
- Operational characteristics: presence of exclusive pedestrian phase, high-speed street onto which RTOR turns, inadequate capacity of the receiving lane
- Environmental conditions: closely spaced to railroad crossing, school crossing, neighborhoods with large numbers of children or elderly
- Crash experience: historical accident rates

Overall, there are five mandatory criteria in Group I and eight optional criteria in Group II. Table 9 presents and explains these guidelines.

Table 9   Existing Guidelines on RTOR
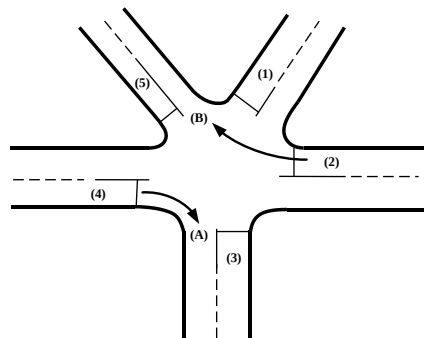
Level	Factors	Criteria	Explanation	References
RTOR shall be prohibited (I)	Sight distance (I-A)	Speed (mph) Sight distance (ft) 20 120 30 190 40 270 50 360	An acceptable gap for the RTOR maneuver must be visible. The sight distance criteria are calculated based on stopping requirement for the cross-street traffic.	(5,7,31, 32)
	Complex intersections (I-B)	More than four approaches	For RTOR vehicles, unexpected conflicts can occur. There are mainly two kinds of unexpected conflicts: RTOR motorists (A) may look for cross-street traffic from approach (1) and may be unaware of cross-street traffic from approach (5), or RTOR motorists (B), observing a safe gap in traffic from approach (3), could turn right onto leg (5) and, as a result, get into a dangerous conflict situation with vehicles from approach (1). 	(5,7,31, 32)
	Restrictive geometrics (I-C)	Highly-skewed intersections	When right turns are made at highly-skewed intersections, the maneuver is difficult to negotiate, even on a green light, because the right-turn radius is small. That may result in drivers making incorrect judgments about gaps, since the right turns may take longer than they do at right-angle intersections. In addition, when the angle of the intersection is sharp, there are sight-distance issues for right-turn drivers. (Vehicles in the adjacent through lane may block the driver's view.)	(7, 32)

Table 9 Existing Guidelines on RTOR (Continued)

Level	Factors	Criteria	Explanation	References
RTOR shall be prohibited (I)	Exclusive pedestrian phase (I-D)	Exclusive pedestrian phase: red lights for vehicles in all approaches and the pedestrian signals display a steady WALK	Where an exclusive pedestrian phase is used, pedestrians cross the intersection with complete freedom. The RTOR vehicles are unexpected by pedestrians.	(5,7,31, 32)
	Railroad grade crossing (I-E)	Within 200 ft of a railroad grade crossing	The prohibition only applies to the approach from which right turns are made onto the lane that crosses the railroad. If RTOR is allowed, the RTOR driver may turn into the railroad crossing without the knowledge of exposing himself to a conflict with the train.	(5,7,31, 32)
RTOR may be prohibited (II)	Significant pedestrian conflicts (II-A)	50 to 100 pedestrians per hour during eight hours of an average weekday	Risk for pedestrians may increase as the RTOR drivers may lack patience and try to make the maneuver between the pedestrians' gaps, which is a hazardous situation for pedestrians. There is also a potential hazard to RTOR drivers, as they need to pay more attention to pedestrians; they may fail to yield to the cross -street through vehicles in some cases.	(5,7,31, 32)
	Dual right-turn or left-turn lanes (II-B)	Prohibit RTOR from the inside lane of dual right-turn lanes	For RTOR from dual right-turn lanes, maneuvers can be more dangerous, because there may be two right-turn vehicles turning abreast. The driver's view from the vehicle on the curb right-turn lane may be blocked by the turning vehicle on the inside right-turn lane. The potential for sideswipe crashes also increases. Therefore, it is desirable to prohibit RTOR from the inside right-turn lane.	(31, 32)
		Prohibit RTOR if the receiving lane is shared with opposing left turns	At intersections with dual left-turn lanes, if the right-turn vehicles share the same receiving lane with the opposing left-turn vehicles, it is more likely that the drivers that are turning right will fail to yield to the drivers turning left during the protected left-turn phase. Subject right-turn lane	
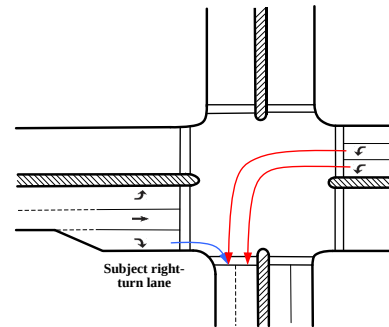
Table 9   Existing Guidelines on RTOR (Continued)

Level	Factors	Criteria	Explanation	References
RTOR may be prohibited (II)	Conflicts with left-turn movements (II-C)	Protected opposing left-turn phase	The RTOR drivers usually pay more attention to yield to the cross-street through vehicles than that to the opposing left turns. Therefore, during the protected left-turn phase, the RTOR driver may look for gaps in cross-street traffic flow but forget the traffic that might be turning left into the same lane during a left-turn phase. This potential conflict is more serious if there is only one lane on the receiving link.	(5, 32)
	High speed limit on the cross street (II-D)	≥ 50-55 mph	RTOR drivers have difficulty in identifying safe gaps in the cross-street traffic because of the high speeds.	(32)
	Crash history (II-E)	≥ 1 crash per year	If the RTOR related crash rate is higher than the average, it should be considered that the intersection has potential design flaws. A field study should be conducted to identify the operational and geometric issues associated with the intersection.	(5,7, and 32)
	Not enough RTOR opportunities (II-F)	• No appreciable right turns • Short red interval	There are two circumstances for this factor: (1) where there are no appreciable right turns, there is little opportunity for reducing delays; (2) when the red-light interval is short, there is less chance for RTOR vehicles to proceed.	(32)
	Capacity problem for receiving lane (II-G)	Capacity is not enough	During traffic congestion period, the acceptance of departure lanes may be backed up, leaving little or no space for RTOR vehicles. When this occurs with regularity, RTOR should be prohibited.	(32)
	Special areas (II-H)	School crossing, large numbers of children or elderly people	For the safety of children and elderly people	(5,7, and 31)

For these existing guidelines, the mandatory criteria in Group I are easy to follow by traffic engineers, because RTOR shall be prohibited if any of these criteria is met; otherwise, it may result in significant safety problems. On the other hand, for the optional criteria in Group II, traffic engineers may have difficulties following some criteria, because they may not necessarily cause significant safety problems even if they are met; this leaves the traffic engineers to rely on their judgment for making decisions. In practice, many intersections may still allow RTOR even though they meet some criteria in Group II. For example, as proposed by Criterion II-B, RTOR from the inside lane of a dual right-turn lane should be prohibited. However, in a study conducted by Cooner et al. (*33*), among the 25 intersection approaches with dual right-turn lanes under study, only one approach prohibited RTOR from the inside right-turn lane. To give another example, Criterion II-C suggested that it is desirable to prohibit RTOR if there is a protected left-turn phase in the opposing direction. However, in practice, more than 50% of all intersections have a protected left-turn phase (*34*), and most of them allow the RTOR maneuver. Furthermore, there are also many intersections that still allow RTOR even though the speed limit on the cross-street is 50 mph or greater, which might not be consistent with Criterion II-D. Therefore, these criteria should be investigated further to determine more detailed and specific conditions under which it would be risky to allow RTOR.

CHAPTER 6: DEVELOPMENT GUIDELINES FOR THE USE OF RTOR

The purpose of this chapter is to develop warrant and comprehensive guidelines to support the decision making process related to prohibition of RTOR operation. The guidelines were developed in light to the results of previous chapters:

- Findings of existing studies on safety performance and driver behavior of RTOR, (Chapters 2 and 3)
- Field observation of RTOR driver behavior on dual right-turn lanes (Chapter 4), and
- Existing nationwide guidelines on RTOR (Chapter 5).

According to the results from Chapters 2 through 5, guidelines for installation of RTOR at signalized intersections were developed. The guidelines development will include two types of guidelines: I) mandatory criteria for prohibiting RTOR (RTOR shall be prohibited), which means RTOR must be prohibited at an intersection if one or more of criteria are met, and II) optional criteria for prohibiting RTOR (RTOR may be prohibited), which means RTOR may be prohibited at an intersection if one or more of the criteria are met.

6.1 Complementary Guidelines Proposed Based on Field Observation

Based on the field observation, existing guidelines could be enhanced by providing more mandatory criteria in Group I and by adding more detailed and specific explanations for some criteria in Group II. The complementary guidelines found by this research that can be added to the existing guidelines are summarized and explained below:

1. RTOR shall be prohibited if there are significant conflicting U-turn movements.

   When left turns from the right-hand cross street are turning under the protected phase, the right turns are shadowed by these left-turning vehicles (Figure 4), which allow more efficient RTOR operation. However, safety issues will arise if there are significant numbers of U-turn movements from the cross street. This is because RTOR drivers may assume that they are "shadowed" and become less cautious, thereby failing to yield to the U-turns that have the right-of-way during the protected left-turn phase.
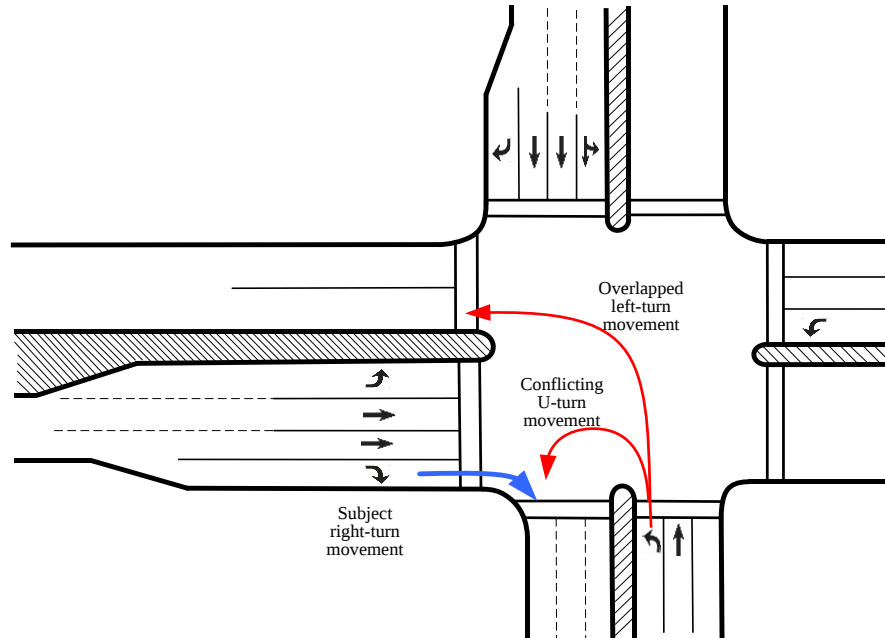
Figure 4   Illustration of Right-Turn Overlap

2. RTOR may be prohibited if the speed limit difference on the two streets is greater than 20 mph (a supplement of Criterion II-D).

The existing guideline, i.e., Criterion II-D, proposed that RTOR may be prohibited when vehicles turn right onto a high-speed road (50 to 55 mph). During the field observation, it was found that RTOR may be prohibited when the speed limits on the two streets are quite different, i.e., the difference is more than 20 mph, because it is difficult for the right-turning drivers in slow traffic flow to correctly judge the gaps in the fast traffic flow. Usually, right-turning drivers in slow traffic flow tend to underestimate the gaps in the fast traffic flow and take turns in an inadequate gap, which may result in collisions with the crossing through vehicles.

3. RTOR may be prohibited if split signal phasing is used (a supplement of Criterion II-C).

As shown in Figure 5, split phasing represents an assignment of the right-of-way to all movements of a particular approach, followed by all of the movements of the opposing approach (*35*). When the opposing approaches are served, the opposing left turns are protected and move together with the through vehicles. Compared to the typical protected left-turn phase, the left-turn operation in split phasing will have the following two features: 1) left-turn vehicles tend to move more quickly, because they are not blocked by

36

through vehicles in the same direction and 2) there are more opportunities to have large gaps in the left-turn traffic flow, because more green-light time is usually provided for left-turn movements in the split signal phase. Due to these two characteristics, the RTOR maneuver becomes risky with split signal phasing. The RTOR drivers tend to make turns once there are gaps in the left-turn traffic flow because they feel protected by the opposing through vehicles and become less cautious to other conflict movements (Figure 6). Moreover, RTOR drivers have more difficulty in correctly judging the gaps in the opposing left-turn flow because of the relatively high speed. Therefore, the RTOR maneuver with split signal phasing is more risky than that under the typical protected left-turn phase.
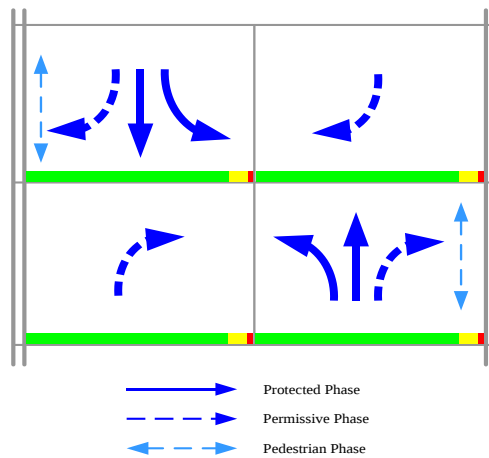

**FIGURE 5   Signal Diagram Showing Split Phasing**
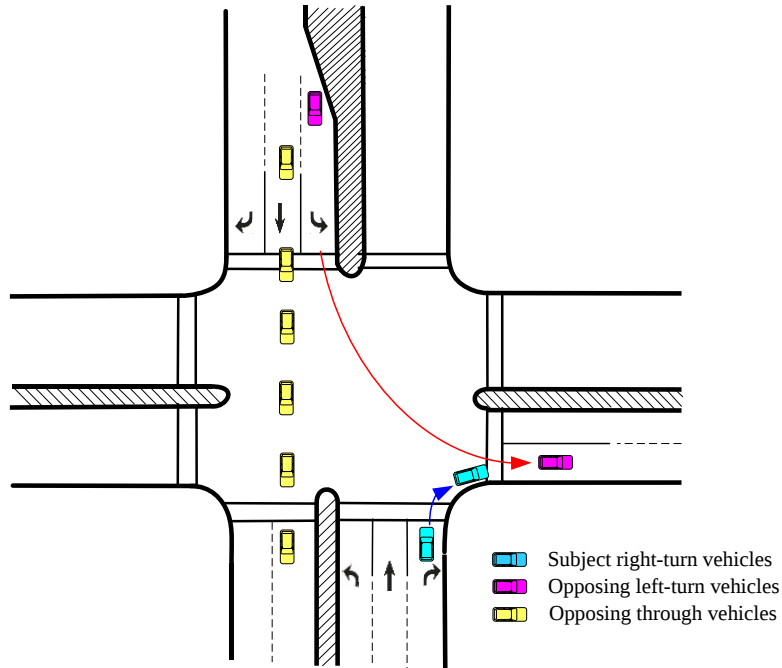
FIGURE 6   Potential Conflicts between RTOR Vehicles and Left-Turn Vehicles Operated under Split Phasing

6.2   Recommended Guidelines

Recommended guidelines for the use of RTOR are developed based on a review of the pertinent literatures and the field observation. Table 10 summarizes the recommended guidelines, which include six mandatory criteria in Group I and seven optional criteria in Group II. The shaded cells are the guidelines that are proposed or enhanced by this study, which extends the previous guidelines on RTOR.

The five mandatory criteria in Group I of the existing guidelines are all maintained. Furthermore, one criterion (Criterion I-F) is added, which suggests prohibiting RTOR when there are significant conflicting U-turn movements on the cross street. For the optional criteria in Group II, two criteria in the existing guidelines are enhanced, and one criterion is excluded, as explained below:

1. Criterion II-C: In the existing guideline, RTOR may be prohibited when the vehicles on the cross street are traveling at high speeds. This criterion is enhanced by specifying that the difference of the speed limits on the two intersecting streets should be greater than 20

mph. If the two streets have similar speed limits, then the RTOR drivers probably will not have a problem making correct judgments on the gap size.

2. Criterion II-D: In the existing guideline, RTOR may be prohibited when the opposing left-turn movement is operated under protected phase. This criterion is enhanced by specifying the protected opposing left-turn phase as split phasing, which will lead to more risky situations for RTOR vehicles.

3. Criterion II-F: In the existing guideline, RTOR may be prohibited under two situations: 1) there are no appreciable right turns and 2) right-turn vehicles have a short red-light interval. It is recommended to exclude this criterion, as allowing RTOR at this kind of intersection does not bring many benefits nor lead to any costs. Allowing RTOR will provide more flexible and easier operation.

It should be noted that whether RTOR should be allowed is a case-specific issue. Field evaluation still needs to be conducted location by location, especially for the criteria in Group II.

Table 10   Recommended Guidelines for the Use of RTOR

Level	Criteria No.	Criteria

RTOR shall be prohibited (I)	I-A	**Limited sight distance**
		Speed (mph) sight distance (ft)
		    20 120
		    30 190
		    40 270
		    50 360

	I-B	More than four approaches
	I-C	Highly-skewed intersections
	I-D	Exclusive pedestrian phase
	I-E	Within 200 ft of a railroad crossing
	I-F	Significant conflicting U-turn movements
RTOR may be prohibited (II)	II-A	Significant pedestrian conflicts (50 to 100 pedestrians per hour during eight hours of an average weekday)
	II-B	Dual right-turn or left-turn lanes (for dual right-turn approach, prohibit the inside lane)
	II-C	High speed limit on the cross street ($\geq$ 50-55 mph), especially when the difference between the speed limits on the two streets is greater than 20 mph
	II-D	Presence of protected opposing left-turn phase, especially under split phasing
	II-E	Crash history proved ($\geq$ 1 crashes per year)
	II-G	Inadequate capacity problem for receiving lane
	II-H	**Special areas:** School crossing Community with large numbers of children or elderly people

CHAPTER 7: CONCLUSIONS

In this study, the major findings of existing studies about the safety performance of RTOR were synthesized and the guidelines for the use of RTOR were developed. To expand these studies, field studies were conducted at six intersections with dual right-turn lanes in Houston, Texas, and the driver behavioral patterns was reviewed, observed, and studied.

Based on the data collected from the field studies, a lane-specific gap-acceptance model was developed, which is capable of representing the unequal effects of conflicting traffic streams from different cross-street lanes on the gap-acceptance decisions of individual RTOR drivers from dual right-turn lanes. These findings can be used to enhance the modeling of the RTOR capacities of dual right-turn lanes.

According to findings, from the literature review and field observations, a set of comprehensive guidelines were recommended for future applications to ensure safe implementation of RTOR. Note that, although the proposed criteria are supported by the results of the study, a significant amount of additional research, such as crash data analysis based research, should be conducted to further validate the recommended guidelines. Furthermore, in implementation, the developed guidelines should be used in conjunction with the judgment and experience of field traffic engineers. Even if an intersection meets some proposed criteria, RTOR may still be allowed if an engineering study suggests that RTOR will not result in serious safety problems and the benefits of prohibiting RTOR do not outweigh the costs.

REFERENCE

1. 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.

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

3. 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.

4. Abu-Lebdeh, G., R.F. Benekohal, and B. Al-Omari. Models for Right-Turn-on-Red and Their Effects on Intersection Delay. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1572, 2008, pp. 131–139.

5. *No Turns on Red Implementation Guidelines*. City of Minneapolis, MN, October 18, 2005.

6. Ray, J.C. The Effect of Right Turn on Red on Traffic Performance and Traffic Accidents. Berkeley, California, 1956.

7. Love, G., and J. True. An Emerging National Policy on Right-Turn-on-Red. *Traffic Engineering*, November 1976, pp. 29-32.

8. Parker, M. R. *The Impact of General Permissive Right and Left Turn on Red Legislation in Virginia*. Virginia Highway & Research Council, Charlottesville, Virginia, 1978.

9. Lord, D. Synthesis on the Safety of Right Turn on Red in the United States and Canada. Presented at 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2002.

10. Fleck, J.L., and B.M. Yee. Safety Evaluation of Right Turn on Red. *ITE Journal*, No. 6, 2002, pp. 46-48.

11. Parker, M.R., R.F. Jordan, J.A. Spencer, and M.D. Beale. *Right Turn on Red: A Report to the Governor and General Assembly of Virginia*. Virginia Highway & Research Council, Charlottesville, Virginia, 1976.

12. Compton, R. P. and E. V. Milton. Safety impact of permitting right-turn-on-red (RTOR): Report to Congress. Publication DOT HS 80. National Highway Traffic Safety Administration, U.S. Department of Transportation, 1994.

13. ITE Technical Council Committee 4M-20. Driver Behavior at Right-Turn-on-Red Locations. *ITE Journal*, Vol. 62 (4), 1992, pp. 18-20.

14. Yan, X., and S. H. Richards. *Influence of Restricted Sight Distances on Gap-Acceptance and Non-Gap-Acceptance RTOR Driving Behaviors*. Submitted to Southeastern Transportation Center, 2009.

15. *Design Element: Traffic Control for Right-Turn/RTOR Movements at Signalized Intersections*. Highway Design Handbook, Publication No. FHWA-RD-01-103 http://www.tfhrc.gov/humanfac/01103/ch1.htm

16. Troutbeck, R.J. and Brilon, W. (2005). "Unsignalized Intersection Theory, Revised Monograph on Traffic Flow Theory." FHWA, U.S. Department of Transportation.

17. Miller, A.J. (1972). "Nine estimators of gap acceptance parameters." In: Traffic Flow and Transportation (Ed. Newell). Proc., International Symposium on the Theory of Traffic Flow and Transportation, American Elsevier Publishing Co.

18. Dagonzo, C. (1981). "Estimation of gap acceptance parameters within and across the population from direct roadside observation." Transp. Res. Part B, 15, 1–15.

19. Mahmassani, H. and Sheffi, Y. (1981). "Using gap sequences to estimate gap acceptance functions." Transp. Res. Part B, 15, 143–148.

20. Ben-Akiva, M. and Lerman, S.R. (1987). "Discrete choice analysis." MIT Press: Cambridge, MA.

21. Cassidy, M.J., Madanat, S.M., Wang, M., Yang, F., and Troutbeck, R.J. (1995). "Unsignalized intersection capacity and level of service: revisiting critical gap." Transportation Research Record, 1484, 16–23.

22. Taylor, D. and Mahmassani, H. (1999). "Bicyclist and motorist gap acceptance behavior in mixed-traffic." Proc., 78th Annual Meeting of Transportation Research Board, Washington, D.C.

23. Huang, L. and Wu, J. (2004). "A study on cyclist behavior at signalized intersections." IEEE Transactions on Intelligent Transportation Systems, 5 (4), 293–299.

24. Liu, P., Wang, X., Lu, J., and Sokolow, G. (2007). "Headway Acceptance Characteristics of U-Turning Vehicles at Unsignalized Intersections." Transportation Research Record, 2027, 52–57.

25. Brilon, W., Koenig, R., and Troutbeck, R.J. (1999). "Useful Estimation Procedures for Critical Gaps." Transp. Res. Part A, 33, 161–186.

26. Tian, Z., Vandeheya, M., Robinsona, B.W., Kittelson, W., Kyte, M., Troutbeck, R., Brilon, W., and Wu, N. (1999). "Implementing the maximum likelihood methodology to measure a driver's critical gap." Transp. Res. Part A, 33, 187–197.

27. Rosenthal, R.E. (2008). "GAMS User's Guide." GAMS Development Corporation,

Washington, DC, USA.

28. Chen, X., Qi, Y., and Li. D. (2012). "Estimating right turn on red capacity for dual right-turn lanes at signalized intersections." Proc., 91st Annual Meeting of Transportation Research Board, Paper #12-0284, Washington, D.C. and Transportation Research Record, in press.

29. Transportation Research Board. (2000). "Special Report 209: Highway Capacity Manual." National Research Council, Washington, D.C.

30. Berry, C.J. (2009). "An Introduction to Statistics." University of Louisiana, Lafayette. 113–138.

31. ITE. Update of the Guidelines for "Prohibition of Turns on Red" Recommended Practice. ITE Journal, No. 8, 2002, pp. 20-21.

32. McGee Hugh, W., P.E. *Guidelines for Prohibiting Right Turn on Red at Signalized Intersections*. Traffic Engineering, January 1978, pp. 27-31.

33. Cooner A. S., Ranft, E. S., et al. *Development of Guidelines for Triple Left and Dual Right-Turn Lanes: Technical Report*. Publication No. FHWA/TX-11/0-6112-1, Texas Department of Transportation, January 2011.

34. Yu, L., Y. Qi, et al. *Development of Left-Turn Operations Guidelines at Signalized Intersections*. Publication No. FHWA/TX-09/0-5840-1, Texas, Department of Transportation, August 2008.

35. *US DOT Traffic Signal Timing Manual. Federal Highway Administration. U.S. Department of Transportation. http://ops.fhwa.dot.gov/publications/fhwahop08024/chapter4.htm*