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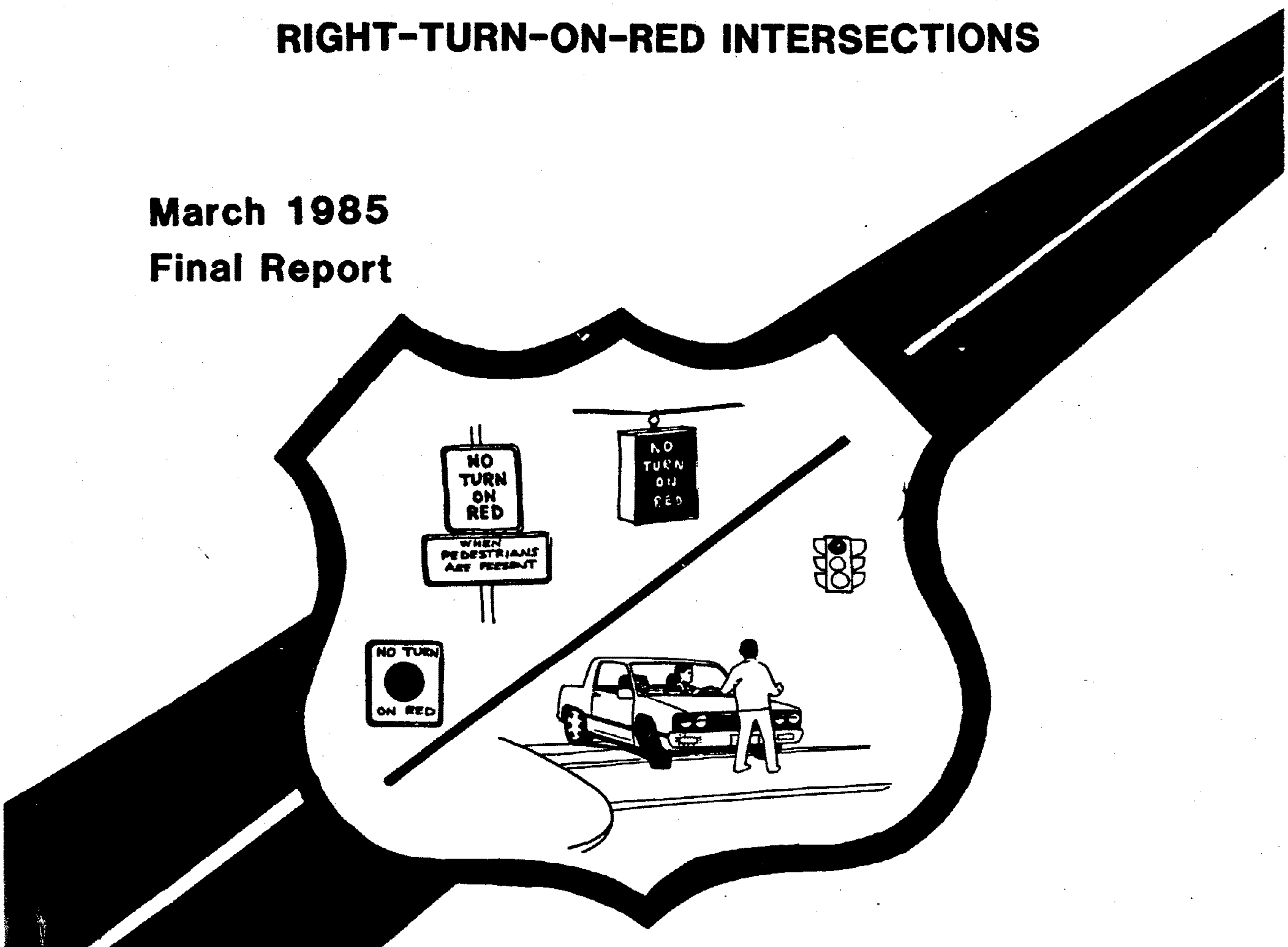
METHODS OF INCREASING PEDESTRIAN SAFETY AT RIGHT-TURN-ON-RED INTERSECTIONS

March 1985

Final Report



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16. Abstract

The purpose of this study was to determine current motorist compliance to RTOR regulations, develop and field test countermeasures for RTOR pedestrian accidents, and develop improved warrants and guidelines for prohibition of RTOR. Based on data from several U.S cities, only 3.7 percent of all right-turning drivers violate NO TURN ON RED (NTOR) signs. However, of drivers with an opportunity to turn right on red, 20 percent violated the sign. At locations with RTOR allowed, 56.9 percent of motorists do not come to a complete stop before turning right on red.

Based on conflict and violation data, 30 countermeasures were developed as possible treatments for RTOR-pedestrian accidents. Seven of these were field tested, including an offset stop bar, a red ball (symbolic) NTOR sign, a larger 30x36-in (75x90-cm) NTOR sign, a LOOK FOR TURNING VEHICLES pavement marking, a NTOR WHEN PEDESTRIANS ARE PRESENT sign, and an electronic variable message (blank-out) NTOR sign. Several promising applications for the devices were recommended. A critique was made of the current MUTCD guidelines on RTOR prohibition. Based on an analysis of conflicts at 199 intersection approaches, improved guidelines were recommended.

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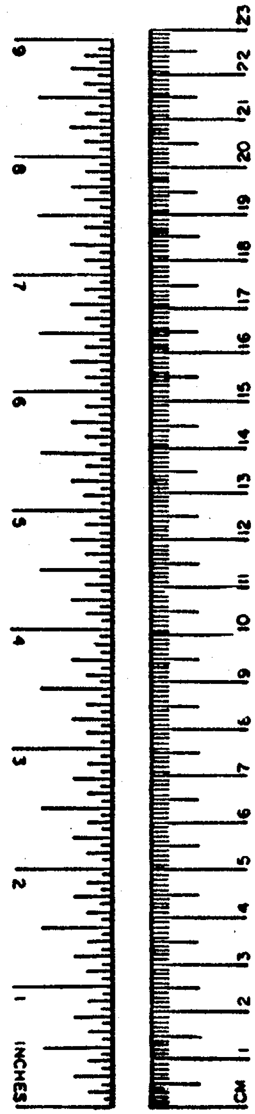
NOTICE

METRIC CONVERSION FACTORS

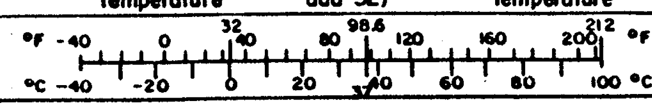
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The practice of legally permitting motorists the option of right-turn-on-red (RTOR) at signalized intersections after stopping and yielding the right-of-way to pedestrians and other traffic is now a widely accepted traffic regulation in the United States. RTOR maneuvers are generally permitted nationwide at all signalized intersection approaches unless the turn is specifically prohibited by a sign. The only exception to the general rule is New York City where RTOR maneuvers are prohibited unless specifically permitted by a sign. In addition to RTOR, many states now permit left-turn-on-red (LTOR) from a one-way street onto a one-way street, unless the maneuver is specifically prohibited by a sign.

In spite of the widespread adoption of RTOR, the issue remains controversial. Proponents of RTOR cite over 40 years of successful experience with the maneuver in California and other western States and suggest that RTOR results in savings of time and motor fuel by reducing vehicle delay. They also feel that RTOR reduces congestion and is not hazardous, since RTOR-related crashes represent a small percentage of accidents at signalized intersections. Opponents of the measure suggest that RTOR is hazardous to pedestrians and bicyclists, especially children, elderly, and handicapped persons. They also feel that motorists disregard the law by failing to stop and yield to traffic and that the time savings are not significant compared to the hazards associated with RTOR.

Perhaps the most controversial and important aspect of RTOR is safety. Although a number of investigations have been conducted, several safety issues associated with RTOR have not been conclusively proven. Also, substantially different conclusions have been developed by different researchers using the same data. While no studies have been completely successful in isolating and quantifying the safety impacts of RTOR, considered together the studies provide considerable evidence which suggests that RTOR is associated with an increase in the potential for pedestrian accidents.

Four major issues of concern relative to RTOR are:

1. What is the current level of motorist compliance to RTOR prohibition (NO TURN ON RED) signs?
2. At sites where RTOR is allowed, what is the current level of motorist compliance to the requirement to come to a complete stop before making a RTOR?
3. What are some of the RTOR-related countermeasures which would improve motorist compliance and/or reduce the hazard to pedestrians under various site conditions?
4. Are the Manual on Uniform Traffic Control Devices (MUTCD) warrants for RTOR prohibition appropriate, and if not, what new warrants or guidelines should be adopted?

These four basic issues are addressed in the following chapters. Chapter I involves an analysis of motorist compliance to RTOR regulations in three major U.S. cities (Issues 1 and 2 above). Chapter II is a summary of countermeasure effectiveness based on field testing. Chapter III documents a review of MUTCD guidelines for RTOR prohibitions and corresponding recommendations. A summary of conclusions and recommendations is given in Chapter IV. The appendix contains an assessment of current practices and impacts of RTOR.

CHAPTER I
OBSERVATIONAL STUDIES OF RTOR COMPLIANCE

INTRODUCTION

The recent adoption of the Western Rule in the U.S. relative to right-turn-on-red (except for New York City) has resulted in the right of motorists to turn right on a red signal (except when otherwise signed) after stopping and yielding to pedestrians and motorists. However, two of the reported problems of the generally permissive RTOR rule involves motorists:

1. Turning right on red at RTOR-prohibited locations (i.e., NO TURN ON RED signs exist), and
2. Turning right on red (where permitted) without stopping.

It has been speculated that one of the causes of violations of RTOR prohibitions is the "carry-over effect" to motorists due to the current RTOR permissive rule which causes them to expect to be able to turn right on red at all intersections. One confounding problem is that the NO TURN ON RED (NTOR) sign is not always placed in the same position, and may not be noticeable to drivers, even when the sign is placed in accordance with MUTCD standards. Other problems involve the lack of police enforcement of RTOR prohibition in many areas. The current MUTCD warrants for a NO TURN ON RED sign has led to a very high use of RTOR prohibitions in some cities and little or no use in other cities. Many believe that RTOR is not hazardous, and so prohibitions are rarely if ever needed. Others view RTOR as a detriment to safety which should never have been implemented.

The other compliance problem with RTOR relates to RTOR vehicles which fail to come to a full stop before turning right on red where RTOR is allowed. Previous studies have shown that between 3 percent and 65 percent of vehicles commit such RTOR violations.[1,2] However, only about 1 to 3 percent of RTOR violations (i.e., failing to stop) resulted in an unsafe act or hazardous situation.[2]

With evidence of these two types of RTOR violations, a need exists to determine the current status of motorist compliance with RTOR prohibition. Therefore, the purpose of this chapter is to:

1. Conduct observational studies at signalized intersections in several cities to determine current motorist compliance to:
   - RTOR prohibition (NO TURN ON RED signs).
   - The requirement to make a full stop before turning right on red (where RTOR is permitted).

2. Collect traffic, geometric, and other physical site characteristics and determine what site factors are associated with high and low rates of RTOR violations.

Based on this and other information, a list of candidate countermeasures was developed, as discussed in Chapter II. Then, the most promising countermeasures were selected and field tested to determine their effect on pedestrian safety and operations, as evidenced by pedestrian-vehicle conflicts and other measures.

MOTORIST COMPLIANCE WITH RTOR LAWS

One of the objections to the generally permissive RTOR regulation is that motorists frequently do not stop before turning on red. Such concerns have recently been expressed in several studies.[1,2,3] An assessment of motorist compliance with stopping is presented below, followed by a discussion of motorist violation of turning on red where the maneuver is prohibited.

Compliance Where RTOR is Permitted

The generally permissive RTOR rule requires that motorists must come to a full stop and yield to pedestrians and other traffic in the intersection before turning on red. There have been several examinations of motorist compliance and violations to the RTOR law. In a 1983 study of five intersections in New Jersey, Davis and Mullowney [5] found that overall, 40 percent of the drivers who turned on red failed to come to a stop before turning. Violation rates per site ranged from 38 percent to 71 percent of RTOR vehicles. Under the sign-permissive rule in Virginia, Parker [6] found that 9 percent of the RTOR motorists at 15 approaches did not come to a full stop before turning. A study conducted at 11 sites in Providence, Rhode Island, found that 65 percent of the motorists did not stop.[7] At 12 locations in Springfield, Massachusetts, only 28 percent of the RTOR motorists did not come to a full stop.[7] The low violation rate in Springfield was attributed to the newness of the RTOR maneuver and the sign reminding motorists to stop. Baumgaertner [2] collected compliance data at 13 approaches in Maryland and also found the noncompliance rate, under the sign permissive rule, was 64.4 percent which compares closely with the Providence data.

RTOR violation data were collected for generally permissive RTOR in two studies in which the general rule had only been adopted for 1 year. [1,5] At seven approaches in North Carolina, Parker [6] found that 2.0 percent of the RTOR motorists did not stop. However, after generally permissive legislation was enacted in Virginia, Parker [1] found that 11.5 percent of the RTOR motorists violated the law. It is important to note that the violation rate varied considerably with 48 percent of the violations reported at two approaches.

A high violation rate creates a law enforcement problem and may lead to a serious safety problem. In their studies, Baumgaertner [2] and Parker [1] also recorded the number of unsafe turns where the RTOR motorists did not stop or yield to other traffic in the immediate vicinity of the intersection. In both studies, less than 2 percent of the motorists made an unsafe turn. Additional studies of motorist compliance are needed periodically to examine trends over time and to identify unsafe approaches so that appropriate countermeasures can be applied.

The magnitude of the RTOR violation problem can be put in perspective by comparing it with motorist compliance at stop sign locations. In a Chicago study, 53 to 76 percent of all drivers failed to come to a complete stop at stop signs. However, only 5 to 10 percent of all vehicles traveling in excess of 5 mph (8 kph) violated the stop sign.[8] A 1976 study by Beaubien [9] was conducted in Troy, Michigan, to determine whether stop signs were effective for speed control in residential areas. At the three locations, full stops ranged from 6 to 51 percent of vehicles, rolling stops ranged from 34 to 54 percent, and no-stops ranged from 15 to 47 percent.[9] Based on this data, the violation rate involving stop signs appears to be considerably higher than the RTOR noncompliance rate.

A 1978 study observed motorist obedience to the stop signs in Barton, Springfield, and Providence. The percent of vehicle violations (not stopping) ranged from 31 to 39 percent. Of those vehicles not forced to stop by cross-street traffic, the percent of violations (nonstopping vehicles) ranged from 35.2 to 71.2 percent.[7]

Violations Where RTOR is Prohibited

Another major concern is whether motorists are violating the law by turning right on red at locations where the maneuver is prohibited. There is evidence that violations do occur. The most recent study was conducted in New Jersey in 1983, and found that 6 percent of right-turn vehicles turned on red (at five intersections) where RTOR was prohibited.[5]

Benke et al. [10] collected violation data at 11 sites where RTOR maneuvers were prohibited under the sign permissive and generally permissive rules and found that the violation rates were 1.23 and 9.56 percent, respectively (i.e., 1.23 percent of the motorists made an illegal RTOR maneuver). The authors attributed the high violation rate, which occurred at 4 of the 11 sites, to poor visibility of the sign resulting from poor sign placement and a busy signing environment at one location. In Indiana, Mamlouk [11] found that 1.4 percent of the motorists made an illegal RTOR maneuver under the sign permissive rule. It was also reported that the violation rate varied considerably with one site having an 18 percent violation rate. At that location, sign placement made it difficult for motorists to see the traffic control device. A detailed state-of-the-art summary on RTOR is given in the appendix.

METHODOLOGY

Data were collected to investigate two problems associated with RTOR: (1) to determine if RTOR prohibitions are being obeyed; and (2) to determine if motorists are coming to a complete stop prior to making a RTOR maneuver where RTOR is permitted. Each of these problems required separate data collection plans and procedures, as discussed below.

Data Collection Plan For Violations of RTOR-Prohibited Locations

The data collection plan for this phase of the study consisted of the following activities:

- Selection of cities for data collection.
- Selection of data collection sites.
- Development of data collection forms and procedures.
- Observer training and data collection.
- Data reduction, checking, and verification.

Each activity is described below.

Selection of Cities for Data Collection

One of the factors that could have a major impact on RTOR compliance is the recent history of RTOR in the area, since this could influence the level of motorist knowledge and understanding of RTOR and RTOR prohibition. For example, motorists in cities which have had the Western Rule for many years (e.g., Los Angeles) may respond differently to RTOR prohibition than motorists in eastern cities which have used the Eastern Rule until recently (e.g., Washington, D.C.). Other factors such as level of police enforcement of RTOR, area characteristics, local driver characteristics may also effect the level of compliance and vary from city to city or State to State, although such factors are difficult or impossible to quantify.

To allow for collecting data for a variety of conditions, three U.S. metropolitan areas were selected:

- One city in the Western United States which has had the Western Rule (RTOR permissive law) in effect for many years.
- One city in the Eastern United States which has only recently adopted the Western Rule (within 4 or 5 years).
- One city in a neutral part of the country such as the Midwest.

After discussions with the FHWA and numerous cities, it was decided to use Washington, D.C. to represent the city which until recently had the Eastern Rule. The cities of Dallas and Austin, Texas, were selected to represent cities with the Western Rule, and Detroit, Michigan, was selected from the Midwest. Washington, D.C. currently prohibits RTOR (for either part of the day or all day) at approximately 70 percent of its intersections. RTOR is prohibited at only a small percentage of intersections in Dallas and Austin, while RTOR prohibition is used at an estimated 10 to 20 percent of signalized intersections in the Detroit area.

Selection of Data Collection Sites

Sites were selected to provide a variety of geometric, volume, and other conditions throughout the city. One of the site selection criteria was moderate to high levels of pedestrian volume. However, some sites with low pedestrian volumes were selected which exhibited unusual geometrics. Also, intersections having two or more approaches prohibiting RTOR were selected in many instances to facilitate data collection.

To select the sites and approaches, a list of sites with RTOR prohibition was obtained from each city. The sites were field reviewed by the project engineers prior to data collection. During this review, basic site information was obtained and observation points and data collection time periods were selected. Violation data were collected for a total of 110 approaches, to provide a variety of site characteristics.

Develop Data Collection Forms and Procedures

Data collection forms and procedures were developed to assist observers in obtaining accurate and consistent data. Two basic types of data were collected; (1) site data, and (2) violation data. Site data collected included all traffic control devices (signs, signals, and pavement markings), intersection geometrics, posted speed limits, sight distance for the right-turn vehicle, and pertinent signal data. A copy of the data collection form is shown in figure 1.

The reverse side of the form was used for the condition diagram, and observers were instructed to draw a detailed site diagram with street widths, location of pavement markings, signs and signals, special turn lanes, intersection geometry, type of development on each corner, location of on-street parking (if any), and other physical features. Observation data were collected in 10-minute intervals on the form shown in figure 2. Such data included:

- Start time and end time of the data collection period (military time).
- Approach (northbound, eastbound, southbound, etc.).
- The number of right-turn-on-green (RTOG) vehicles. Right-turn-on-green vehicles were categorized into:
  - Arrive on green - The vehicle arrives at the crosswalk or stop bar during the green/amber interval to turn right. If a vehicle is second or third in line to turn right and is waiting at the light on red but arrives at the crosswalk on green, it is considered to have arrived on green.
  - Arrive on red: RTOR opportunity - The vehicle is at the crosswalk or stop bar during the red interval (i.e., first in line to turn right) and has at least one opportunity to make a RTOR maneuver, but chooses not to do so. A RTOR opportunity is defined as a gap in cross traffic and pedestrian traffic of approximately 6 seconds or more.
  - Arrive on red: No RTOR opportunity - The vehicle is at the crosswalk or stop bar during the red interval (i.e., first in line to turn right) and does not have at least one opportunity to turn right on red.

- Right-Turn-on-Red Maneuvers. Right turns on red were categorized into the following:

RTOR - SITE DATA FORM

INTERSECTION [redacted] AND [redacted] DATE 3-15-83

CITY/COUNTY Warren / Macomb STATE Mich

OBSERVER B.C.

AREA TYPE

Rural ___
Residential ___
Commercial X
Industrial ___
CBD ___

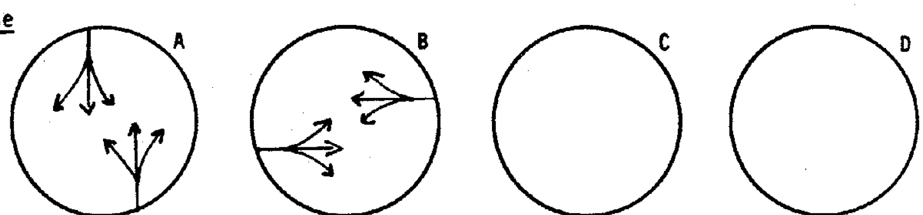
WEATHER Cloudy TEMPERATURE 40°

PAVEMENT CONDITION Good

Approach	Sight Distance	Posted Speed	Offset Stop Bar	RTOR Prohibitions	RTOR Sign Mounting
NB	>500 ft	40	5 ft	None	None
SB	>500 ft	40	5 ft	None	None
EB	>500 ft	40	5 ft	NTOR	Post
WB	>500 ft	40	5 ft	NTOR	Post

Signal Timing

Phase



Duration During Each Phase

Interval	A	B	C	D	E
Red	30	26			
Green	26	30			
Amber	4	4			
Walk					
Clearance					
DONT WALK					

Cycle Length 60

Figure 1. RTOR site data form.

RTOR - VOLUME AND CONFLICTS DATA FORM

CITY: WASHINGTON, D.C. OBSERVER: MB

LOCATION: ______ WEATHER: SUNNY 60°

DATE: 5-27-83

VH = Vehicle Hesitation
VS = Vehicle Swerve
PH = Pedestrian Hesitation
PR = Pedestrian Run
I = Interaction (within 20 feet)

Period	Time		Approach	Right Turn on Green					Right Turn on Red				Pedestrian Volume	
				Arrive on Green	Arrive on Red		Conflict With Pedestrian		No Conflict	Conflict With Traffic	Conflict With Pedestrian			
	From	To			RTOR Opportunity	No RTOR Opportunity	Near X-Walk	Far X-Walk			Near X-Walk	Far X-Walk	Near X-Walk	Far X-Walk
1	7:30	7:40	WB	14	—	—	—	PR I-2 VH	—	—	—	—	33	23
2	7:40	7:50	WB	10	1	—	—	I-6 VH	3	—	I-2	—	30	36
3	7:50	8:00	WB	19	3	—	—	VH-4 I-8	1	—	—	—	36	24
4	8:16	8:26	NB	9	1	—	—	VH-5 I-5	2	—	—	PR	67	47
5	8:26	8:36	NB	3	1	—	—	VH-3 I-5	3	—	—	—	65	56
6	8:36	8:46	NB	9	3	—	—	VH-5 I-6	—	—	—	—	73	50
TOTAL				64	9	0			9	0			304	236

Figure 2. RTOR volume and conflicts data form.

- No conflict - No conflict with cross traffic or pedestrians during the RTOR maneuver.
- Conflict with traffic.
- Conflict with pedestrians. Pedestrian conflicts were recorded based on whether they occurred at the near or far crosswalk and the type of conflict. The near and far crosswalk is illustrated in figure 3. Conflict type is defined as:

  Vehicle Hesitation (VH) - Vehicle slows or stops to avoid hitting a pedestrian while executing a RTOR maneuver.

  Vehicle Swerve (VS) - Vehicle swerves to avoid hitting a crossing pedestrian.

  Pedestrian Hesitation (PH) - Pedestrian slows, stops, or reverses his direction of travel to avoid a collision.

  Pedestrian Run (PR) - Pedestrian increases his speed or runs to avoid a collision.

  Interaction (I) - Neither the vehicle nor the pedestrian reacts but the pedestrian is in a moving lane and is within 20 feet (6 m) downstream of a RTOR vehicle.

- Pedestrian volume - The total number of crossing pedestrians recorded separately for the near and far crosswalks (figure 3) regardless of their direction of travel or compliance to the pedestrian/traffic signal.

When two or more conflict types occurred during a single event (i.e., a vehicle hesitates and a pedestrian runs during the same RTOR event) only the most severe conflict was recorded. Only one conflict was recorded per RTOR vehicle, regardless of the number of pedestrians involved in the conflict.

A minimum of 4 hours of data were collected on each approach. Eight or more hours of data were collected on several approaches to test for data repeatability.

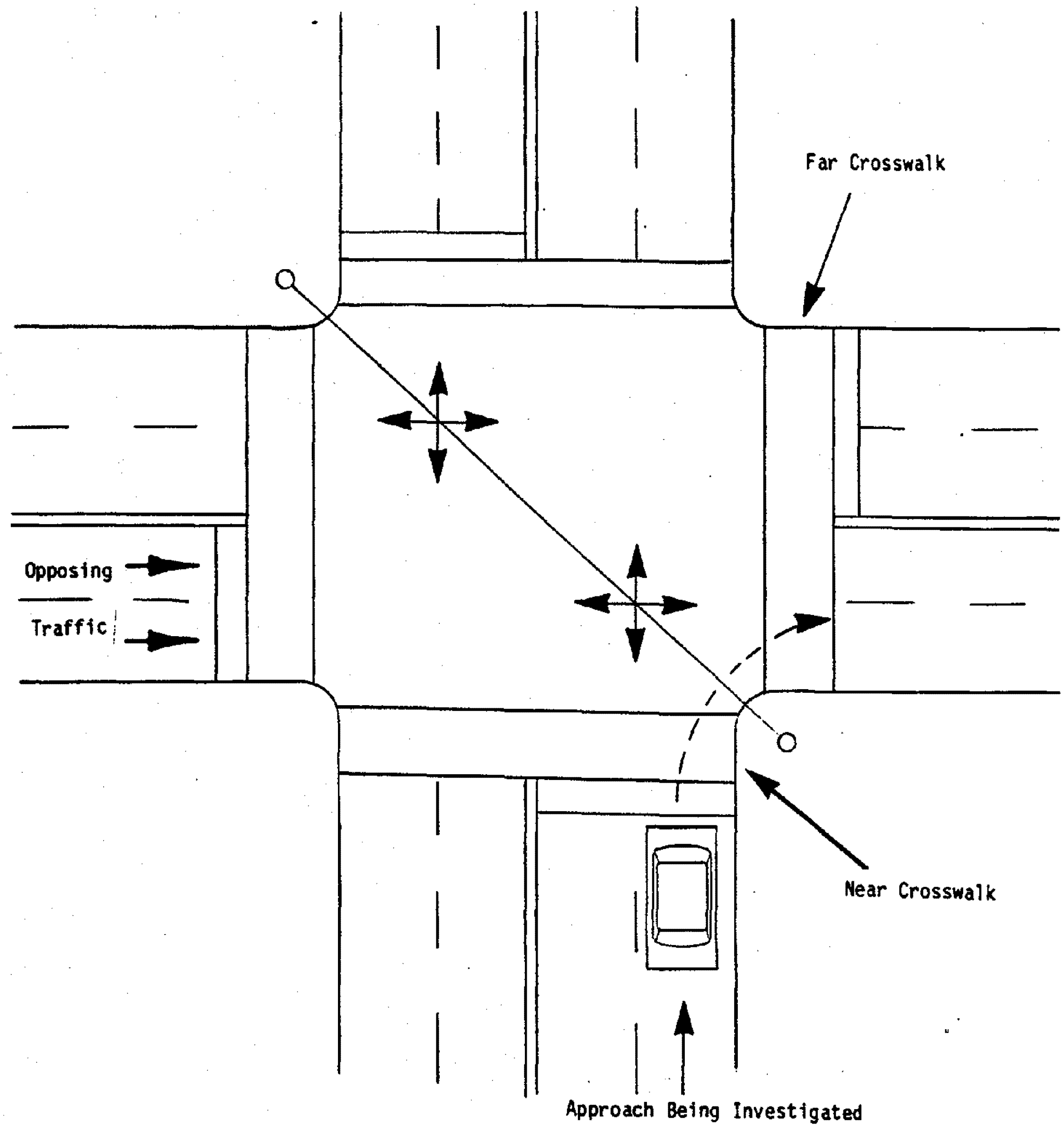


Figure 3. Illustration of the near and far crosswalks.

Observer Training and Data Collection

Training consisted of individual and group instruction in collecting complete, accurate, and consistent data. To insure consistency between the observers, all four were trained by collecting data on the same approach during the same time intervals. Data were compared for each event, and discussions were held to allow necessary adjustments to be made in data collection procedures until a high degree of reliability was attained.

Data collection was started in January 1983 and was completed in September 1983. Data were obtained for 110 approaches prohibiting RTOR. At least two different observers collected data in a city to minimize data collector bias. Data collection involved first collecting detailed site information, including a condition diagram at the site. Site distance data were collected by first viewing the driver's visual perspective using a scaled reference stick, marked at the approximate driver eye height (3.75 ft, 1.1 m) from the spot a driver would be situated prior to making a right turn. The sight distance would be measured to the worst case condition (due to parked cars, etc.), using a measuring wheel. Specific sight distances were measured up to 300 ft (90 m) (above which a greater than 300 ft (90 m) designation was given).

The conflicts, violations, and pedestrian volume data were normally collected on two approaches of an intersection. Data were usually collected for a total of 8 hours, alternating between the two approaches every 30 minutes.

Data Reduction, Checking, and Verification

Data were transcribed onto coding forms and then keypunched into the computer. Several measures were taken to insure data quality and reliability. This process began with a thorough training program and with several observe-the-observer visits by project engineers out in the field. At least two different data collectors were in each of the four cities, and some approaches were collected by different observers at different times to compare data consistency between observers. In the processing of data, all data coding was double checked and all keypunched data were verified. Computer programs were developed to identify missing, illogical, or inconsistent data in the data base. Data inconsistencies or errors were then corrected.

Data Collection Plan for Violation Data at RTOR-Permitted Approaches

This portion of the study involved collecting violation data at RTOR-permitted sites to determine if vehicles were making a complete stop prior to their right-turn-on-red maneuver. These data were later compared to stopping characteristics data for right-turn motorists at stop sign locations.

The purpose of this data collection was to:

- Collect field data and quantify problems related to motorist violations due to failing to stop before turning right on red (at sites where RTOR is permitted).
- Use the violation data (i.e., motorist failure to stop) along with physical site information (i.e., geometrics, signal information, traffic, and pedestrian volumes, etc.) to develop appropriate locational treatments.

The data were collected at sites within Washington, D.C., Dallas/Austin, Texas, and Detroit, Michigan.

The activities for this data collection effort consisted of:

- Selection of data collection sites.
- Development of data collection forms and procedures.
- Observer training and data collection.
- Data reduction, checking, and verification.

Selection of Data Collection Sites

Sites selected included signalized intersections with at least two approaches having RTOR permitted or intersections with at least two approaches controlled by stop signs. Initial site selection was made by selecting a list of potential test sites. Final site selection was made by reviewing candidate sites with high right-turn volume, high RTOR volume (signalized locations), and moderate to high pedestrian volumes. The sites selected were in the vicinity of the RTOR-prohibited locations used for collection of violation data relative to prohibition signs. Data were collected for 29 total approaches of signalized intersections and 28 stop sign approaches.

Development of Data Collection Forms and Procedures

Data collected included site information and stopping characteristics (observation) data. Site data were also collected as described earlier (see figure 1). Observation data were collected on the RTOR and Stop Sign Stopping Characteristics Data form, as shown in figure 4. A total of 4 hours of data were collected on each approach, or a total of 8 hours at each intersection. Data collection was alternated between two approaches with 30 minutes of data collected on an approach (summarized and recorded in 10-minute intervals). In this manner, data were sampled from both approaches throughout the day.

Data collected on the RTOR and Stop Sign Stopping Characteristics Data form included:

- Intersection name, city, location, etc.
- Intersection control - Traffic signal or stop sign.
- Time period data collection began and ended (military time).
- Approach data collected on - Northbound, eastbound, southbound, etc.
- Right-turn-on-green - The number of vehicles that turn right on green signal indications (for signalized approaches only).
- Right-turn-on-red vehicles - The type of stop for right-turn-on-red or stop sign right-turn vehicles defined as:

RTOR AND STOP SIGN STOPPING CHARACTERISTICS DATA FORM

CITY: Washington, D.C. OBSERVER: GL

LOCATION: [redacted] WEATHER: Clear 90°

DATE: 8-9-83

Check One: ✓ Traffic Signal; ___ Stop Sign

Period	Time		Approach	Right Turn On Green (Signalized Locations Only)	Right-Turn-On-Red				Pedestrian Volume		Opposing Traffic
	From	To			No Stop	Rolling Stop	Full Stop Voluntary	Full Stop Forced	Near Side	Far Side	
1	12:19	12:29	NB	2	—	—	—	—	37	17	46
2	12:30	12:40	NB	4	—	—	—	—	40	9	77
3	12:41	12:51	NB	8	—	1	—	1	56	14	90
4	12:53	1:03	EB	19	—	3	2	1	12	44	60
5	1:04	1:14	EB	13	—	1	—	2	10	42	63
6	1:16	1:26	EB	28	—	—	1	1	10	34	73
TOTAL	—	—	—	74	0	5	3	5	165	160	409

Figure 4. RTOR and stop sign stopping characteristics data form.

- No Stop: The vehicle slows only to negotiate the right turn and does not make any effort to stop.
- Rolling Stop: The right-turn vehicle slows more than the no stop condition but at no time do the wheels come to a complete stop in the vicinity of the stop bar or crosswalk.
- Full Stop-Voluntary: The vehicle comes to a complete stop in the vicinity of the stop bar or crosswalk but is not forced to stop by pedestrians in the crosswalk or cross-street traffic.
- Full Stop-Forced: The vehicle comes to a complete stop in the vicinity of the stop bar or crosswalk and does so due to the existence of pedestrian crosswalk activity or through traffic. Note that this does not necessarily mean the vehicles would not have voluntarily stopped if no pedestrian or cross-traffic were present.

- Pedestrian volume - Crossing pedestrian traffic on the near side or far side crosswalk, as defined in figure 3.
- Opposing traffic - The cross-traffic potentially conflicting with RTOR or right turns at stop signs. For an approach intersecting a two-way street, only the direction of cross-traffic conflicting with the right-turn maneuver would be counted.

Observer Training and Data Collection

Training included individual and group sessions and centered on the definition of a full-stop (voluntary or forced), rolling stop, and a no stop. Training was completed after a high degree of consistency was obtained between the observers from independent data collection tests on the same approach at the same time. Data were collected in June through September 1983 at a total of 29 RTOR-permitted approaches at signalized locations and 28 approaches controlled by stop signs.

Data collection included developing site diagrams as described with the RTOR-prohibited sites and collecting observation data. Observation data collection involved 8 hours on an intersection (4 hours for each of two approaches). Data were sampled by alternating between approaches every 30 minutes to collect from both approaches during all times of the day.

Data Reduction, Checking, and Verification

Data were recorded in-house and checked for inconsistencies or missing information. Data were keypunched, checked, and verified. Programs were developed to identify data inconsistencies and logic errors. Other checking was conducted on the data file to ensure a high degree of data quality.

RESULTS

The results of this phase of the study consisted of several basic types of analyses, including:

- The status of violations to RTOR-prohibition signs.
- The status of violations to the stopping requirement at RTOR-permitted sites.
- Determination of locational factors related to RTOR violations.

These three issues are discussed below.

Status of Violations to RTOR-Prohibition Signs

Violation data were collected at a total of 110 intersection approaches relative to vehicles illegally turning right on red. The violation rate for a group of sites may be expressed in several different ways, including:

- "Overall RTOR Violation Rate" - The overall percentage of right-turn vehicles which turn right on red (i.e., total number of RTOR events at a group of sites divided by the total right-turn volume). This was a common way of expressing violations in past studies.
- "Mean RTOR Violation Rate" - The average percentage of right-turn vehicles which turn right on red (i.e., the mean percent violations of a sample of intersection approaches). This can only be computed for a sample of two or more sites.

- "Overall RTOR Violation Rates Per Opportunity" - The percentage of vehicles turning right on red of those vehicles having an opportunity to do so. In the first two definitions above, all right-turning vehicles are included in the denominator, regardless of whether they arrive on red, arrive on green, or had an opportunity to make a RTOR (i.e., they were the second or third car stopped in the right-turn lane, or a lack of gaps in cross-street traffic prevented them from turning right on red). This definition only includes those vehicles stopped first in line at the red light which have an adequate gap and an opportunity to turn right on red. It is really a measure of the percentage of motorists which "would violate the RTOR prohibition if given the chance." This definition will result in a higher percent violation rate than the previous two definitions.
- "Mean RTOR Violation Rate Per Opportunity" - This is the same as the definition above, except a mean of the violation rates of the sites is used.

To illustrate the three definitions of violation rate, consider hypothetical data on three intersection approaches, A, B, and C (1 hour of data per approach) when each have NO TURN ON RED signs.

Approach	Total Right Turns	RTOR Violations	RTOR Opportunities	Percent Vehicles Turning On Red	Percent Vehicles Turning Right On Red Which Had an Opportunity
A	50	3	10	6.0	30.0
B	45	5	20	11.1	25.0
C	40	10	30	25.0	33.3
Totals	135	18	60		

From the example above, the overall RTOR violation rate for the three approaches is the total RTOR (18) divided by the total right turns (135), or 13.3 percent. The mean RTOR violation rate for the three approaches is the average of 6.0 percent (approach A), 11.1 percent (approach B), and 25.0 percent (approach C), or 14.0 percent. This differs slightly from the 13.3 percent overall RTOR violation rate.

To compute the overall and mean RTOR violation rate per opportunity, only the RTOR opportunities are used in the denominator. Thus, in the example above, the "overall RTOR violation rate per opportunity" for the three approaches is the total number of violations (18) divided by the total opportunities (60), or 30.0 percent. The mean RTOR violation rate per opportunity is computed as the average violation rate of Site A (30.0 percent), Site B (25.0 percent), and Site C (33.3 percent), or 29.4 percent, which differs slightly from the 30.0 overall rate.

The actual violation rates are summarized in table 1 for each of the three cities and for the overall data base. Of the 110 intersection approaches, 59 were from Detroit, 27 from Washington, D.C., and 24 from the Dallas/Austin area. A total of 2,500 violations were observed for the 67,347 total turning vehicles, or 3.7 percent overall. The overall violation rates ranged between 3.4 percent (Detroit) and 4.4 percent (Dallas/Austin). The mean violation rate was 5.1 for all sites and ranged from 4.6 percent (Washington, D.C.) to 6.9 percent (Dallas/Austin). These numbers compare closely with the 6 percent overall violation rate found by Davis and Mullowney [5] in New Jersey at 11 sites in a 1983 study.

Table 1. Summary of RTOR violations at RTOR-prohibited sites.

City	Total Approaches	Right Turns	Total RTOR Violations	Violation Rate		Total RTOR Opportunities	Violation Rate Per Opportunity	
				Overall Rate (%)	Mean Rate (%)		Overall Rate (%)	Mean Rate (%)
Detroit	59	33,400	1,119	3.4	4.7	5,904	19.0	22.0
Washington, D.C.	27	22,742	888	3.9	4.6	4,122	21.5	19.4
Dallas/Austin	24	11,205	493	4.4	6.9	2,288	21.5	24.6
Totals	110	67,347	2,500	3.7	5.1	12,314	20.3	21.9

Other information in table 1 relates to RTOR violation rates per opportunity. For example, of the 67,347 right-turns at the 110 sites, only 12,314 (18.3 percent) had an opportunity to turn right-on-red. This is because many arrived and turned right on green or were not the lead vehicle stopped in the right-turn lane (could not physically make the turn on red). In a few cases, no opportunity existed for a RTOR violation due to high pedestrian or cross-street traffic.

The overall RTOR violation rate per opportunity was 20.3 percent, and was consistent among the cities, ranging from 19.0 percent (Detroit) to 21.5 percent (Washington and Dallas/Austin). This indicates that about 1 out of every 5 motorists turns right on red when given the opportunity when it is prohibited.

One additional analysis was also conducted of the percentage of overall RTOR violations which resulted in a conflict, as summarized in table 2. Of the 2,500 total RTOR violations at the 110 approaches, 585 of them (23.4 percent) resulted in some type of conflict. Of the 2,500 violations, 187 (7.5 percent) involved cross-traffic, 139 (5.6 percent) involved pedestrians in the near crosswalk, and 259 (10.4 percent) involved pedestrians in the far crosswalk.

Table 2. Summary of violations and conflicts at RTOR-prohibited sites.

City	Total Number of Violations	Number of RTOR Violations Resulting in Conflicts (%)				
		Total Conflicts	Conflicts With Traffic	Pedestrian Conflicts		
				Total Conflicts With Pedestrians	Near Crosswalk Only	Far Crosswalk Only
Detroit	1,119	246 (22.0)	79 (7.1)	167 (14.9)	61 (5.5)	106 (9.5)
Washington, D.C.	888	199 (22.4)	28 (3.2)	171 (19.3)	44 (5.0)	127 (14.3)
Dallas/Austin	493	140 (28.4)	80 (16.2)	60 (12.2)	34 (6.9)	26 (5.3)
Total	2,500	585 (23.4)	187 (7.5)	398 (15.9)	139 (5.6)	259 (10.4)

In terms of individual cities, RTOR violations in Dallas/Austin resulted in a conflict 28.4 percent of the time compared to approximately 22 percent in the other two cities. In particular, 16.2 percent of RTOR violations in Dallas/Austin resulted in a cross-traffic conflict, compared to 3.2 percent and 7.1 percent in Washington, D.C., and Detroit, respectively. However, pedestrian-related conflicts ranged from 19.3 percent of RTOR violations in Washington, D.C., compared to 14.9 percent (Detroit) and 12.2 percent (Dallas/Austin), probably due to the higher densities of pedestrians at the Washington sites.

These pedestrian conflicts occurred most frequently on the near crosswalk in Dallas/Austin (6.9 percent on the near crosswalk to 5.3 percent on the far crosswalk). However, the far crosswalks experienced more of the pedestrian conflicts than the near crosswalk at the sites in Washington (14.3 percent to 5.0 percent) and Detroit (9.5 percent to 5.1 percent). RTOR violations with pedestrians in the far crosswalk could be largely the result of pedestrian violations, since during a red phase, pedestrians in the near crosswalk would normally have the WALK interval.

From the discussion above, it should be remembered that while 23.4 percent of all RTOR violations resulted in conflicts, only 3.7 percent of all right-turning vehicles committed a RTOR violation. Thus, only (0.234) x (0.037) = 0.9 percent (less than 1 in 100) of the right-turn vehicles was involved in any kind of a RTOR-related conflict (585 RTOR-related conflicts for 67,347 total right-turning vehicles). Further, RTOR-pedestrian conflicts resulted from only 398 of 67,347 right-turning vehicles, or 0.59 percent, or about 6 out of every 1,000 right-turning vehicles. It should also be remembered that a majority of the sample sites were in areas with moderate to high pedestrian volumes, so these percentages of pedestrian conflicts are likely higher than would be expected at the overall sample of intersections in a city.

As discussed earlier, details were also recorded for the specific types of pedestrian conflicts resulting from each RTOR violation, as summarized in table 3. Of the 398 resulting pedestrian conflicts, the most prevalent types were pedestrian-vehicle interactions (36.5 percent), pedestrian hesitations (30.9 percent), and vehicle hesitations (27.1 percent). Only 16 pedestrian runs and 6 vehicle swerves were observed during the 573 hours of data collection. Vehicle hesitations were more prevalent in the far crosswalk than the near crosswalk (31.3 percent to 19.4 percent) and pedestrian/vehicle interactions were more common on the near crosswalk than the far crosswalk (41.7 percent to 33.6 percent).

Table 3. Summary of types of pedestrian conflicts resulting from violation of RTOR prohibition.

Type of Pedestrian Conflict	Number of Conflicts (% in Parenthesis)		
	Near Crosswalk	Far Crosswalk	Totals
Vehicle Hesitation	27 (19.4)	81 (31.3)	108 (27.1)
Vehicle Swerve	2 (1.5)	4 (1.5)	6 (1.5)
Pedestrian Hesitation	48 (34.5)	75 (29.0)	123 (30.9)
Pedestrian Run	4 (2.9)	12 (4.6)	16 (4.0)
Pedestrian/Vehicle Interaction	58 (41.7)	87 (33.6)	145 (36.5)
Totals	139 (100.0)	259 (100.0)	398 (100.0)

A comparison was also made between RTOR-related conflicts and RTOG (right-turn-on-green) conflicts for a sample of the data sites, as summarized in table 4. The sample includes 37,962 right-turn vehicles, of which 1,488 (3.9 percent) illegally turned right on red, and 96.1 percent turned right on green. In terms of pedestrians, 14.2 percent of RTOR maneuvers resulted in a pedestrian conflict compared to 19.5 percent of RTOG maneuvers which resulted in pedestrian conflicts. However, an additional 126 RTOR maneuvers (8.5 percent) resulted in cross-traffic conflicts. Thus, a total of 22.7 percent (14.2 + 8.5) of illegal RTOR maneuvers resulted in a conflict, compared to 19.5 percent of RTOG conflicts. Thus, while illegal RTOR maneuvers result in a slightly higher rate of total conflicts than RTOG (22.7 to 19.5 percent), fewer pedestrian conflicts occurred with illegal RTOR maneuvers than with RTOG (14.2 percent compared to 19.5 percent). It should be mentioned that pedestrians may legally cross the street in the near crosswalk with RTOR and the far crosswalk with RTOG.

Table 4. Comparison of pedestrian conflicts occurring with RTOR and RTOG.

City	Total Right Turns	RTOR	RTOG	Percent RTOR	RTOR With Conflict						RTOG With Conflict			
					Cross Traffic		Peds Near		Peds Far		Peds Near		Peds Far	
					#	%	#	%	#	%	#	%	#	%
Detroit	20,867	761	20,106	3.6	49	6.4	39	5.1	60	7.9	149	0.7	3,547	17.6
Washington, D.C.	9,000	334	8,666	3.7	5	1.5	17	5.1	57	17.1	87	1.0	2,628	30.3
Dallas/Austin	8,095	393	7,702	4.9	72	18.3	20	5.1	19	4.8	35	0.5	690	9.0
Total	37,962	1,488	36,474	3.9	126	8.5	76	5.1	136	9.1	271	0.7	6,865	18.8

Status of Violations to the Stopping Requirement at RTOR-Permitted Sites

Data were collected at 29 RTOR-allowed approaches in the three cities relative to the frequency of vehicles making a full stop, rolling stop, or no stop when turning right on red, as summarized in table 5. In addition, stopping data were also collected at 28 stop sign locations for comparison purposes. A total of 4 hours of data were collected per approach, for a total of approximately 228 hours of data. Conflict data were not collected relative to stopping characteristics data.

For the 29 signalized approaches (with RTOR allowed), 26.2 percent of right-turn vehicles turned right on red overall, with a small variation between cities (from 24.2 percent in Dallas/Austin to 29.3 percent in Washington, D.C.). Of all the vehicles turning right on red at the 29 approaches, 14.8 percent were recorded as no-stops (turned as if a green light existed), 42.1 percent made rolling stops, and 43.1 percent made full stops. Thus, 56.9 percent (42.1 + 14.8 percent) of motorists violated

Table 5. Summary of data collected at RTOR-permitted and stop sign approaches.

Approach	Right Turns Per Hour	RTOR Per Hour	Percent RTOR	Stopping Violations Per Hour	Percent Stopping Violations			Percent Full Stops			Number of Approaches
					Total Violations	Rolling Stop	No Stop	Total Full Stop	Voluntary Full Stop	Forced Full Stop	
RTOR Allowed Approaches (Totals)	67.3	16.3	26.2	9.2	56.9	42.1	14.8	43.1	7.2	36.0	29
Detroit	64.1	15.1	25.0	9.3	59.1	46.5	12.6	40.9	8.5	32.4	9
Washington, D.C.	69.3	19.5	29.3	11.7	61.4	41.7	19.7	38.6	4.6	34.0	10
Dallas/Austin	68.0	14.1	24.2	6.7	50.3	38.4	11.9	49.7	8.7	41.0	10
Stop-Sign Approaches (Totals)	38.3		NA	27.1	68.2	57.3	10.9	31.8	7.1	24.7	28
Detroit	59.3		NA	43.5	67.3	56.5	10.8	32.7	6.0	26.7	10
Washington, D.C.	35.5		NA	22.5	63.0	49.5	13.5	37.0	10.1	26.9	8
Dallas/Austin	19.5		NA	14.3	73.3	64.4	8.9	26.7	5.9	20.8	10

the RTOR law by not making a full stop before turning right on a red signal. Of the 43.1 percent full stops, 36.0 percent were "forced" to stop (i.e., by oncoming traffic or pedestrians) and 7.1 percent were voluntary stops.

An analysis by city showed that total violations (no-stops plus rolling stops) were the highest in Washington, D.C. (with 61.4 percent of vehicles not fully stopping) and Detroit (59.1 percent of vehicles not fully stopping), and lowest in Dallas/Austin (50.3 percent of vehicles not fully stopping).

The percent of right-turning vehicles stopping at RTOR-allowed sites was compared to those at stop sign locations, since motorists under both situations are required to make a full stop and then turn right after yielding to pedestrians and cross-street traffic. Thus, the relative magnitude of nonstopping motorists at RTOR-allowed locations could be discussed in terms of another type of traffic control. Such comparisons of compliance between RTOR-allowed sites and stop sign locations has been made in several previous RTOR studies.

The overall violation rate (i.e., motorists not fully stopping) of right-turn vehicles was found to be 68.2 percent at stop sign locations, compared to 56.9 percent at the RTOR-permitted sites, a difference of 11.3 percent. Rolling stops were higher at the stop sign locations (57.3 percent) compared to RTOR-allowed locations (42.0 percent). However, the percent of no-stops was 14.8 percent at the RTOR-permitted locations, compared to 10.9 percent at the stop sign locations.

The overall percentage of voluntary stops was approximately 7 percent at both the RTOR-allowed sites and the stop sign locations. However, 36 percent of the RTOR motorists were forced to stop at the RTOR-allowed locations, compared to 24.7 percent at the stop sign locations, a difference of 11.3 percent. Note that a difference of 11.3 percent was also found between RTOR-allowed and stop sign approaches in terms of overall violations. This indicates that the slightly higher percent vehicles stopping at the RTOR locations (43.1 percent) compared to the stop sign locations (31.8 percent) could be largely the result of more opportunities for a rolling or no stop at the stop sign locations. Thus, little difference in driving behavior seems apparent in terms of stopping compliance between the RTOR-permitted locations and the stop sign locations.

The overall 56.9 percentage of vehicles not fully stopping (before turning right on red) is higher than the 40 percent found by Davis and Mullowney [5] in a 1983 study of intersections in New Jersey. Part of the differences could be slight variations in the definitions of a rolling or full stop, differences in site characteristics, or differences in motorist behavior at the New Jersey sites. However, a 1978 study of 11 sites in Providence, Rhode Island, and 12 locations in Springfield, Massachusetts, found that 65 percent and 28 percent of the motorists, respectively, did not stop before turning right on red. The high compliance rate in Springfield was attributed to the newness of the RTOR maneuver and the sign reminding them to stop.[7] In a 1981 study, Baumgaertner [2] found that 64.4 percent of drivers failed to stop in Maryland before turning right on red. Thus, other recent studies have found rates of nonstopping to range from about 28 percent to 65 percent, and the finding of 56.9 percent in this study falls within this range. It seems apparent, however, that the percentage of nonstopping vehicles varies from city to city and may have changed in recent years.

It should also be mentioned that <u>conflict data</u> were not collected relative to stopping characteristics of RTOR vehicles. The conflicts resulting from RTOR are highly dependent on pedestrian volumes, RTOR volume, side-street volume, and numerous locational factors. Thus, a direct comparison of conflicts is not appropriate between sites with RTOR-allowed and RTOR-prohibited, since sites may differ greatly in terms of pedestrian volume, RTOR volume, etc. It is possible, however, that a conflict problem on an intersection approach may exist due to the failure of RTOR vehicles to make a full stop. The magnitude of this RTOR conflict problem can only be determined based on stopping characteristics data and corresponding conflict data at a large number of sites with RTOR allowed (i.e., 100 or more) with a variety of site and volume conditions.

Locational Factors Related to RTOR Violations

The next phase of the study involved determining the geometric, traffic control, and other locational characteristics which are associated with high RTOR violation rates. The basic analysis approach for determining such related factors involved a safety engineering study of individual sites. This first involved ranking approaches by violation rate and then identifying common locational factors associated with high violation sites and low violation sites. This ranking was generated first for the 110 sites with RTOR prohibition, and then a separate ranking was developed for the 29 RTOR-allowed sites. A discussion is given below of these two situations.

Locational Factors for RTOR-Prohibited Sites

Violation rates (turning right on red) at the RTOR-prohibited sites ranged from 0 to 25.6 percent. A distribution of the violation rates of the 110 sites was as follows:

Number of Sites	Percent Violations	
13	0 to 1	Low Violation Approaches
21	1 to 2	
19	2 to 3	
11	3 to 4	
6	4 to 5	
11	5 to 6	
7	6 to 8	High Violation Approaches
4	8 to 10	
7	10 to 12	
8	13 to 18	
3	18 to 30	
110	Total	

The top 29 approaches (26.3 percent) were found to have a violation rate above 6.0 and were labeled as the high violation group. A total of 34 approaches (30.9 percent) had a violation rate of 2 percent or less and were labeled as the low violation group.

For the locations in the two violation groups, factors were identified which were related to high and low violations based on field inspections, a review of site diagrams, and a review of computer summaries of traffic data, signal data, and other information at each site (figure 5). Location factors were identified as related to high violations if they were routinely found in the high violation group but not in the low violation group. Traffic and roadway factors found to be typically associated with high violation rates include the following variables (individually or in various combinations):

- Confusing or inappropriate partial prohibition signs (i.e., NTOR-School Days Only sign located near a university, since motorists aren't sure whether classes are in session on Saturdays, during summer sessions, etc. Another NTOR sign near an elementary school prohibited RTOR during times after children had already arrived at school (9:00 a.m. to 2:00 p.m.) and ended prior to children leaving for home in the afternoon).
- NTOR signs which are located far-side or are inconspicuous to the motorists, particularly when placed far side across wide streets.
- Combinations of low cross-street volume and low pedestrian volumes
- Approaches with easy right-turn maneuvers or right turns less than 90 degrees such as at Y-intersections, particularly with low conflicting movements.
- Long cycle lengths resulting in excessive waiting time for right-turn motorists.
- High speed ramps forming a T-intersection with a low-volume cross-street.
- Wide one-way streets on the cross street with low volume in the curb lane.
- Confusing, multi-leg intersection approaches or approaches with an offset cross street.
- Approaches where RTOR prohibition appears not to be justified for some or all periods of the day due to low traffic volumes and little or no pedestrian traffic.

CITY: DETROIT

SITE: 13 INTERSECTION: ANTHONY WAYNE RD AND WARREN RD

APPROACH: SOUTHBOUND OPERATION: 2-WAY NUMBER OF LEGS: 4

RTOR: PROHIBITED SIGN LOCATION: COMBINATION SIGN MOUNTING: SPAN

RIGHT LANE: MULTIPLE LN AREA TYPE: SCHOOL SPEED: 25 MPH SIGHT DISTANCE: 164 FT

SKEWNESS: 90 DEG NEAR X-WALK: 45 FT FAR X-WALK: 46 FT CYCLE LENGTH: 70 SEC PHASES: 2

V O L U M E S P E R H O U R

TOTAL TIME	TOTAL RIGHT	RIGHT TURNS ON GREEN					RIGHT TURNS ON RED					PEDESTRIAN VOLUME		
			ARRIVE ON		CONFLICTS			NO	CONFLICTS WITH					
HOURS	TURNS	TOTAL	GREEN	RED	NEAR	FAR	TOTAL	CONFLICT	TRAFFIC	NEAR PEDS	FAR PEDS	NEAR	FAR	TOTAL
8.50	194.35	188.82	140.12	41.29	2.67	11.33	5.53	3.76	1.29	0.0	0.47	76.8	44.1	120.9
		97.15%					2.85%							

RIGHT TURN ON GREEN CONFLICTS

CONFLICT	NEAR X-WALK		FAR X-WALK		TOTAL	
TYPE	NUMBER	PER HOUR	NUMBER	PER HOUR	NUMBER	PER HOUR
VH	2.	0.44	22.	4.89	24.	5.33
VS	0.	0.0	0.	0.0	0.	0.0
PH	4.	0.89	2.	0.44	6.	1.33
PR	0.	0.0	3.	0.67	3.	0.67
I	6.	1.33	24.	5.33	30.	6.67
TOTAL	12.	2.67	51.	11.33	63.	14.00

RIGHT TURN ON RED CONFLICTS

CONFLICT	NEAR X-WALK		FAR X-WALK		TOTAL	
TYPE	NUMBER	PER HOUR	NUMBER	PER HOUR	NUMBER	PER HOUR
VH	0.	0.0	0.	0.0	0.	0.0
VS	0.	0.0	0.	0.0	0.	0.0
PH	0.	0.0	2.	0.24	2.	0.24
PR	0.	0.0	0.	0.0	0.	0.0
I	0.	0.0	2.	0.24	2.	0.24
TOTAL	0.	0.0	4.	0.47	4.	0.47

Note:
1 ft = 0.3 m
1 mph = 1.6 kph

Figure 5. Typical approach summary for sites where RTOR violation data were collected (RTOR-prohibition sites).

- Low right-turn volume per hour was also associated with a high percent violations. However, this is somewhat misleading, since the percent violations is the total RTOR vehicles divided by the right-turn vehicles (including RTOG). As right-turn volume increases, a higher percentage of right-turn vehicles are trapped second, third, or fourth in line and cannot physically make a RTOR.

The intersection approaches with low RTOR violation rates were also studied to determine related factors. These factors typically found at <u>low</u> violation sites included:

- Double NTOR signs located near side and far side, or NTOR signs which were located overhead or in a conspicuous location for stopped motorists.
- High pedestrian volumes in either the near or far crosswalk (reduced opportunity for a RTOR).
- High cross-street volume (reduced number of gaps and lower opportunity for a RTOR).
- Crosswalk set back from the intersection further than normal, combined with high pedestrian volumes.
- Short signal cycle length.
- A sharp right-turn maneuver (greater than 90 degrees) combined with poor sight distance.
- High right-turns per hour was also associated with a low violation rate. However, this is misleading, as discussed previously.
- A cross street with on-street parking on the right, which forces a RTOR vehicle to make a wide turn beyond parked cars.

These results seem to indicate that motorist violations to NTOR signs are high when the signs are obscure, or when it is not obvious to the driver why RTOR is prohibited (i.e., low pedestrian and cross-street volume and good sight distance). Drivers are particularly likely to run a NTOR sign at sites with long cycle lengths (when waiting time may be long). Some of the factors listed above were found to be useful for developing countermeasures, as will be discussed later.

Consideration was given to conducting more formal statistical analysis techniques to further support the factors which are associated with high and low violation rates. A branching analysis was conducted to identify roadway variables (independent variables) that account for the largest amount of explained variance in the violation rate (dependent variable). Each data sample in the analysis was represented by a 30-minute data period, using a total of 1,030 data points. The results of the analysis are shown in figure 6 which indicates that important factors include right-turn volume, number of phases, pedestrian volume, roadway operation (one- or two-way) and roadway configuration (with respect to the cross street). Most of these results are in basic agreement with the more detailed engineering analysis. However, the results of the branching analysis must be treated with caution, since: (1) the branching analysis produces more reliable results for very large samples of sites; and (2) the interaction effect of two or more important locational variables may not be properly accounted for with a branching analysis to explain variation in conflicts.

In addition to the branching analysis, preliminary Pearson correlation analysis and ANOVA tests were conducted. However, correlation coefficients were low (below 0.3) for individual variables, and the ANOVA test required a larger data base of approaches to control for the interaction of traffic and roadway variables as they affect RTOR violation rates. It was evident that an engineering analysis of each approach was most useful in determining individual factors or combinations of factors that were related to high or low violation rates.

Locational Factors for RTOR-Permitted Sites

A detailed study was also made of traffic, geometric, and other factors (figure 7) at each of the 29 RTOR-permitted approaches to identify factors related to stopping violations (i.e., not making a full stop before turning right on red). At the 29 signalized approaches with RTOR permitted, no-stops ranged from 0 percent to 45.2 percent, and total stopping violations (no stops plus rolling stops) ranged from 21.2 percent to 88.9 percent. One approach that had a sign posted "RIGHT TURN ON RED

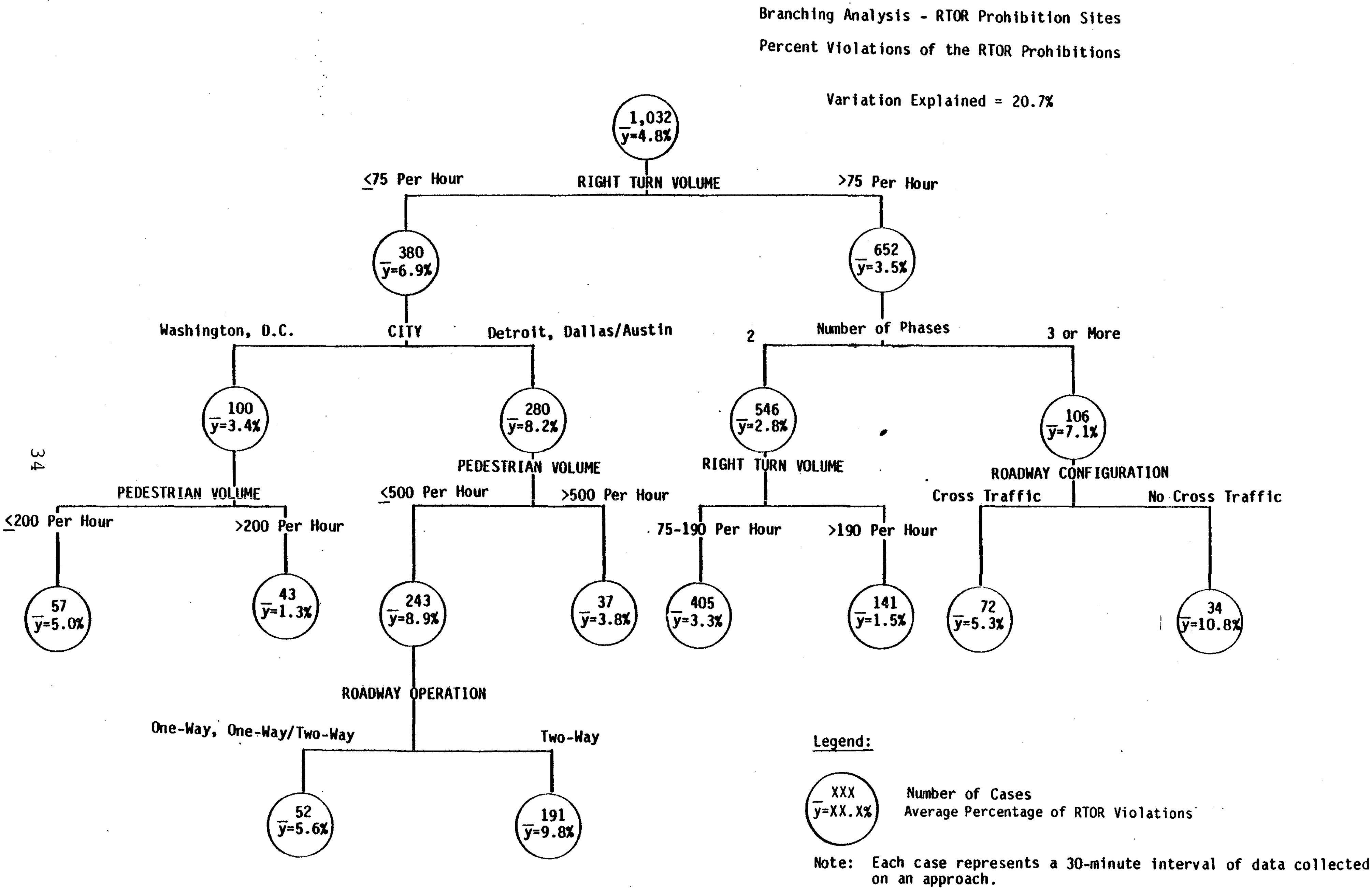


Figure 6. Branching diagram of the percent violations of RTOR prohibitions.

CITY: WASHINGTON

SITE: 71

APPROACH: SOUTHBOUND STREET: 7TH ST CONTROL: SIGNAL

AREA TYPE: COMM SPEED: 35 MPH SIGHT DISTANCE: 181 FT SKEWNESS: 90

		RIGHT TURN ON RED				PED VOLUME		
TOTAL TIME	RIGHT TURN ON GREEN	NO STOP	ROLLING STOP	FULL STOP VOL.	FULL STOP FORCED	NEAR X-WALK	FAR X-WALK	OPPOSING VOLUME
240 MIN	207	32	54	8	44	49	55	877
4.0 HRS	60.0%	9.3%	15.7%	2.3%	12.8%			
	----	23.2%	39.1%	5.8%	31.9%			

CITY: WASHINGTON

SITE: 71

APPROACH: WESTBOUND STREET: MAINE CONTROL: SIGNAL

AREA TYPE: COMM SPEED: 35 MPH SIGHT DISTANCE: 300 FT SKEWNESS: 90

		RIGHT TURN ON RED				PED VOLUME		
TOTAL TIME	RIGHT TURN ON GREEN	NO STOP	ROLLING STOP	FULL STOP VOL.	FULL STOP FORCED	NEAR X-WALK	FAR X-WALK	OPPOSING VOLUME
240 MIN	196	19	15	2	6	86	27	191
4.0 HRS	82.4%	8.0%	6.3%	0.8%	2.5%			
	----	45.2%	35.7%	4.8%	14.3%			

Note:
1 ft = 0.3 m
1 mph = 1.6 kph

Figure 7. Typical approach summary for sites where stopping characteristics data were collected (stop sign or RTOR-allowed sites).

ALLOWED AFTER STOP" experienced 26.7 percent no-stops and 68.6 percent total stopping violations, compared to an overall average of the 29 sites of 14.8 percent no-stops and 56.9 percent total violations. It is possible that the sign had an effect of increasing stopping violations at the site, although insufficient data existed to verify this.

Locational factors found to be associated with a high rate of stopping violations include:

- Good sight distance with low pedestrian volume and low cross-street volume.
- High right-turn volume.
- Low pedestrian volume.
- Low cross-street volume.
- Unusual signal timing, such as split phasing, which minimized or eliminated conflicting traffic for part of the red interval.
- Offset cross street (which lowered or delayed conflicting traffic and increased the opportunity for a RTOR rolling stop or no-stop).
- Nearby signalized intersection on the cross street upstream, which created artificial gaps in cross-street traffic and provided greater opportunities for RTOR rolling stops or no-stops.

The factors found to be associated with low stopping violations at RTOR-allowed approaches included:

- High cross-street volume.
- Poor sight distance (i.e., on-street parking on the cross street to the left of the approaching right-turn motorist).
- High speed of cross street.
- High pedestrian volume.

These results indicate that drivers were more likely to comply with the stopping requirement when forced to do so (i.e., high pedestrian volume or cross-street traffic). Also, poor sight distance was a factor associated with high compliance, since drivers often made a full stop to look for cross-street traffic. During intervals of little or no pedestrian or conflicting traffic (such as with special signal phasing), motorists were less likely to make a full stop before turning right on red.

More formal statistical analysis techniques were not utilized for identifying related factors, since such analyses are not particularly appropriate for relatively small sample sizes of this type. These factors listed above were considered for development of possible countermeasures relative to RTOR stopping violations, as discussed in the next section.

SUMMARY OF FINDINGS AND CONCLUSIONS

The purpose of this analysis was to conduct observational studies at signalized intersections to determine the current motorist compliance to RTOR prohibition and the requirement to make a full stop before turning right on red (where permitted). Traffic, geometric, and other physical site characteristics were collected in Detroit, Washington, D.C., and the Dallas/Austin area; and an in-depth engineering study was conducted at each of 110 intersection approaches where RTOR is prohibited. Data were also collected at 29 RTOR-allowed intersection approaches and 28 stop sign approaches relative to stopping characteristics (i.e., percentage of full stops, rolling stops, and no stops of RTOR vehicles). Then locational factors were identified relative to high and low violation rates. The following is a summary of key findings and conclusions :

1. Overall, only 3.7 percent of all right-turning drivers violate the RTOR prohibition signs, based on a sample of over 67,000 drivers. However, of those motorists given an opportunity to commit a RTOR violation, about 20 percent of them violate the NO TURN ON RED sign.

2. Of the drivers who commit a RTOR violation, about 23.4 percent of them result in conflicts with pedestrians or cross-street traffic. However, less than 1 in 100 of the total right-turn vehicles is involved in a RTOR-related conflict.

3. At a sample of RTOR-prohibited sites 22.7 percent of the illegal RTOR maneuvers resulted in a conflict to cross-traffic or pedestrians. However, only 14.2 percent of RTOR maneuvers resulted in a conflict to pedestrians, compared to 19.5 percent RTOG maneuvers which involve a pedestrian conflict.

4. Of the 29 intersection approaches with RTOR allowed, 26.2 percent of right-turn vehicles turned right on red. Of the vehicles turning right on red the violation rate (not making a full stop) was 56.9 percent. This rate was higher for Washington (61.4 percent of vehicles not fully stopping) and Detroit (59.1 percent), compared to Dallas/Austin (50.3 percent).

5. The overall violation rate (percent not fully stopping) at the 28 stop sign approaches was 68.2 percent, compared to 56.9 percent for signalized approaches with RTOR allowed, a difference of 11.3 percent. However, 36 percent of vehicles were found to stop at RTOR-allowed approaches, compared to 24.7 percent at stop sign locations. Thus, the 11 percent higher violation rate at stop sign locations may be at lest partly explained by the greater percent of opportunities for a rolling stop or no-stop.

6. Examples of physical site factors found from in-depth site studies to be related to high RTOR violation rates include:

   - Confusing or inappropriate partial prohibition signs.
   - Far side or inconspicuous NTOR signs.
   - Long cycle lengths.
   - Confusing multi-leg intersection approaches.
   - Unjustified RTOR prohibition.
   - Split-phasing of the signal which creates low opposing traffic for RTOR maneuvers.
   - Combinations of a low volume or high speed of cross-street traffic, and low pedestrian volumes.

CHAPTER II
DEVELOPMENT AND TESTING OF COUNTERMEASURES

INTRODUCTION

The primary RTOR accident countermeasure used to date has been to prohibit RTOR on an approach. Total as well as part-time prohibitions have been used. However, there is strong evidence that RTOR prohibitions are not the only solution to the problem. In fact, an unwarranted RTOR prohibition may result in a high violation rate.

Past research has failed to clearly demonstrate the types of countermeasures which will most likely minimize the adverse effects of RTOR. A wide variety of site conditions such as geometrics, vehicle speeds, traffic volumes, pedestrian activity, and other factors may affect the safety and operations of RTOR maneuvers. Thus, there is a need to develop and test countermeasures which would reduce pedestrian hazards from RTOR vehicles for various site characteristics.

The purpose of this chapter is to: (1) develop potentially cost-effective countermeasures for RTOR-related pedestrian hazards; (2) field test the most promising countermeasures; and (3) recommend the ones which are found to be most effective for various site conditions. These may include countermeasures to:

- Reduce motorist violation of RTOR prohibitions signs.
- Reduce the number of drivers that fail to come to a full stop before turning right on red at locations where RTOR is allowed.
- Minimize the potential hazard to pedestrians resulting from motorists turning right on red (either legally or illegally).
- Improve conditions at the approach to allow motorists to make a safer RTOR maneuver.

The general types of countermeasures which are considered in this analysis include physical roadway improvements, such as: (1) signing options, (2) signal modifications, (3) pavement markings, (4) design changes, and (5) other treatments (i.e., adding intersection lighting, removing roadside clutter, etc.). The use of selective traffic enforcement and public (driver or pedestrian) education programs is recognized as a potential treatment for a RTOR problem, as with many other traffic safety problems. It is also recognized that changes in local or national laws regarding RTOR could impact RTOR safety and operations. However, the development and testing of countermeasures in this study is limited only to the physical roadway improvements, and does not include the testing of education, enforcement, or changes in laws or regulations.

BACKGROUND

The number and scope of countermeasures for RTOR accidents indentified in the literature are somewhat limited. However, several authors have addressed this issue. Parker [1] developed a list of recommendations to consider when implementing RTOR prohibitions. These considerations included:

- Increase sign size.
- Illuminate the NTOR sign.
- Modify sign location (post mounted or overhead).
- Improve legislation and enforcement to protect pedestrians in RTOR situations.
- Offset stop bars to allow a "clear view" for motorists in the right lane.
- Improve public awareness of RTOR regulations and safety.
- "Fine Tune" traffic signal timing.
- Replace or install presence detectors at intersections which are traffic actuated to improve the efficiency of traffic operations.

McGee [12] also developed some recommendations for utilizing RTOR and RTOR prohibitions which included:

- Improve the wording of sign messages prohibiting RTOR.
- Provide variable RTOR time restrictions (i.e., during school hours or specific times or days).
- Install more than one RTOR prohibition sign facing each approach.

- Use YIELD TO PEDESTRIAN signs in areas of high pedestrian volumes.
- Use RIGHT TURN ON RED AFTER STOP signs.

In their 1981 study, of RTOR related to pedestrians and bicyclists, Preusser et al. [13] suggested the following potential countermeasures as worthy of further analysis and development:

- Provide bicyclist and pedestrian education programs.
- Modify warrants for RTOR prohibition to include considerations for bicycle traffic.
- Use exclusive pedestrian signal phasing which would include an illuminated NO TURN ON RED message.
- Set back the pedestrian crosswalk so the pedestrians would cross the street behind the RTOR vehicle.

In 1984, Technical Committee 4A-17 of the Institute of Transportation Engineers [14] developed guidelines for prohibiting RTOR. Some of their study recommendations addressed countermeasures related to RTOR, including:

- Use a disappearing legend sign for part-time prohibitions and approaches near railroad crossings.
- Consider less restrictive prohibition signs instead of full prohibitions (i.e., NO TURN ON RED TO HENRY STREET).
- Provide education and enforcement programs.

COUNTERMEASURE DEVELOPMENT

The development of countermeasures for RTOR-pedestrian accidents may be based on the sequence of events leading to such an accident, as well as the actions and contributing causes. For example, figure 8 illustrates the sequence of events of RTOR pedestrian accidents beginning with the total population of signalized intersection approaches. Vehicles turning right on red (whether permitted or prohibited) when combined with pedestrians may lead to accidents. When evasive action is taken by either the driver or pedestrian, a RTOR pedestrian accident is avoided. However, when neither reacts in time, a RTOR pedestrian accident results.

It may be possible to prevent a RTOR-pedestrian accident by interjecting countermeasures at two specific stages in the sequence of events, namely, at points A and B as shown in figure 8. Actions at point A address the problem of vehicles turning right on red, even though a RTOR prohibition exists on the approach. Countermeasures of this type are designed to reduce RTOR violations.

At point B in figure 8, motorists turn right on red with pedestrians present, and neither the drivers nor the pedestrians take adequate evasive action to avoid a RTOR-pedestrian accident. Countermeasures directed at point B would be involved primarily with changing the behavior or awareness of pedestrians or motorists to avoid a RTOR-pedestrian accident.

The development of possible RTOR-related accident countermeasures for field testing in this study involved treatments to break the chain of events leading to a RTOR-pedestrian accident. Sources used in countermeasure development included:

- Published and unpublished literature.
- Treatments used in the past by highway agencies.
- Considerations to eliminate specific types of violation problems discovered in the Chapter I analysis.
- Brain-storming sessions conducted by the study team with assistance from selected highway agency officials.

The countermeasures for RTOR-related accidents from the literature were discussed in the previous section. Other countermeasures based on the RTOR violation data (see Chapter I) were developed next. The factors related to high and low RTOR violations were studied and then grouped into corresponding "high violation" and "low violation" categories, as listed in table 6. For example, one of the factors related to high violation of NTOR signs was "long cycle length" (excessive delay to right-turn motorist). A corresponding factor related to low violation rates was "short cycle length." Thus, by grouping these factors, candidate countermeasures were developed, such as improving signal timing or installing traffic actuation devices.

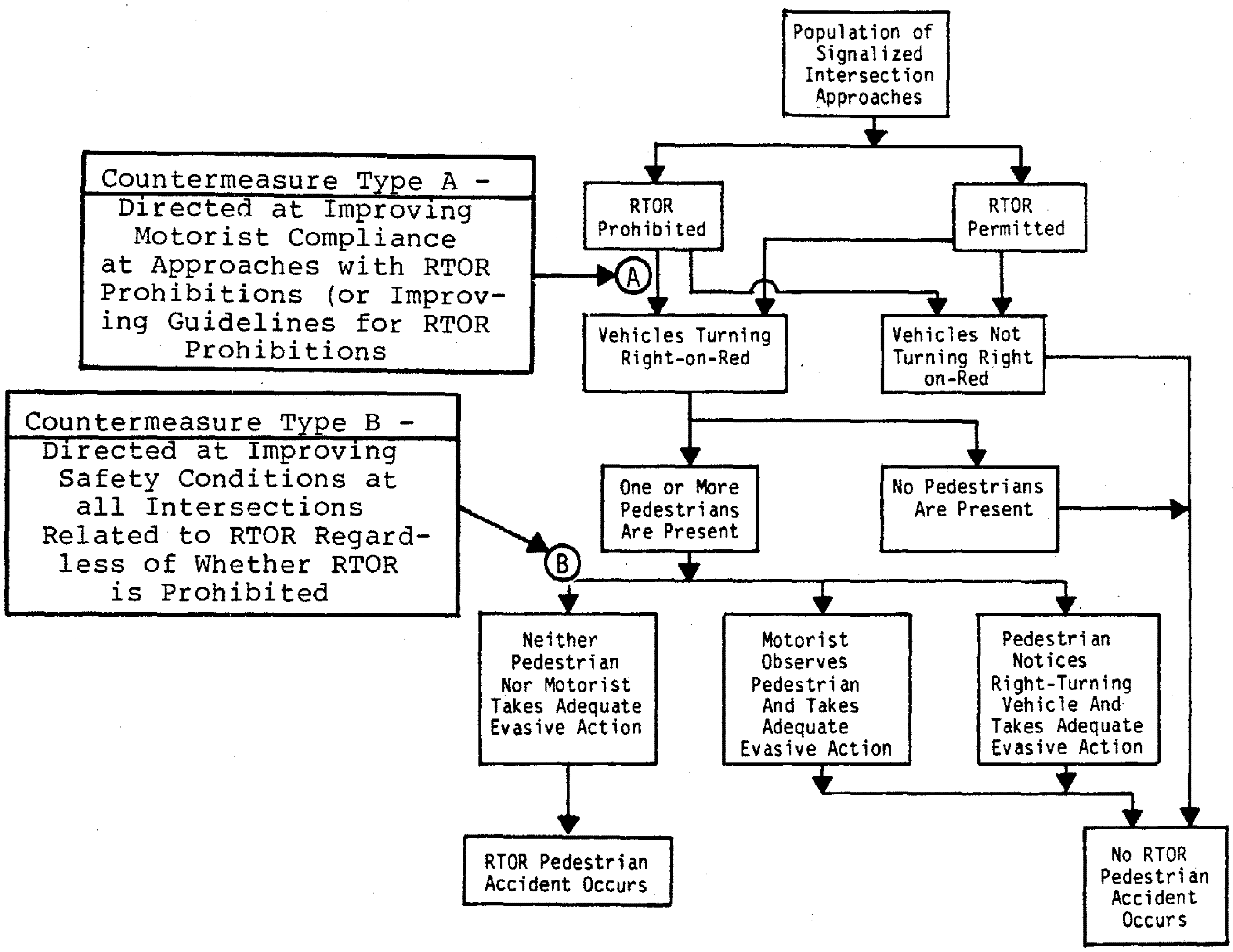


Figure 8. Application of countermeasure types to the chain of events for RTOR pedestrian accidents.

Table 6. Summary of development of candidate countermeasures based on factors related to RTOR violations.*

High/Low Situation	Type of Violation Problem	Factors Related to High RTOR Violations	Factors Related to Low RTOR Violations	Candidate Countermeasures
1.	RTOR Where Prohibited	NO TURN ON RED signs located far side or inconspicuous to the motorist.	Double NTOR signs located near side and far side, or NTOR signs which are located overhead or in a conspicuous location for stopped motorists.	1. Illuminate NO TURN ON RED sign. 2. Increase sign size to improve visibility. 3. Relocate signs to near signal placement. 4. Use double NTOR signs for redundancy. 5. Utilize NTOR signs with red ball. 6. Advanced warning of NTOR. 7. Remove roadside clutter (to make NTOR sign more conspicuous). 8. Provide or improve intersection lighting.
2.	RTOR Where Prohibited	Confusing or inappropriate partial prohibition signing.	Clear and visible NO TURN ON RED signing.	1. Prohibit RTOR only during the hours of heavy pedestrian travel. 2. Utilize full RTOR prohibition on the approach. 3. Utilize variable message NTOR signs. 4. NTOR illuminated signal to be activated only during periods when RTOR is prohibited.
3.	RTOR Where Prohibited	Long cycle lengths (excess waiting time for right-turn motorists).	Short signal cycle lengths.	1. Improve pedestrian signal display. 2. Retime the traffic signal to provide better operations. 3. Install presence detectors at traffic actuated approaches to provide more efficient signal operation. 4. Remove unwarranted traffic signals.
4.	RTOR Where Prohibited	Easy right-turn maneuver.	Crosswalk set back from intersection further than normal combined with high pedestrian volumes.	1. Relocate crosswalk. 2. Offset or angled stop bar. 3. Special pavement marking in crosswalk.

Table 6. Summary of development of candidate countermeasures based on factors related to RTOR violations* (continued).

High/Low Situation	Type of Violation Problem	Factors Related to High RTOR Violations	Factors Related to Low RTOR Violations	Candidate Countermeasures
5.	Stopping Violations Where RTOR Allowed	Unusual signal timing.	Lack of opportunity due to consistent traffic flow on cross street.	1. Install flashing red right turning arrow to encourage full stop. 2. Install NO TURN ON RED sign if warranted. 3. Retime traffic signal. 4. Install part-time RTOR prohibition sign or variable message NO TURN ON RED display. 5. Install RIGHT TURN ON RED AFTER STOP sign to encourage full stops. 6. Use special pedestrian signal display (i.e., WALK WITH CARE signal message during the WALK interval). 7. Install special pavement markings in crosswalk (i.e., LOOK FOR TURNING VEHICLES).
6.	Stopping Violations Where RTOR Allowed	Good sight distance.	Poor sight distance.	1. Install RIGHT TURN ON RED AFTER STOP sign to encourage full stops. 2. Install YIELD TO PEDESTRIAN sign. 3. Relocate crosswalk further from intersection.
7.	Stopping Violations Where RTOR Allowed	High right-turn volume, low pedestrian volume, or low cross-street volume.	Low right-turn volume, high pedestrian volume, or high cross-street volume (or speed).	1. Install RIGHT TURN ON RED AFTER STOP sign to encourage full stops. 2. Install NO TURN ON RED sign if warranted. 3. Install part-time RTOR-prohibition sign or variable-message NO TURN ON RED display. 4. Install YIELD TO PEDESTRIAN sign. 5. Install PEDESTRIANS WATCH FOR TURNING VEHICLES sign.

Table 6. Summary of development of candidate countermeasures based on factors related to RTOR violations* (continued).

High/Low Situation	Type of Violation Problem	Factors Related to High RTOR Violations	Factors Related to Low RTOR Violations	Candidate Countermeasures
7. (Continued)				6. Use special pedestrian signal display (i.e., "WALK WITH CARE" signal message during the WALK interval. 7. Re-time traffic signal. 8. Remove unwarranted traffic signals. 9. Relocate crosswalk further from intersection. 10. Use special pavement marking in crosswalk (i.e., LOOK FOR TURNING VEHICLES). 11. Construct pedestrian overpass/ underpass. 12. Construct separate right-turn lane.

* The countermeasures in this table were intended to correspond to traffic engineering treatments (i.e., improvement of traffic control devices and/or transportation facilities). It is recognized that providing selective police enforcement and use of public education programs may also be of considerable benefit with respect to improving compliance and/or understanding of RTOR requirements and devices.

As shown in table 6, seven basic situations were found for which countermeasures could be proposed. Four of these situations related to violations of RTOR prohibitions, and three of them involved the incidence of stopping violations (vehicles not making a full stop prior to a RTOR maneuver) where RTOR is allowed. For several of the violation causes, countermeasures were suggested which may either have an effect on the violation rates, or may reduce the degree of hazard resulting from the violations. For example, for RTOR violations involving not making full stops before turning right on red, countermeasures which may reduce the danger of such violations may include:

- Relocating the crosswalk further from the intersection.
- Warning pedestrians of possible right turn danger through the use of WALK WITH CARE pedestrian signals or LOOK FOR TURNING VEHICLES pavement markings.
- Construction of a pedestrian overpass or underpass to physically separate pedestrians and motorists.

Although RTOR motorists should yield to pedestrians, pedestrians should also be alert whenever crossing the street, since the pedestrian is usually the one who is injured in the event of a vehicle-pedestrian accident. Thus, some of the countermeasures listed in table 6 are intended to reduce violations related to RTOR, and other countermeasures are intended to reduce the potential hazard of RTOR maneuvers (either legal or illegal).

Based on all of the sources discussed previously, 30 potential RTOR-related accident countermeasures were summarized in table 7. These were categorized under five general categories:

- Signs (12 countermeasures).
- Signals (6 countermeasures).
- Pavement markings (3 countermeasures).
- Design treatments (5 countermeasures).
- Others (4 countermeasures).

Table 7. Countermeasures developed for RTOR.

Category	Device	Description	Selected for Field Study	Comments
SIGNS	1. Full prohibition of RTOR	Install NTOR sign at locations with high traffic or pedestrian volumes, poor sight distances, at school crossings, or where other such factors influence the safe right-turn-on-red maneuver.	No	There are some locations where RTOR maneuvers are unduly hazardous. Although the MUTCD has guidelines on the application of NTOR signs, they are general and prone to a wide variety of interpretations. This leads to a non-uniform application of RTOR prohibitions. Since conditions may change based on time of day, day of week and season, a full-time prohibition may not always be warranted at a site.
	2. Partial prohibition of ROTR for certain lanes or during specific times of the day.	Install special signs that prohibit RTOR for certain times (7 a.m. to 7 p.m.), days (school days), conditions (when children present), seasons (Sept. to June), lanes (NTOR - except curblane) or other factors.	Yes	Since conditions may change at a site (by time of day or day of week, etc.) the prohibition should ideally only cover those times and conditions where warranted. However, some of the legends may require special knowledge by the motorists (school days), require motorists to drive "with one eye on the clock", or may be difficult to read.
	3. YIELD TO PEDESTRIAN sign.	Install a yield sign directed at turning motorists advising them to yield right-of-way to pedestrians.	No	This device was tested in a previous FHWA study on pedestrian signalization alternatives and was found to be effective in reducing total right-turn conflicts with pedestrians.
	4. Illuminate NO TURN ON RED sign.	Illuminate the NTOR sign for increased visibility. This could be accomplished using ar illuminated case sign (internal source) or external lighting.	No	Designed for areas where there is a nighttime RTOR-related problem and/or where no intersection lighting exists.
	5. Larger NO TURN ON RED sign.	Use a NTOR larger than the current MUTCD standard of 24x30 inches or 24x24 inches (60x75-cm or 60x60-cm).	Yes	NTOR sign should ideally be placed near the signal. Applicable for near signal placement when the signal is located on the far side of a wide street or is otherwise difficult to read. May be particularly helpful in cities or locations where overhead sign placement is not possible.
	6. Near-signal placement of NO TURN ON RED sign.	Install NTOR sign on span arm, span wire or signal pole near the signal head where motorist tends to look.	No	The MUTCD guidelines for NTOR sign placement state that signs should be located adjacent to the signal face to which they apply. Many communities do not follow these guidelines and have the sign post mounted at the corner of the intersection.
	7. Redundant NO TURN ON RED signs.	Install two or more NTOR signs on both posts (near or farside) and overhead to increase visibility of sign.	No	While this countermeasure is applicable for some locations with high violation rates, high conflict rates, or poor sign visibility, redundant sign placement should be minimized.
	8. RIGHT TURN ON RED AFTER STOP sign.	Install a sign which reminds motorist to come to a complete stop before turning on red.	No	This device is intended to remind the driver to come to a full stop before making the RTOR maneuver, or to encourage more RTOR maneuvers where motorists are hesitant (and there are no conflicting pedestrian crossings or cross-

Table 7. Countermeasures developed for RTOR (continued).

Category	Device	Description	Selected for Field Study	Comments
SIGNS	9. NO TURN ON RED sign with red ball.	Install a modified NTOR sign with a red ball in the center to draw attention to the sign.	Yes	A sign with a red ball may catch the motorist's eye better. This device is currently used in some cities.
	10. Advance warning of NO TURN ON RED.	Install a sign in advance of the intersection to warn motorists that there is a RTOR prohibition at the next intersection.	No	This allows advance warning of conditions at the intersection and is consistent with positive guidance concepts. This sign may only add to the visual clutter of the roadside and have minimal effect for those stopped at the signal.
	11. Electrical/mechanical variable message NO TURN ON RED sign.	Install signs which can display different messages for different signal intervals, times of day, or days of week, etc.	Yes	This device has two applications: (1) prohibit RTOR during portions of the day having high pedestrian volumes or cross-street volumes, or (2) prohibit RTOR during portions of a cycle where a protected movement may conflict with the RTOR, (such as an opposing protected left-turn maneuver). A blank-out display would avoid confusion when the message is not needed or other safety messages could be displayed. The cost for this device is expected to be high.
	12. PEDESTRIANS WATCH FOR TURNING VEHICLES warning sign.	Install a warning sign directed toward pedestrians to warn of turning vehicles. This device supplements the pedestrian signals.	No	This sign will not affect motorist behavior and is only applicable to pedestrians crossing the street. This may lead to additional visual clutter and is not effective for small children who cannot read. This device was tested in a previous FHWA study on pedestrian signalization alternatives and was found to be effective in reducing right-turn conflicts.
SIGNALS	13. Special pedestrian signal display (WALK WITH CARE).	Use a 3-head signal having a WITH CARE or other indication in yellow displayed during the WALK interval to warn of possible conflicts (i.e., WALK WITH CARE).	No	Special signal indications can be provided to remind the pedestrians to watch for turning vehicles. This type of device should only be used at locations where a known or potentially hazardous pedestrian problem exists, since overuse of such device could result in reduced effectiveness. This device was tested in a previous FHWA study on pedestrian signalization alternatives and was found to be effective in reducing right-turn pedestrian conflicts.
	14. Retime traffic signal.	Retime signal to reduce the conflicts and minimize delay. Options include improved timing to accommodate flows, special pedestrian phasing or use of multi-phase operation.	No	This is applicable to locations with high volumes of vehicle and pedestrian traffic, where turning movements are high and where congestion is a problem. Exclusive pedestrian crossing intervals, which have been shown to be related to lower pedestrian accidents, also increases delay and congestion to pedestrians and motorists.

Table 7. Countermeasures developed for RTOR (continued).

Category	Device	Description	Selected for Field Study	Comments
SIGNALS	15. Traffic actuated signal.	Use presence detectors to determine the right-turn demand and actuated signals to accommodate the demand and reduce the number of RTOR's.	No	May be applicable to some intersections with heavy right-turn demand.
	16. Remove unwarranted traffic signals.	Remove unwarranted signals and replace with other types of traffic control.	No	Motorists lose respect for unwarranted signals, thereby increasing violations. Many communities have begun programs to remove unwarranted signals where they no longer meet the warrants. While this may have the benefit of improving flow, reducing operating costs, and saving energy, pedestrians must cross the street without signal assistance.
	17. Flashing red right-turn arrow.	Install a flashing right-turn arrow to encourage motorists to come to a full stop before turning right on red.	No	The flashing red arrow has been used in the past for right and left-turn on red situations to stress the need for stopping before making a RTOR. This would require an extra signal lens. It may not convey a clear and simple meaning to all motorist and would require FHWA approval prior to use. It is currently not in the MUTCD.
	18. NO TURN ON RED signal installed in pedestrian signal hardware.	Install an illuminated signal directed at motorists in pedestrian signal hardware to prohibit RTOR.	No	This device uses existing pedestrian signal hardware (with a different lens) to display a blank-out or a NO TURN ON RED indication to motorists. Applicable for partial RTOR prohibitions. Blank-out device minimizes confusion during RTOR allowed periods.
PAVEMENT MARKINGS	19. Relocate crosswalk further from intersection.	Move the crosswalk further from the intersection to increase visibility of pedestrians.	No	Moving the stop bar and crosswalk further from the intersection may discourage RTOR's and increase the visibility of pedestrians. However, motorists failing to stop at the stop bar will block the crosswalk. This device may result in less sight distance of cross-street traffic and may encourage jaywalking.
	20. Offset or angled stop bars.	Angle or offset the stop bar so that drivers in the middle lanes are stopped further back from the intersection than right-turn vehicles in the curb lane.	Yes	For sites where RTOR is allowed. Applicable to multi-lane approaches where there is a high incidence of truck and bus traffic which obstructs the drivers' view. Allows the RTOR vehicle to see cross-street traffic and pedestrians for a safer turn. The effectiveness may be reduced if vehicles in the middle lanes do not observe the offset stop bar.
	21. Pavement marking.	Pavement marking message in crosswalk to remind pedestrians to watch for RTOR vehicles. (i.e., LOOK FOR TURNING VEHICLES").	Yes	The message is not visible to the motorist and will have no effect on driver reactions. Installing pavement markings could create a slick surface for pedestrians, unless a textured surface is used.

Table 7. Countermeasures developed for RTOR (continued).

Category	Device	Description	Selected for Field Study	Comments
DESIGN	22. Pedestrian barriers.	Install barriers to channelize pedestrians to the crosswalk thereby minimizing the conflict area.	No	The pedestrian barrier is also expected to reduce other types of pedestrian accidents particularly dart-out and jaywalking-related accidents. However, barriers may cause difficulty in accessing parked vehicles along the curb, may be unsightly, and may create another roadside obstacle.
	23. Pedestrian overpass/underpass.	Grade separation of pedestrians and motorists eliminating conflicts.	No	Applicable to wide, high-speed intersections with safety problems. Very expensive countermeasure, and the cost cannot be justified based on RTOR accidents alone. There may also be difficulties in accommodating elderly and handicapped pedestrians and bicyclists.
	24. Far side bus stops.	Allow buses to stop to drop-off and pick up passengers only after crossing the intersection.	No	Applicable where RTOR is allowed. Eliminates congestion at the approach but may create a sight obstruction. Far-side bus stops are being used by many transit agencies to reduce intersection delays.
	25. Eliminate parking near the intersection.	Remove on-street parking near the intersection on either site or both sides of the street.	No	On-street parking poses a site obstruction when near the crosswalk. This countermeasure may reduce other types of accidents at the intersection and may also increase capacity. However, it reduces parking availability. Parking restrictions must be enforced to be effective.
	26. Separate right-turn lane.	Provides a separate lane for right turns and thus increases the opportunities for vehicles to make a RTOR.	No	Applicable to sites with high volumes of right-turn traffic. Increases the use of RTOR where RTOR is allowed. Reduces intersection delay and increases capacity.
OTHER	27. Intersection lighting.	Illuminate the intersection to provide better visibility of pedestrians at night.	No	Applicable to locations with high nighttime pedestrian volumes, and nighttime safety problems exist. May reduce other types of nighttime accidents at the intersection and may be useful in reducing crime at night.
	28. Education campaign.	Educate the public using various forms of media to increase awareness and to teach proper understanding of RTOR.	No	Educational campaigns can be directed at both the motorists and pedestrians related to RTOR safety and other safety issues. Educational programs may not reach all individuals and may not have a lasting impact. Difficult to evaluate, especially relative to RTOR.
	29. Clear roadside clutter.	Remove roadside items to increase motorist visibility of pedestrians and traffic control devices.	No	Removing all but essential roadside items should improve the motorist's ability to perceive pedestrians and traffic control devices and reduce distractions. May reduce other types of intersection accidents and improve aesthetics.
	30. Selective traffic enforcement.	Enforce violations of the NTOR sign and the requirement to complete a full stop before turning right on red where permitted. Other pedestrian and motorist laws can also be enforced simultaneously.	No	Enforcement or police presence near the intersection may reduce other violations. Effectiveness may diminish once the police leave. Since manpower is limited in most agencies, police time may be better spent in other areas of traffic enforcement or crime protection.

For each countermeasure, a description is given along with comments and an indication regarding whether the countermeasure was selected for field testing. Many of these countermeasures may relate not only to RTOR and RTOR-pedestrian accidents, but to pedestrian accidents in general. A few of the countermeasures (i.e., eliminating unwarranted signals and retiming signals) may also affect other types of accidents (rear-end, right angle, etc.) and intersection operations (delay, congestion).

COUNTERMEASURE SELECTION AND FABRICATION

Of the 30 countermeasures which were developed and described, efforts were made to select the 7 or 8 most promising ones for field testing. A panel of traffic engineers and project team members was assembled for the purpose of reviewing each of the candidate countermeasures and evaluating each one based on:

- Expected effects on safety and operations.
- Costs for installation, operation, and maintenance.
- Practical considerations, including possible adverse effects and geometric and traffic limitations.

After discussing and evaluating each countermeasure, the following were selected for field testing:

1. A NO TURN ON RED sign with a red ball in the center - Due to the preponderance of signs and information at many intersections, the red ball sign is expected to be more easily seen and remembered by an approaching RTOR motorist.
2. Larger 30 x 36-in (75 x 90-cm) NO TURN ON RED SIGN - At intersections where the standard-sized 24 x 30-in (60 x 75-cm) sign is not easily seen, such as on the far side of a wide intersection, the larger sign is expected to be more conspicuous.
3. NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT sign - The WHEN PEDESTRIANS ARE PRESENT supplementary message was thought to be preferable to time-designated restrictions. This would allow

motorists to turn right on red when conditions allowed, but would require them to yield to pedestrians.

4. A red ball NO TURN ON RED sign with a WHEN PEDESTRIANS ARE PRESENT legend - This is intended to test the combination of countermeasure numbers 1 and 3 above.
5. Offset stop bar - This is intended to provide improved sight distance to RTOR vehicles in the right lane by moving back the stop bar of adjacent stopped vehicles (in the left or "middle" lanes) by approximately 6 to 10 ft (1.8 to 3 m). Thus, RTOR motorists may get a better view of cross-street traffic coming from the left.
6. LOOK FOR TURNING VEHICLES pavement marking in the crosswalk - This low-cost countermeasure is intended to remind pedestrians to be alert for turning vehicles, including RTOR and other turning vehicles.
7. Variable message NO TURN ON RED/Blank-out sign - This is another alternative to a time-designated RTOR prohibition, but would illuminate the NO TURN ON RED message only during times, seasons, days, or intervals when RTOR prohibition is justified.

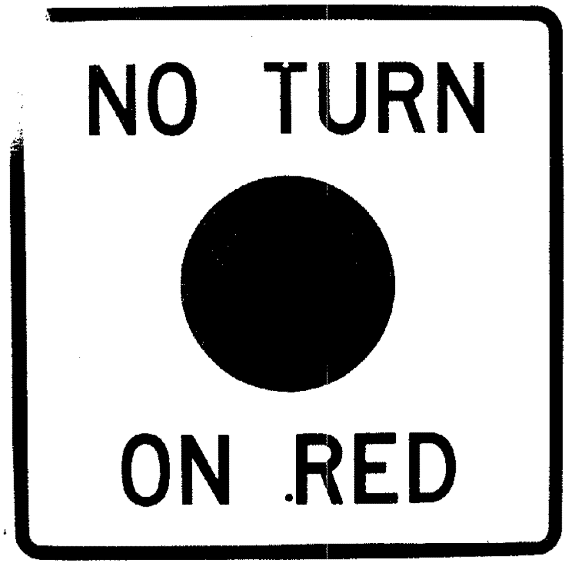
Photographs or illustrations of these devices are illustrated in figure 9.

METHODOLOGY

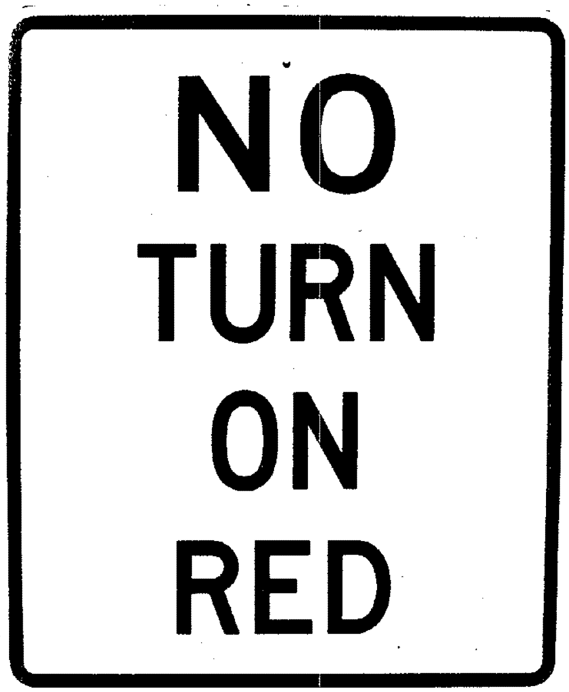
The data collection plan for the testing of devices consisted of the following activities:

- Selection of test sites.
- Measures of effectiveness (MOE's).
- Data collection procedures.
- Statistical tests.

Each activity is described below.



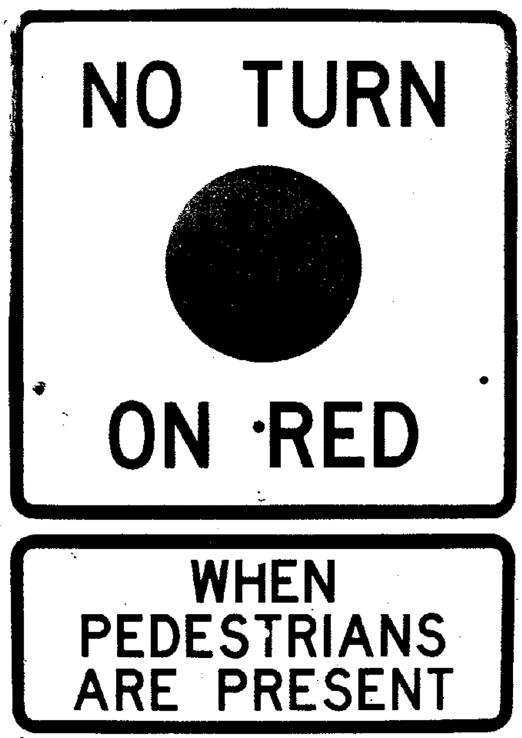
Countermeasure 1. Red ball NO TURN ON RED sign



Countermeasure 2. Larger NO TURN ON RED sign

Figure 9. Photographs of the experimental devices.

Countermeasure 3. NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT sign



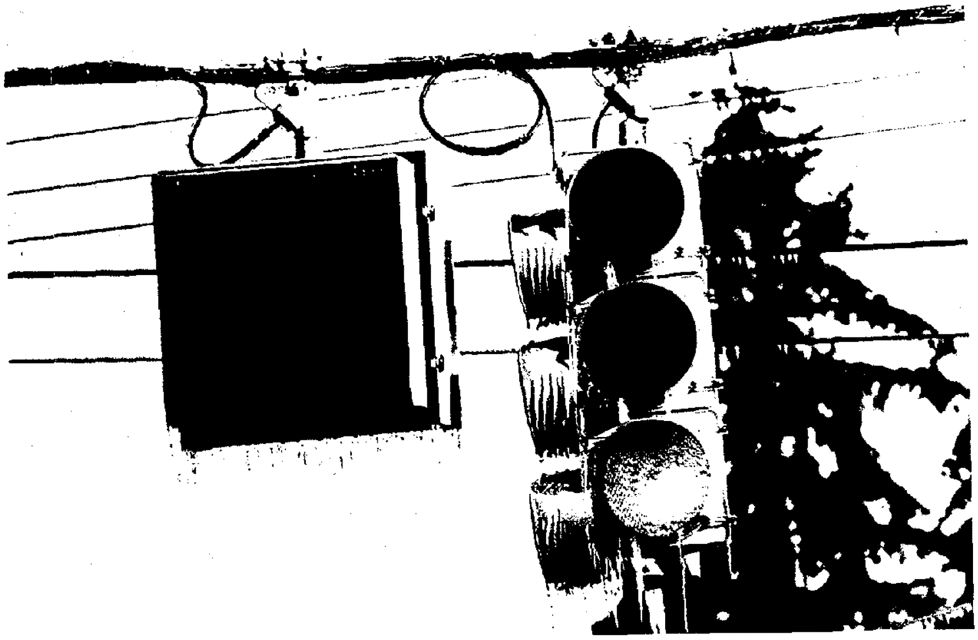
Countermeasure 4. Red ball NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT sign

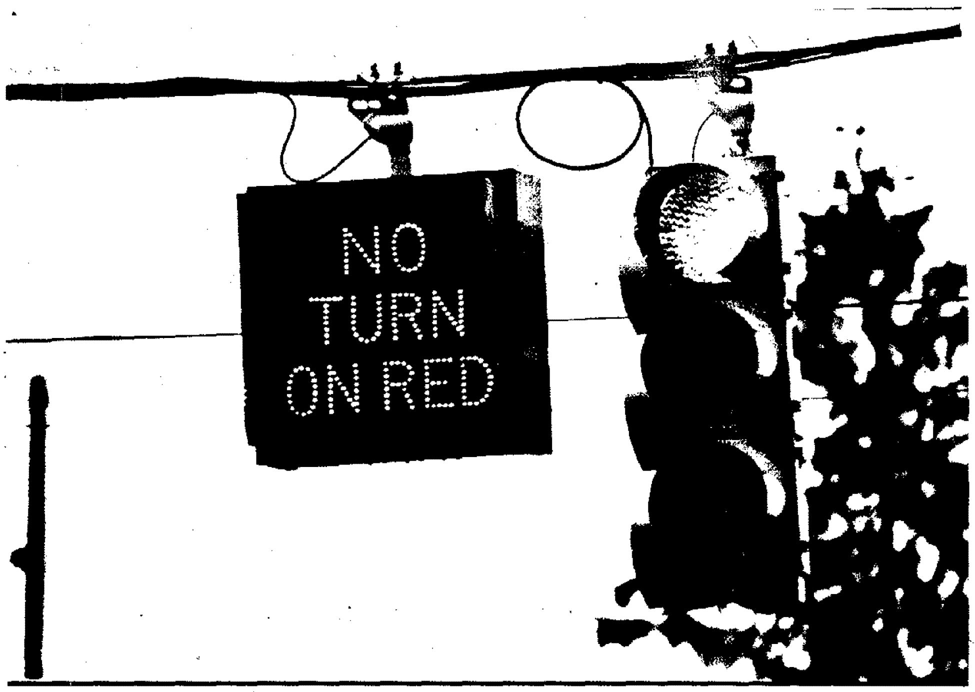
Figure 9. Photographs of the experimental devices (continued).

Countermeasure 5. Offset stop bar

Countermeasure 6. LOOK FOR TURNING VEHICLES pavement markings

Figure 9. Photographs of the experimental devices (continued).





Countermeasure 7. Variable message NTOR/blank-out sign

Figure 9. Photographs of the experimental devices (continued).

Selection of Test Sites

Sites selected for countermeasure testing included those which had a deficiency and were thought to be correctable by the device. Several general criteria and inputs were used in the initial site selection process. Each device was intended to be tested in at least two of the selected cities. A list of candidate cities and types of sites were developed for each device. For example, the red ball NTOR sign was not tested in Dallas, since the device is already used there. In addition, the offset stop bar and the pavement markings were tested at sites where RTOR is allowed, since these devices are intended to encourage a safer RTOR maneuver. Other criteria used in identifying the sites for each countermeasure are summarized in table 8.

Using the criteria in table 8 and RTOR conflict and violation data collected for 199 approaches, several sites were tentatively selected for testing purposes. Discussions were held with local engineering officials from Dallas, Detroit, Austin, and Washington, D.C. on the proposed sites, and the list of test sites was finalized. The variable message/blank-out NTOR sign was tested in conjunction with work underway by the Michigan DOT to install several of these devices in the Lansing and Grand Rapids areas.

Selection of MOE's

The ultimate goal of the selected countermeasures was to improve RTOR safety and reduce RTOR-pedestrian accidents. However, accident data is a poor measure of effectiveness (MOE) for use in testing such devices, since:

- RTOR accidents are extremely rare events at a given location. In order to have an adequate sample of RTOR accidents before and after countermeasure installation, it may be necessary to install countermeasures at thousands of locations and then wait several years for the after accident data.
- RTOR-related accidents are often difficult, if not impossible, to identify from the accident report form.

Table 8. Criteria used to select countermeasure test sites.

Countermeasure	Site Criteria
1. Red Ball NTOR Sign	- Full RTOR prohibition currently exists. - Moderate to high pedestrian volumes. - Moderate to high right-turn volumes. - High violations of the RTOR prohibition. - Considerable amount of visual clutter from other signs, traffic control devices and development near the intersection.
2. Larger NO TURN ON RED Sign	- Full RTOR prohibition currently exists. - Moderate to high pedestrian volumes. - Moderate to high right-turn volumes. - Moderate to high violations of the existing RTOR prohibition. - The NTOR sign is located near the signal on the far side of the street, where the cross street is wide (approximately four lanes or more).
3. NTOR WHEN PEDESTRIANS ARE PRESENT Sign	- Partial or full NTOR prohibition currently exists. - Fluctuating pedestrian volumes throughout the day, such as in the CBD or near a school. - High violation of the NTOR prohibition when the prohibition was not warranted (i.e., pedestrians and cross traffic not present). - Adequate sight distance to make a safe RTOR.
4. Red Ball NTOR Sign with the WHEN PEDESTRIANS ARE PRESENT Sign	- Partial or full NTOR prohibition currently exists - Fluctuating pedestrian volumes throughout the day, such as in the CBD or near a school. - High violation of the NTOR prohibition when the prohibition was not warranted (i.e., pedestrians and cross traffic not present). - Considerable visual clutter may exist at the approach.
5. Offset Stop Bar	- RTOR allowed at the approach. - Moderate to high right-turn and RTOR volumes. - Low to moderate pedestrian volume. - Two or more lanes in one direction on the approach. - Trucks, buses or other traffic in the middle lanes causing a sight distance obstruction for motorists in the right-turn lane. - Streets intersecting at an angle causing difficulty for those in the right turn lane to see cross-traffic.
6. LOOK FOR TURNING VEHICLES Pavement Markings	- RTOR allowed at the approach. - Moderate pedestrian volumes. - Moderate to high right-turn and RTOR volumes. - Adequate sight distance for a RTOR maneuver. - Instances of pedestrians entering the street without looking.
7. Variable Message NTOR/Blank-out Sign	Condition A: Fluctuating pedestrian volume based on time of day. - Full or partial no-turn-on-red prohibition currently exists at the site. - Fluctuating pedestrian volumes which would warrant RTOR prohibitions during specified times of day (i.e., near a school or the CBD). - Moderate to high right-turn volume. - Adequate sight distance to make a safe RTOR maneuver when conditions permit. - High violation of the NTOR prohibitions when the prohibition was not warranted. Condition B: Protected opposing left-turn maneuver during a portion of the cycle. - Full or partial RTOR prohibition currently exists. - High right-turn volumes. - High opposing left-turn volumes in a protected movement during a portion of the cycle. - Adequate sight distance to make a RTOR maneuver. - Low pedestrian volumes.

- Many devices will result in small or subtle changes in pedestrian and/or motorist behavior. The detection of such changes may be possible only through the use of conflicts or other operational MOE's.

To date, no proven operational MOE's have been validated as "surrogates" or substitutes for RTOR-pedestrian accidents. However, the alternatives being tested are designed to reduce or change certain types of pedestrian and/or motorist behavior which are contributory accident causes. A device which significantly reduces motorist violations of RTOR or reduces near-accidents between motorists and pedestrians at a site may be considered to have a high likelihood of improving pedestrian safety.

The specific types of conflicts and events used as MOE's as described earlier, were:

- Vehicle Hesitation (VH).
- Vehicle Swerve (VS).
- Pedestrian Hesitation (PH).
- Pedestrian Run (PR).
- Interaction between a right-turn vehicle and a pedestrian (I).

In addition to these events, RTOR violations and RTOR conflicts with cross-street vehicles were also collected for additional countermeasure evaluation. Other information collected included pedestrian volume in each crosswalk (near and far), total right-turn volume, and RTOR volume using the data collection form shown earlier.

All of the above measures were collected separately for the red signal phase and the green (plus amber) phase. This was thought to be essential, since a device may significantly reduce RTOR conflicts but merely cause a corresponding increase to RTOG conflicts. Thus, the effect of the conflicts during the entire cycle (green + red + amber interval) was also of importance.

Because of the low frequency of conflicts at each site, the conflict types were combined for analysis purposes. Thus, the term "conflicts" in the analysis refers to vehicle hesitations and swerves plus pedestrian hesitations and runs (VH + VS + PH + PR). Pedestrian-vehicle interactions (I) were kept separate for analysis purposes. The term "conflicts and interactions" was used to indicate cases when the two measures were combined. The four basic forms of the conflict measures (MOE's) were expressed as follows:

- RTOR Conflicts.
- RTOR Conflicts and Interactions.
- Total (RTOR + RTOG) Conflicts.
- Total (RTOR + RTOG) Conflicts and Interactions.

Each of these measures is self-explanatory. Note that the last two measures incorporate events occurring in the entire signal cycle.

A summary is given in table 9 of the specific MOE's which were selected for each of the seven countermeasures. For example, all of the countermeasures were expected to have some effect in RTOR conflicts, as well as interactions. Also, there was a possible "carry-over" effect into green phase conflicts and interactions, since a reduction in RTOR violations or conflicts may result in a corresponding increase in RTOG conflicts. Thus, there was a need to analyze the effect of the devices on total (RTOR and RTOG) conflicts and interactions.

RTOR violations were not expected to be affected by the pavement markings. The RTOR conflicts with cross-street vehicles were not expected to be affected by:

- The LOOK FOR TURNING VEHICLES pavement marking - This is intended to cause pedestrians to be more cautious but is not expected to affect RTOR vehicles as they interact with cross-street vehicles.
- NTOR WHEN PEDESTRIANS ARE PRESENT sign - This is intended to remind RTOR motorists to yield to pedestrians and should not impact conflicts with cross-street vehicles.

Table 9. Summary of the MOE's selected for analyzing countermeasures.

Countermeasure	No. of Approaches	RTOR Violations	RTOR Ped. Conflicts	RTOR Ped. Conflicts + Interactions	Total (RTOR + RTOG) Ped. Conflicts	Total Ped. (RTOR + RTOG) Conflicts + Interactions	RTOR Vehicle Conflicts
1. Red Ball NO TURN ON RED Sign	6	●	●	●	●	●	●
2. Larger NO TURN ON RED Sign	5	●	●	●	●	●	●
3. NTOR "WHEN PEDESTRIANS ARE PRESENT"	4	●	●	●	●	●	
4. Red Ball NTOR Sign WHEN PEDESTRIANS ARE PRESENT	3	●	●	●	●	●	●
5. Offset Stop Bar	3		●	●	●	●	●
6. LOOK FOR TURNING VEHICLES Pavement Marking	8		●	●	●	●	
7. Variable Message NTOR/ Blankout Sign	3	●	●	●	●	●	●

● = Selected MOE's

Data Collection Methods

The data collection forms and procedures used for countermeasure testing were similar to those discussed in Chapter I. At sites where the offset stop bar was tested, information was also collected relative to motorist compliance to the offset stop bar. When a motorist was observed making a RTOR movement at these sites, the observer would note if the RTOR vehicle came to a full stop, a rolling stop, or no stop. If the RTOR motorist came to a full stop, the observer would note if the vehicle stopped behind or past the stop bar. In addition, the observer would also note if other vehicles were stopped at the stop bar on the approach (in the left or middle lanes) and if these vehicles stopped behind or past the offset portion of the stop bar.

The RTOR Volume and Conflicts form (figure 2) was modified slightly when used to collect data at the variable message NTOR/blank-out sign in Grand Rapids. At this site, the NTOR sign would appear for an interval during a protected opposing left-turn maneuver. Therefore, for each 10-minute data collection period, the right-turn-on-red maneuvers and conflicts were collected separately for the RTOR-allowed and RTOR-prohibited intervals.

At many of the sites, 4 hours of data were collected followed by another 4-hour data collection period several weeks later to assess the repeatability of the data and to provide an adequate sample of events (conflicts, violations, etc.).

Two different data collectors were generally sent to each city for data collection purposes to minimize data collector biases. While data were collected for approximately 8 hours on each approach, more emphasis was placed on the times of day when pedestrian volumes were highest or when the RTOR prohibitions were in effect.

Data were recorded, checked, and entered into a computer file. Programs were developed to identify data inconsistencies and logic errors.

Other checking was conducted on the data file to ensure a high degree of data quality. After the countermeasures were installed, a 2-4 week acclimation period was used before collecting the after data so that motorists and pedestrians would become accustomed to the devices. Approximately 8 hours of after data were collected on each approach.

Statistical Analysis Techniques

The Z-test for proportions was selected as the statistical test. This test is used to determine if the proportion of occurrences in one sample (before period) is significantly different from the proportion of occurrences in a second sample (after period). This test is applicable for continuous data (proportions), and has the following underlying assumptions.[15]

1. The distributions are binomial (i.e., either an event does or does not occur).
2. The observations are independent.
3. The sample of events is greater than 30 in each sampling period (each of the before and after conditions).

In this analysis, the events are pedestrian-vehicle conflicts (and interactions) and the opportunity for an event is either a pedestrian crossing or a RTOR maneuver. The proportion of conflicts and interactions in the before period were compared to the proportion of events in the after period at each site and a Z-value was computed. At sites where one of the MOE's was RTOR violations, the event was a RTOR maneuver and the occurrences were the total number of right turns. Then sites were grouped with similar treatments and within the same city, and the analysis was repeated. If the calculated Z-value is greater then the critical Z-value, then the difference in proportions is statistically significant.

One other consideration was whether to use "control" (or "comparison") sites to determine whether any changes observed in the conflicts and interactions were caused by the experimental devices and not by external factors. The use of control or comparison sites is particularly important when conducting accident-based evaluations where several years elapse between data collection periods. However when conducting an evaluation using conflicts or other non-accident MOE's, the simple before and after experimental design is generally appropriate under most circumstances, due to the relatively short period of time (a few weeks or months) between the before and after periods, as discussed by Perkins [15]. Therefore, for this analysis, the before-after experimental design was used.

RESULTS

A summary table of the Z-test for proportions results is given for each device. For each Z-test, one of the following outcomes resulted:

- A: Significant differences were found in favor of the after (experimental) condition.
- B: Significant differences were found in favor of the before (base) condition.
- NC: No significant differences were found between the before and after periods.
- "-": Insufficient sample sizes to conduct the Z-test.

In each case, an indication is given relative to the significance at the 0.05 level and also the 0.01 level. Using the two-tailed test with the Z-test for proportions, a Z_C (Z-critical) value of 1.96 corresponds to the 0.05 level, and a Z_C of 2.58 corresponds to the 0.01 level (assuming a sample size of 30 or more events). Z-values of each test were compared with the critical values to test whether the proportion of conflicts in the after period is significantly different from the proportion in the before period. The results of testing of the seven devices is discussed below.

Red Ball (Symbolic) NTOR Sign

The results of the testing of the red ball (symbolic) NTOR sign are summarized in table 10. The sign resulted in an overall reduction in RTOR violations (turning right-on-red when prohibited) from 7.6 percent (of

Table 10. Summary of results for the red ball (symbolic) NO TURN ON RED sign.

Measure of Effectiveness	Opportunity Measure	Detroit (4 Sites)		Washington, D.C. (2 Sites)		All Combined (6 Sites)	
		0.05 Level	0.01 Level	0.05 Level	0.01 Level	0.05 Level	0.01 Level
RTOR Violations	Right-Turn Volume	B	B	A	A	A	A
RTOR Ped. Conflicts	RTOR Volume	-	-	-	-	-	-
RTOR Ped. Conflicts + Interactions	RTOR Volume	-	-	-	-	-	-
Total (RTOR + RTOG) Ped. Conflicts	Right-Turn Volume	A	A	A	A	A	A
	Pedestrian Volume	NC	NC	A	A	A	A
Total (RTOR + RTOG) Ped. Conflicts + Interactions	Right-Turn Volume	A	A	A	A	A	A
	Pedestrian Volume	NC	NC	A	A	A	A
RTOR Vehicle Conflicts	RTOR Volume	-	-	-	-	-	-

Legend:
A = Significant difference in favor of after (experimental) condition.
B = Significant difference in favor of before (base) condition.
NC = No significant difference between before and after conditions.
- = Insufficient sample size.

10,164 right turns) in the before period to 6.2 percent (of 7,615 right turns) in the after period. This is significant at the 0.01 level. However, the overall reduction in violations is due solely to the Washington, D.C. sites, which experienced a drop in RTOR violations from 8.1 percent to 2.9 percent after installing the red ball sign. On the other hand, there was an increase in RTOR violations from 7.3 percent to 9.4 percent at the combined Detroit sites. This may be due to the sign placement. The NTOR signs were mounted on signal poles adjacent to the traffic signals in Washington, D.C., as specified in the MUTCD. At the Detroit sites the NTOR signs were post-mounted on the far or near side corner of the intersection (not near the signal). Such sign placement at the Detroit sites may not have been conspicuous to the motorist.

An insufficient sample of RTOR-pedestrian conflicts was available to apply the Z-test (i.e., less than 30 conflicts in each of the before and after periods). Only 22 RTOR conflicts (of the 770 RTOR vehicles) were observed in the before period, or 2.9 percent, compared to 0 conflicts (of 473 RTOR vehicles) in the after period. Similarly, an insufficient sample of RTOR conflicts plus interactions were observed, with only 41 in the before period (5.3 percent) and 6 in the after period (1.3 percent). Thus, the pedestrian conflicts resulting from RTOR violations were too infrequent for statistical testing.

The proportion of total (RTOR + RTOG) conflicts showed significant reduction (from 2.6 percent to 0.8 percent) at the combined Washington, D.C., sites due to the red ball NTOR sign. In Detroit, when right-turn volume was the basis of analysis, the red ball was also associated with a significant reduction in proportion of conflicts (reduced from 10.8 percent to 8.6 percent). No significant reduction occurred in Detroit, however, using conflicts as a proportion of pedestrian volume.

The proportion of total (RTOR + RTOG) conflicts plus interactions dropped significantly for all sites combined in nearly all situations. Again, no significant reduction occurred at the four Detroit sites when pedestrian volume was used as the basis of analysis. Combining all six sites from the two cities, a significant reduction was again observed in the proportion of conflicts. A sufficient sample of RTOR conflicts with cross-street vehicles was not available to conduct any analysis of that conflict type.

In summary, the red ball NTOR sign was found overall to be effective in reducing the proportion of RTOR violations, total (RTOR + RTOG) conflicts, and total (RTOR + RTOG) conflicts plus interactions at the six sites combined. However, the sign was more effective at the two approaches in Washington, D.C. than at the four Detroit approaches. This could be the result of differences in sign placement in the two cities, and/or due to site-related differences.

Larger NO TURN ON RED Sign

The larger 30x36-in (75x90-cm) NTOR sign was tested at one approach in Detroit and four approaches in Washington, D.C. as summarized in table 11. At the Washington, D.C. sites, the proportion of RTOR violations decreased significantly (at the 0.01 level). However, no significant difference resulted in RTOR violations when combining the Detroit site with the four Washington, D.C. sites. Overall, the violation rate, remained constant at 3.0 percent, even though RTOR violations at the Washington, D.C. sites dropped from 7.1 percent to 2.7 percent (Z-value of 4.86 at the Washington D.C. sites).

Sample sizes of RTOR conflicts, RTOR conflicts + interactions, total (RTOR + RTOG) conflicts, and RTOR conflicts with cross-street vehicles were insufficient for any valid analysis. In fact, of 2,186 right-turn vehicles and 899 pedestrians in the before period, only 35 total conflicts occurred. Only 23 total conflicts occurred in the after period out of 3,333 right-turn vehicles.

The proportion of total conflicts plus interactions for all five sites combined was significantly reduced with the larger NTOR sign (using right-turn volume as the base). No significant change occurred, however, when comparing the proportion of total conflicts plus interactions with respect to pedestrian volume.

Table 11. Summary of results for the larger NO TURN ON RED sign.

Conflict Measure	Opportunity Measure	Detroit (1 Site)		Washington, D.C. (4 Sites)		All Combined (5 Sites)	
		0.05 Level	0.01 Level	0.05 Level	0.01 Level	0.05 Level	0.01 Level
RTOR Violations	Right-Turn Volume	-	-	A	A	NC	NC
RTOR Ped. Conflicts	RTOR Volume	-	-	-	-	-	-
RTOR Ped. Conflicts + Interactions	RTOR Volume	-	-	-	-	-	-
Total (RTOR + RTOG) Ped. Conflicts	Right-Turn Volume	-	-	-	-	-	-
	Pedestrian Volume	-	-	-	-	-	-
Total (RTOR + RTOG) Ped. Conflicts + Interactions	Right-Turn Volume	-	-	-	-	A	A
	Pedestrian Volume	-	-	-	-	NC	NC
RTOR Vehicle Conflicts	RTOR Volume	-	-	-	-	-	-

Legend:
A = Significant difference in favor of after (experimental) condition.
B = Significant difference in favor of before (base) condition.
NC = No significant difference between before and after conditions.
\- = Insufficient sample size.

In summary, a sufficient sample of RTOR conflicts was not available for making any conclusive statements concerning the use of the larger NTOR signs. There were some indications, however, that the signs may be effective under certain situations. For example, it resulted in a significant reduction in proportion of violations at the four combined test sites in Washington, D.C.

NTOR WHEN PEDESTRIANS ARE PRESENT Sign

All four of the approaches where this device was tested were in Detroit. The results are summarized separately for each approach in table 12. In each case, the supplemental WHEN PEDESTRIANS ARE PRESENT sign was used to replace either a full prohibition, or a time-related prohibition (i.e., 7 a.m. to 7 p.m.). Thus, the before data were collected when a RTOR prohibition was in effect. These data were then compared to the NTOR WHEN PEDESTRIANS ARE PRESENT sign, which allows a RTOR after a motorist yields to pedestrians and other motorists.

Because this device changed the RTOR requirement from a prohibition to an allowed movement (after yielding to pedestrians), it was expected to cause an increase in RTOR maneuvers, hopefully without causing an increase in RTOR-pedestrian conflicts. As expected, RTOR maneuvers increased from 3.3 percent (270 of 8,172 right-turn vehicles) in the before period (all of which were illegal RTOR maneuvers), to 5.6 percent in the after period. However, these RTOR maneuvers in the after period were legal if the motorist made a full stop and yielded to pedestrians and cross-street vehicles before making a RTOR. The increase in proportion of RTOR maneuvers was significant at the 0.01 level. This device could reduce unnecessary vehicle delay in many cases.

A total of 32 RTOR-pedestrian conflicts occurred in the before period, which was 11.9 percent of the 270 RTOR maneuvers for all sites combined. This compared with no RTOR-pedestrian conflicts out of the 256 RTOR maneuvers in the after period. Even though the proportion of RTOR-pedestrian conflicts dropped from 11.9 percent to 0 percent, the sample of conflicts was too small to be considered statistically signifi-

Table 12. Summary of results for the NTOR WHEN PEDESTRIANS ARE PRESENT sign.

Measure of Effectiveness	Opportunity Measure	Site 1 (Detroit)		Site 2 (Detroit)		Site 3 (Detroit)		Site 4 (Detroit)	
		0.05 Level	0.01 Level	0.05 Level	0.01 Level	0.05 Level	0.01 Level	0.05 Level	0.01 Level
RTOR Maneuvers	RTOR Volume	B	B	B	B	-	-	-	-
RTOR Ped. Conflicts	RTOR Volume	-	-	-	-	-	-	-	-
RTOR Ped. Conflicts + Interactions	RTOR Volume	-	-	-	-	-	-	-	-
Total (RTOR + RTOG) Ped. Conflicts	RTOR Volume	B	NC	B	B	A	A	A	A
Total (RTOR + RTOG) Ped. Conflicts + Interactions	Right-Turn Volume	NC	NC	B	B	A	A	A	A

Legend:
A = Significant difference in favor of after (experimental) condition.
B = Significant difference in favor of before (base) condition.
NC = No significant difference between before and after conditions.
\- = Insufficient sample size.

cant. Similarly, RTOR-pedestrian conflicts plus interactions dropped from 17.8 percent (48 of 270) in the before period to only 0.3 percent (1 of 331) in the after period, although the sample was too small for statistical testing.

An analysis was conducted of each of the four approaches individually because of the diversity of traffic and pedestrian volumes and the different effect of the device. For example, approach 1 indicated no significant effect of the device for three of the four MOE's. At approach 2, the sign was associated with a significantly higher proportion of conflicts (0.01 level) in three of the four analyses. Approaches 3 and 4 resulted in a significantly lower proportion of conflicts in most cases. A sufficient sample of RTOR conflicts with cross-street vehicles was not available to conduct any analysis of that conflict type.

The reason for the inconsistencies in results was investigated by reviewing differences in site characteristics. This sign was most effective at the sites with low right-turn volumes. This sign appeared less effective at the sites with high right-turn volumes, perhaps because the high turning demand resulted in less willingness by motorists to yield to pedestrians, particularly since RTOR was allowed in the after period.

Red Ball NTOR WHEN PEDESTRIANS ARE PRESENT Sign

The red ball NO TURN ON RED sign was tested in conjunction with the WHEN PEDESTRIANS ARE PRESENT message at one approach in Austin, two approaches in Dallas, and one approach in Washington, D.C., as summarized in table 13. The Austin approach differed from the other three approaches in several ways, including higher right-turn volumes. Thus, it was separated from the other three approaches for analysis purposes.

The experimental device (after period) allows a RTOR after yielding to pedestrians, while RTOR was prohibited in the before period. Thus, the device was expected to increase RTOR maneuvers, without increasing conflicts. As expected, RTOR maneuvers increased from 5.7 percent to 17.4 percent at the three sites combined (significant at the 0.01 level).

Table 13. Summary of results for the red ball NTOR WHEN PEDESTRIANS ARE PRESENT sign.

Measure of Effectiveness	Opportunity Measure	Site 1 (Austin)		Sites 2 and 3 (Dallas) and Site 4 (Washington, D.C.)	
		0.05 Level	0.01 Level	0.05 Level	0.01 Level
RTOR Maneuvers	Right-Turn Volume	B	NC	B	B
RTOR Ped. Conflicts	RTOR Volume	-	-	-	-
RTOR Ped. Conflicts + Interactions	RTOR Volume	-	-	-	-
Total (RTOR + RTOG) Ped. Conflicts	Pedestrian Volume	A	A	-	-
Total (RTOR + RTOG) Ped. Conflicts + Interactions	Pedestrian Volume	A	A	-	-
RTOR Vehicle Conflict	RTOR Volume	-	-	-	-

Legend:
A = Significant difference in favor of after (experimental) condition.
B = Significant difference in favor of before (base) condition.
NC = No significant difference between before and after conditions.
- = Insufficient sample size.

The biggest increase in RTOR maneuvers occurred at approach 3, (from 7.0 percent to 40.5 percent). Increases in the proportion of RTOR maneuvers were significant at the 0.05 level at approach 1 and at the 0.01 level at the other two sites combined. This indicates a probable reduction in delay for right-turn motorists.

The number of RTOR-pedestrian conflicts and interactions were insufficient for statistical testing. The proportion of pedestrians involved in total (RTOR + RTOG) pedestrian conflicts were found to be reduced at approach 1 from 6.7 percent in the before period (72 conflicts out of 1,074 crossing pedestrians) to 3.2 percent in the after period (69 conflicts of 2,155 pedestrians). This was a significant reduction at the 0.01 level. Insufficient samples of conflicts were observed at the other three approaches.

A similar result was also found regarding the proportion of pedestrians involved in total (RTOR + RTOG) pedestrian conflicts plus interactions At approach 1 (Austin site), the proportion of these events dropped from 14.2 percent (152 events of 1,074 pedestrians) to 5.5 percent (118 of 2,155 pedestrians), which resulted in a Z-value of 8.39 (significant at the 0.01 level). Insufficient samples again prevented formal analysis at the other three approaches. Due to intersection geometrics at the Austin and Washington, D.C., approaches, there was no cross-street traffic. There was noted, however, a problem in reading the WHEN PEDESTRIANS ARE PRESENT legend in some cases. At the Austin approach, the sign was located on an overhead mast arm on the far side of the intersection adjacent to the signal face. At the Dallas approaches, the sign was mounted on a signal pole on the far side. At this distance the 10 x 24-in (25x60-cm) sign (having 2-in (5-cm) letters) was difficult for motorists to read. The observers noted that some motorists reacted conservatively and did not make a RTOR maneuver. This was particularly true at the Austin approach, which was a three-legged intersection with no cross-street traffic to inhibit a RTOR.

The sign location at the Austin and Dallas red ball NTOR WHEN PEDESTRIANS ARE PRESENT approaches are different than the Detroit NTOR

WHEN PEDESTRIANS ARE PRESENT test approaches. The Detroit signs were located on the near side of the intersection at the corner, which makes it much easier to read by the right-turn motorist.

In summary, the red ball NTOR WHEN PEDESTRIANS ARE PRESENT sign resulted in an increase in RTOR maneuvers, as intended at all four sites. Although RTOR-pedestrian conflicts were too infrequent for statistical testing, a significant reduction resulted in proportion of total pedestrian conflicts at one of the sites which had a high right-turn volume and high pedestrian volume. Thus, at this site, motorist turning delay was reduced and the proportion of pedestrian conflicts was also reduced, which was a desirable result. However, due to the size of the legend, the location of the sign is an important consideration prior to its application.

Offset Stop Bar

The results of the offset stop bar are summarized in table 14 for two approaches in Dallas and one in Washington, D.C. Samples of RTOR conflicts and interactions were insufficient for conducting any statistical tests. In fact only 11 RTOR conflicts plus interactions occurred of the 3,808 RTOR vehicles, or only 0.3 percent at the three approaches combined.

For the site in Washington, D.C. the proportion of total (RTOR + RTOG) pedestrian conflicts was 3.5 percent in the before period (132 conflicts of 3,756 pedestrians) and 3.2 percent in the after period (263 conflicts for 8,177 pedestrians). This corresponded to no significant change (Z-value of 0.85). An insufficient sample of pedestrian conflicts (less than 30) was obtained at the Dallas approaches for any statistical testing.

The proportion of total (RTOR + RTOG) pedestrian conflicts plus interactions was not significantly changed at the Washington, D.C., approach (Z-value of 0.70). The proportion of pedestrians involved in a conflict or

Table 14. Summary of results of offset stop bar.

Measure of Effectiveness	Opportunity Measure	Washington, D.C. (1 Site)		Dallas (2 Sites)	
		0.05 Level	0.01 Level	0.05 Level	0.01 Level
RTOR Ped. Conflicts	RTOR Volume	-	-	-	-
RTOR Ped. Conflicts + Interactions	RTOR Volume	-	-	-	-
Total (RTOR + RTOG) Ped. Conflicts	Right-Turn Volume	NC	NC	-	-
	Pedestrian Volume	NC	NC	-	-
Total (RTOR + RTOG) Ped. Conflicts + Interactions	Right-Turn Volume	NC	NC	-	-
	Pedestrian Volume	NC	NC	-	-
RTOR Vehicle Conflicts	RTOR Volume	-	-	-	-

Legend:
A = Significant difference in favor of after (experimental) condition.
B = Significant difference in favor of before (base) condition.
NC = No significant difference between before and after conditions.
\- = Insufficient sample size.

interaction dropped only from 5.0 percent in the before period to 4.7 in the after period. The two Dallas sites again had an insufficient sample of events for any statistical testing.

In terms of RTOR conflicts with cross-street traffic, 79 conflicts were observed in the before period, or 4.6 percent, compared to only 0.62 percent in the after period. This is a significant reduction in the proportion of conflicts at the 0.01 level of confidence.

A separate analysis was conducted to determine how motorists reacted to the offset stop bar and to assist in determining the effect on RTOR stopping characteristics. Stopping location data were collected relative to the RTOR vehicle and for vehicles in the middle (offset stop bar) lanes during the after period. Information was collected to see if the RTOR vehicle: (1) stopped at or behind the stop bar, (2) stopped over or past the stop bar, or (3) did not make a full stop. At the same time, conditions in the middle lanes were examined to see if: (1) no vehicles were present, (2) vehicles stopped at or behind the offset stop bar, or (3) vehicles stopped past the offset stop bar. A summary of this information is given in table 15.

Stopping data characteristics were collected for 1,184 RTOR vehicles at the three offset stop bar sites, a majority of which were at the two Dallas sites. Of the 1,184 RTOR vehicles, 22.6 percent, came to a full stop behind the stop bar, 38.7 percent came to a full stop past the stop bar, and 38.7 percent came to a rolling stop or did not stop prior to making their turn. This compares to 56.9 percent of the motorists making a rolling or no stop at the 29 RTOR-allowed approaches where RTOR stopping characteristics were analyzed in an earlier part of this study (Chapter I). While 38.7 percent of the RTOR vehicles stopped past the stop bar, this percentage increased to 51.6 when vehicles in the middle lanes stopped past the offset stop bar and was somewhat lower (35.6 percent) when vehicles in the middle lanes stopped behind the offset stop bar. While 22.6 percent of RTOR vehicles stopped behind the stop bar, this percentage was higher when no vehicles were in the middle lanes or the vehicles in the middle lanes stopped behind the offset stop bar, and was

Table 15. Summary of stopping characteristics data for the offset stop bar.

RTOR Vehicles	Vehicles in Middle Lanes			Total
	No Vehicle	Stop at or Behind the Offset Stop Bar	Stop Past the Offset Stop Bar	
Stop at or Behind the Stop Bar (Percent)	52 (31.0%)	181 (26.5%)	28 (9.0%)	268 (22.6%)
Stop Past the Stop Bar (Percent)	54 (28.4%)	243 (35.6%)	161 (51.6%)	458 (38.7%)
Rolling or No Stop (Percent)	77 (40.5%)	258 (37.8%)	123 (39.4%)	458 (38.7%)
Total (Percent)	190 (16.0%)	682 (57.6%)	312 (26.3%)	1,184 (100.0%)

Note: The location of the vehicle behind or past the stop bar was based on the position of the right front wheel.

lower when vehicles in the middle lanes stopped past the offset stop bar. This implies that if vehicles in the middle lanes complied with the offset stop bar (or vehicles are not present in the middle lanes), there is a greater likelihood that the RTOR vehicle would stop behind the stop bar prior to making the turn.

Overall 68.6 percent of the motorists in the middle lanes stopped behind the offset stop bar, while 31.4 percent stopped past the stop bar. This percentage varied between sites. At one site in Dallas, 81.4 percent of the vehicles in the middle lanes stopped behind the offset stop bar while at another Dallas site, 56.4 percent stopped behind the offset stop bar. The overall percentage of rolling or no stop RTOR vehicles remained relatively unchanged regardless of the presence and location of vehicles in the middle lanes (behind or past the offset stop bar).

In summary, conflict data for the offset stop bar revealed a significant reduction in conflicts to cross-street vehicles at all sites combined. At the one Washington, D.C. approach, no significant change occurred in the proportion of pedestrian conflicts or interactions. In terms of stopping characteristics, the offset stop bar in the middle lane(s) resulted in more RTOR vehicles making a full stop behind the stop bar. Overall 68.6 percent of middle lane vehicles stopped behind the offset stop bar, and when this occurred there was a higher likelihood of the RTOR vehicle stopping behind the stop bar. More testing would be desirable to verify the overall effects of the offset stop bar for various site characteristics.

LOOK FOR TURNING VEHICLES Pavement Marking

A summary of the results of the LOOK FOR TURNING VEHICLES pavement marking is summarized in table 16. This device was tested on eight approaches in Detroit, Austin, and Dallas. The proportion of the RTOR-pedestrian conflicts was significantly reduced (0.01 level) for all eight approaches combined. The proportion of RTOR conflicts plus interactions was also significantly reduced in Austin and for all sites combined after the markings were applied. The overall reduction was from 9.7 percent to 2.6 percent, which corresponds to a Z-value of 7.56.

Table 16 . Summary of results for the LOOK FOR TURNING VEHICLES pavement markings.

Conflict Measure	Opportunity Measure	Detroit (4 Sites)		Dallas (4 Sites)		Austin (2 Sites)		All Combined (8 Sites)	
		0.05 Level	0.01 Level	0.05 Level	0.01 Level	0.05 Level	0.01 Level	0.05 Level	0.01 Level
RTOR Ped. Conflicts	RTOR Volume	-	-	-	-	-	-	A	A
RTOR Ped. Conflicts + Interactions	RTOR Volume	-	-	-	-	A	A	A	A
Total (RTOR + RTOG) Ped. Conflicts	Right-Turn Volume	A	A	-	-	NC	NC	A	A
	Pedestrian Volume	A	A	-	-	A	A	A	NC
Total (RTOR + RTOG) Ped. Conflicts + Interactions	Right-Turn Volume	A	A	B	B	A	NC	A	A
	Pedestrian Volume	NC	NC	B	B	A	A	A	NC

Legend:
A = Significant difference in favor of after (experimental) condition.
B = Significant difference in favor of before (base) condition.
NC = No significant difference between before and after conditions.
- = Insufficient sample size.

The proportion of total conflicts was also significantly lower (0.01 level) for the Detroit approaches and all approaches combined as a result of the markings. Overall conflicts (per right-turn volume) dropped from 5.5 percent (408 of 7,454 vehicles) to 4.2 percent (278 of 6,563 vehicles). In terms of proportion of conflicts with respect to pedestrian volume, the pavement markings also had a similar effect at the two Austin sites (i.e., significantly less in the after period at the 0.01 level).

Based on the total (RTOR + RTOG) conflicts plus interactions, results were somewhat more varied. Significant reductions in the proportion of conflicts and interactions were found in Austin and Detroit (0.05 level or better) with a significant increase (0.01 level) in Dallas. The eight sites combined showed an improvement (significant at the 0.05 level), when the proportion of total conflicts plus interactions (with respect to rightturn vehicles) was reduced from 10.2 percent to 8.6 percent. While collecting the after data, the observers also noted several instances of people walking into the crosswalk while looking down, and after reading the pavement marking would look both ways. While a formal analysis on this information was not conducted, these observations indicate a potential benefit of having these messages to caution pedestrians while crossing.

In summary, the LOOK FOR TURNING VEHICLES pavement marking showed an overall reduction in conflicts and interactions for RTOR vehicles and also for total (RTOR + RTOG) vehicles. However, the results were mixed for different cities. While it was effective at the Detroit and Austin sites, it was ineffective at the Dallas sites. One possible explanation is that there may indeed be real differences in the effectiveness of such devices, depending on area and/or locational characteristics. The markings do appear to be of value in reducing conflicts at some sites, as found in this analysis.

A practical consideration with these devices is they may be covered by snow in winter months and tend to wear away quickly on poor pavement surfaces. A few of the pavement markings were worn-away within a few weeks after application (when the pavement was poor), while others were fully visible after 3 to 4 months.

Electronic NTOR/Blank-Out Sign

The electronic NTOR/blank-out sign was tested at four approaches in Lansing, Michigan, and one approach in Grand Rapids, Michigan. The four Lansing approaches were at school zones, where pedestrian activity consisted predominantly of school children who crossed the street only within a limited amount of time each school day. Thus, very few RTOR-pedestrian conflicts occurred during either the before or after periods, which prevented any formal evaluation based on pedestrian conflicts.

Regarding compliance to the NO TURN ON RED message, several interesting results were found. At one intersection in Lansing, the NTOR/blank-out sign was installed on two approaches (eastbound and southbound) to replace standard NTOR signs (full prohibition). The analysis involved combining data at the two approaches. In the before period (with standard NTOR sign), 62 of 3,396 right-turn motorists (1.83 percent) violated the sign by making a RTOR. During the after period with the electronic NTOR sign illuminated (i.e., during the prohibition period) only one motorist out of 622 (0.2 percent) violated the sign. This reduction was not significant due to an insufficient sample of violations in the after period. A different analysis was then made in the after period of the RTOR maneuver which occurred during the blank-out period (RTOR allowed) versus the NTOR-illuminated period (RTOR prohibited). As expected, 16.8 percent or 298 of 1,767 of right-turn motorists made a RTOR when allowed, compared to only 0.2 percent (1 of 622) when prohibited. This illustrates that the electronic sign effectively allowed RTOR maneuvers when justified (i.e., few or no pedestrians crossing) and virtually eliminated RTOR maneuvers during periods when children were present.

At the second intersection in Lansing, electronic NTOR/blank-out signs already were operational on two separate approaches. Thus, no data were available for the before period. The two approaches were combined for analysis purposes, and RTOR maneuvers were compared between the blank-out period (RTOR allowed) versus the illuminated (RTOR prohibited) time of day. During the blank-out periods, 194 of 672 right-turn vehicles made a RTOR maneuver, or 28.8 percent (i.e., maneuvers which were allowed after stop and after yielding to pedestrians). When the sign was illuminated NO TURN ON RED, 5.1 percent (19 of 369) of motorists made an illegal RTOR maneuver. This was a significant reduction in RTOR maneuvers, even though 19 motorists made an illegal RTOR maneuver while the sign was illuminated. However, none of these illegal maneuvers resulted in a pedestrian conflict or interaction.

The third intersection with the NTOR blank-out sign consisted of only one approach in Grand Rapids, Michigan (southbound approach only). The electronic sign was tested under three separate operations:

Operation 1: The sign shows an illuminated NO TURN ON RED message only during a 17-second interval of each cycle, during an opposing left-turn phase which conflicts with the RTOR vehicles.

Operation 2: The sign was illuminated NO TURN ON RED continuously for 24-hours per day.

Operation 3: The sign was illuminated NO TURN ON RED during the entire red interval for the approach. (60 seconds of NTOR for the 90 second off-peak cycle lengths and 70 seconds of NTOR for the 105 second peak period cycle lengths).

The opposing (northbound) approach was used as a comparison site, since it had a standard NO TURN ON RED (post-mounted) sign.

A summary was prepared of the RTOR violations for each of the conditions listed above (including the comparison site) as shown in table 17. For each of the conditions, between 13 and 30 hours of data were collected. For Operation 1 (a NTOR illuminated only 17 seconds each phase) and Operation 2 (NTOR illuminated continuously), 1.9 percent of motorists committed a RTOR violation (i.e., turned right when the sign was illuminated NTOR). When the sign was illuminated during the entire red phase (Operation 3), a 2.9 percent violation rate resulted, which was comparable to the 2.6 percent violation rate at the comparison site.

Table 17. Summary of RTOR violations resulting from electronic NTOR/blank-out sign.

Operation No.	Type of RTOR Prohibition	Total Data Collection Time (Hours)	Total Right-Turn Volume (No./Hr.)	RTOR Volume		Percent RTOR		No. Pedestrian Conflicts + Interactions	
				Legal	Illegal	Legal	Illegal	RTOR	RTOG
1 Test Site 3	Illuminated NTOR: 17 Sec./cycle. During opposing left-turn phase.	30.3	12,241 (404)	3,950	227	32.3	1.9	3	9
2 Test Site 3	Continuous illumination of NTOR	14.8	6,372 (431)		118		1.9	0	3
3 Test Site 3	Illimination of NTOR. During full red phase.	13.3	5,769 (434)		170		2.9	0	2
Comparison Site	Standard NTOR Sign.	16.5	977 (59)		25		2.6	0	2

The proportion of violations (1.9 percent) for operation types 1 and 2 were significantly lower than either the comparison site or from Operation 3. However, note that the right-turn volume at the test site was nearly constant at 400 to 434 for various test periods, while the comparison site had only 59 right turns per hour. Thus, the RTOR violations at the comparison site might be expected to differ (i.e., perhaps a higher rate) if right-turn volume increased up to 400 per hour. The pedestrian conflicts and interactions for all conditions were negligible for the RTOR period (3 total) and RTOG period (16 total).

In summary, the electronic NTOR/blank-out signs were found to be generally effective in terms of a low RTOR violation rate (less than 2 percent in most cases). The effectiveness of this electronic device compared to the standard NTOR sign appears to be better in some instances, although differences are slight. However, the variable message device also results in increased use of RTOR during periods when RTOR is appropriate (i.e., blank-out message) and thus reduces unnecessary motorist right-turn delay. The use of the device was associated with a negligible number of RTOR pedestrian conflicts.

The blank-out device, however, eliminates the confusion of motorists when a prohibition is in effect as with legends which state NTOR 7:30 a.m. to 9:30 a.m. or NTOR SCHOOL DAYS ONLY or NTOR WHEN PEDESTRIANS ARE PRESENT. One of the devices at a school site in Lansing was equipped with an actuation device which could only be used by an authorized person, such as the crossing guard. Once activated, the device would display the NTOR prohibition for a pre-set time period (45 to 90 minutes during the time when children were present) and would automatically shut-off.

FINDINGS AND CONCLUSIONS

The purpose of this analysis was to develop countermeasures for RTOR-related pedestrian hazards, to field test the most promising countermeasures, and to recommend the ones which are most effective for various site conditions. A total of 30 candidate countermeasures were developed related to modification of signs, traffic signals, pavement markings, intersection design changes and others. The seven countermeasures which were selected for field testing included:

- Red Ball - NO TURN ON RED sign.
- Larger 30x36-in, (75x90-cm) NO TURN ON RED sign.
- NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT sign.
- Red Ball - NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT sign.
- Offset Stop Bar.
- LOOK FOR TURNING VEHICLES pavement marking (in the crosswalk).
- Variable message NO TURN ON RED/Blank-out sign

Field tests were conducted at a total of 34 intersection approaches in Washington, D.C., Dallas and Austin, Texas, and Detroit, Lansing, and Grand Rapids, Michigan.

Various types of conflicts, interactions, and violations were used as measures of effectiveness, including RTOR-related events, as well as total (RTOR & RTOG) events. The Z-test for proportions was applied to determine the effects of each countermeasure after installation, compared to the before (untreated) condition. Significant effects (at the .05 and .01 levels) were reported. The following are some of the key findings and conclusions.

1. The red ball NTOR sign was found to be effective in reducing the proportion of RTOR violations, total conflicts, and total conflicts and interactions at the six test sites combined. The sign was more effective at the Washington, D.C., site than the Detroit sites, due possibly to the differences in sign placement and/or other site-related differences.

2. The larger NTOR sign resulted in a significant reduction in the proportion of violations at the four test sites combined in Washington, D.C., (.01 level) with no significant change at the one Detroit site. An insufficient sample of RTOR conflicts and interactions prohibited statistical testing. The proportion of total conflicts and interactions (using right-turn volumes as a

base) reduced significantly at the five sites combined. There is evidence that the larger NTOR sign is effective under certain conditions.

3. The NTOR WHEN PEDESTRIANS ARE PRESENT sign was tested at four intersection approaches in Detroit to replace a full-time or partial prohibition sign. At one of the sites, no significant effect was found in most of the MOE's. At the second site, the sign was associated with a significantly higher proportion of conflicts in most cases. Approaches 3 and 4 had significantly lower proportions of conflicts in most cases. A further investigation of individual site characteristics revealed that the sign was most effective at sites with low right-turn volumes. The sign was less effective at sites with high right-turn volumes, perhaps because the high turning demand resulted in less willingness by motorists to yield to pedestrians, particularly since RTOR was allowed in the after period.

4. The red ball NO TURN ON RED sign was tested in conjunction with WHEN PEDESTRIANS ARE PRESENT sign at one approach in Austin, two approaches in Dallas, and one approach in Washington, D.C. The Austin approach differed greatly from the other three (in terms of right-turn volume and other factors) and was thus analyzed separately. The device resulted in an increase in RTOR maneuvers as intended at all sites. Although RTOR-pedestrian conflicts were too infrequent for statistical testing, a significant reduction resulted in the proportion of total pedestrian conflicts at the one Austin site with a high right-turn volume and high pedestrian volume. Thus, at that site, motorist right-turn delay was reduced; and the proportion of pedestrian conflict was also reduced, which was a desirable result. The WHEN PEDESTRIANS ARE PRESENT sign was too small for motorists to see when mounted adjacent to the signal on the far side of the intersection. This, however, would be true of any time or partial restriction legend.

5. The offset stop bar was tested at two approaches in Dallas and one approach in Washington, D.C. Conflict data for the offset

stop bar revealed a significant reduction in conflicts to cross-street vehicles at all sites combined. At the one Washington, D.C. approach, no significant change occurred in the proportion of pedestrian conflicts or interactions. In terms of stopping characteristics, the offset stop bar in the middle lane(s) resulted in more RTOR vehicles making a full stop behind the stop bar. Overall, 68.6 percent of middle lane vehicles stopped behind the offset stop bar, and when this occurred there was a higher likelihood of the RTOR vehicle stopping behind the stop bar.

6. The LOOK FOR TURNING VEHICLES pavement marking was tested on eight approaches in Detroit, Austin, and Dallas. An overall improvement resulted in conflicts and interactions for RTOR vehicles and also for total (RTOR and RTOG) vehicles. However, the results were mixed for different sites. While it was effective at the Detroit and Austin sites, it was ineffective at the Dallas site. One possible explanation in that there may be real differences in the effectiveness of such devices, depending on area and/or locational characteristics. The markings do appear to be of value in reducing conflicts at some sites. One practical problem with the markings is that some of them wore away after application, particularly when the pavement was in poor condition. Others were fully visible after 3 to 4 months.

7. The electronic NTOR/blank-out sign was tested at three approaches in Lansing and one approach in Grand Rapids (Michigan). The devices were found to be generally effective in terms of a low RTOR violation rate when the NO TURN ON RED was illuminated (less than 2 percent in most cases). The effectiveness of this device compared to the standard NO TURN ON RED sign appears to be better in some instances although differences are slight. However, the variable message device also results in increased use of RTOR during periods when RTOR is appropriate (i.e., blank-out mode) and this reduces unnecessary motorist right-turn delay. The use of the device was associated with a negligible number of RTOR conflicts.

CHAPTER III
RECOMMENDATIONS FOR RTOR PROHIBITION

INTRODUCTION

At the present time, RTOR is allowed at signalized intersections in all States, unless otherwise signed. In New York City, however, RTOR is only allowed where permitted by a sign. Concern over the permissive RTOR rule initially caused many local agencies to install signs prohibiting RTOR at many intersections. Section 2B-37 of the MUTCD [16] currently stipulates that a NO TURN ON RED sign (R10-11a) "may be considered" when one or more of the following conditions are found based on an engineering study:

- Sight distance to vehicles approaching from the left (or right, if applicable) is inadequate.
- The intersection area has geometrics or operational characteristics which may result in unexpected conflicts.
- There is an exclusive pedestrian phase.
- Significant pedestrian conflicts are resulting from RTOR maneuvers.
- More than three RTOR accidents per year have been identified for the particular approach.
- There is a significant crossing activity by children, elderly, or handicapped people.

Many people contend that these current guidelines for RTOR prohibition are highly subjective and have resulted in considerable uncertainty and differing interpretations by local and State agencies. As a result, the application of the RTOR prohibition has not been uniform nationwide.

Many city traffic engineers have attempted to conscientiously utilize the MUTCD guidelines and have been confused or frustrated. Some cities which initially prohibited RTOR at a high percentage of intersections after the implementation of the permissive RTOR laws, have been slowly removing a portion of those prohibition signs. Other cities particularly in the Western U.S. have reacted by installing few or no RTOR prohibitions.

These problems and inconsistencies related to RTOR prohibitions indicate possible inadequacies with the current guidelines. The purpose of this task was to critically review the current MUTCD guidelines for RTOR prohibition and develop improved guidelines if necessary.

The review and recommendation of guidelines for RTOR prohibition in this chapter is discussed under the following topics:

- Background of RTOR prohibition warrants and guidelines.
- Methodology.
- Analysis results.
- Review of guidelines.
- Conclusions and recommendations.

The following is a discussion of each of these topics.

BACKGROUND

Negative guidelines or warrants have been used under the generally permissive RTOR regulation to prohibit turns on red. Prior to the general permissive rule (i.e., Western rule) both negative and positive guidelines were used to allow RTOR with signs (i.e., RTOR ALLOWED AFTER STOP). A negative warrant specifies conditions where RTOR should be prohibited, whereas positive warrants outline conditions where RTOR should be permitted. Some warrants have been quantitative while others were qualitative.

Little agreement has been reached concerning the factors that should be considered in developing warrants for RTOR. Based on data collected by McGee [17], a summary of the factors considered by the States in developing warrants for prohibiting turns on red are shown in table 18. It is interesting to note that pedestrian volume was the most frequently considered factor, which is consistent with the general concern for pedestrian safety at RTOR intersections.

An example of the quantitative guidelines that were used by Kansas to permit RTOR are shown in figure 10, while an example of negative qualitative guidelines that were used in Indiana to prohibit RTOR are given in figure 11. A problem with these and similar warrants is that they appear to be based primarily on engineering judgement instead of empirical data. For example, the Indiana criterion (figure 11) requiring RTOR prohibition because of little benefit (i.e., few opportunities or a small demand for a RTOR) from the maneuver is not supported by research results.[17] Based on analysis of safety and operational data collected during a study conducted for FHWA, McGee [12] recommended the guidelines shown in figure 12 for prohibiting RTOR under the generally permissive rule. After considering the study results and receiving comments from the States, the guidelines were modified and used in the adoption of the current edition of the Manual on Uniform Traffic Control Devices [16], as listed earlier.

The MUTCD guidelines are primarily qualitiative, which provides the traffic engineer with considerable flexibility and discretion. There have been concerns expressed regarding the need for developing more quantitative guidelines which would add more objectivity to the subjective nature of the guidelines. Proponents of quantitative guidelines suggest specific values are needed to defend their decision when they prohibit RTOR.[14] Opponents argue that they prefer the flexibility of qualitative guidelines and point out that it may not be possible to develop quantitative guidelines due to the absence of a cause and effect relationship between RTOR intersection conditions and accident experience.

Another problem associated with existing warrants is that there is little uniformity in current practices, and prohibitions are primarily based on subjective evaluation of intersection and traffic conditions. Parker [6] and Mamlouk [11] found that RTOR prohibitions varied widely

Table 18. Summary of factors considered in prohibiting RTOR.

	Criteria	No. of States Using Criteria
1.	Significant Pedestrian Volumes	12
2.	Restrictive Geometrics	9
3.	Five or More Approaches	8
4.	Inadequate Sight Distance	6
5.	Speeds Through Intersection	5
6.	RTOR Conflicts with Other Vehicle Movements, e.g., Left Turn Phase	4
7.	Exclusive Pedestrian Phase (All-Red)	3
8.	Vehicle Conflict is Serious	3
9.	Signals Under School Crossing Warrant	3
10.	History of Accidents Related to RTOR (5 or more)	2
11.	Complex Signal Phasing	2
12.	Pedestrian Signal Locations	2
13.	No Appreciable Right Turns	1
14.	Short Red Interval	1
15.	Fully Actuated Signals	1
16.	High Cross Street Volumes	1

Source: McGee, 1974.[17]

In using these criteria, each approach to an intersection will be considered separately. Traffic and pedestrian volumes refer to a single approach or a single crosswalk. Section 8-514 Traffic Control Signal Legend, K.S.A.

A. Right Turn Volumes

1. The number of motorists turning right should be:

   a. Urban -- At least 75 vehicles for each hour of eight hours in the 7 a.m.-6 p.m. period
   b. Rural -- At least 50 vehicles for each hour of eight hours in the 7 a.m.-6 p.m. period
   c. At least 25 percent of the total volume entering the intersection from the approach under study.

2. If two approaches to an intersection meet this requirement, "Right Turn on Red After Stop" may be used on all approaches if all other criteria are satisfied.

3. This requirement will be waived if a channelized right turn lane is available-use Yield Sign.

B. Pedestrians in First Crosswalk

1. If the number of pedestrians using the first crosswalk to be traversed by motorists turning right exceeds 50 persons per hour during each of eight hours of an average weekday, "Right Turn on Red After Stop" shall not be used.

2. "Right Turn on Red After Stop" shall not be used if the "first crosswalk" is regularly used by 25 or more children on their route to or from school.

3. Crosswalks through channelized right turn lanes will be exempted from these requirements.

C. Cross Street Sight Distance

1. The minimum sight distance of vehicles approaching from the left shall be as follows:

Figure 10. Quantitative guidelines used in Kansas to permit RTOR.

Source: McGee, 1974.[17]

Cross Street Speed Limit	Minimum Sight Distance
25 mph	140 feet
30 mph	175 feet
35 mph	215 feet
40 mph	260 feet
45 mph	310 feet
50 mph	370 feet

2. If available sight distance fails to meet these requirements, "Right Turn on Red After Stop" shall not be used.

D. General Criteria

1. "Right Turn on Red After Stop" shall not be used at intersections with accident history of serious accident or injury rates.

2. "Right Turn on Red After Stop" will not be permitted if the motorists would thereby be permitted to turn across a crosswalk while the "Walk" signal is shown to pedestrians.

3. "Right Trun on Red After Stop" will not be used at pedestrian actuated or full-traffic actuated signals.

4. "Right Turn on Red After Stop" will not be used on approaches where the cross street speed limit is greater than 50 mph.

Figure 10. Quantitative guidelines used in Kansas to permit RTOR (Continued).

Source: McGee, 1974.[17]

Note: 1 ft = 0.3 m
1 mph = 1.6 kph

A. RTOR should be prohibited for safety reasons where:

1. Sight distance of cross street traffic as shown below is not available to the potential RTOR motorists at the Stop Line on his approach.

Minimum Sight Distance

Speed in mph	Sight Distance in Feet
20	217
25	271
30	325
35	379
40	434
45	488
50	542
55	596

2. A separate signal phase for a turning movement exists at the intersection which would conflict with a RTOR movement (the RTOR motorist may not be aware of this movement and hence not look for it).

3. The intersection has more than four approaches (at such locations cross street traffic which conflicts with the RTOR may not be quickly identified by the RTOR motorist or the RTOR motorist may be able to turn into more than one street, thus creating unexpected conflicts).

B. RTOR may be prohibited because of little benefit from the maneuver at locations where:

1. There is very short red time for the approach.

2. Cross street traffic is heavy for many hours of the signal-operating day (where cross street is operating at capacity for many hours of the day).

3. Pedestrian use of the crosswalk on the approach is heavy for many hours of the signal-operating day (at least one pedestrian is in the crosswalk during the red time for the RTOR motorist for many cycles during the day).

4. Little right turn demand exists and there is no right-turn only lane available.

C. RTOR may be prohibited because of possible adverse public reaction where:

1. A school crossing route passes through the intersection.

2. There are moderate to high pedestrian volumes.

Figure 11. Qualitative guidelines used in Indiana to prohibit RTOR.

Source: McGee, 1974.[17]

Note: 1 ft = 0.3 m

RTOR should be prohibited where:

1. Sight distance of vehicles approaching from the left is less than the following minimums:

Cross Street Speed Limit (MPH)	*Minimum Sight* Distance (Feet)*
20	120
25	150
30	190
35	220
40	270
45	320
50	360
55	410

2. The intersection has more than four approaches or has restricted geometrics which cause additional conflicts. (The restriction should apply only to approaches which have multiple or unusual conflicts that are not easily identified by the motorist.)

3. There is an exclusive pedestrian signal phase during which pedestrians can use all crosswalks.

4. The intersection is within 200 feet of a railroad grade crossing, and the signal controller is preempted during train crossings. (The prohibition should apply only to the approach from which right turns are made into the lane crossing the railroad. See Sec. 8B-7, MUTCD.)

RTOR may be prohibited where:

1. Significant pedestrian conflicts are resulting from RTOR maneuvers.

2. More than one RTOR accident per year has been identified for any particular approach.

3. There is an unusual movement, such as double-left turns, that would not be anticipated by the RTOR driver.

4. There are school crossings or large numbers of children or elderly expected.

*Sight distance as measured from the stop line if pedestrian crosswalks are presented or, if none, from the edge of the cross-street pavement or curb line.

Note: 1 ft = 0.3 m

Figure 12. Suggested guidelines for prohibiting RTOR under the general permissive rule.

Source: McGee, 1978.[12]

among jurisdictions after generally permissive RTOR was adopted in Virginia and Indiana.

In recognition of the need for a national set of guidelines for RTOR prohibition, the Institute of Transportation Engineers appointed Technical Commitee 4A-17. In February 1984, the committee's report was published in the ITE Journal, which provided proposed recommended guidelines for prohibition of turns on red [14]. A list of these recommendations is given in figure 13, but the committee also encourages local authorities to consider intersections on an individual basis. While these guidelines appear quite helpful and appropriate, they are also somewhat general in nature.

METHODOLOGY

The data collection and analysis activities were initiated to obtain information useful in reviewing current MUTCD guidelines on RTOR prohibitions. The information was also considered to be of value for developing more specific guidelines or warrants to replace or supplement the current MUTCD guidelines. The output of the analysis was, therefore, information on which traffic conditions, geometrics, and traffic control devices are associated with unsafe RTOR conditions.

Two different approaches were considered for use in this analysis. One approach was to analyze RTOR accident data at selected intersections and determine the variables associated with RTOR accidents. However, after reviewing previous research and accident studies on RTOR, it became apparent that an extremely small number of RTOR accidents per intersection (i.e., about one RTOR-related accident per 20 years per site) existed on the average, as discussed later. Such low RTOR accident experience would not readily allow for determining the association between specific site conditions and safety.

The analysis approach which was selected was the use of Right-Turn-On-Red (RTOR) and Right-Turn-On-Green (RTOG) conflicts as a measure of hazard. Although no proven relationship currently exists between RTOR conflicts and RTOR accidents, there is a need to minimize near-accidents

1. Engineering judgment is the basis for each potential turn on red prohibition. Prohibition should be considered only after the need has been fully established and less restrictive methods have been considered.
2. Part-time prohibitions should be discouraged; however, they are preferable to full-time prohibitions when the need occurs for only short periods of time. It is not good engineering practice to prohibit right turns on red on the grounds that it is of little benefit during some hours of the day. The use of disappearing legend signs for part-time prohibitions and where desired in the vicinity of railroad crossings is recommended.
3. Less restrictive alternatives should be considered in lieu of prohibiting turns on red. Some examples of less restrictive measures are signs such as "No Turns on Red to Henry Street" or "Right Turn on Red Right Lane Only." Such devices can provide the intended prohibitions without inconveniencing all right-turning traffic.
4. Although many authorities do not perceive the need to prohibit turns on red at multiphased signals, others find there is a need. Where such prohibitions are considered necessary, consideration should be given to the providing of right turn indications for the main street during the cross street left-turn phases.
5. The definition of specific right turn on red accident criteria may be inappropriate. The accident history of the intersection should be analyzed with prohibition of turns on red as one possible remedy. Experience may indicate that severe sight distance restrictions or deceptive geometrics can be related to turn on red accidents.
6. Universal prohibition at "school crossings" should not be made but rather restrictions should be sensitive to special problems of pedestrian and/or bicycle conflict, such as the unpredictable behavior of children or the problems of the elderly and handicapped, or failure of motorists to yield to pedestrians and/or bicycles within a crosswalk. Pedestrian volumes, as such, should not be the only criteria for prohibiting turns on red.
7. Education and enforcement play a significant role in the benefits and safety of right turns on red. The public needs to be educated concerning the benefits of right turns on red and their responsibilities when making this maneuver. Enforcement is important to ensure that the turns are made *after stopping* and that the necessary prohibitions are being observed.

Figure 13. ITE Technical Committee 4A-17 recommendations for RTOR.

Source: Reference.[14]

or "close-calls" between RTOR vehicles and pedestrians. Conflicts can be easily measured, and numerous RTOR-related conflicts may be assumed to be a measure of "potential" RTOR accidents or operational problems.

The data collection and analysis plan was structured to collect detailed data on traffic and pedestrian volumes, intersection geometrics, RTOR devices, signal information, and pedestrian-vehicle conflicts (RTOR and RTOG conflicts separately). Then, appropriate statistical tests were applied to determine the association between these variables and conflicts under various conditions. The analysis was conducted to address the following sequence of analysis questions:

1. What are the characteristics of the data base in terms of the cities used, traffic and pedestrian volumes, and site characteristics for various types of RTOR controls?
2. What are the overall characteristics of the conflicts and interactions that occur relative to RTOR and RTOG for sites with and without RTOR prohibition?
3. What variables are most highly correlated with pedestrian-vehicle conflicts at sites with and without RTOR prohibitions?
4. What traffic and roadway variable combinations explain the greatest amount of variation in pedestrian-vehicle conflicts and interactions (continuous variables only)?
5. What site features are associated with a significant difference in pedestrian vehicle conflicts?

The data collection for this phase of the study consisted of the following activities.

- Selection of data collection sites.
- Development of data collection forms and procedures.
- Observer training and data collection.
- Data reduction, checking, and verification.

Each activity is described below.

Selection of Data Collection Sites

Data were collected in the cities of Washington, D.C., Detroit, Michigan, Dallas, Texas, and Austin, Texas. These cities were selected to provide sample areas of the country having different experience with RTOR prohibitions, as explained in Chapter I. Washington, D.C., represented a city having the Eastern rule, until recently. Dallas and Austin, Texas, represented cities with the Western law in effect for many years and Detroit represented a city in another part of the country which represents somewhat of a compromise between the other cities in terms of RTOR philosophy and practice.

A list of intersections was obtained from each of the cities which included samples of full time RTOR prohibitions, partial RTOR prohibitions (by time of day, day of week, etc.) and no RTOR prohibitions. Selected sites also represented a wide range of pedestrian volumes, turn volumes, geometric conditions, operational conditions, and areas of the city (i.e., CBD, school, commercial). Although it was impossible to collect data for every possible site condition, it was determined that a sample of approximately 200 approaches would provide an adequate sample size for statistical analysis and also allow for a variety of conditions for meaningful insights into developing RTOR guidelines.

Development of Data Collection Form and Procedures

The data forms used in this phase of the study were the RTOR site data form (figure 1) and the RTOR volume and conflicts data form (figure 2). The site data form was used to record site conditions and signal timing and to draw a condition diagram of the intersection. The RTOG and RTOR conflict and volume data were collected using the RTOR Volume and Conflicts data form. Both the RTOR and the RTOG conflicts and volumes were collected for use in the development of RTOR guidelines. The definition of conflict types and the near and far crosswalk are the same as discussed in Chapter I. A minimum of 4 hours of data were collected on each approach. Eight or more hours of data were collected on several approaches to test data repeatability.

Observer Training and Data Collection

Data collection for this phase of the study was conducted simultaneously with the observational studies of RTOR compliance. As previously mentioned, additional training was only necessitated by employee turnover and/or from spot-checking of the data collectors by collecting observe-the-observer data throughout the project. Tests of inter-rater reliability were also conducted to insure data consistency.

The procedure for collecting the data was also the same as described in Chapter I. Data were usually collected on two approaches to the intersection. The observer would generally collect data for a period of 8 hours or more at the intersection, alternating between the two approaches every 30 minutes. When only one approach to an intersection was suitable, the observer would alternate with a nearby approach or would collect a continuous 4 hours of data on that approach.

Data Reduction, Checking, and Verification

As discussed with other data collected in this study, data were reduced in-house and carefully checked for inconsistencies or missing information. After data were keypunched, checked, and verified, programs were developed to identify data inconsistencies and logic errors. Other checking was also conducted on the data file to ensure a high degree of data accuracy.

ANALYSIS RESULTS

To answer the basic analysis questions listed earlier, several types of analyses were conducted. These are discussed in the following sections:

- Characteristics of the data base.
- Characteristics of conflict data.
- Correlation analysis.
- Branching analysis.
- Analysis of covariance.

Characteristics of the Data Base

The data base consisted of 199 total intersection approaches, which included 98 from the Detroit area, 51 from the Washington, D.C., area, 36 from Dallas, and 14 from Austin (table 19). The intersection approaches included 108 with RTOR allowed, 46 with partial (i.e., part-time) prohibitions, and 45 with full-time RTOR prohibitions. The selected approaches were mostly at 4-legged intersections (170 or 85.4 percent), while 15 were at 3-legged intersections and 14 at 5-legged intersections.

In terms of area type, most of the approaches were in CBD areas (103 approaches) with 65 approaches in commercial areas, 4 approaches in residential areas, 25 school area approaches, and 2 approaches in industrial areas. Approaches were most commonly at the intersection of 2 two-way streets (111 approaches) or one-way/two-way combinations (76 approaches), while 12 approaches were one-way streets intersecting with one-way streets. Cycle lengths ranged from 50 seconds to 120 seconds at the intersection approaches.

The speed limits at the approaches consisted of 131 sites with speed limits of 25 mph (40 kph) or less. Sight distances on the approaches ranged from less than 50 feet (15 m) to virtually unlimited. The sign locations for RTOR prohibitions included near-side signing at 46 sites (mostly in the Detroit area), 35 sites with far-side signs (many involving prohibition signs on far-side signal poles in the Washington, D.C. area) and 10 sites with overhead and/or redundant signing. It should be mentioned that the NO TURN ON RED signs are typically post mounted on the near-side corner in the Detroit area, and Washington, D.C., generally mounts their signs on near-side and/or far-side traffic signal poles, since signals are not span-mounted overhead.

In summary, intersection approaches were selected with a wide variety of conditions for use in the analysis. Emphasis was placed on selecting most of the sites which had at least a moderate volume of pedestrians, since RTOR pedestrian safety was a major concern.

Table 19. Summary of number of selected approaches by city and type of prohibition.

City	Type of Prohibition			Totals
	Full	Partial	None	
Detroit	16	32	50	98
Washington	13	12	26	51
Dallas	10	2	24	36
Austin	6	0	8	14
Totals	45	46	108	199

Characteristics of Conflict Data

The conflict data collected at the 199 intersection approaches were analyzed to determine the overall characteristics of pedestrian conflicts and interactions relative to RTOR and RTOG at sites with and without prohibition. This basic issue was addressed by answering a series of more detailed questions, as discussed below.

Question 1: What is the average frequency of RTOR maneuvers and their resulting conflicts at the selected sites?

Response 1: A summary is given in table 20 which shows an average of 17.13 RTOR maneuvers per hour (8,507 in 496.7 hours of data collection) at the 108 RTOR-allowed sites. This compares with 5.11 (illegal) RTOR movements per hour at the 91 RTOR-prohibited sites. At RTOR-allowed sites, the occurrence of RTOR conflicts per hour was 0.65 involving cross-street vehicles and 0.86 involving pedestrians. This compares to RTOR-prohibited sites with 0.31 RTOR conflicts per hour with cross-street vehicles and 0.31 per hour with pedestrians. Of all RTOR vehicles, only 4.3 percent resulted in a conflict with cross-street vehicles, and 5.2 percent with pedestrians. When both conflicts plus interactions were considered, 9.4 percent resulted in conflicts with cross-street vehicles and 13.7 percent involved pedestrians.

Question 2: What specific types of pedestrian conflicts are most prevalent relative to RTOR and RTOG?

Response 2: Of the RTOR pedestrian conflicts and interactions, 44.5 percent involved a vehicle interaction with a pedestrian, (i.e., pedestrian is within 20 ft. (6 m) of a RTOR vehicle) and 38.5 percent were vehicle hesitations (i.e., vehicle slows or stops to avoid hitting a pedestrian during a RTOR maneuver). This compares with 13.1 percent vehicle hesitations and few "pedestrian run" conflicts (3.0 percent) or vehicle swerves (0.9 percent). RTOG conflicts were mostly vehicle hesitations (60.6 percent) followed by interactions (33.7 percent), pedestrian hesitations (3.8 percent), and a small portion of other types. This information is shown in table 21.

Table 20. Summary of RTOR maneuvers and resulting conflicts.

	Total Number of Hours	Number of Approaches	Number of RTOR Maneuver (No. per Hour)	Number of RTOR Conflicts (Per Hour)		Percent RTOR Vehicles Involved in Conflict			Number of RTOR Conflicts Plus Interactions (No. per Hour)	Percent of RTOR Vehicles Involved in Conflicts or Interactions	
				Cross Street Vehicles	Pedestrians	Cross Street Vehicles	Pedestrian	Total	Pedestrians	Pedestrians	Pedestrians Plus Cross Street Traffic
RTOR-Allowed Sites	496.7	108	8,507 (17.13)	324 (0.65)	428 (0.86)	3.8	5.0	8.8	792 (1.59)	9.3	13.1
RTOR-Prohibited Sites	435.8	91	2,225 (5.11)	133 (0.31)	135 (0.31)	6.0	6.0	12.0	222 (0.51)	10.0	16.0
Total Sites	932.5	199	10,732 (11.51)	457 (0.49)	563 (0.60)	4.3	5.2	9.5	1,014 (1.09)	9.4	13.7

Table 21. Summary of pedestrian conflicts by conflict type.

Type of Conflict	RTOR Conflict		RTOG Conflict		RTOR+RTOG Conflict	
	Number	Percent	Number	Percent	Number	Percent
Vehicle Hesitation (VH)	390	38.5	9,645	60.6	10,035	59.3
Vehicle Swerve (VS)	10	0.9	57	0.4	67	0.4
Pedestrian Hesitation (PH)	133	13.1	603	3.8	736	4.4
Pedestrian Run (PR)	30	3.0	246	1.5	276	1.6
Interaction	451	44.5	5,359	33.7	5,810	34.3
Totals	1,014	100.0	15,910	100.0	16,924	100.0

Question 3: How do pedestrian conflicts and interactions vary by near and far crosswalk?

Response 3: At RTOR-allowed sites, 0.92 RTOR conflicts plus interactions occur on the far crosswalk compared to 0.67 on the near crosswalk. The conflicts in the far crosswalk resulted from pedestrians crossing against the light. However, RTOG conflicts and interactions are 26 times more prevalent on the far crosswalk (14.9 per hour) compared to the near crosswalk (0.56). At RTOR-prohibited sites, RTOR conflicts occur an average of 0.22 per hour on the far crosswalk compared to 0.09 on the near crosswalk, while RTOR interactions represent 0.10 per hour for each case. With respect to RTOG, conflicts are much higher on the far crosswalk (12.01 compared to 0.42 per hour), as well as interactions (6.09 compared to 0.32). Thus, the far crosswalk is where a great majority of RTOR and RTOG pedestrian conflicts and interactions occur, as shown in table 22.

Question 4: How do specific types of pedestrian conflicts vary with and without RTOR prohibition?

Response 4: Information is summarized in table 23 on total pedestrian conflicts (RTOR + RTOG) by type. For RTOR pedestrian conflicts, vehicle hesitations and interactions are more prevalent at RTOR-allowed sites than at RTOR-prohibited sites (0.65 to 0.15 per hour for vehicle hesitations and 0.73 to 0.20 per hour for interactions). For RTOG conflicts, RTOR-prohibited sites account for more pedestrian hesitations (11.21 to 9.59 per hour) and more interactions (6.41 to 5.16 per hour) compared to RTOR-allowed sites. Other RTOG conflict types were also higher at the RTOR-prohibited sites. Considering conflicts for all periods (RTOR plus RTOG), RTOR-prohibited sites account for more overall conflicts and interactions than RTOR-allowed sites (19.35 compared to 17.10 per hour). This could be partly due to higher pedestrian volume and/or right-turn volume at the RTOR-prohibited sites. In any case, it is apparent that the RTOR prohibition shifts conflicts from the red interval to the green interval.

Correlation Analysis

One key analysis issue was to determine the traffic and site conditions which were most highly correlated to RTOR pedestrian conflicts.

Table 22. Summary of total and hourly pedestrian conflicts and interactions for the data sites.

Type of Sites	Hours of Data Collected	Type of Conflict	Near Crosswalk			Far Crosswalk			Total Crosswalks		
			Conflicts	Interactions	Totals	Conflicts	Interactions	Totals	Conflicts	Interactions	Totals
RTOR - Allowed	496.7	RTOG	118 (0.24)	161 (0.32)	279 (0.56)	5,018 (10.10)	2,404 (4.84)	7,422 (14.94)	5,136 (10.34)	2,565 (5.16)	7,701 (15.50)
		RTOR	151 (0.30)	185 (0.37)	336 (0.67)	277 (0.56)	179 (0.36)	456 (0.92)	428 (0.86)	364 (0.73)	792 (1.59)
		Totals	269 (0.54)	346 (0.70)	615 (1.24)	5,295 (10.66)	2,583 (5.20)	7,878 (15.86)	5,564 (11.20)	2,929 (5.90)	8,493 (17.10)
RTOR- Prohibited	435.8	RTOG	181 (0.42)	140 (0.32)	321 (0.74)	5,234 (12.01)	2,654 (6.09)	7,888 (18.10)	5,415 (12.43)	2,794 (6.41)	8,209 (18.84)
		RTOR	40 (0.09)	44 (0.10)	84 (0.19)	95 (0.22)	43 (0.10)	138 (0.32)	135 (0.31)	87 (0.20)	222 (0.51)
		Totals	221 (0.51)	184 (0.42)	405 (0.93)	5,329 (12.23)	2,697 (6.19)	8,026 (18.42)	5,550 (12.74)	2,881 (6.61)	8,431 (19.35)

Table 23. Summary of conflicts per hour by conflict type and RTOR status.

Type of Conflict	RTOR Pedestrian Conflicts		RTOG Pedestrian Conflicts		Total (RTOR + RTOG) Pedestrian Conflicts	
	RTOR-Allowed Sites	RTOR-Prohibited Sites	RTOR-Allowed Sites	RTOR-Prohibited Sites	RTOR-Allowed Sites	RTOR-Prohibited Sites
VH	0.65	0.15	9.59	11.21	10.24	11.36
VS	0.01	0.01	0.06	0.07	0.06	0.08
PH	0.16	0.12	0.50	0.82	0.66	0.94
PR	0.04	0.03	0.20	0.33	0.24	0.36
I	0.73	0.20	5.16	6.41	5.90	6.61
Total	1.59	0.51	15.50	18.84	17.10	19.35

This analysis is useful in the selection of variables and levels of exposure for the development of guidelines or warrants for RTOR prohibition. Pearson Correlation coefficients were computed between continuous independent variable and the following conflict measures (dependent variables):

- (RTOR + RTOG) conflicts per hour.
- Total (RTOR + RTOG) conflicts plus interactions per hour.
- RTOR conflicts per hour.
- RTOR conflicts plus interactions per hour.

The continuous independent (i.e., traffic or roadway) variables used were:

- Right-turn volume.
- RTOR volume.
- Total pedestrian volume (near and far crosswalk).
- Pedestrian volume - near crosswalk only.
- Pedestrian volume - far crosswalk only.
- Near crosswalk length (feet).
- Far crosswalk length (feet).
- Sight distance for cross-street traffic (feet).

A separate set of correlation coefficients (r-values) were computed for RTOR-allowed sites (table 24) and RTOR-prohibited sites (table 25). In both tables, the r values are given along with the number of approaches used in the analysis (n) and the level of significance (p).

For RTOR-allowed sites (table 24), data samples (approaches) ranged from 95 to 108. The shaded cells are those in which the r-value exceeds approximately 0.4 and the level of significance is 0.05 or less (i.e., 95 percent confidence or greater). The independent variables found to be most highly correlated with RTOR conflicts and interactions were right-turn volume and RTOR volume, although r values were only about 0.3. The independent variables most highly correlated to total (RTOR + RTOG) conflicts and interactions were, in order of importance:

Table 24. Summary of Pearson correlation coefficients for various dependent and independent variables - RTOR-allowed sites.

SITES WITH RTOR ALLOWED

Conclict Measure	Right Turn Volume (Per Hour)	RTOR Volume (Per Hour)	Ped. Vol. (Per Hour)	Ped. Vol. Near Crosswalk (Per Hour)	Ped. Vol. Far Crosswalk (Per Hour)	Near Crosswalk Length (Feet)	Far Crosswalk Length (Feet)	Sight Distance (Feet)
Total Conflicts Per Hour (RTOR + RTOG)	r = 0.444 n = 108 p = 0.000	r = 0.015 n = 108 p = 0.439	r= 0.810 n = 108 p = 0.000	r = 0.685 n = 108 p = 0.000	r = 0.825 n = 108 p = 0.000	r = 0.036 n = 108 p = 0.357	r = 0.103 n = 108 p = 0.145	r =-0.055 n = 95 p = 0.297
Total Conflicts + Interactions Per Hour (RTOR + RTOG)	r = 0.485 n = 108 p = 0.000	r = 0.027 n = 108 p = 0.390	r = 0.805 n = 108 p = 0.000	r = 0.691 n = 108 p = 0.000	r = 0.809 n = 108 p = 0.000	r = 0.044 n = 108 p = 0.324	r = 0.112 n = 108 p = 0.13	r =-0.009 n = 95 p = 0.464
RTOR Conflicts Per Hour	r = 0.304 n = 108 p = 0.001	r = 0.297 n = 108 p = 0.001	r = 0.129 n = 108 p = 0.091	r = 0.081 n = 108 p = 0.202	r = 0.162 n = 108 p = 0.047	r = 0.024 n = 108 p = 0.403	r = 0.054 n = 108 p = 0.289	r =-0.065 n = 95 p = 0.266
RTOR Conflicts + Interactions/Hour	r = 0.406 n = 108 p = 0.000	r = 0.383 n = 108 p = 0.000	r = 0.186 n = 108 p = 0.027	r = 0.177 n = 108 p = 0.033	r = 0.168 n = 108 p = 0.041	r = 0.106 n = 108 p = 0.137	r = 0.107 n = 108 p = 0.136	r = 0.024 n = 95 p = 0.409

- Pedestrian volume in the far crosswalk (r value of 0.81).
- Total pedestrian volume - near plus far crosswalk (r value of 0.81).
- Pedestrian volume in the near crosswalk (r value of 0.69).
- Right-turn volume (r value of 0.49).

For the RTOR-prohibited sites (table 25), the independent variable most highly correlated with RTOR conflicts and interactions was RTOR volume (r value of 0.47). The independent variables most highly correlated to total (RTOR + RTOG) conflicts and interactions were, in order of importance:

- Pedestrian volume in the near plus far crosswalk (r value of 0.73)
- Pedestrian volume in the far crosswalk (r value of 0.73).
- Pedestrian volume in the near crosswalk (r value of 0.72).
- Right-turn volume (r value of 0.35).
- Near crosswalk length (r value of 0.30).

Strong intercorrelations between certain independent variables were also found in many cases, as expected. Particularly high r values (above 0.90) were found between the various pedestrian volume measures (i.e., near crosswalk volume, far crosswalk volume and total volume).

In summary, RTOR conflicts are correlated most highly with RTOR traffic volume, and are not as strongly related to pedestrian volumes. This occurred due to the fact that many approaches had few RTOR maneuvers (and related pedestrian conflicts), and thus the frequency of RTOR maneuvers was more important in determining pedestrian conflicts during the red interval. On the other hand, various measures of pedestrian. volume are mostly highly correlated with total conflicts and interactions (RTOR + RTOG).

Branching Analysis

The next major issue to be addressed was:

Table 25. Summary of Pearson correlation coefficients for various dependent and independent variables - RTOR-prohibited sites.

SITES WITH RTOR PROHIBITED

Conflict Measure	Right Turn Volume (Per Hour)	RTOR Volume (Per Hour)	Ped. Vol. (Per Hour)	Ped. Vol. Near Crosswalk (Per Hour)	Ped. Vol. Far Crosswalk (Per Hour)	Near Crosswalk Length (Feet)	Far Crosswalk Length (Feet)	Sight Distance (Feet)
Total Conflicts Per Hour (RTOR + RTOG)	r = 0.315 n = 91 p = 0.001	r =-0.102 n = 91 p = 0.168	r = 0.802 n = 91 p = 0.000	r = 0.709 n = 91 p = 0.000	r = 0.776 n = 91 p = 0.000	r = 0.331 n = 91 p = 0.001	r = 0.212 n = 90 p = 0.022	r =-0.136 n = 76 p = 0.121
Total Conflicts + Interactions Per Hour (RTOR + RTOG)	r = 0.349 n = 91 p = 0.000	r =-0.119 n = 91 p = 0.130	r = 0.784 n = 91 p = 0.000	r = 0.721 n = 91 p = 0.000	r = 0.734 n = 91 p = 0.000	r = 0.303 n = 91 p = 0.002	r = 0.223 n = 90 p = 0.014	r =-0.155 n = 76 p = 0.090
RTOR Conflicts Per Hour	r = 0.130 n = 91 p = 0.109	r = 0.416 n = 91 p = 0.000	r = 0.118 n = 91 p = 0.133	r = 0.018 n = 91 p = 0.433	r = 0.193 n = 91 p = 0.033	r =-0.053 n = 91 p = 0.309	r =-0.079 n = 90 p = 0.230	r =-0.129 n = 76 p = 0.133
RTOR Conflicts + Interactions/Hour	r = 0.211 n = 91 p = 0.022	r = 0.470 n = 91 p = 0.000	r = 0.119 n = 91 p = 0.130	r = 0.041 n = 91 p = 0.350	r = 0.174 n = 91 p = 0.049	r =-0.057 n = 91 p = 0.297	r =-0.104 n = 90 p = 0.166	r =-0.101 n = 76 p = 0.192

What combinations of traffic and roadway variables explain the greatest amount of variation in pedestrian-vehicle conflicts and interactions?

This issue was considered to be important for determining the measures used for developing improved guidelines and for determining the "break-point" levels of each variable which are critical in explaining pedestrian conflicts. Branching analysis was used to identify the critical variables and the break-point levels. Branching runs were generated using four separate dependent variables (measures of pedestrian conflicts):

- RTOR pedestrian conflicts per hour (figure 14).
- RTOR pedestrian conflicts plus interactions per hour (figure 15).
- Total (RTOR + RTOG) pedestrian conflicts per hour (figure 16).
- Total (RTOR + RTOG) pedestrian conflicts and interactions per hour (figure 17).

The branching runs involved analyzing 30-minute periods as sample points, resulting in 1,771 data samples. Thus, the independent variables selected for this analysis were ones which fluctuate over time, and include RTOR volume, total turn volume, pedestrian volume on the near crosswalk, pedestrian volume on the far crosswalk, and total pedestrian volume (near and far crosswalks combined). The city and RTOR status (i.e., RTOR allowed or prohibited) were also considered in this analysis.

A total of 12 branching runs were conducted, as summarized in table 26. Some of the runs involved "forcing" separate branches based on RTOR-allowed versus RTOR-prohibited groupings.

The major findings of the branching analyses are as follows:

- The dependent variables corresponding to various levels of explained variance were:

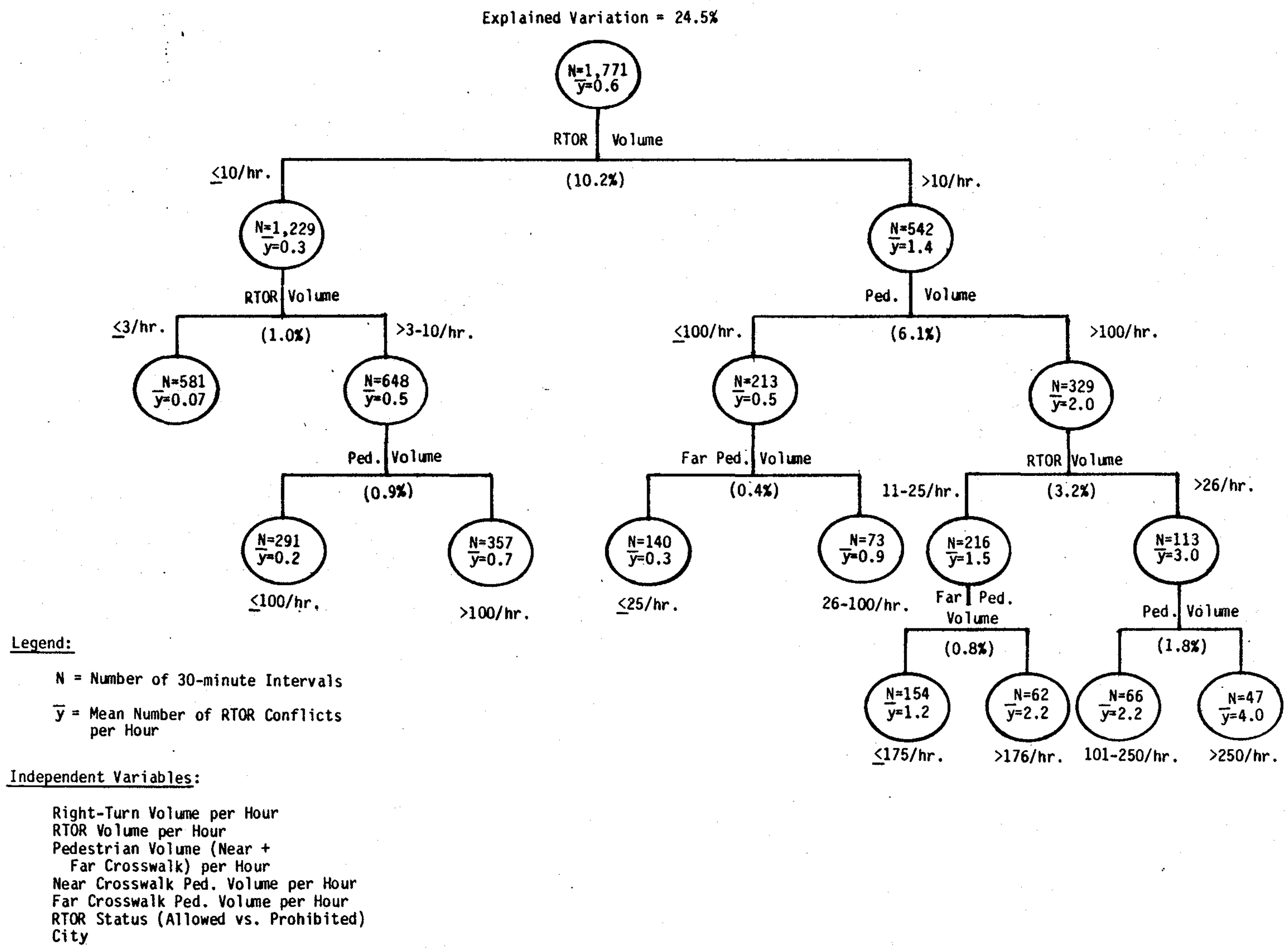


Figure 14. Branching diagram for the number of RTOR conflicts per hour.

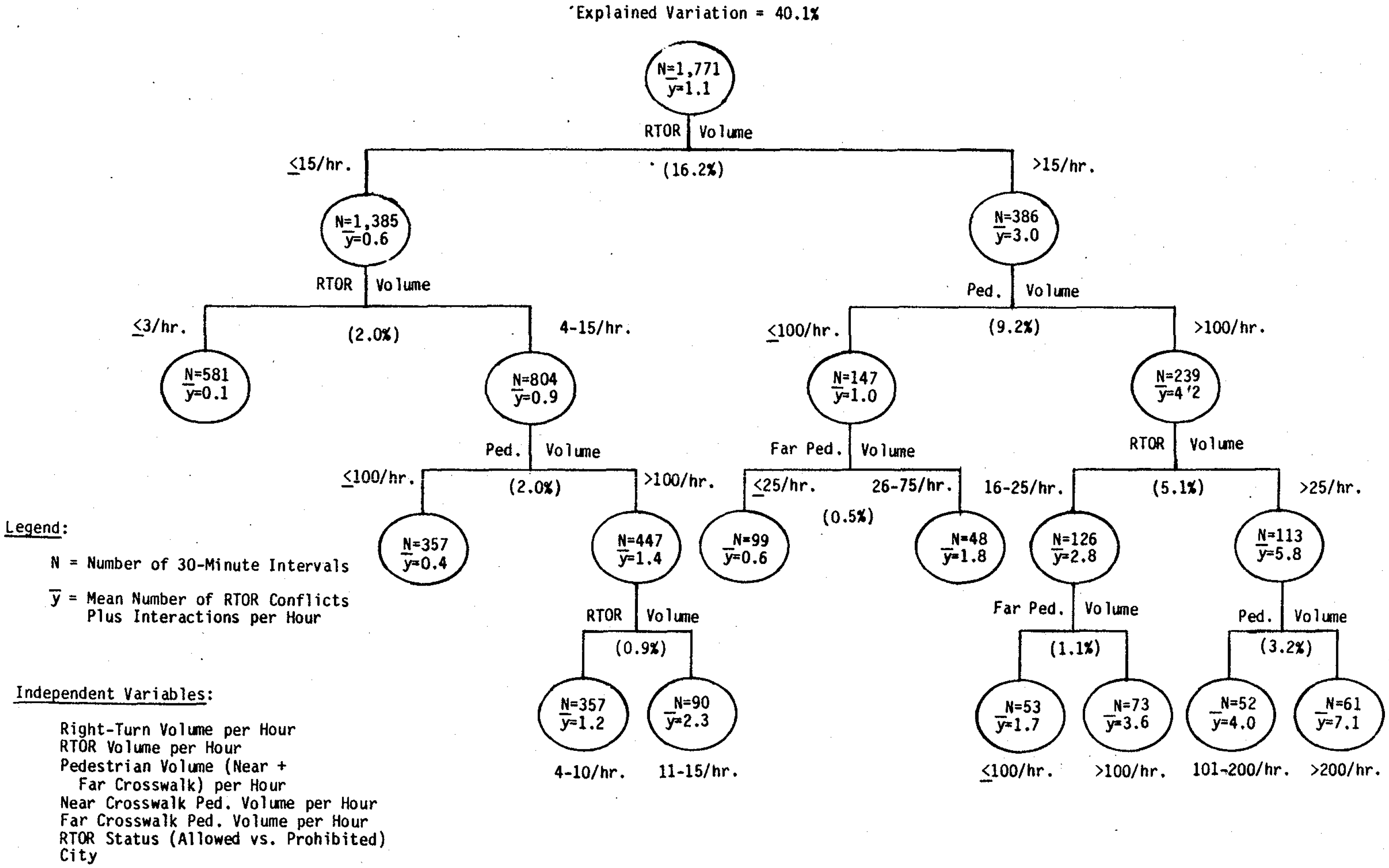
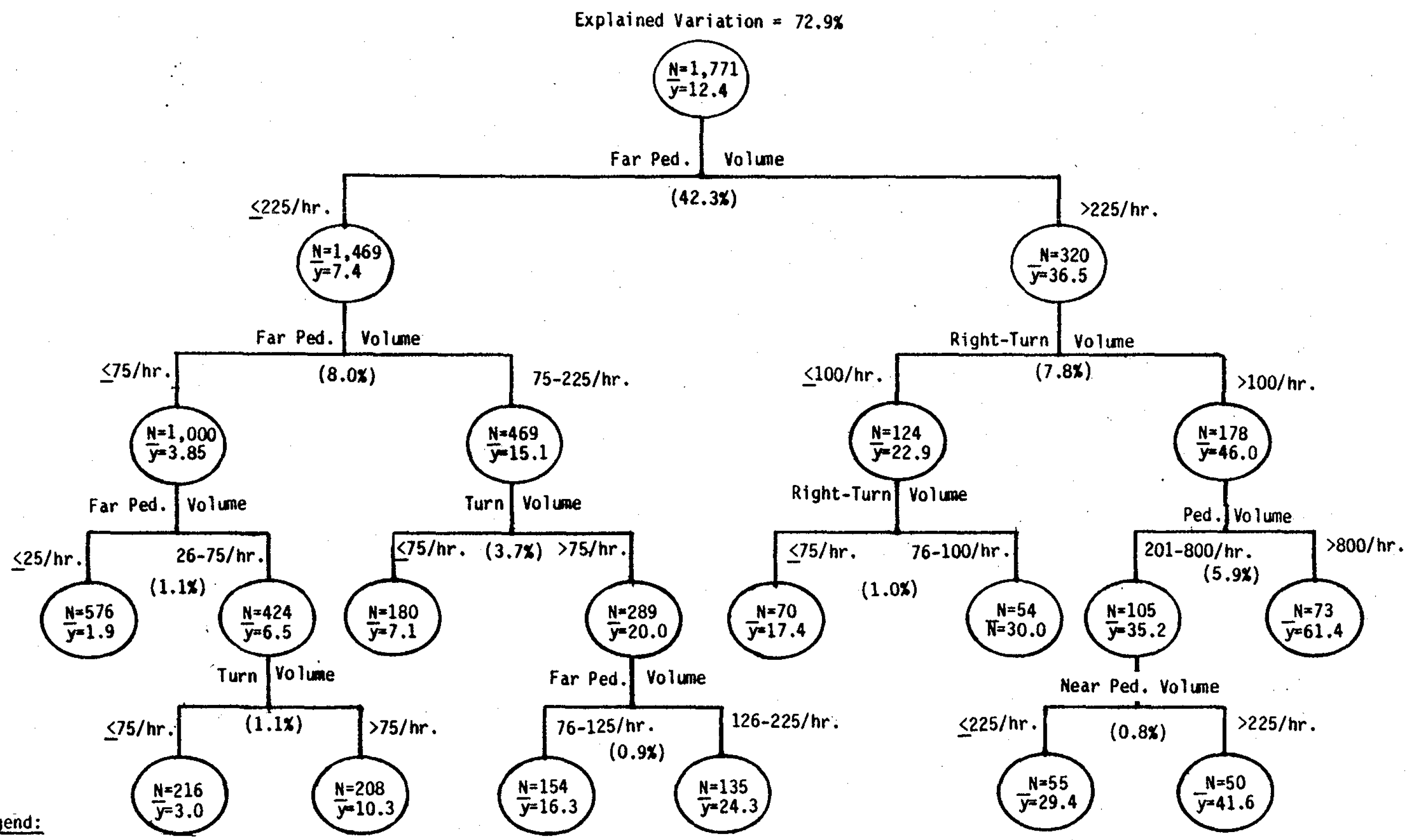


Figure 15. Branching diagrams for RTOR conflicts plus interactions per hour.



Legend:

N = Number of 30-Minute Intervals

$\overline{y}$ = Mean Number of Total (RTOG + RTOR) Conflicts per Hour

Independent Variables:

Right-Turn Volume per Hour
RTOR Volume per Hour
Pedestrian Volume (Near + Far Crosswalk) per Hour
Near Crosswalk Ped. Volume per Hour
Far Crosswalk Ped. Volume per Hour
RTOR Status (Allowed vs. Prohibited)
City

Figure 16. Branching diagrams for total (RTOG + RTOR) conflicts per hour.

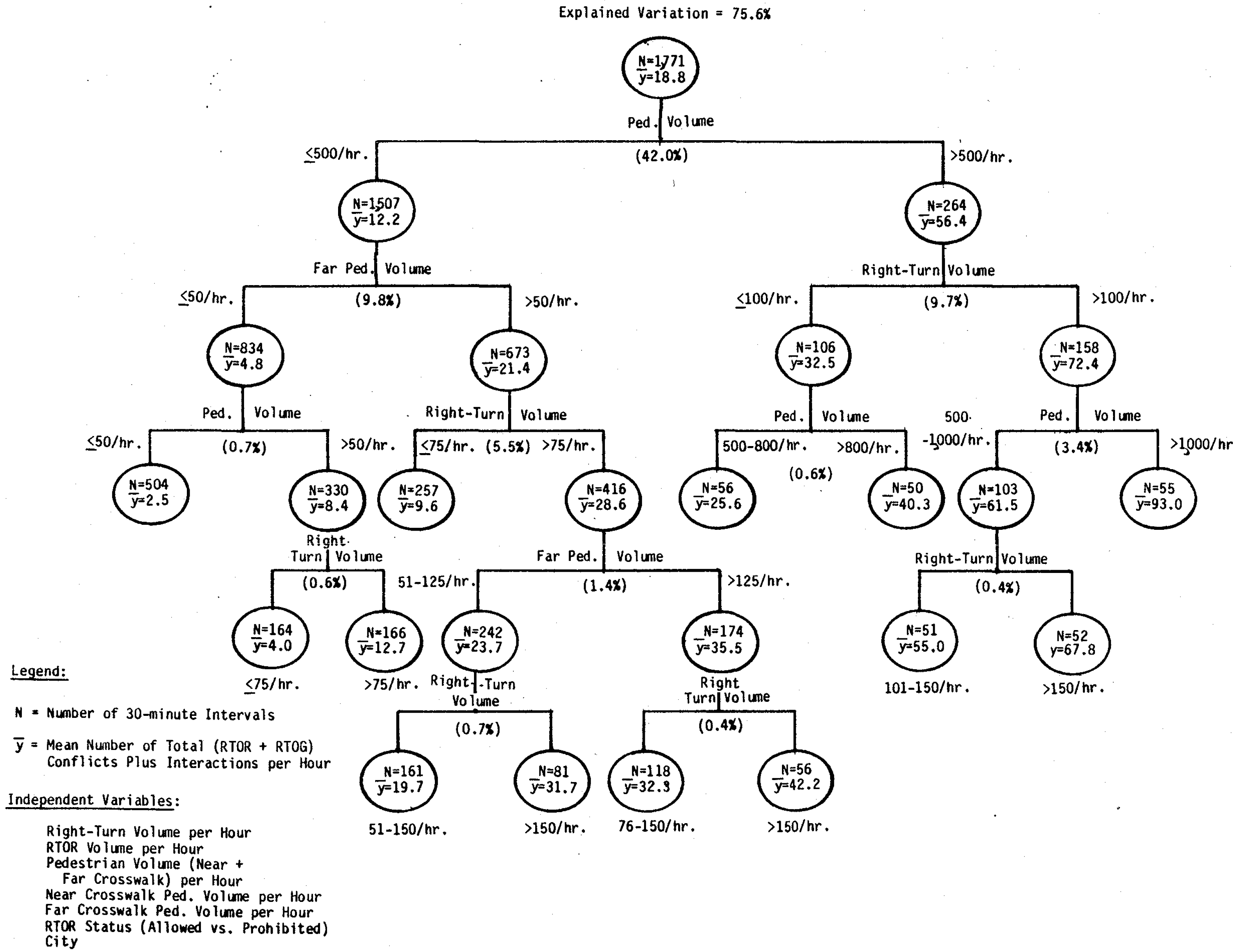


Figure 17. Branching diagram for total (RTOG + RTOR) conflicts plus interactions per hour.

Table 26. Summary of branching analysis runs.

Run	Dependent Variable Used	Sample and/or Forced Splits	Independent Variables Considered	Total Percent Explained Variance	Data Set	Sample Points	Conflict Means
1-A	RTOR Conflicts per Hour	All Sites Combined	RTOR Status, Ped. Volume City, Near Ped. Volume RTOR Volume, Far Ped. Volume Turn Volume	24.5	All Sites	1,771	0.6
1-B	RTOR Conflicts per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	City, RTOR Volume Turn Volume, Ped. Volume	23.8	RTOR-Allowed	938	0.9
					RTOR-Prohibited	833	0.3
1-C	RTOR Conflicts per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	Turn Volume, Near Ped. Volume RTOR Volume, Far Ped. Volume Ped. Volume, City	24.0	RTOR-Allowed	938	0.9
					RTOR-Prohibited	833	0.3
2-A	RTOR Conflicts and Interactions per Hour	All Sites Combined	RTOR Status, Ped. Volume City, Near Ped. Volume RTOR Volume, Far Ped. Volume Turn Volume	40.1	All Sites	1,771	1.1
2-B	RTOR Conflicts and Interactions per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	City, RTOR Volume Turn Volume, Ped. Volume	38.5	RTOR-Allowed	938	1.7
					RTOR-Prohibited	833	0.5
2-C	RTOR Conflicts and Interactions per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	Turn Volume, Near Ped. Volume RTOR Volume, Far Ped. Volume Ped. Volume, City	38.5	RTOR-Allowed	938	1.7
					RTOR-Prohibited	833	0.5
3-A	Total (RTOR + RTOG) Conflicts per Hour	All Sites Combined	RTOR Status, Ped. Volume City, Near Ped. Volume RTOR Volume, Far Ped. Volume Turn Volume	72.9	All Sites	1,771	12.4
3-B	Total (RTOR + RTOG) Conflicts per Hour	Forced Split RTOR-Allowed vs. RTOR-Prohibited	Turn Volume, Ped. Volume City	64.2	RTOR-Allowed	938	11.7
					RTOR-Prohibited	833	13.2
3-C	Total (RTOR + RTOG) Conflicts per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	Turn Volume, Near Ped. Volume RTOR Volume, Far Ped. Volume Ped. Volume, City	66.9	RTOR-Allowed	938	11.7
					RTOR-Prohibited	833	13.2

Table 26. Summary of branching analysis runs (continued).

Run	Dependent Variable Used	Sample and/or Forced Splits	Independent Variables Considered	Total Percent Explained Variance	Data Set	Sample Points	Conflict Means
4-A	Total (RTOR + RTOG) Conflicts and Interactions per Hour	All Sites Combined	RTOR Status, City, RTOR Volume, Turn Volume, Ped. Volume, Near Ped. Volume, Far Ped. Volume	75.6	All Sites	1,771	18.8
4-B	Total (RTOR + RTOG) Conflicts and Interactions per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	Turn Volume, City, Ped Volume	69.3	RTOR-Allowed	938	17.8
					RTOR-Prohibited	833	19.9
4-C	Total (RTOR + RTOG) Conflicts and Interactions per Hour	Forced Split: RTOR-Allowed vs. RTOR-Prohibited	Turn Volume, Ped. Volume, City, Near Ped. Volume, Far Ped. Volume	73.1	RTOR-Allowed	938	17.8
					RTOR-Prohibited	833	19.9

	Percent Explained Variance
- Total (RTOR + RTOG) pedestrian conflicts and interactions per hour	75.6
- Total (RTOR + RTOG) pedestrian conflicts per hour	72.9
- RTOR pedestrian conflicts plus interactions per hour	40.1
- RTOR pedestrian conflicts per hour	24.5

- The variables which are most important in explaining variation in RTOR Pedestrian Conflicts per Hour are, in order of importance:
  - RTOR volume at a break-point of 10 RTOR vehicles per hour.
  - Pedestrian volume at a break-point of 100 pedestrians per hour.

Other break-points of lesser importance are also shown in figure 14.

- The variables which explain the most variation in RTOR Pedestrian Conflicts plus Interactions per Hour are, in order of importance:
  - RTOR volume at a break-point of 15 RTOR vehicles per hour.
  - Pedestrian volume at a break-point of 100 pedestrians per hour.

Other break points of lesser importance are shown in figure 15.

- The variables which explain the most variation in Total Pedestrian Conflicts (RTOR + RTOG) per Hour are, in order of importance:
  - Pedestrian volume in the far crosswalk, with a break-point of 225 per hour.
  - Right-turn volume at a break-point of 100 per hour.

Other break-points of lesser importance are shown in figure 16.

- The variables which explain the most variation in Total Pedestrian Conflicts (RTOR + RTOG) and Interactions per Hour are, in order of importance:

  - Pedestrian volume at a break-point of 500 per hour.
  - Far side pedestrian volume with a break-point of 50 per hour.
  - Right-turn volume at a break-point of 100 per hour for situations with more than 500 pedestrians per hour.

- Break-point levels were found independently for RTOR-allowed and RTOR-prohibited sites. These are summarized in table 27. Note that variables and important break-points differ for each dependent variable that is used.

Analysis of Covariance

The previous analyses were primarily involved with determining the effects of the continuous traffic and roadway variables on pedestrian conflicts. For example, the Pearson correlation test is not appropriate for the categorical variables, such as sign location, area type, type of RTOR prohibition (full prohibition, partial prohibition, or RTOR allowed). The analysis of variance (or covariance) test allows for determining whether significant variation exists in pedestrian conflicts for different groups (or categories) of traffic or roadway variables.

The ANOVA was applied to each of 13 roadway variables, as listed in table 28. The ANOVA test is applied to test the hypothesis: "Are the means of two groups equal or are any significantly different from the others?" For each independent variable, four dependent variables were analyzed, including:

- RTOR conflicts.
- RTOR conflicts and interactions.
- Total (RTOR + RTOG) conflicts.
- Total (RTOR + RTOG) conflicts and interactions.

Table 27. Summary of important independent variables and break-points.

Dependent Variable	RTOR-Allowed Sites		RTOR-Prohibited Sites	
	Independent Variables	Break Point	Independent Variables	Break Point
1. RTOR Conflicts per Hour	RTOR Volume	10 per Hour	RTOR Volume	15 per Hour
	Pedestrian Volume	100 per Hour		
2. RTOR Conflicts + Interactions per Hour	RTOR Volume	25 per Hour	RTOR Volume	15 per Hour
	Pedestrian Volume	200 per Hour		
3. Total Conflicts (RTOR + RTOG) per Hour	Pedestrian Volume	500 per Hour	Right-Turn Volume	100 per Hour 150 per Hour
	Right-Turn Volume	75 per Hour 125 per Hour		
4. Total Conflicts (RTOR + RTOG) + Interactions per Hour	Pedestrian Volume	450 per Hour	Pedestrian Volume	500 per Hour
	Right-Turn Volume	75 per Hour 100 per Hour	Right-Turn Volume	150 per Hour

Table 28. Summary of ANOVA results of relationships of roadway variables and their pedestrian conflict measures.

Independent Variable	RTOR Ped. Conflicts	RTOR Ped. Conflicts + Interactions	Total Ped. Conflicts	Total Ped. Conflicts + Interactions
Number of Intersection Legs	-*	-	-	-
Intersection Operation	-	-	-	-
Area Type	.05	.01	-	-
Cycle Length	-	-	-	-
No. of Phases	-	-	.01	.01
RTOR Prohibition	-	.01	.05	.01
Right Lane Use	-	-	-	-
Near Cross-Walk Length	-	-	-	-
Far Cross-Walk Length	-	-	-	-
Intersection Angle	-	-	-	-
Speed Limit	-	.05	-	-
Sight Distance	.05	-	-	-

* The "-" indicates a significance level of .05 was not found.

For the RTOR-related pedestrian conflicts and interactions, covariates used in the analysis were pedestrian volume and RTOR volume. For the ANOVA tests of total (RTOR + RTOG) pedestrian conflicts and interactions, the covariates were right-turn volume and pedestrian volume. The covariates were selected based on the results of the Pearson correlation tests and the branching analyses.

Of the 13 independent variables which were tested, the ones found to have groups with significantly different mean pedestrian conflicts (at the 0.05 or 0.01 level) include:

- Area type.
- Number of signal phases.
- Type of RTOR prohibition.
- Speed limit.
- Sight distance.

Detailed ANOVA results are summarized in table 29 for each of these five independent variables. The adjusted group means are given for each variance along with the dependent variable and significance level. For example, sight distance was one of the six variables exhibiting significant differences in RTOR pedestrian conflicts for groups with <150 feet (<45 m) sight distances (mean of 0.72 per hour), compared to sites with >150 feet (>45 m) (mean of 0.41 per hour). Thus, sight distances below 150 feet (45 m) were associated with significantly higher conflicts than sites with sight distances above 150 feet (45 m) (0.04 level).

Based on information in table 29, the following may be inferred:

- CBD sites are associated with significantly higher RTOR pedestrian conflicts than non-CBD sites.
- RTOR-allowed sites have higher RTOR pedestrian conflicts than sites with partial or full prohibitions. Sites with full prohibitions have significantly lower total conflicts than sites with partial or no prohibition.
- Sites with speed limits below 25 mph (40 kph) (i.e., mostly CBD

Table 29. Summary of group means of significant variables from the ANOVA results.

Independent Variable	Groups	Adjusted Group Means	Dependent Variable	Significance Level
Area Type	CBD Other	.79 .42	RTOR Ped. Conflicts/hr.	.015
Area Type	CBD Other	1.43 0.72	RTOR Ped. Conflicts + Interations/hr.	.001
RTOR Prohibition	RTOR-Allowed Partial NTOR Full NTOR	1.38 0.61 0.88	RTOR Ped. Conflicts + Interactions/hr.	.007
RTOR Prohibitions	RTOR-Allowed Partial NTOR Full NTOR	12.62 13.82 8.91	Total Ped. Conflicts/hr.	.014
RTOR Prohibition	RTOR-Allowed Partial NTOR Full NTOR	19.11 20.90 12.78	Total Ped. Conflicts + Interactions/hr.	.004
Speed Limit	$\leq$25 mph $>$25 mph	1.24 0.81	RTOR Ped. Conflicts + Interactions/hr.	.050
Sight Distance	$\leq$150 ft. $>$150 ft.	0.72 0.41	RTOR Ped. Conflicts/hr.	.040
No. of Phases	2 3 or more	13.16 7.50	Total Ped. Conflicts/hr.	.001
No. of Phases	2 3 or more	19.84 10.71	Total Ped. Conflicts + Interactions/hr.	.001

Note: 1 ft = 0.3 m
1 mph = 1.6 kph

sites) are associated with significantly higher RTOR pedestrian conflicts and interactions than sites with speed limits above 25 mph (40 kph).

- Multi-phase signal approaches are associated with significantly lower total pedestrian conflicts and interactions than two-phase approaches.

REVIEW OF GUIDELINES

Each of the six MUTCD guidelines on prohibitions of RTOR were reviewed and based on the following criteria:

- Criterion 1 - Safety Implications: How will it affect RTOR accidents or other accident types? How will it affect pedestrian-vehicle conflicts and motorist conflict rates? How will it affect overall respect and compliance of RTOR prohibitions at other locations?
- Criterion 2 - Reasonableness: What percent of intersections would be subject to RTOR prohibitions? Is it realistic for small towns as well as big cities? Does it account for the variety of traffic speeds, street widths, vehicle and pedestrian volumes, and other real-world conditions?
- Criterion 3 - Practicality of Implementation: What data must be collected by the agency to apply the warrant? Are extensive pedestrian volume data needed before the warrant can be applied? Must the agency study every intersection accident to determine if it is RTOR-related? What would be the cost of implementing the warrant?
- Criterion 4 - Complexity: Can the warrant be easily understood and applied by traffic engineers, technicians, and others who may be responsible for applying it in a given city or county? Does it require simple computations?
- Criterion 5 - Acceptability: Will the warrant be accepted by the traffic engineering community? Is it flexible enough to account for a variety of intersection conditions and yet specific enough to provide useful guidance for prohibiting RTOR?

The effect on traffic operations was a secondary consideration, since a RTOR restriction would also result in some increase in delay and fuel consumption, depending on the number of RTOR vehicles and other factors. The use of a warrant for only selected portions of a day would minimize the adverse impact on traffic operations.

The following is a discussion of a review of each MUTCD warrant using the five criteria. Ratings of excellent, good, fair, and poor were assigned to each warrant based on the five criteria.

Warrant 1 - Sight distance to vehicles approaching from the left (or right, if applicable) is inadequate.

- Criterion 1 - Safety Implications: There is an obvious safety advantage to prohibiting RTOR manuevers at sites where RTOR vehicles cannot adequately see cross-street vehicles from left. Sight distances of less than 150 feet (45 m) are associated with significantly greater conflicts than sight distances above 150 feet (45 m), as found from the analysis of covariance tests.
- Criterion 2 - Reasonableness: It is quite reasonable to have a warrant based on sight distance restriction. However, no specific sight distance values are provided for the warrant in the MUTCD, so application of this warrant is left to the judgement of individual agency officials.
- Criterion 3 - Practicality of Implementation: No specific guidance is given on the specific sight distance values, so the warrant may be difficult to apply.
- Criterion 4 - Complexity: The concept of sight distance is easy to understand, but guidelines would be helpful on measurement, interpretation, and quantification of unsafe sight distances for RTOR prohibition.
- Criterion 5 - Acceptability: Many agencies cannot accept or use this warrant until it provides more specific guidance.

In summary, there is conceptually clear justification for prohibiting RTOR when sight distance of a RTOR vehicle is inadequate to observe cross-street traffic. The use of sight distance as a warrant should also consider the speeds of cross-street vehicles, parking on the approaches, and geometrics.

Numerous problems exist, however, regarding consistent measurement of sight distance. First of all, sight distance is highly dependent on driver eye height, which varies widely for different vehicle types. Secondly, sight distance for RTOR motorists depends heavily on the position of the vehicle on the approach (when the RTOR motorist looks to the left). If stopped behind the stop bar, the motorist may have limited sight distance. However, many motorists encroach upon the stop bar and crosswalk and have much greater sight distance. Also, if no stop bar or crosswalk exists on an approach, the sight distance measurement may not be measured consistently.

Most proposed RTOR warrants involving sight distance specify that the measurement assumes the vehicle is behind the stop bar, behind the crosswalks, or behind the curb line (if no pavement marking exists). While this would allow for consistent measurement of sight distance, it may be contrary to the actual behavior of RTOR motorists.

The third problem with sight distance measurements at intersections involves the fact that sight distance may fluctutate over the day, depending on the presence or absence of parked cars on the cross street. Some cities have time-based parking restrictions (i.e., NO PARKING 7:00 a.m. to 9:00 a.m. and 3:00 p.m. to 6:00 p.m.). Thus, sight distance might be more restricted during nonpeak hours (when parking is allowed). Even when full-time parking is allowed, a parked van (or vehicle with dark windows) could create a temporary but severe sight distance restriction. Sight distance problems may also be created by illegally parked or standing vehicles.

Because of problems with consistency in sight distance measurements, the use of a specified sight distance (for various vehicle speeds) warrant for RTOR is difficult to properly quantify. No specific sight distance values would be appropriate for all cities, intersections, or vehicle types. Reasonable sight distance guidelines as a function of cross-street vehicle speeds should at least be available for consideration by local traffic engineers, such as those proposed by McGee (see figure 12). Thus, Warrant 1 could be improved by the addition of these criteria.

Warrant 2 - The intersection area has geometrics or operational characteristics which may result in unexpected conflicts.

- Criterion 1 - Safety Implications: Conceptually, there is a need to minimize unexpected conflicts due to unsafe geometric or operational characteristics. However, the wording is so vague that it could apply to nearly any intersection or to very few intersections, depending on its interpretation.
- Criterion 2 - Reasonableness: This warrant is too vague.
- Criterion 3 - Practicality of Implementation: Is of virtually no value for implementation unless more information is provided.
- Criterion 4 - Complexity: Not complex, but requires a great deal of judgement by the user.
- Criterion 5 - Acceptability: Needs to be better defined before it can be accepted.

As stated, Warrant 2 is too vague to provide any real guidance in determining where to prohibit RTOR. However, there may be justification for prohibiting RTOR manuevers on approaches with certain types of geometric or operational problems, as evidenced by more specific warrants proposed by McGee [12] and others. Recommended guidelines to replace Warrant 2 would be to prohibit RTOR if:

1. The intersection has five or more approaches and substantial traffic exists on all approaches. Depending on the geometrics, traffic and pedestrian flows, RTOR may be prohibited on all approaches, only on critical legs, or only for critical movements (i.e., NO TURN ON RED TO FIRST AVENUE).
2. For approaches with double right turns, right-turn-on-red may be prohibited on both lanes or only for the left lane (i.e., NO TURN ON RED EXCEPT CURB LANE).

Warrant 3 - There is an exclusive pedestrian phase.

- Criterion 1 - Safety Implications: There are definite safety benefits for crossing pedestrians from this warrant.
- Criterion 2 - Reasonableness: An exclusive pedestrian phase implies that pedestrians have a fully protected crossing. RTOR prohibition should logically be used in conjunction with this phase in the interest of pedestrian safety.
- Criterion 3 - Practicality of Implementation: Highly practical and easy to interpret.
- Criterion 4 - Complexity: Simple and clear meaning.
- Criterion 5 - Acceptability: This should be accepted by most traffic engineers. Some traffic engineers rarely, if ever, prohibit RTOR, although exclusive pedestrian phasing is uncommon in most cities.

This warrant to prohibit RTOR if an exclusive pedestrian phase exists is highly desirable, as summarized above. An exclusive pedestrian phase is intended to provide a "protected" interval for pedestrians to cross. With scramble (Barnes Dance) timing, for example, pedestrians are allowed to cross diagonally as well as directly across any street during the pedestrian phase. The presence of RTOR vehicles would have an obvious detrimental effect on pedestrian safety, as well as defeating the basic purpose of an exclusive pedestrian phase.

The current RTOR warrant relative to an exclusive pedestrian phase is an optional warrant, based on the MUTCD wording for all RTOR-related warrants. Section 2B-37 states "A NO TURN ON RED sign may be considered........" [16]. Thus, a traffic engineer may or may not decide to prohibit RTOR at an intersection with an exclusive pedestrian phase. It is recommended that this warrant and several others (as discussed later) be made a requirement. Thus, a NO TURN ON RED sign should be installed at an intersection or approaches with an exclusive pedestrian phase. This recommendation also is in basic agreement with recommendations by McGee [12] in his 1978 study.

Warrant 4 - Significant pedestrian conflicts are resulting from RTOR maneuvers.

- Criterion 1 - Safety Implications: Pedestrian conflicts with RTOR vehicles may be indicative of potential accidents. Thus, elimination of RTOR at such sites will likely have a positive safety impact.
- Criterion 2 - Reasonableness: While it is reasonable to prohibit RTOR where significant RTOR pedestrian conflicts exist, the lack of information on how to collect or define conflicts and what number of conflicts are "significant" makes it difficult to interpret.
- Criterion 3 - Practicality of Implementation: The warrant is impractical to implement until more guidance or information is made available on pedestrian conflicts.
- Criterion 4 - Complexity: Definitions are needed with respect to types of conflicts and what is meant by "significant numbers" of them.
- Criterion 5 - Acceptability: More specific information is needed before this warrant will gain wide acceptance.

In summary, a warrant to prohibit RTOR is justified at sites where a measureable amount of RTOR-related conflicts are occurring. However, the problem with this warrant is that there is no specific information on what is the definition of a RTOR conflict, how should they be measured, or what should be considered as "significant numbers" of such conflicts.

As a part of this research study, detailed conflict data were collected at 199 intersection approaches in several U.S. cities, and data were analyzed and used to assist in formalizing warrants, as described earlier.

Specific levels of RTOR pedestrian conflicts were better quantified based on conflict data from the previous analysis. A summary was made of peak hour RTOR pedestrian conflicts for 11.0 RTOR-allowed sites and the 95 RTOR-prohibited sites, as shown in table 30. Notice that 20 (18 percent) of the RTOR-allowed sites have RTOR pedestrian conflicts of 5 or more in the peak hour, whereas only 3 (3.2 percent) of RTOR-prohibited sites have 5 or more RTOR pedestrian conflicts in the peak hour. Three of the RTOR-allowed sites have 10 or more RTOR pedestrian conflicts (peak hour), compared to none of the RTOR-prohibited sites with 9 or more conflicts.

Distributions of sites in table 30, can be used to determine the critical levels of RTOR pedestrian conflicts. For example, assume that the top 10 percent of conflict sites should be considered for possible RTOR prohibition. This corresponds to 90 percent cummulative percent of sites, or a critical value of six or more RTOR pedestrian conflicts in the peak hour. The 10 percent value is strict enough to only address those sites with a clear problem with RTOR pedestrian conflicts. Of course, other sites may also be considered for RTOR prohibition which meet one of the other warrants. Thus, a value of six or more RTOR pedestrian conflicts per peak hour is suggested as a conflict value for this warrant.

<u>Warrant 5</u> - <u>More than three RTOR accidents per year have been identified for the particular approach</u>.

- Criterion 1 - Safety Implications: Related accidents may represent an appropriate criterion for warranting installation of traffic control devices.
- Criterion 2 - Reasonableness: Past studies of RTOR accidents indicate that they are relatively rare events at a single intersection. Three RTOR accidents per year per approach is an unrealistically high level that is unlikely to ever be met for most cities (as discussed later).
- Criterion 3 - Practicality of Implementation: Highly impractical due to the strict level which must be met. Also, many agencies may not be able to identify which accidents are RTOR-related because of the lack of this information on their accident report form.
- Criterion 4 - Complexity: Easy to understand, but accidents

Table 30. Summary of RTOR-pedestrian conflicts for the peak hour at selected intersection approaches.

Number of RTOR-Pedestrian Conflicts in the Peak Hour	Number of Sites with Various Levels of RTOR Pedestrian Conflicts					
	RTOR-Allowed Sites			RTOR-Prohibited Sites		
	No. of Sites	Percent of Sites	Cummulative Percent	No. of Sites	Percent of Sites	Cummulative Percent
0	30	27.3	27.3	53	55.8	55.8
1	20	18.2	45.5	19	20.0	75.8
2	20	18.2	63.7	12	12.6	88.4
3	13	11.8	75.5	6	6.3	94.7
4	7	6.4	81.9	2	2.1	96.8
5	9	8.2	90.1	1	1.1	97.9
6	4	3.6	93.7	0	0	97.9
7	4	3.6	97.3	0	0	97.9
8	0	0.0	97.3	0	0	97.9
9	0	0.0	97.3	2	2.1	100.0
10	2	1.8	99.1	0	0	100.0
20	1	0.9	100.0	0	0	100.0
Totals	110	100.0	100.0	95	100.0	100.0

relating to RTOR are difficult or impossible to determine in many instances.

- Criterion 5 - Acceptability: Unlikely to be accepted due to: (1) high level of RTOR accidents and (2) difficulty in determining which accidents are RTOR-related.

To shed light on this warrant, information was obtained from a study by McGee [18] relative to RTOR-related accidents at signalized intersections in major U.S. cities where necessary information was available. Average number of total accidents, RTOR accidents, and RTOR-pedestrian accidents were computed for the sample sites in each city as summarized in table 31. Total accidents ranged from 6.4 (per site per year) in Los Angeles to 14.8 in San Francisco. Total RTOR accidents ranged from 0.04 and 0.053 for three cities (Los Angeles, Denver, and San Francisco) and 0.21 to 0.27 (per intersection per year) in Chicago and Omaha.

The overall average accidents for all 4,473 intersections considered equally was:

- RTOR accidents = 0.050/intersection/year.
- RTOR-pedestrian accidents = 0.007/intersection/year.

Thus, for the average intersection, a RTOR accident would be expected once every 20 years (1/0.050 = 20). A pedestrian-related RTOR accident would be expected at an average intersection once every 142 years on the average. This assumes, of course, that the RTOR accident data from the McGee study is of reasonable accuracy. It should be mentioned that even if the RTOR accident data from those five western cities are accurate, they are not necessarily representative of other cities.

Using the 78 Chicago sites for analysis (since they are the highest average RTOR accidents), the averages are:

- RTOR accidents = 0.269/intersection/year.
- RTOR pedestrian accidents = 0.077/intersection/year.

Table 31. Summary of RTOR accident data from McGee.[18]

City	No. Years of Accident Data	No. of Intersections	Intersection Accidents		RTOR-Related Accidents			Accidents/Intersection/Year		
			Total	Per Year	Pedestrian-Related	Cross-Traffic	All RTOR Accidents	Totals	Total RTOR	RTOR-Pedestrian
Los Angeles	2	3,235	41,316	20,658	54	233	287	6.4	0.044	0.008
Denver	1	1,059	7,431	7,431	0	50	50	7.0	0.047	0.000
Chicago	1	78	694	694	6	15	21	8.9	0.269	0.077
San Francisco	3	75	3,328	1,109	4	8	12	14.8	0.053	0.018
Omaha	2	26	497	248	0	11	11	9.5	0.212	0.000
Totals		4,473	53,266		64	317	381			

This would correspond to one RTOR accident every 3.7 years (at an average signalized intersection) and one RTOR-pedestrian accident every 13 years at an average signalized intersection. Assumming an average of four approaches per intersection, this would correspond to:

- RTOR accidents = 0.269/4 = 0.067 accidents/approach/year.
- RTOR pedestrian accidents = 0.077/4 = 0.019 accidents/approach/year.

Statistical quality control techniques can be used to determine the critically high number (or rate) of accidents based on the Poisson distribution. This may be computed for total accidents or for any specific accident type. The equation, as discussed in a 1975 study by Zegeer [19], for critically high accident frequency is as follows:

$$N_C = N_A + K\sqrt{N_A} + 1/2$$

Where:

N_C = The critical number of accidents under average traffic volume conditions,

K = A probability factor determined by the level of statistical significance desired for the equation.

N_A = The average number of RTOR accidents per year per intersection leg.

Values of K are as follows for various probability (P) levels:

P	K
0.1000	1.282
0.05	1.645
0.01	2.326
0.005	2.576
0.001	3.090

Thus, a K value of 3.09 would correspond to a probability level of 99.9 percent (p = 0.001).

Using this equation, one may determine with any desired level of confidence what the critical number of RTOR accidents may be for urban intersections, such as for those reported above. Since the Chicago values are the highest, they were assumed along with a 99.9 percent probability (K = 3.09) and applied into the equation. To add data stability (less chance of one or two random events), a 3-year period can be used along with an average value of N_A = 0.067 RTOR accidents per approach per year x 3-years = 0.20 RTOR accidents per intersection approach per 3-year period.

Therefore,

N_C (for RTOR accidents) = $0.20 + 3.09\sqrt{N_A} + 1/2$

$N_C = .20 + 3.09\sqrt{0.20} + 0.5$

N_C = 2.08 accidents/approach/3-year period.

Thus, if an average intersection approach has two RTOR accidents per 3-year period, it may be considered to have a critically high number of RTOR accidents (with 99.9 percent confidence).

Similarly, a critically high number of RTOR pedestrian accidents can also be determined. For a single intersection approach, the critical number of RTOR pedestrian accidents for a 3-year period can be determined as follows:

N_A = 0.019 x 3 years = 0.057

N_C (for RTOR pedestrian accidents) = $0.057 + 3.09\sqrt{0.057} + 0.5$

N_C = 1.3 pedestrian RTOR accidents/ approach /3-year period

However, a warrant should not be based on only one accident due to the chance of one random event occurring. Therefore, the accident based warrant should be based upon total RTOR accidents, as follows:

"A NO TURN ON RED sign should be installed"

- If the number of total RTOR accidents is two or more for an approach in a 3-year period.

Warrant 6 - There is significant crossing activity by children, elderly or handicapped.

- Criterion 1 - Safety Implications: Conceptually, high volumes of such pedestrians (or any pedestrians) would justify prohibiting RTOR.
- Criterion 2 - Reasonableness: While it is reasonable to prohibit RTOR due to high pedestrian volumes, the lack of specific values make this warrant subject to interpretation by the traffic engineer.
- Criterion 3 - Practicability of Implementation: Provides no real guidance for implementation due to its generality.
- Criterion 4 - Complexity: Not complex, but open totally to engineering judgement.
- Criterion 5 - Acceptability: Accepted in concept by many agencies, but they must essentially develop their own specific volume criteria.

In summary, Warrant 6 is conceptually useful to provide for consideration of RTOR prohibition for children, elderly, or handicapped people. The ITE Technical Committee 4A-17 [14] made the following recommendation concerning this warrant:

> Universal prohibition at "school crossings" should not be made but rather restrictions should be sensitive to special problems of pedestrian and/or bicycle traffic, such as the unpredictable behavior of children or the problems of the elderly and handicapped, or failure of motorists to yield to pedestrians and/or bicyclists within a crosswalk. Pedestrian volumes, as such, should not be the only criterion for prohibiting turns on red.

Thus, according to this recommendation, RTOR prohibitions at school zones should be used only when the need exists, such as when a particular problem is found. Also, mere volumes of pedestrians should not necessarily be the only basis for prohibiting RTOR. The branching analysis identified the combination of 10 or more RTOR maneuvers/hour and 100 or more pedestrians per hour as a combination associated with a high RTOR pedestrian conflicts (2.0 per hour), as shown in figure 14. However, the combination of 26 or more RTOR vehicles with 250 or more pedestrians is associated with the highest pedestrian conflict level (4.0 per hour on the average).

It should also be remembered that installing RTOR prohibitions were found in some situations to merely shift the pedestrian conflicts to the green phase. Thus, it is reasonable to provide some guidance (i.e., 26 or more RTOR vehicles/hour with 250 or more pedestrians per hour) to allow the local traffic or safety engineer to review each site individually and then decide whether to prohibit RTOR. A provision for prohibiting RTOR based on elderly or handicapped activity is also justified.

Based on the previous discussion, the following guidelines should be used to replace Warrant 6:

"A NO TURN ON RED sign <u>may</u> be installed":

1. In school zones where field studies indicate that motorists fail to yield to pedestrians before making a RTOR,
2. In areas with an unusually high number of elderly or handicapped people, or
3. At approaches with 250 or more pedestrian per hour (total of near and far crosswalks) combined with 26 or more RTOR maneuvers per hour.

Review of Other Warrants

In addition to the MUTCD warrants, other guidelines have been used or proposed for prohibiting RTOR. Also, the data analysis identified several traffic and roadway variables as important in terms of pedestrian conflicts and interactions. For example, the traffic and roadway variables which were found to have a significant impact on RTOR pedestrian conflicts and/or total pedestrian conflicts include:

- RTOR volume.
- Pedestrian volume.
- Right-turn volume.
- Type of RTOR prohibition.
- Sight distance.
- Speed limit.
- Signal phasing.
- Area type.

Most of these variables have been accounted for in some manner in the recommended warrants mentioned previously.

A review of other warrants or guidelines used (or recommended) by others, resulted in the following observations:

- High speed cross-street approaches were recognized as a problem relative to RTOR, particularly where sight distance is limited. The recommended sight distance warrant incorporates consideration of vehicle speeds on the cross street.
- Another warrant which appears justified for safety considerations near railroad crossing locations was recommended by McGee [12], as follows:

  "The intersection is within 200 feet (60 m) of a railroad crossing, and the signal controller is pre-empted during train crossings. (The prohibition should apply only to the approach from which right turns are made into the lane crossing the railroad.)"

A summary of all recommended guidelines and warrants for RTOR prohibition is given in the next section.

FINDINGS AND CONCLUSIONS

The purpose of this analysis was to develop improved warrants or guidelines for the prohibition of right-turn-on-red. This was accomplished by: (1) reviewing existing warrants from the MUTCD; (2) reviewing warrants proposed in the literature; and (3) conducting conflict analyses at 199 intersection approaches to determine what site characteristics are associated with a higher levels of pedestrian conflicts (potential for accidents).

The following is a summary of key findings.

1. Review of the RTOR volume data and conflict data indicated that there was an average of 17.1 RTOR maneuvers per hour at the RTOR-allowed sites, compared to 5.1 RTOR maneuvers per hour at the RTOR-prohibited sites. At RTOR-allowed sites, 3.8 percent resulted in conflicts with cross-street vehicles and 5.0 percent resulted in conflicts with pedestrians.

2. Total (RTOR + RTOG) pedestrian conflicts plus interactions were slightly higher at the RTOR-prohibited sites (19.35 per hour) than the RTOR-allowed sites (17.10 per hour). Thus, it appears that RTOR prohibition causes shifts of many of the conflicts to the green phase.

3. RTOG conflicts plus interactions were 26.7 times higher on the far crosswalk than the near crosswalk at the RTOR-allowed sites and 24.4 times higher at the RTOR-prohibited sites. RTOR conflicts plus interactions were 1.4 times higher on the far crosswalk than the near crosswalk at the RTOR-allowed sites and 1.6 times higher at the RTOR-prohibited sites.

4. Pearson correlation analyses were conducted to determine the traffic volumes and other continuous site variables most highly correlated to RTOR pedestrian conflicts and total pedestrian conflicts. The independent variables most highly correlated to total (RTOR + RTOG) pedestrian conflicts were pedestrian volume and right-turn volume. RTOR pedestrian conflicts were most highly correlated with RTOR traffic volume to a lesser degree with

pedestrian volume. Similar results were found from the branching analysis, and important brake-point levels were identified.

5. The analysis of covariance was used to determine the effects of categorical site characteristics on total pedestrian conflicts and RTOR pedestrian conflicts. Pedestrian volume, right-turn volume and RTOR volume were used as covariates, because of their strong relationship to conflicts. The following roadway characteristics were found to have a significant effect on pedestrian conflicts:

   - Area type.
   - The number of signal phases.
   - RTOR prohibition.
   - Speed limit.
   - Sight distance.

6. The recommended guidelines to replace the existing MUTCD warrants for RTOR prohibition are as follows:

   Right-Turn-on-Red <u>should</u> be prohibited where:

   - There is an exclusive pedestrian phase during which pedestrians can use all crosswalks.
   - The number of total RTOR accidents is two or more for an approach in a 3-year period.
   - The intersection is within 200 feet (60 m) of a railroad crossing, and the signal controller is pre-empted during train crossings (the prohibition should apply only to the approach from which right turns are made into the lane crossing the railroad).

   Right-Turn-on-Red <u>may</u> be prohibited where:

   - Sight distance of vehicles approaching from the left is less than the following minimums:

Cross-Street Speed Limit (mph)	Minimum Sight Distance (feet)
20	120
25	150
30	190
35	220
40	270
45	320
50	360
55	410

Note:
1 ft. = 0.3 m
1 mph = 1.6 kph

- The intersection has five or more approaches and substantial traffic exists on all approaches. Depending on the geometrics, traffic and pedestrian flows, RTOR may be prohibited on all approaches, only on critical legs, or only for critical movements (i.e., NO TURN ON RED TO FIRST AVENUE).
- For approaches with double right turns, RTOR may be prohibited on both lanes or only for the left lane (i.e., NO TURN ON RED EXCEPT CURB LANE).
- A total of six or more RTOR conflicts with pedestrians occur during the peak hour for an approach.
- For intersection approaches in school zones where field studies indicate that motorists often fail to yield to pedestrians before making a RTOR.
- At approaches with 250 or more pedestrians in the peak hour (total of near and far crosswalks) combined with 26 or more RTOR maneuvers per hour.
- In areas with an unusually high number of elderly or handicapped people.

CHAPTER IV – SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The practice of legally permitting motorists the option of making a right-turn-on-red (RTOR) at signalized intersections after stopping and yielding the right-of-way to pedestrians and other traffic is now a widely accepted traffic regulation in the United States. Based on numerous past studies of the safety and operational effects of RTOR, there is evidence that RTOR may create a potential safety problem for pedestrians. Thus, the purpose of this study was to: (1) Determine the current level of motorist compliance relative to RTOR (Chapter I); (2) Develop and field test countermeasures related to RTOR accidents (Chapter II); and (3) Review the current MUTCD warrants for RTOR prohibition and develop improved warrants, if necessary (Chapter III).

The major conclusions and recommendations are summarized below:

1. Overall, only 3.7 percent of all right-turning drivers violate the RTOR prohibition signs, based on a sample of over 67,000 drivers. However, of those motorists given an opportunity to commit a RTOR violation, about 20 percent of them violate the NO TURN ON RED sign. Intersection approaches with a high violation rate should be carefully reviewed in terms of where the prohibition is warranted. If the prohibition is not warranted, it should be removed. If warranted, consideration should be made to utilize one or more of the RTOR-related countermeasures (i.e., double signing of NO TURN ON RED, larger sign, etc.).

2. Of the drivers who commit a RTOR violation, about 23.4 percent of them result in conflicts to pedestrians or cross-street traffic. However, less than 1 in 100 of the total right-turn vehicles is involved in a RTOR-related conflict.

3. The overall violation rate (percent not fully stopping) at the 28 stop-sign approaches was 68.2 percent, compared to 56.9 percent for signalized approaches with RTOR allowed, a difference of 11.3 percent. However, 36 percent of vehicles were found to stop

at RTOR-allowed approaches, compared to 24.7 percent at stop sign locations. Thus, there is an 11 percent higher violation rate at stop sign locations. This may be at least partly explained by the greater percent of opportunities for a rolling stop or no-stop. The high rate (56.9 percent) of vehicles not making a full stop before turning right on red is cause for concern, and indicates that most motorists are not aware of the stopping requirement or else choose to ignore it. The use of police enforcement and/or other countermeasures (i.e., offset stop bars) is recommended to minimize the problem.

4. Examples of physical site factors found from in-depth site studies to be related to high RTOR violation rates include:

   - Confusing or inappropriate partial prohibition signs.
   - Far side or inconspicuous NTOR signs.
   - Long cycle lengths.
   - Confusing multi-leg intersection approaches.
   - Unwarranted RTOR prohibition.
   - Split-phasing of the signal which creates low opposing traffic for RTOR maneuvers.
   - Combinations of a low volume or high speed of cross-street traffic, and low pedestrian volumes.

5. The red ball NO TURN ON RED (NTOR) sign was found overall to be more effective than the standard black and white NTOR sign in terms of RTOR violations and pedestrian conflicts. However, the overall reduction was due solely to the Washington, D.C. sites, possibly due to the sign placement on signal poles in that city. The red ball sign was less effective at the Detroit sites, where signs were post mounted on the near or far corner of the intersection. The red ball sign appears to be more conspicuous to motorists than the current sign because of its distinctive color and shape. This should, however, be verified by laboratory testing. It is recommended that the red ball NTOR sign be added to the MUTCD as an alternative to the existing sign. Subject to

laboratory testing and/or additional field testing, the black and white NTOR sign should be eliminated from the MUTCD in the future and replaced with the red ball NTOR sign.

6. The larger 30x36-in (75x90-cm) NO TURN ON RED sign reduced the proportion of violations at most of the test sites in one city and reduced total conflicts in some situations. It is recommended that the larger sign be considered by agencies at sites where the sign is currently hard to read, such as for farside post mounting when overhead mounting is not possible.

7. The NO TURN ON RED sign with the supplementary WHEN PEDESTRIANS ARE PRESENT message was effective at sites where right turn vehicle volume was low or moderate but was less effective when RTOR volumes were high. It was effective in increasing RTOR maneuvers (as desired) during periods when pedestrian volume was light. It is recommended that the supplemental message WHEN PEDESTRIAN ARE PRESENT be added to the MUTCD as an accepted message which may be used with a NTOR sign when right-turn volume is light to moderate, and also pedestrian volumes are light or occur primarily during intermittant periods (i.e., in school zones). However, due to the small letter size of the supplementary WHEN PEDESTRIANS ARE PRESENT message, care should be taken to place the sign close enough to the driver so it can be easily read. A farside sign placement or overhead placement above a wide intersection may be difficult for a motorist to read.

8. The red ball NTOR sign in conjunction with the WHEN PEDESTRIANS ARE PRESENT message reduced total pedestrian conflicts in one instance, and increased RTOR usage overall, as desired (from 5.7 percent to 17.4 percent) compared to full-RTOR prohibitions. It should be added to the MUTCD as an optional sign as described in items 6 and 7 above.

9. The offset stop bar was tested to provide better sight distance to the left for RTOR motorists. It was effective overall in

reducing RTOR conflicts with cross-street traffic and also resulted in more RTOR vehicles making a full stop behind the stop bar. The offset stop bar is a recommended countermeasure at RTOR-allowed sites which have two or more lanes in each direction, particularly where conflicts or accidents are resulting between RTOR vehicles and cross-street traffic.

10. The LOOK FOR TURNING VEHICLES pavement marking was effective in reducing RTOR pedestrian conflicts and total pedestrian conflicts at several sites and ineffective at others, depending on the city and specific site characteristics. Such markings should be considered as possible treatments only at sites with particular problems with pedestrian accidents or conflicts from right- turning vehicles. Since the markings may wear away quickly, thermoplastic or durable paint should be used.

11. The electronic NO TURN ON RED/blank-out sign was found to be slightly better than the standard NO TURN ON RED sign in terms of violations. The device was also effective in increasing RTOR maneuvers when RTOR was appropriate (i.e., blank-out mode) and thus reduced unnecessary vehicle delay. Although this electronic device is more expensive than signs and markings (i.e., approximately $1,500 per sign, plus installation and operating cost), it may be justified in situations: (1) Where pedestrian protection is critical during certain periods (i.e., school zones); or (2) During a portion of the signal cycle where a separate opposing left-turn phase may conflict with an unsuspecting RTOR motorist.

12. The recommended guidelines to replace the existing MUTCD warrants for RTOR prohibition are as follows:

    Right-Turn-on-Red <u>should</u> be prohibited where:

    (1) There is an exclusive pedestrian phase during which pedestrians can use all crosswalks.
    (2) The number of total RTOR accidents is (a) two or more for an approach in a 3-year period.

(3) The intersection is within 200 feet (60 m) of a railroad crossing, and the signal controller is pre-empted during train crossings (the prohibition should apply only to the approach from which right turns are made into the lane crossing the railroad).

Right-Turn-On-Red may be prohibited where:

(1) Sight distance of vehicles approaching from the left is less than the following minimums:

Cross Street Speed Limit (mph)	Minimum Sight Distance (feet)
20	120
25	150
30	190
35	220
40	270
45	320
50	360
55	410

Note:
1 ft. = 0.3 m
1 mph = 1.6 kph

(2) The intersection has five or more approaches, and substantial traffic exists on all approaches. Depending on the geometrics, traffic and pedestrian flows, RTOR may be prohibited on all approaches, only on critical legs, or only for critical movements (i.e., NO TURN ON RED TO FIRST AVENUE).

(3) For approaches with double right turns, RTOR may be prohibited on both lanes or only for the left lane (i.e., NO TURN ON RED EXCEPT CURB LANE).

(4) A total of six or more RTOR conflicts with pedestrians occur during the peak hour for an approach.

(5) For intersection approaches in school zones where field studies indicate that motorists often fail to yield to pedestrians before making a RTOR.

(6) At approaches with 250 or more pedestrians in the peak hour (total of near and far crosswalks) combined with 26 or more RTOR maneuvers per hour.

(7) In areas with an unusually high number of elderly or handicapped people.

13. Recommended areas for future research relative to RTOR are:

- Testing of additional RTOR-related countermeasures based on field experience to determine their effect on conflicts and accidents for various traffic and roadway conditions. For example, laboratory testing or additional field testing of the red ball NTOR sign versus the standard black and white NTOR sign may help to confirm whether the red ball sign is more conspicuous to motorists. This should aid in the decision of whether to approve the red ball NTOR sign to replace the standard NTOR sign in the MUTCD.
- Efforts should be made to further develop and test measures to increase the percentage of RTOR motorists which comply with the stopping requirement (i.e., making a full stop before turning right on red). This may include physical treatments (i.e., RIGHT TURN ON RED AFTER STOP signs or offset stop bars) as well as education and enforcement programs.
- There is growing concern that motorist and pedestrian respect for traffic signals (and traffic laws in general) may be eroding. A coordinated effort should be made to monitor motorist compliance to RTOR regulations as well as other traffic control devices (stop signs, traffic signal violations) for selected cities and sites.

APPENDIX–ASSESSMENT OF CURRENT PRACTICES AND IMPACTS

INTRODUCTION

The practice of legally permitting motorists the option of right-turn-on-red (RTOR) at signalized intersections after stopping and yielding the right-of-way to pedestrians and other traffic is now a widely accepted traffic regulation in the United States. RTOR maneuvers are generally permitted nationwide* at all signalized intersection approaches unless the turn is specifically prohibited by a sign. The only exception to the general rule is New York City where RTOR maneuvers are prohibited unless specifically permitted by a sign. In addition to RTOR, many States now permit left-turn-on-red (LTOR) from a one-way street onto a one-way street, unless the maneuver is specifically prohibited by a sign.

In spite of the widespread adoption of RTOR, the issue remains controversial. Proponents of RTOR cite over 40 years of successful experience with the maneuver in California and other western States and suggest that RTOR results in savings of time and motor fuel by reducing vehicle delay. They also feel that RTOR reduces congestion and is not hazardous, since RTOR-related crashes represent a small percentage of accidents at signalized intersections. Opponents of the measure suggest that RTOR is hazardous to pedestrians and bicyclists, especially children, elderly, and handicapped persons. They also feel that motorists disregard the law by failing to stop and yield to traffic and that the time savings are not significant compared to the hazards associated with RTOR.

Perhaps the most controversial and important aspect of RTOR is safety. Although a number of investigations have been conducted, several safety issues associated with RTOR have not been conclusively proven. Also, substantially different conclusions have been developed by different researchers using the same data. While no studies have been completely successful in isolating and quantifying the safety impacts of RTOR,

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* In the Virgin Islands, where the left-hand driving rule is used, left-turns-on-red are generally permitted which is analogous to RTOR.

considered together, these studies provide a preponderance of evidence which suggests that RTOR is associated with an increase in the potential for pedestrian accidents. Due to the widespread use of RTOR in urban areas, there is a need to identify and evaluate countermeasures for RTOR-related pedestrian accidents. Also, should the evaluation indicate a need to modify existing practices, guidelines should be prepared and validated to identify conditions for permitting or restricting RTOR at intersections.

This state-of-the-art review of RTOR practices critically examines past and current experiences with RTOR including pedestrian safety and operational impacts, warrants, liability issues, motorist compliance, countermeasures, and costs. The assessment was based on a review of the research and operational studies summarized in table 32.

The purpose of this section is to summarize the assessment of current practices relating to RTOR and to provide information that can be used in conjunction with additional research to improve pedestrian safety and operations at signalized intersections.

HISTORY OF RTOR AT SIGNALIZED INTERSECTIONS

The concept of allowing motorists to turn-right-on-red predates the invention of the automated traffic signal. In this section, a brief history of State and local use of RTOR is examined followed by a review of the laws and guidelines that have been used for permitting and prohibiting RTOR.

State and Local RTOR Practices

An examination of historical documents by Hochstein [20] indicates that RTOR maneuvers were legally permitted in New York City when manually operated semaphores were used to direct traffic. During the time traffic lights were installed in New York City (between 1918 and 1925) by Dr. John A. Harries, Deputy Police Commissioner, the traffic regulations permitted a right- and left-turn-on-red.[21] Under the regulation, motorists were

Table 32. Summary of RTOR-related accident and operational studies.

Author & Title	Date	History of RTOR		Current Use	Warrants	Liability Issues	Safety Impacts	
		Practices	Laws				Intersection Accidents	Pedestrian Accidents
1. Atkins, S.T., "Left-Turn-On-Red: Should Be Given the Green Light"	1978						●	●
2. Barnhart, R.A., Re: IIHS RTOR report	1981							
3. Baumgartner, W.E., "... After STOP Compliance with RTOR After Stop"	1981	●		●				
4. Benke, R.J., and Ries, G.L., "RTOR Permissive Signing vs. Basic Law"	1973	●	●					
5. Biotechnology, Inc., "Model Pedestrian Safety Program - User's Manual"	1978							
6. Chamberlain, Gary, M., "Traffic Engineers Fight RTOR Proposal"	1972						●	
7. Chang, Man-Feng, et al., "Observations of Fuel Savings Due to Right-Turn-On-Red"	1977	●						
8. Clark, J.E., et al., "The Public Good Relative to RTOR in S. Carolina and Alabama"	1982	●					●	●
9. Cross, S., "Right-Turn-On-Red Signal"	1968	●			●		●	●
10. FHWA, Manual on Uniform Traffic Control Devices	1978				●			
11. Galin, D., "LTOR Signal - A Matter of Controversy"	1979						●	●
12. Galin, D., "Re-evaluation of Accident Experience with RTOR"	1981						●	●
13. Glauz, William D., "Application of Traffic Control Analysis at Intersections"	1980							
14. Habib, Philip, "Pedestrian Safety: The Hazards of Left-Turning Vehicles"	1980							

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author & Title	Date	History of RTOR		Current Use	Warrants	Liability Issues	Safety Impacts	
		Practices	Laws				Intersection Accidents	Pedestrian Accidents
15. Hochstein, Sam, "Now is the Time For All Good Traffic Engineers..."	1981						●	●
16. Hooper, K.G., "ITE Technical Council Reacts to the Latest RTOR Controversy"	1981						●	●
17. Howard, H., "Analysis of Right-Turn Accidents at Signalized Intersections"	-						●	●
18. IIHS - "RTOR Laws Raise Intersection Toll"	1980						●	●
19. ITE RTOR Task Force - "Final Report"	1981							
20. ITE Committee 4A-17, "Guidelines for Prohibition of Turns on Red"	1982	●			●			
21. ITE Committee 3M(65), "Right-Turn-On-Red"	1968	●					●	●
22. Josey, J.L., "Right-Turn-On-Red"	1972	●		●			●	●
23. Kearny, E.F., "State Laws Allowing Drivers to Turn on Red Lights"	1977		●					
24. Mamlouk, M.S., "Right-Turn-On-Red: Utilization and Impact"	1976	●	●	●	●		●	●
25. Mass. Dept. of Public Works - "RTOR Safety Study for Massachusetts"	1978	●	●	●	●	●	●	●
26. May, Ronald L., "RTOR: Warrants and Benefits"	1974	●			●		●	●
27. McGee, H.W., "Accident Experience With RTOR"	1977						●	●
28. McGee, H.W., "Guidelines for Proh. RTOR at Signalized Intersections"	1978				●			
29. McGee, H.W., et al., "Right-Turn-On-Red" Volumes I and II	1976	●	●	●	●	●	●	●

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author & Title	Date	History of RTOR		Current Use	Warrants	Liability Issues	Safety Impacts	
		Practices	Laws				Intersection Accidents	Pedestrian Accidents
30. McGee, H.W., "RTOR: Current Practices and State-of-the-Art"	1974	●	●	●	●		●	●
31. Minnesota Dept. of Highways - "Right-Turn-On-Red Accident Study"	1971						●	●
32. Nemeth, Zolton, A., "Development of Guidelines for RTOR Prohibition"	1977	●			●			
33. Norman, M.R., "Institute Holds RTOR Forum"	1981							
34. Nowak, D.A., "RTOR: Safety vs. Operation Benefits-City of Milwaukee Experience"	1981	●		●			●	●
35. Oklahoma City Dept. of Traffic Control "Some Right-Turn-On-Red Facts"	1971				●		●	
36. Orne, et al., (AASHTO Committee) - "Safety and Delay Impacts of RTOR"	1979	●		●			●	●
37. Pagan - "Pagan's Perspective: Right-Turn-On-Red, a multisided issue"	1978							
38. Parker, et al., "Right-Turn-On-Red (Virginia report)"	1975	●	●	●	●	●	●	●
39. Parker, "The Impact of General Permissive R- and LTOR Legislation in Virginia"	1978	●	●	●	●		●	●
40. Preusser et al., "The Effect of RTOR on Pedestrian and Bicyclist Accidents"	1981	●	●					●
41. Ray, James C., "Effect of Right-Turn-On-Red on Traffic Performance and Accidents"	1956						●	●
42. Ray, James C., "Experience with Right-Turn-On-Red"	1957						●	●
43. Robertson, H.D., et al., "Urban Intersection Improvements for Pedestrian Safety	1977							

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author & Title	Date	History of RTOR		Current Use	Warrants	Liability Issues	Safety Impacts	
		Practices	Laws				Intersection Accidents	Pedestrian Accidents
44. Scott, P.M. III, "Economic Benefits of Reduced Delay Due To Selected Control Procedures"	1967						●	●
45. Senate Subcommittee - "Right-Turn-On-Red Signal"	1975							
46. VanGelder, William G., "Stop on Red Then Right Turn Permitted"	1959							
47. Wagner, F.A., "Energy Impacts of Urban Transportation Improvements"	1980			●				
48. Zador, P. et al., (IIHS), "Adoption of RTOR; Effects on Crashes at Signalized Intersections"	1980	●					●	●

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author	Motorist Compliance		Operational Impacts				Countermeasures		Counter-measure Costs	Economic Impacts	General
	RTOR Permitted	RTOR Prohibited	Vehicle Delay	Pedestrian Delay	Vehicle/Ped Conflicts	Other	Pedestrian	Other Treatments			
1. Atkins	●		●			●					●
2. Barnhart											●
3. Baumgartner	●							●			●
4. Benke	●	●	●								●
5. Biotechnology							●				
6. Chamberlain											
7. Chang			●			●					●
8. Clark			●			●				●	●
9. Cross	●		●		●						●
10. FHWA, MUTCD											
11. Galin			●		●	●					●
12. Galin											●
13. Glauz					●						
14. Habib					●		●				

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author	Motorist Compliance		Operational Impacts				Countermeasures		Counter-measure Costs	Economic Impacts	General
	RTOR Permitted	RTOR Prohibited	Vehicle Delay	Pedestrian Delay	Vehicle/Ped Conflicts	Other	Pedestrian	Other Treatments			
15. Hochstein											●
16. Hooper	●										●
17. Howard											
18. IIHS											●
19. ITE RTOR Task Force											●
20. ITE Committee 4A-17							●	●			●
21. ITE Committee 3M(65)			●								
22. Josey	●				●						●
23. Kearny											●
24. Mamlouk	●	●		●	●			●			●
25. Mass. DPW	●	●	●		●	●	●	●			●
26. May			●	●	●						●
27. McGee											
28. McGee											
29. McGee			●	●	●	●	●	●		●	●

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author	Motorist Compliance		Operational Impacts				Countermeasures		Counter-measure Costs	Economic Impacts	General
	RTOR Permitted	RTOR Prohibited	Vehicle Delay	Pedestrian Delay	Vehicle/Ped Conflicts	Other	Pedestrian	Other Treatments			
30. McGee		●	●	●							●
31. Minn. Dept. of Hwys.			●								
32. Nemeth											●
33. Norman											●
34. Nowak			●			●	●	●		●	●
35. Oklahoma City Dept. of Traffic Control											
36. Orne			●			●					●
37. Pagan											●
38. Parker	●	●	●		●	●	●	●	●	●	●
39. Parker	●	●	●		●	●	●	●		●	●
40. Preusser							●				●
41. Ray			●	●							●
42. Ray											
43. Robertson							●				

Table 32. Summary of RTOR-related accident and operational studies (continued).

Author	Motorist Compliance		Operational Impacts				Countermeasures		Counter-measure Costs	Economic Impacts	General
	RTOR Permitted	RTOR Prohibited	Vehicle Delay	Pedestrian Delay	Vehicle/Ped Conflicts	Other	Pedestrian	Other Treatments			
44. Scott											
45. Senate Subcommittee											●
46. VanGelder			●								
47. Wagner			●			●		●		●	●
48. Zador											●

required to come to a full stop and yield to pedestrians and other traffic before turning with caution. A new traffic code, signed by Mayor La Guardia on December 22, 1936, prohibited turns on red except at intersections where signs permitted the maneuver. Most of the reasons cited for adopting the ban on generally permissive turns-on-red were summarized in an article by Dr. Miller McClintock [22], Director of the Bureau of Street Traffic Research at Harvard University. Excerpts of Dr. McClintock's remarks, which appeared in the New York Times on December 20, 1936, are given below.

> "Most cities in the United States have already ruled against turning right on red lights. Under the old New York City law allowing right-turns on the red signal the drivers were supposed to come to a full halt before turning, but in practice few did so.
>
> "The fourth National Conference on Street and Highway Safety, held in Washington in 1934, was emphatic against the practice of making right-hand turns on red lights. Section 32 of Act V of the Uniform Vehicle Code adopted by the Conference is definite on this point, and sets up as the standard practice that vehicles shall proceed straight through and turn right or left on a green "go" signal only, ---.
>
> "In adopting a new manual on uniform traffic control devices for streets and highways, the Conference pointed out:
>
> "Permitting vehicle operators to make right- or left-turns during the showing of the red light with no modifying arrow is bad practice. It weakens the meaning of the red indication. The practice cannot be permitted at all intersections, therefore, cannot be followed uniformly. It adds to pedestrian hazards and inconvenience in crossing streets. It creates hazards and delays vehicle movement if the discharge capacity of the outlet highway is inadequate for both the regular through movement and the irregularly permitted turn.
>
> "Perhaps the strongest plea for control of vehicular right-hand movements is made in behalf of pedestrian safety.
>
> "Aside from the safety of pedestrians, it is argued that traffic is not materially facilitated by the permission to turn right against the stop signal, but that in fact such a maneuver adds to confusion, delay, and hazard in vehicular movements.
>
> "In addition, it is maintained that right-turns against a red signal are very difficult to control. Drivers are rarely willing to come to a full stop before turning."

In an earlier interview Dr. McClintock warned:

> "It (banning generally permissive turns on red) will only bring moderate comfort to the pedestrian, however, since his life is chiefly menanced by the green-turners, whether left or right, who came upon him from behind, as red-turners never do, if he is careful."

On February 22, 1937, the day the ban on generally permissive turns on red became effective, an editorial in the New York Times suggested that some people felt that RTOR should be generally permitted unless the maneuver was prohibited by a sign.[23] The editor accurately foresaw that:

> "The prohibition of right-hand turns on red will doubtlessly continue for a time to be the subject of controversy."

Following the switch from the generally permissive rule to the sign permissive regulation, "Right (or Left) Turn on Red Signal Permitted" signs were installed at approximately 1,000 intersections in the city.[24] According to the newspaper accounts several weeks after the new sign law was effective, permissive signs were installed at approximately 100 additional intersections.

It is interesting to note that implied in the periodicals is the fact that New York City was perhaps the last city at that time to change to sign permissive RTOR. Later, it has been reported, most of the signs were removed due to public protests and safety considerations.[25]

Ironically, in 1937 sign permissive RTOR was adopted in California and in 1947 the State switched to the generally permissive rule, i.e., RTOR maneuvers were allowed at an intersection approach unless specifically prohibited by a sign.[17] Other western States slowly began adopting RTOR; however, the practice did not gain widespread acceptance, since by 1968 only 20 States reported using RTOR.[26]

The 1934, 1954, and 1961 editions of the Manual on Uniform Traffic Control Devices discouraged the use of RTOR. The sign permissive rule was first incorporated in the Uniform Vehicle Code [27] in 1968 and in the Manual on Uniform Traffic Control Devices [28] in 1971.

Although the practice of permitting turns on red was slowly gaining nationwide acceptance, several events in the 1970's rapidly accelerated the use of RTOR. First, in August 1972, the National Highway Traffic Safety Administration proposed that all States enact legislation to generally permit RTOR unless the maneuver was prohibited by a sign.[29] Opponents of the measure suggested that the National Advisory Committee on Uniform Traffic Control Devices should determine the accepted method. In October 1973, the Committee amended the Manual on Uniform Traffic Control Devices to permit either the sign permissive or the generally permissive rule.

The Arab Oil Embargo of 1973-74 increased national interest in RTOR as an energy conservation measure. As of October 1974, McGee [17] reported that only four States and the District of Columbia totally prohibited RTOR. The various RTOR regulations used by the States prior to October 1974 are shown in table 33.[17] During the summer of 1975, Senate Bill S.2049 was introduced in Congress to make RTOR mandatory nationwide.[30] Also in 1975, the Uniform Vehicle Code was changed to generally permit right-turn-on-red unless prohibited by a sign. Finally, in December 1975, Congress passed the Energy Policy and Conservation Act requiring each State to develop an energy conservation plan to include:

> A traffic law or regulation which, to the maximum extent practical consistent with safety, permits the operator of a motor vehicle to turn such vehicle right at a red stop light after stopping.

Table 33. Summary of State RTOR practices as of October 1974.

RTOR Practice	Number of States
Totally permitted	2
Generally permitted	22
Permitted by sign	21
Permitted by flashing arrow	1
Totally prohibited	4

Source: McGee, 1974, pg. 9, reference.[17]

By September 1975, 27 States had adopted generally permissive legislation and other States were rapidly moving to adopt the regulation.[6] As of July 1, 1978, 49 States and Puerto Rico had adopted general permissive RTOR.[1] Many of the States with generally permissive RTOR also generally permitted left-turn-on-red (LTOR) from a one-way street onto a one-way street.[31,32,33] Currently in the United States, RTOR maneuvers are generally permitted at all signalized intersections unless prohibited by a sign, except in New York City, where the sign permissive rule is used.

One of the primary reasons for adopting RTOR legislation nationwide was the results of several studies which indicated that substantial time and fuel savings could be realized without adversely affecting safety. (The safety and operational impacts of RTOR are discussed in a subsequent section of this report). The generally permissive rule was especially endorsed because RTOR maneuvers are typically allowed at considerably more intersections than are permitted under the sign permissive rule. For example, McGee [17] reported that the average percentage of intersections where RTOR is permitted under the generally permissive legislation is 88 percent; however, under the sign permissive rule, only an average of 8 percent of the intersections were signed to permit RTOR maneuvers.

Another important consideration in adopting generally permissive RTOR was to provide a uniform practice that would be understood by all motorists. Prior to 1975, when one-half of the States were using generally permissive RTOR, incidences were reported of out-of-State motorists making illegal turns on red in States where RTOR was permitted only with a sign or where the maneuver was totally prohibited.[17] To add to the confusion, a number of different signing and signal configurations were used to permit RTOR. For example, in Michigan, right-turn-on-red was permitted only when a flashing red arrow was displayed. Variations also existed within States. In Alabama, six jurisdictions generally permitted RTOR, however, at that time, the sign permissive rule was used in the State.[17]

An extension of the generally permissive RTOR legislation has recently been adopted in Indiana. Effective September 1, 1982, Indiana motorists are permitted to drive through on red after stopping and yielding to pedestrians and other traffic at T-type intersections, unless the maneuver is prohibited by a NO THRU ON RED sign. As shown in figure 18, the legal through-on-red maneuver is permitted only on the unopposed approach to the intersection. No studies were found during the literature review concerning the safety or operational impacts of through-on-red at T intersections. Depending upon the results of the Indiana experience, other States may consider adopting similar legislation in the future. It should be noted, however, that the through-on-red practice is currently in violation of Sections 4B-5-3 and 4B-6-1 of the Manual on Uniform Traffic Control Devices.[16] As previously mentioned, many States adopted RTOR for a number of years before the Manual was revised to approve the practice.

A review of the controversial history of RTOR prompts one to question the future of the practice in the United States. Will generally permissive RTOR be a widely accepted practice for the next 10 or 50 years? If so, what other extensions of the practice are forseeable? Or will general permissive RTOR be banned as it was in New York City 45 years ago? Although the answer is admittedly speculative, the history of RTOR suggests that the maneuver will continue to be a common feature of American driving practices. This study and future research and operational studies will identify specific intersection and traffic (including pedestrian) characteristics where RTOR should be prohibited, but currently there is no scientific evidence to suggest that the maneuver will be generally prohibited in the forseeable future. In fact, a left turn on red from a one-way street onto a one-way street was already allowed by law in 32 States in 1979.[31] With regard to future extensions of RTOR, a number of existing practices provide an indication that future developments can be expected. If the basic premise that RTOR increases the efficiency of an intersection (the operational impacts of RTOR will be discussed in a subsequent section of this report), then through-on-red from the unopposed approach at a T intersection is a logical extension of RTOR. Allowing permissive left turns on green (or red) is simply another approach to increasing intersection efficiency.

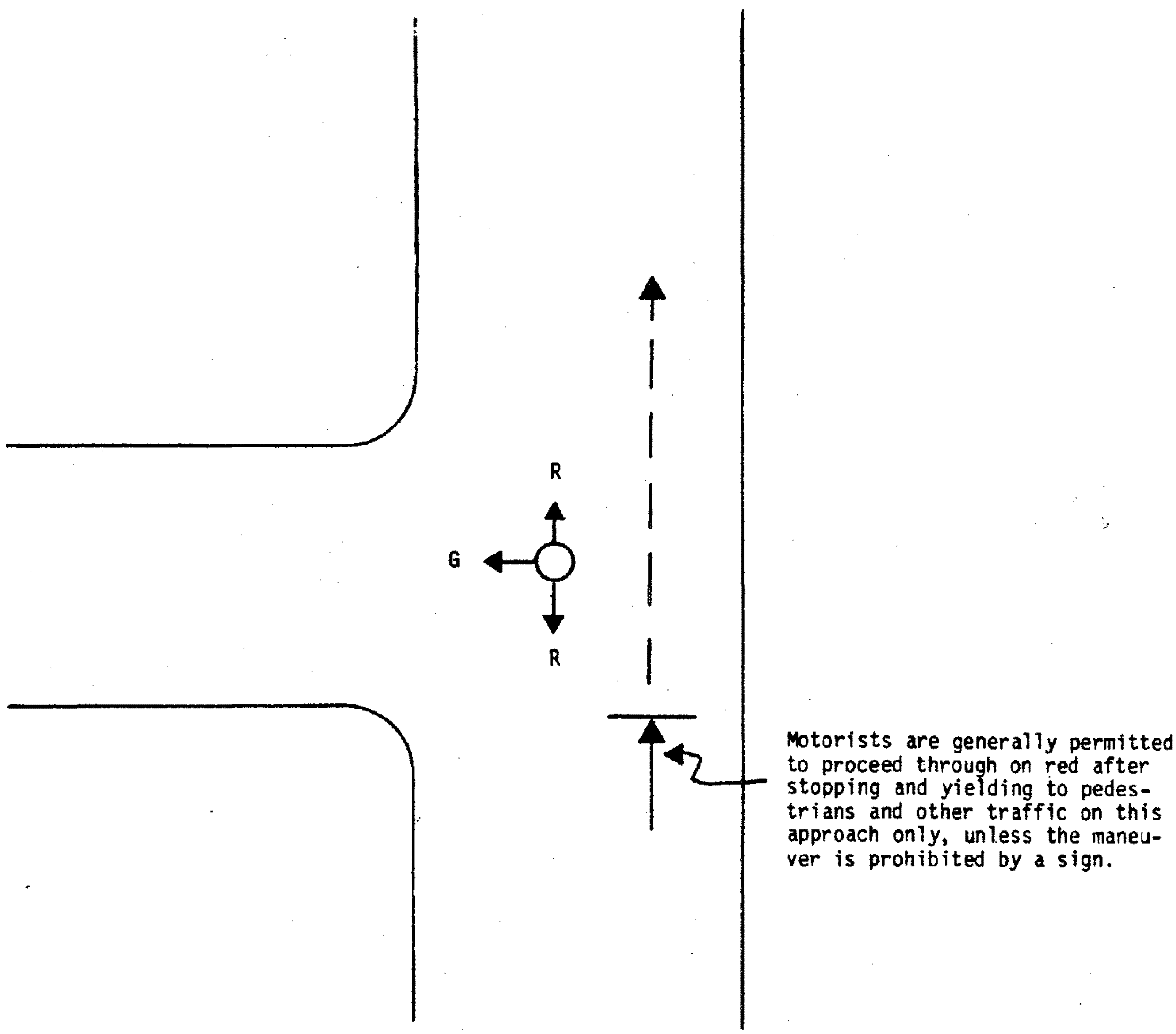

Figure 18. Generally permitted through on red maneuvers at T-type intersections in Indiana.

There are, of course, a number of other measures that are being implemented to increase intersection efficiency which minimize the number of vehicles that turn on red. For example, RTOR maneuvers could be reduced by:

- Installation of highly efficient actuated signal hardware.
- More widespread use of flashing operations during periods of low traffic volume.
- Periodically retiming existing signals to better accommodate changing traffic patterns and volume demands.
- Eliminating unwarranted signals.

In view of limited manpower and funding and the large number of traffic signals in the United States, it is unlikely that major improvements in efficiency are feasible at most signalized intersections in the forseeable future. In the meantime, it is highly likely that the general permissive RTOR practice will continue. Whether or not RTOR will remain controversial is perhaps a function of the credibility of the scientific evidence that must be used to determine the safety and operational impacts of the practice.

Overview of Past RTOR Laws and Guidelines

A review of the literature clearly indicates that past laws and ordinances used by States and cities to permit RTOR maneuvers were not uniform. Also prior to 1975, the majority of the laws were not in conformance with the Uniform Vehicle Code or the Manual on Uniform Traffic Control Devices. While a comprehensive review of past laws and guidelines is beyond the scope of this report (that effort has been documented by others), a summary of several notable exceptions to the general law is provided.[3,6,31,32,33] These exceptions may have implications regarding the implementation of the research results.

Prior to February 19, 1937 when generally permissive right and left turns on red were allowed in New York City, there were no provisions in the regulations for prohibiting turns on red. Drivers were required to come to a full stop and yield the right-of-way to pedestrians and other traffic. In 1976, McGee [3] reported that in three States (Nevada, New Mexico, and Oregon) regulations allowed RTOR at all signalized intersections. However, the current wording in the Nevada and Oregon laws is now similar to the Uniform Vehicle Code.

Prior to 1976, the RTOR regulations in Arkansas, New Jersey, Oregon, and Tennessee did not require motorists to stop and yield before turning on red.[3] Subsequent legislation on RTOR was enacted in those States to be more consistent with the Uniform Vehicle Code. In a study conducted in 1972, Josey [34] reported that two States and the cities of San Jose, California and Salt Lake City, Utah, required pedestrians to yield to RTOR vehicles.

Another variation in the State laws concerns LTOR. In Alaska, Alabama, Michigan, Idaho, Oregon, and Washington State, a LTOR maneuver is permitted from a two-way street onto a one-way street.[32] General guidelines developed as a result of this research may not be applicable for these conditions.

Based on a 1979 review of State RTOR laws, it is apparent that the majority of the State's RTOR laws were in conformance with the Uniform Vehicle Code.[33] Shown in figure 19 is Section 11-202 of the revised Uniform Vehicle Code pertaining to RTOR.[35] The paragraph of Section 4B-5 of the Manual on Uniform Traffic Control Devices pertaining to RTOR is given in figure 20.[16] It should be noted that these documents provide essentially the same definition of generally permissive RTOR.

As pedestrian safety is a primary concern in permitting RTOR, pedestrian as well as bicycle regulations can have an impact on RTOR accidents and countermeasures. In 1976, McGee [3] reviewed pedestrian and bicycle laws in each State and the District of Columbia and found that 25 States have regulations which prohibit a pedestrian from crossing the intersection on a red signal. In these States, the RTOR motorist has the right-of-way as the pedestrian would be using the crossing illegally.

§ 11-202—Traffic-control signal legend

(c) Steady red indication

1. Vehicular traffic facing a steady circular red signal alone shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection and shall remain standing until an indication to proceed is shown except as provided in subsection (c)3. (REVISED, 1975.)

2. Vehicular traffic facing a steady red arrow signal shall not enter the intersection to make the movement indicated by the arrow and, unless entering the intersection to make a movement permitted by another signal, shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection and shall remain standing until an indication permitting the movement indicated by such red arrow is shown except as provided in subsection (c)3. (NEW, 1975.)

3. *Except when a sign is in place prohibiting a turn, vehicular traffic facing any steady red signal may cautiously enter the intersection to turn right, or to turn left from a one-way street into a one-way street, after stopping as required by subsection (c)1 or subsection (c)2. After stopping, the driver shall yield the right of way to any vehicle in the intersection or approaching on another roadway so closely as to constitute an immediate hazard during the time such driver is moving across or within the intersection or junction of roadways. Such driver shall yield the right of way to pedestrians within the intersection or an adjacent crosswalk. (REVISED AND RENUMBERED, 1975; REVISED, 1979.)*

4. Unless otherwise directed by a pedestrian-control signal as provided in § 11-203, pedestrians facing a steady circular red or red arrow signal alone shall not enter the roadway. (REVISED AND RENUMBERED, 1975.)

Figure 19. Current Uniform Vehicle Code definition of RTOR.

Source: Uniform Vehicle Code and Model Traffic Ordinance.[27]

3. Steady red indications shall have the following meanings:
   (a) Vehicular traffic facing a steady CIRCULAR RED signal alone shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection and shall remain standing until an indication to proceed is shown except as provided in (c) below.
   (b) Vehicular traffic facing a steady RED ARROW signal shall not enter the intersection to make the movement indicated by the arrow and, unless entering the intersection to make a movement permitted by another signal, shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection and shall remain standing until an indication permitting the movement indicated by such red arrow is shown except as provided in (c) below.
   (c) Except when a sign is in place prohibiting a turn, vehicular traffic facing any steady red signal may cautiously enter the intersection to turn right, or to turn left from a one-way street into a one-way street, after stopping as required by (a) and (b) above. Such vehicular traffic shall yield the right-of-way to pedestrians lawfully within an adjacent crosswalk and to other traffic lawfully using the intersection.
   (d) Unless otherwise directed by a pedestrian signal, pedestrians facing a steady CIRCULAR RED or RED ARROW signal alone shall not enter the roadway.

Figure 20. Current MUTCD definition of RTOR.

Source: <u>Manual on Uniform Traffic Control Devices for Streets and Highways.</u>[16]

Several States, including Virginia and Kentucky, do not have restrictions requiring pedestrians to obey traffic signals. As a result of a study conducted in Virginia, which revealed that pedestrians crossing against the signal were involved in three times more fatalities than pedestrians crossing with the signal, it was recommended that the Virginia Code be amended to require pedestrians to obey traffic signals.[36] RTOR pedestrian accident countermeasures may not be effective in cities and States where pedestrians routinely disobey the traffic and pedestrian signals. The assumption that pedestrians obey traffic signals is tenuous at best in many areas, based on pedestrian accident studies conducted throughout the nation which indicate that approximately half of all pedestrian deaths occur after the pedestrian has violated a traffic law or committed some other unsafe act.[37]

Other States use pedestrian controls that are unique to their area which may influence the effectiveness of RTOR pedestrian accident countermeasures. For example, Massachusetts uses a red and yellow pedestrian signal that does not conform to the requirements of the Uniform Vehicle Code.[7] Thus, a RTOR pedestrian accident countermeasure developed in another State may not be appropriate for the Massachusetts intersection with red and yellow pedestrian signals.

As reported by McGee [3], bicyclists must obey the general rules of the road in all States. Thus, bicyclists can also turn right on red. At the time the survey data were assembled, 38 jurisdictions required bicyclists to travel on the right-hand edge of the roadway. If followed in practice, this rule implies that RTOR may improve bicycle safety by reducing the number of conflicting right-turning vehicles during the green phase, assuming the bicyclist desires to continue through the intersection. If the bicyclist desires to make a right-turn, there is no conflicting movement with RTOR. In fact, Preusser [13] found that 75 percent of all RTOR bicycle accidents involved bicyclists riding on the wrong (left) side of the street crossing in front of the RTOR vehicle.

CURRENT USE OF RTOR

The current use of RTOR is measured by the percentage of intersections at which the maneuver is permitted and by the percentage of vehicles turning on red.

Percentage of Intersections Permitting RTOR

The percentage of intersections where RTOR was permitted is well documented in the literature. Based on a 1974 survey of States, McGee [17] reported that the average percentage of intersections where RTOR was permitted under the sign permissive rule was 8 percent. In states with the generally permissive rule, RTOR was permitted about 88 percent of the signalized intersections. While current nationwide survey data are not available, a review of the research studies provide substantial evidence that RTOR is permitted at a high percentage of intersections. In 1978, Parker [1] reported that under the generally permissive regulation in Virginia, RTOR was permitted at 84 percent of the State's signalized intersection approaches, and LTOR was permitted at 73 percent of the approaches on one-way streets. Mamlouk [11] conducted a survey in Indiana and found that RTOR was permitted at 88 percent of the total intersection approaches. A 1979 nationwide study conducted by AASHTO [38] revealed that RTOR was permitted at 84 percent of the intersections. Also, Clark et al. [39] found that RTOR was permitted at 90 percent of the signalized intersections in South Carolina; and Novak [40] reported as of January 1, 1981, that 90 percent of the signalized intersections in the city of Milwaukee permitted RTOR.

Based on these data, it appears that under the generally permissive regulation, RTOR is allowed on the average at 85 to 90 percent of the nation's signalized intersections. In New York City, the only jurisdiction with the sign permissive rule, it has been reported that RTOR is permitted at approximately 100 intersections of the 10,000 signalized intersections in that city (about 1 percent).[30]

There is considerable evidence indicating that RTOR was not uniformly implemented, especially in the period immediately following enactment of the generally permissive legislation. For example, Mamlouk [11] reported that in small cities in Indiana, the percent of approaches with RTOR ranged from 17 to 100 percent. In Virginia, Parker [1] found that some cities totally prohibited RTOR while others totally permitted the maneuver. Both Parker [1] and McGee [17] note, however, that following initial implementation of generally permissive RTOR, most jurisdictions removed some of the prohibitive signs due to public complaints. Over time, it is conceivable that RTOR may be permitted at more intersections. States such as California which have used generally permissive RTOR for over 35 years, prohibit RTOR at less than 1 percent of the intersection approaches.

Percentage of Vehicles Turning Right on Red

Utilization of RTOR is determined by expressing the RTOR volume as a percentage of the total right-turn volume; therefore, utilization could be used as an exposure measure for RTOR-related accidents. McGee [3] reported an average utilization rate of 21 percent for the generally permissive RTOR law and 17 percent for the sign permissive practice. Mamlouk [11] found an average utilization rate of 19.5 percent 1 year after generally permissive legislation was implemented in Indiana. However, Parker [1] noted the utilization rate was 34 percent in Virginia 1 year after the general rule was adopted. An intensive statewide publicity campaign may have attributed to the high utilization rate in Virginia. In a 1979 study by AASHTO [38], 23 percent of the right-turning vehicles turned on red.

Under the sign permissive rule, Parker et al. [6] recorded a utilization rate of 36 percent in Virginia, while Baumgaertner [2] found the rate was 45 percent in Maryland. McGee [3], Parker [6], and Mamlouk [11] found that the RTOR utilization rate was affected by the following factors:

- Area type, i.e., 12 percent for urban areas, 28 percent in rural areas.
- Peak vs. off-peak, i.e., 18 vs. 22 percent.
- Presence of right-turn lane, i.e., 28 percent with right-turn lane and 13 percent without the lane.

- Pedestrian volume, i.e., 24 percent with 0 to 10 pedestrians per hour and 10 percent with more than 50 pedestrians per hour.
- City size, i.e., 21 percent in large cities and 16 percent in small cities.

Another measure of RTOR utilization is defined as the RTOR volume expressed as a percentage of the motorists who had an opportunity to turn on red, i.e., sufficient gaps in the traffic stream, no pedestrians in the crosswalk, etc. Under the generally permissive rule, the utilization rate was reported as 85 percent in Minnesota [10] and 92 percent in Virginia [1]. Based on these data, it is apparent that most motorists who have an opportunity to turn on red, do so.

Only sparse data are available concerning the utilization rate of generally permissive LTOR. Parker [1] examined five LTOR approaches in Virginia and found that only 15 percent of the left-turn maneuvers were made on red. Also, only 59 percent of the motorists accepted an opportunity to turn left on red. In Indiana, Mamlouk [11] reported that only 1.3 percent of the total left-turn vehicles were LTOR maneuvers. Apparently, LTOR is not utilized as frequently as RTOR.

WARRANTS FOR PROHIBITING RTOR

Negative guidelines or warrants have been used under the generally permissive RTOR regulation to prohibit turns on red, while both negative and positive guidelines were used for the sign permissive rule. A negative warrant specifies conditions where RTOR should be prohibited, whereas positive warrants outline conditions where RTOR should be permitted. Some warrants have been quantitative while others were qualitative.

Little agreement has been reached concerning the factors that should be considered in developing warrants for RTOR. Based on data collected by McGee [17], a summary of the factors considered by the States in developing warrants for prohibiting turns on red are shown in table 18, given previously. It is interesting to note that pedestrian volume was the most frequently considered factor which is consistent with the general concern for pedestrian safety at RTOR intersections.

An example of the quantitative guidelines that were used by Kansas to permit RTOR are shown in figure 10, given previously. Shown in figure 11, given previously, is an example of negative qualitative guidelines that were used in Indiana to prohibit RTOR. A problem with these and similar warrants is that they appear to be based primarily on engineering judgment instead of empirical data. For example, the Indiana criteria requiring prohibition of RTOR because of little benefit from the maneuver is not supported by research results.[12] Based on analysis of safety and operational data collected during a study conducted for FHWA, McGee [12] recommended the guidelines shown in figure 12, given previously, for prohibiting RTOR under the general permissive rule. After considering the study results and receiving comments from the States, the guidelines shown in figure 21 were adopted in the current edition of the Manual on Uniform Traffic Control Devices.[16]

The MUTCD guidelines are primarily qualitative, which provides the traffic engineer with considerable flexibility and discretion. There have been concerns expressed regarding the need for developing quantitative guidelines which would reduce the subjective nature of the guidelines. Proponents of quantitative guidelines suggest they need specific values in order to defend their decision when they prohibit RTOR.[41] Opponents argue that they prefer the flexibility of qualitative guidelines and point out that it may not be possible to develop quantitative guidelines due to the absence of a cause and effect relationship between RTOR intersection conditions and accident experience. Especially needed, however, are improved guidelines concerning RTOR and pedestrian considerations.

Another problem associated with existing warrants is that there is little uniformity in practices as the prohibitions are primarily based on subjective evaluation of intersection and traffic conditions. Parker [1] and Mamlouk [11] found that RTOR prohibitions varied widely among jurisdictions after generally permissive RTOR was adopted in Virginia and Indiana. Further, Parker [1] found that only three jurisdictions admitted that they used the FHWA guidelines. In fact, 28 of the traffic officials did not use formal guidelines.

Section 2B-37

A NO TURN ON RED sign may be considered whenever an engineering study finds that one or more of the following conditions exist.

1. Sight distance to the vehicles approaching from the left (or right, if applicable) is inadequate.

2. The intersection area has geometrics or operational characteristics which may result in unexpected conflicts.

3. There is an exclusive pedestrian phase.

4. Significant pedestrian conflicts are resulting from RTOR maneuvers.

5. More than three RTOR accidents per year have been identified for the particular approach.

6. There is significant crossing activity by children, elderly, or handicapped people.

Figure 21. MUTCD guidelines for prohibiting RTOR at an intersection approach.

Source: Manual on Uniform Traffic Control Devices, 1978.[16]

In recognition of the need for a national set of guidelines that would improve implementation of RTOR by prohibiting the maneuver only at locations where needs exist, the Institute of Transportation Engineers recently appointed a technical committee to develop guidelines that would allow for application of engineering judgment. A draft of the committee report has been completed and forwarded to ITE Technical Council for review.[42] Although in the draft stage, the qualitative guidelines appear to offer a better understanding of conditions that warrant RTOR prohibitions. For example, the following guidelines and recommendations are given in the committee's unpublished, unapproved draft report. It should be noted that this information is provided only for the purpose of illustrating improved warrants for prohibiting turns on red, and it is not intended to reflect views of the committee or the Institute of Transportation Engineers.[42]

QUALITATIVE GUIDELINES FOR PROHIBITING RTOR

> The purpose of the following guidelines and recommendations is to promote the objective of safe movement of vehicular traffic and pedestrians while providing, for, at the same time, the efficient movement of traffic. Since very specific guidelines encourage local authorities to apply them universally, the following guidelines are qualitative, or nonspecific, to encourage local authorities to evaluate intersections on an individual basis:
>
> 1. Engineering judgment is the basis for each potential turn on red prohibition. Prohibition should be considered only after the need has been fully established and less restrictive methods have been considered.
>
> 2. Part-time prohibitions should be discouraged; however, they are preferable to full-time prohibitions when the need occurs for only short periods of time. It is not good engineering practice to prohibit right turns on red on the grounds that it is of little benefit during some hours of the day. The use of disappearing legend signs for part-time prohibitions and where desired in the vicinity of railroad crossings are recommended.
>
> 3. Less restrictive alternatives should be considered in lieu of prohibiting turns on red. Some examples of less restrictive measures are signs such as "No Turns on Red to Henry Street" or "Right Turn on Red -- Right Lane Only". Such

devices can provide the intended prohibitions without inconveniencing all right-turning traffic.

4. Although many authorities do not perceive the need to prohibit turns on red at multiphased signals, others find there is a need. Where such prohibitions are considered necessary, consideration should be given to the providing of right-turn indications for the main street during the cross street left-turn phases.

5. The definition of specific right-turn-on-red accident criteria may be inappropriate. The accident history of the intersection should be analyzed with prohibitions of turns on red as one possible remedy. Experience may indicate that severe sight distance restrictions or deceptive geometrics can be related to turn-on-red accidents.

6. Universal prohibition at "school crossings" should not be made but rather restrictions should be sensitive to special problems of pedestrian and/or bicycle conflict, such as the unpredictable behavior of children or the problems of the elderly and handicapped, or failure of motorists to yield to pedestrians and/or bicycles within a crosswalk. Pedestrian volumes, as such, should not be the only criteria for prohibiting turns on red.

7. Education and enforcement play a significant role in the benefits and safety of right turns on red. The public needs to be educated concerning the benefits of right turns on red and their responsibilities when making this maneuver. Enforcement is important to ensure that the turns are made <u>after stopping</u> and that the necessary prohibitions are being observed.

Although pedestrian considerations are mentioned in the draft guidelines, specific pedestrian problems are not quantified. Due to the importance of pedestrian safety at RTOR approaches, there is an immediate need to identify appropriate countermeasures and warrants for improving pedestrian safety.

LIABILITY ISSUES RELATED TO RTOR

Information concerning the liability aspects of RTOR is sparse. McGee et al. [3] examined state court reports and found only two Louisiana cases related to RTOR. Analyses of these and several related cases led to the following observations:

- If an accident occurred, liability would lie with the RTOR motorist; as under both the sign and generally permissive rule, the RTOR motorist must stop and yield to pedestrians and other traffic in the intersection. Even in cases where vehicles or pedestrians are illegally in the intersection, the predominance of court decisions places much of the burden on the driver of the turning vehicle.
- The use of generally permissive RTOR by all States may create law enforcement problems in jurisdictions such as New York City where RTOR is permitted only with a sign.
- Unless a municipality was negligent of maintaining signs, a missing RTOR prohibition sign at a location where there was an ensuing accident should not present a liability problem.

Parker et al. [6] also examined liability issues related to RTOR in Virginia, which at that time were protected by the doctrine of sovereign immunity. In addition to the conclusions summarized above, the following issues were identifiable.

- A traffic engineer could be sued only if he were acting outside the scope of his authority or acting with gross negligence. For example, if the engineer ignored the criteria established for RTOR signing, then he may be acting outside the scope of his authority. The engineer may also be considered to be negligent if he failed to replace a missing sign within a reasonable amount of time.
- In general, the liability of the highway engineers for RTOR accidents would probably be the same as for any other accident involving a traffic control device.

SAFETY IMPACTS OF RTOR

Most of the RTOR-related studies have included an analysis or reanalysis of accident data which provides an indication of the importance investigators have placed on identifying RTOR safety problems. Prior to summarizing the RTOR-intersection accident studies and pedestrian accident reports, some overall observations of the difficulties associated with identifying and quantifying the RTOR accident problem are presented.

Issues Related to Identifying RTOR Safety Impacts

A review of the accident studies reveals that in a number of cases conflicting results were found; and in other cases, different conclusions were drawn by researchers using the same data base. Much of this contradictory evidence has served to spark further controversy concerning the safety implications of RTOR. Due to a variety of problems that confound the conclusions drawn from RTOR accident studies, it is appropriate to note that none of the studies conducted to date have been completely successful in isolating and quantifying the safety effects of RTOR. The accident data problems are summarized below:

- Due to the low frequency of RTOR accidents at any given intersection, a large sample of intersections is needed to detect changes in accidents that may be attributable to RTOR-related countermeasures, such as determining conditions where prohibitive signs should be installed. A large sample of intersection features and associated accidents has not been collected to date; thus, it is doubtful if an accurate estimate of the overall safety impacts of RTOR can be established.
- While accurate exposure data are essential in identifying and quantifying accident problems, most of the studies have either not included or have grossly estimated exposure data. Because of the absence of appropriate exposure data, (i.e., RTOR maneuvers, total volume, pedestrian volume on red, etc.), the results of the studies conducted to date are tenuous at best.
- In a number of cases, small samples were drawn for a biased set of intersection conditions for a number of reasons including data availability, lack of manpower, time constraints, etc.
- Most of the researchers have assumed that no RTOR maneuvers or accidents occurred prior to the implementation of RTOR. There is evidence that this assumption is erroneous.[6] The effect of this error is to overestimate the RTOR accident frequency at intersections.

- Several of the investigators have only examined a specific accident condition, (i.e., right-turn accidents) and have disregarded the possibility that RTOR may have an effect on other accident patterns at an intersection.
- As noted by several authors, it is difficult to identify a RTOR-related accident, even if copies of accident reports are available. This problem leads to speculation concerning how to assign accidents that clearly were not RTOR or right-turn-on-green related.
- The general problems associated with using accident data as identified by Council et al. [43] (i.e., unreported or inconsistent data, changes in reporting forms, reporting biases, etc.) simply add to the difficulty of using accident data to quantify RTOR safety problems.

In addition, as identified by others, several of the analyses are plagued by methodological problems. In view of these constraints, the results of previous RTOR accident studies should be viewed with caution. Careful consideration of the evidence offered to date, however, suggests that RTOR maneuvers may be responsible for a small but detectable number of intersection accidents. Special interest should be given to the RTOR vehicle-pedestrian accident. A summary of RTOR intersection accident studies is presented below, followed by a discussion of specific RTOR-related pedestrian accident studies.

Motor Vehicle Accidents

Although safety concerns were frequently expressed in early articles describing RTOR in New York City, the earliest accident study that was identified in the literature review was conducted by Ray [44] in 1956. In a study of 3 years of accident data collected at 75 intersections, Ray [44] found that only 12 accidents (0.36 percent) out of 3,328 were RTOR-related. He also noted that right-turn-on-red volume was 18 percent of the right-turning volume but was involved in only 11 percent of the accidents involving right-turning vehicles.

Several other accident studies were also conducted between 1956 and 1975. However, due to sample size problems, the absence of comparison sites, and other difficulties, their overall contribution to estimating the impact of RTOR on total intersection accident experience is questionable.

In 1975, Parker et al. [6] attempted to isolate the effects of RTOR by examining the accident experience at 20 selected intersections using a 1 year-before and 1 year-after accident period. The sample was biased, as RTOR was permitted at that time only at safe locations. Out of the 337 after accidents, 10 (2.97 percent) were defined as definite RTOR crashes and 5 (1.48 percent) were defined as possible RTOR accidents. There was an increase of 29 accidents after RTOR was implemented, but the increase was not statistically significant. Volume data were used to correct the accident frequencies for exposure, and no significant differences were found in the accident rates during the study periods. An interesting observation is offered in the report concerning the effect of RTOR on intersection accidents. While there were no statistically significant differences, categorization of accidents by type indicated that rear-end crashes decreased while angle and sideswipe accidents increased. This trend suggests that RTOR may cause a shift in accident type rather than an increase in accident frequency, although the sample size is too small to draw conclusions.

McGee et al. [3] analyzed RTOR accident experiences in Dallas, Denver, Chicago, and Los Angeles and in two States - Colorado and Virginia. For the generally permissive States, RTOR accidents constituted 0.61 percent of all signalized intersection accidents. For sign permissive jurisdictions, the percentage of RTOR accidents was 3 percent. McGee [3] reported that RTOR accidents were less severe than average intersection accidents. The results of the analyses suggested that accidents resulting from RTOR were insignificant compared to all signalized intersection accidents. Galin [4], however, reanalyzed the data and concluded that RTOR actually results in a deterioration in safety at signalized intersections.

In 1979, the American Association of State Highway and Transportation Officials [38] collected a nationwide sample of accident data at RTOR intersections and reported that:

- Total intersection accidents decreased significantly, i.e., from 12.6 without RTOR to 11.9 accidents per intersection per year with RTOR.
- Fatal and injury accidents decreased.
- Right-turn and left-turn accidents increased.
- Rear-end accidents decreased.

It should be noted that the trend for RTOR to reduce rear-end accidents and increase angle type accidents is also partially supported by these data.

A 1980 study conducted by Zador [45] for the Insurance Institute for Highway Safety found that adoption of RTOR led to a 20 percent increase in all right-turn accidents at signalized intersections. Members of an ITE task force [46] examined the report and identified several erroneous assumptions and methodological problems with the study. Again, the data supported a change in the pattern of intersection accidents.

Clark et al. [39] recently conducted an analysis of signalized intersection accidents in South Carolina and Alabama. The data were categorized as right-turn accidents and non-right-turn accidents. It was found that right-turn accidents tend to be less severe and have lower property damage costs than other accidents reported at signalized intersections.

While each of the studies have one or more of the methodological problems that prevent one from estimating the real impact of RTOR on intersection accident characteristics, the evidence suggests that the total number of RTOR accidents represent a small but detectable percentage of intersection accidents. Also, RTOR accidents tend to be associated with lower accident severities, and RTOR may be influencing a change in accident patterns, i.e., decreasing rear-end accidents and increasing angle and sideswipe collisions.

Pedestrian Accidents

The impact of RTOR on pedestrian accidents has received considerable attention. A summary of some of the key findings related to pedestrian RTOR accidents is presented below. It should be noted that methodological problems including sample biases prevent quantification of the pedestrian accident problem. Nevertheless, the data do suggest a small, detectable accident problem.

- Ray [44] found that the RTOR pedestrian-accident rate was greater than the exposure rate, but the difference was not statistically significant.
- The study by Benke et al. [10] in Minnesota suggested that actual hazards to pedestrians created by RTOR maneuvers appeared to be minimal.
- A study conducted by Scott [47] in Los Angeles suggested that RTOR vehicle-pedestrian accidents were slightly greater than 2 percent of the total vehicle-pedestrian accidents at all signalized intersections.
- McGee et al. [3] found that the percent of pedestrian accidents that were RTOR-related ranged from 0 to 29 percent, with a weighted average of 3.75 percent.
- The AASHTO [38] study revealed that the annual average number of pedestrian accidents at the study intersections did not change after implementation of RTOR.
- Zador [46] reported that right-turn pedestrian-vehicle accidents increased 57 percent with RTOR. In urban areas, the increase was 79 percent and accidents involving children pedestrians increased 30 percent. Accidents involving elderly pedestrians increased 110 percent after adoption of RTOR.
- Clark et al. [39] found no significant difference between pedestrian accidents involving right-turn and non-right-turning maneuvers before and after implementation of RTOR in South Carolina and Alabama.

Novak [40] conducted an analysis of right-turn accidents in Milwaukee and concluded that RTOR had influenced a change in the make-up of signalized intersection accidents with right-turn accidents representing a greater percentage of the total than other accident types. RTOR accidents accounted for 51.1 percent of the average number of right-turn vehicle-pedestrian accidents. In summary, the annual increase of 17 right-turn pedestrian accidents represented only 0.25 percent of the total reported accidents at signalized intersections.

In 1981, Preusser et al. [13] conducted one of the most comprehensive investigations of right-turn intersection accidents to examine the impact of RTOR on safety. As a percentage of all pedestrian accidents, right-turn accidents at signalized locations increased from 1.47 to 2.28 percent following implementation of RTOR. For bicycle accidents, the increase was from 1.40 to 2.79 percent. The increases in bicycle and pedestrian accidents for each of the study areas is shown in figure 22.

It was also found that the typical RTOR pedestrian accident occurred when a motorist stopped at a red light, looked for approaching vehicles from the left and failed to see a pedestrian crossing on the right. The directional movements of RTOR accidents relative to pedestrians and bicyclists are shown in figure 23.[13] As indicated in the report, there appears to be a small, but well-defined pedestrian and bicycle accident problem due to RTOR operations.

MOTORIST COMPLIANCE WITH RTOR LAWS

One of the objections to the generally permissive RTOR regulation in New York City in 1936 was that motorists frequently did not stop before turning on red. Similar concerns have recently been expressed.[1,2,3] An assessment of motorist compliance with stopping is presented below, followed by a discussion of motorist violation of turning on red where the maneuver is prohibited.

Compliance Where RTOR is Permitted

In most States, motorists must come to a full stop and yield to pedestrians and other traffic in the intersection before turning on red.

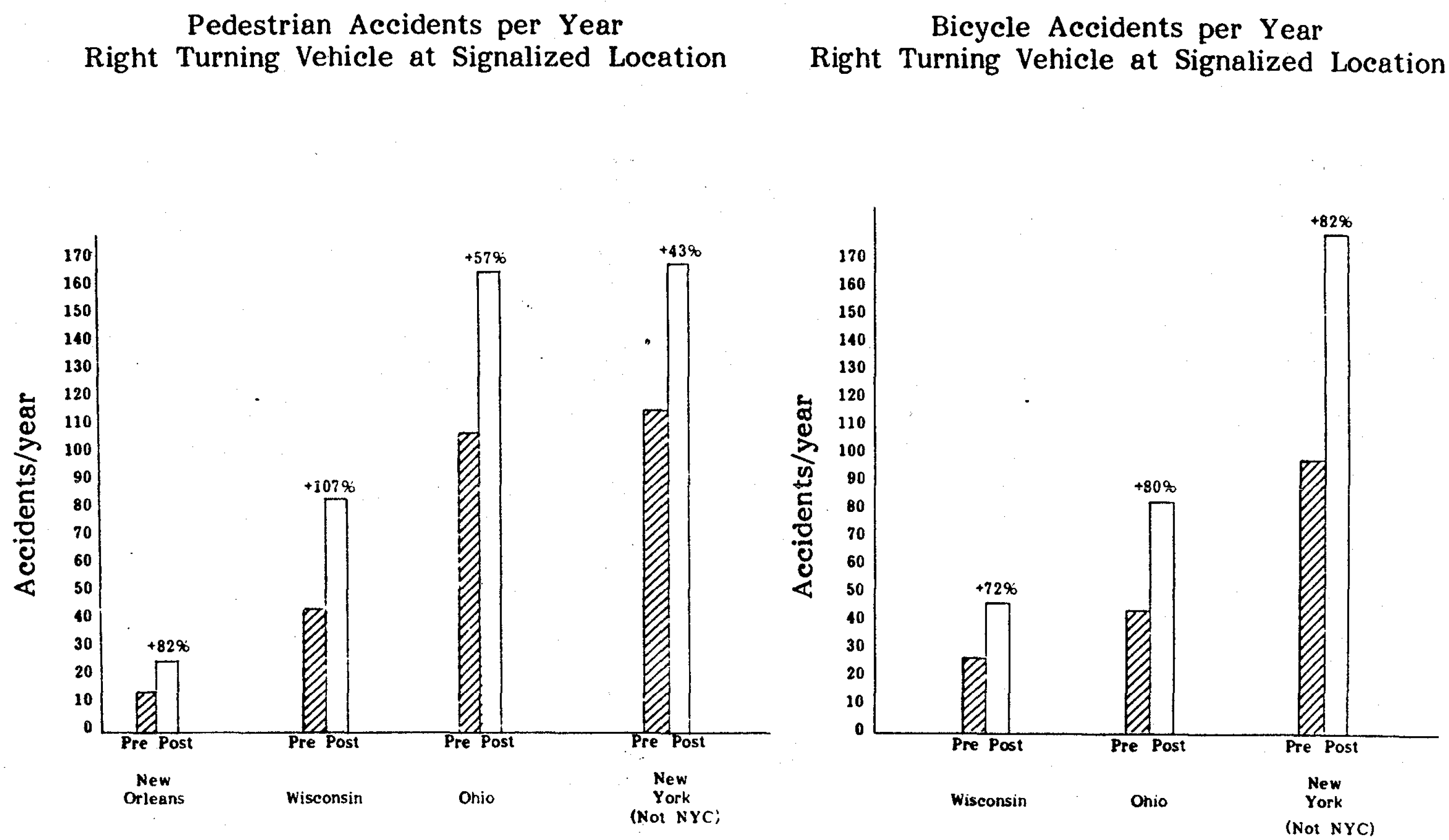

Figure 22. Pedestrian and bicycle accidents before and after implementation of generally permissive RTOR.

Source: Preusser et al., 1981.[13]

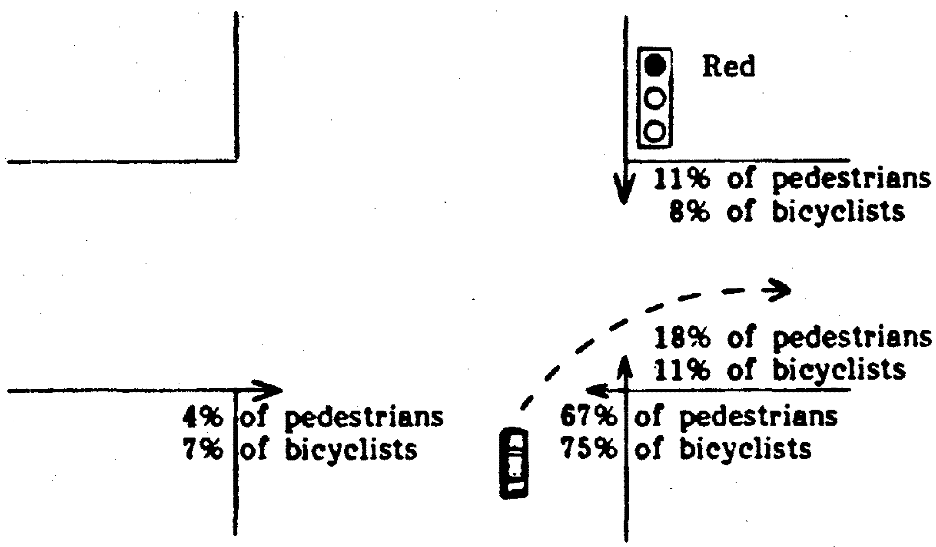

Figure 23. Directional movements of pedestrians and bicyclists involved in RTOR accidents.

Source: Preusser et al., 1981.[13]

As mentioned above, noncompliance with the law was frequently mentioned in the newspaper accounts, but no data were found that quantified the problem. The same objection to RTOR is frequently offered today by traffic and law enforcement officials. However, limited data are available to identify the noncompliance rate.[1,3,4]

There have been several examinations of motorist compliance with the RTOR law. Under the sign permissive rule in Virginia, Parker [6] found that 9 percent of the RTOR motorists at 15 approaches did not come to a full stop before turning. A study conducted at 11 sites in Providence, Rhode Island, found that 65 percent of the motorists did not stop.[7] At 12 locations in Springfield, Massachusetts, 72 percent of the RTOR motorists came to a full stop.[7] The high compliance rate in Springfield was attributed to the newness of the RTOR maneuver and the sign reminding motorists to stop. Baumgaertner [2] collected compliance data at 13 approaches in Maryland and also found the noncompliance rate, under the sign permissive rule, was 64.4 percent which compares closely with the Providence data.

RTOR compliance data were collected for generally permissive RTOR in only two studies.[1,6] In both cases, the general rule had only been adopted for 1 year. At seven approaches in North Carolina, Parker [6] found that 2.0 percent of the RTOR motorists did not stop. However, after generally permissive legislation was enacted in Virginia, Parker [1] found that 11.5 percent of the RTOR motorists violated the law. It is important to note that the violation rate varied considerably with 48 percent of the violations reported at two approaches.

A high noncompliance rate creates a law enforcement problem and may lead to a serious safety problem. In their studies, Baumgaertner [2] and Parker [1] also recorded the number of unsafe turns where the RTOR motorists did not stop or yield to other traffic in the immediate vicinity of the intersection. In both studies, less than 2 percent of the motorists made an unsafe turn. Additional studies of motorist compliance should be periodically conducted to examine trends over time and to identify unsafe approaches so that appropriate countermeasures can be applied.

The magnitude of the RTOR violation problem can be put in perspective by comparing it to motorist compliance at stop sign locations. In a Chicago study, 53 to 76 percent of all drivers failed to come to a complete stop at stop signs. However, only 5 to 10 percent of all vehicles violated the stop sign traveling in excess of 5 mph (8 kph).[8] A 1976 study by Beaubien [9] was conducted in Troy, Michigan, to determine whether stop signs were effective for speed control in residential areas. At the three locations, full stops ranged from 6 to 51 percent of vehicles, rolling stops ranged from 34 to 54 percent and no-stops ranged from 15 percent to 47 percent. Based on this data, the violation rate involving stop signs appears to be considerably higher than the RTOR noncompliance rate.

A 1978 study observed motorist obedience to the stop signs in Barton, Springfield, and Providence, as shown in table 34. The percent of vehicles stopping ranged from 61 to 69 percent. Of those vehicles not forced to stop by side street traffic, the percent of stopping vehicles ranged from 28.8 to 64.8 percent.[7]

Violations Where RTOR is Prohibited

Another major concern of traffic and safety engineers is whether motorists are violating the law by turning right on red at locations where the maneuver is prohibited. There is evidence to suggest that violations do occur.

Benke et al. [10] collected violation data at 11 sites where RTOR maneuvers were prohibited under the sign permissive and generally permissive rules and found that the violation rates were 1.23 and 9.56 percent, respectively, (i.e., 1.23 percent of the motorists made an illegal RTOR maneuver). The authors attributed the high violation rate, which occurred at 4 of the 11 sites, to poor visibility of the sign resulting from poor sign placement and a busy signing environment at one location. In Indiana, Mamlouk [11] found that 1.4 percent of the motorists made an illegal RTOR maneuver under the sign permissive rule. It was also reported that the violation rate varied considerably with one site having an 18 percent violation rate. At that location, sign placement made it difficult for motorists to see. Parker [1] collected data at three approaches in Virginia where RTOR was prohibited and did not observe a violation.

The violation data suggests that motorists are making illegal turns on red at certain types of locations. Additional violation data should be collected to determine the magnitude of the problem, the contributing factors, and possible corrective treatments.

Table 34. Motorist obedience to stop signs.

Obedience to Stop Signs

Location	% Stopping
Chicago standard	95%
Boston	61%
Springfield	69%
Providence	65%

Voluntary Stops

Location	No. of Stop Signs	Total Vehicles Observed	Total Vehicles Not Forced to Stop	% Stopping of Those Forced Not to Stop
Boston	3	417	246	33.7
Springfield	5	489	215	28.8
Providence	6	617	609	64.8

Source: Reference [7]

OPERATIONAL IMPACTS OF RTOR

The primary benefits of permitting RTOR maneuvers are to reduce needless vehicle delay and to conserve vehicle fuel. The operational impacts of RTOR, including vehicle delay, pedestrian delay, vehicle-pedestrian conflicts, and other effects are summarized in this section.

Vehicle Delay

With respect to RTOR, vehicle delay has been measured in terms of stopped delay at the intersection and travel time over a specified route. Although early reports cite that RTOR reduced vehicle delay and congestion, the first documented study that measured delay reductions associated with RTOR was conducted by Ray [44] in 1956. Ray measured travel time over a 14 intersection circuit in the central business district of Berkeley, California. During off-peak hour trips, a 7 percent savings in travel time was measured with an average savings of 0.16 minutes for each right-turn. During the off-peak hour the travel time savings were 10 percent and 0.13 minutes was saved at each intersection with RTOR. VanGelder [48] also conducted a travel time study in Seattle, Washington, using three intersections with RTOR and found that the average time saved over the 1 mile circuit was 25 seconds. Cohen [49] applied the UTCS-1 Network Simulation Model to two networks containing signalized intersections in Washington, D.C., to measure the effect of RTOR on intersection performance characteristics. The results of the study indicated that travel speed increased by 18 and 34 percent and stop delay was reduced between 33 and 42 percent due to RTOR. McGee et al. [3] also used the UTCS-1 simulation model with a wide range of geometric and operating parameters and found that RTOR reduced total delay for all conditions except a one-lane intersection approach. For the grid network studies, McGee reported a 7.8 percent reduction in total delay with RTOR.

In a 1965 study conducted by the Minnesota Department of Highways [50], the mean time saved per right-turning vehicle was 7.8 seconds during peak hours and 9.6 seconds during off-peak hours at intersections with the sign permissive regulation. Minnesota [10] conducted another study after the generally permissive rule was adopted and found that 7.0 seconds were saved during peak hours and 10.7 seconds were saved during off-peak periods. In Virginia, Parker et al. [6] found that RTOR maneuvers reduced delay for right-turning vehicles by 14 seconds. McGee et al.[3] conducted field and computer simulation studies and reported that RTOR produced significant savings in delay for nearly all conditions. McGee et al. found that delay savings were influenced by area type and the presence of a right-turn lane. An overall right-turn delay savings of 4.6 seconds was reported with a savings of 4.3 seconds during peak hours and 5.2 seconds during off-peak conditions. AASHTO [38] also recently conducted field and simulation studies and found that RTOR reduces delay by 6 seconds for approaches with a right-turn lane and 5 seconds for sites without a right-turn lane.

In summary, the studies indicate that RTOR significantly reduces delay for right-turning vehicles under most conditions and also will result in travel time reductions for vehicles traveling in a network.

Pedestrian Delay

There are very little data available on pedestrian delay attributable to RTOR maneuvers. In Berkeley, Ray [44] collected data on delay imposed on RTOR vehicles by pedestrians and found that the average delay to stopped RTOR vehicles was 0.06 seconds. This delay was less than the 0.08 second delay imposed on vehicles making a right-turn-on-green. May [51] attempted to measure pedestrian delay due to RTOR during his study in Indiana; however, during the study not a single pedestrian was delayed by a RTOR vehicle. Mamlouk [11] also attempted to quantify pedestrian delay and found that no pedestrian delays occurred as a result of RTOR at the study approaches.

Vehicle-Pedestrian Conflicts

Several investigators have examined vehicle-pedestrian conflicts due to RTOR motorists. Mamlouk [11] reported that after 600 hours of study at intersections in Indiana, no pedestrian was observed who had been placed in a more hazardous situation due to a RTOR maneuver. He did note that vehicles turning on green were in conflict with a substantial percentage of pedestrians in the cross street.

The results of a study conducted in Springfield, Massachusetts, revealed that 6 percent of the pedestrians experienced a conflict situation with RTOR vehicles at selected intersections.[7] In Providence, Rhode Island, approximately 9 percent of the pedestrians experienced a conflict with a RTOR vehicle. In two-thirds of the conflict cases, drivers yielded to pedestrians. In Boston, it was found that 23 percent of the pedestrians experienced a conflict with RTOR vehicles. Also, 78 percent of the time, the Boston pedestrian yielded to the vehicle.[11]

Parker [1,6] conducted two RTOR-related pedestrian-vehicle conflict studies in Virginia and found that of all RTOR traffic conflicts, pedestrians were involved in 7.7 percent of the conflicts in one study and 8.6 percent of the conflicts in a follow-up study. However, these data are misleading as only 4 pedestrian-vehicle conflicts occurred in each study. Parker noted that most vehicle-pedestrian conflicts occurred during the green phase, but the frequency of these conflicts was not recorded because only RTOR-related conflicts were collected. In his studies, Parker used conflicts definitions similar to those developed by Glauz et al.[52]

Other Impacts

As documented in a number of studies, the delay savings attributable to RTOR maneuvers can be translated into other savings. Most noteable and important of these benefits is motor fuel savings. McGee et al., [3] for example, found through simulation analysis that a fuel consumption savings of 2.6 percent for all vehicles in a network of signalized intersections could be achieved through implementation of RTOR. At isolated intersections, fuel savings ranged from 3.2 to 37 percent, depending on the number of approach lanes and the percentage of right-turn volume. The analysis also indicated that auto emissions were reduced as a result of RTOR.

ACCIDENT AND OPERATIONAL COUNTERMEASURES

While considerable controversy exists over the accident implications of RTOR, a comprehensive list of countermeasures to improve safety and operations has not been developed. The primary accident countermeasure used to date has been to ban RTOR at an approach. Total as well as part-time prohibitions have been used. However, a review of the research studies provides evidence that a variety of countermeasures should be examined. Unfortunately, the effectiveness of most of the countermeasures has not been determined. Given below is a list of pedestrian accident countermeasures followed by a general list of countermeasures for accident and operational problems.

Pedestrian Accident Countermeasures

Countermeasures for pedestrian accidents typically are classified in four categories, i.e., education, legislation, enforcement, and traffic engineering.[36] While none of the categories are independent from the others, the primary concern in this study is the traffic engineering countermeasures. Based on a review of the RTOR-pedestrian accident studies, the countermeasures listed below were developed.

RTOR-Pedestrian Accident Countermeasures

- Totally prohibit RTOR on the approach.
- Prohibit RTOR only during the hours of heavy pedestrian travel.
- Install pedestrian signals.
- Construct pedestrian barriers.
- Relocate crosswalk(s).
- Construct pedestrian overpass.
- Improve pedestrian signal display.
- Relocate bus stops.
- Eliminate parking near the intersection.
- Provide or improve intersection lighting.
- Improve pedestrian awareness of RTOR regulations and safety.
- Install YIELD TO PEDESTRIAN sign(s).

General Countermeasures

Countermeasures that should be considered for general RTOR-related accident and operational problems are listed below.

RTOR-Accident and Operational Countermeasures

- Totally prohibit RTOR at an approach.
- Prohibit RTOR only during hours of heavy conflicting volumes.
- Illuminate NO TURN ON RED sign.
- Increase sign size to improve visibility.
- Relocate sign to near-signal placement.
- Use double indication for redundancy, i.e., post-mounted and signal mounted sign.
- Offset stop bars to improve the placement of the RTOR vehicle so the motorist has a clear view of oncoming traffic and pedestrians.
- Install separate right-turn lane(s).
- Retime traffic signal to provide better operations.
- Install presence detectors at traffic actuated approaches to provide more efficient signal operation.
- Install RIGHT TURN ON RED AFTER STOP sign to encourage utilization of RTOR.
- Use symbolic NO TURN ON RED sign(s).
- Conduct publicity campaign to increase awareness of the RTOR regulation.
- Remove unwarranted signals.
- Modify accident report form to identify RTOR-related accidents.

RTOR COUNTERMEASURE COSTS

The literature revealed that only one researcher developed costs for several RTOR countermeasures.[6] Costs for the other countermeasures, however, can be found in other publications and are not provided in this summary.

As full and part-time prohibitions of RTOR are the major countermeasures that have been implemented to address RTOR-related accident and operational problems, Parker et al. [6] provided the following data concerning sign costs.

- NO TURN ON RED sign installation costs.

$ 9.50	Labor costs
21.50	Material and fabrication costs
19.00	Study costs
$50.00	Total cost per sign.

- Maintenance costs.

  $3.00 Per sign per year.

ASSESSMENT OF RTOR BENEFITS AND COSTS

Several investigators provided an economic assessment of RTOR. On a nationwide basis, McGee et al. [3] estimated that if generally permissive legislation was enacted at 80 percent of the signalized intersections the annual economic loss due to RTOR accidents would be approximately 14.1 million dollars. However, it was estimated that between 135 and 185 million gallons (500 and 700 million liters) of fuel would be saved annually, which would be an economic benefit of 75 to 102 million dollars. These figures do not include costs of other benefits such as time savings and automobile emission reductions. In terms of fuel savings vs. accidents, a benefit-cost ratio of 5.3 to 13.1 may be expected.

Parker et al. [6] estimated that 3.1 million gallons (12 million liters) of fuel would be saved if Virginia adopted generally permissive RTOR legislation. It was estimated that RTOR accident losses would cost $437,800 per year in the State. At that time average fuel costs were only 55¢ per gallon (14¢ per liter) which provided $1,717,000 in fuel savings. If only fuel savings and accident costs were considered, the benefit-cost ratio would be 3.9.

Wagner [53] conducted estimates of energy savings due to implementation of generally permissive RTOR and LTOR and found that approximately 1.6 million gallons (6 million liters) of fuel would be saved annually for an urban population of one million persons. The savings was equvalent to 0.5 percent of the total areawide auto fuel consumption.

Novak [40] recently estimated that during the 5 year period 1976 to 1981, implementation of generally permissive RTOR in Milwaukee resulted in accident losses of $500,000. However, fuel savings alone amounted to 6 million dollars which resulted in a benefit-cost ratio of 12.

Although cost estimates were not developed, Clark et al. [39] estimated that implementation of RTOR resulted in annual fuel savings of 2.7 million gallons (10.2 million liters) in South Carolina and 3.2 million gallons (12.1 million liters) in Alabama. Annual RTOR-related accidents were reported as 118 accidents in South Carolina and 33 in Alabama. The results of the economic assessments clearly indicate that the fuel savings alone outweigh the estimated accident costs attributable to RTOR maneuvers.

CONCLUSIONS

The practice of legally permitting motorists the option of right-turn-on-red (RTOR) at signalized intersections after stopping and yielding to pedestrians and other traffic is now a widely accepted traffic regulation in the United States. Based on available research, there appears to be a small, but well-defined pedestrian and bicycle accident problem due to RTOR operations.

The purpose of this assessment was to examine past and current RTOR practices and provide information that can be used in conjunction with additional research to improve pedestrian safety and operations at signalized intersections. Based on the state-of-the-art review, the following conclusions are offered.

1. The generally permissive RTOR regulation has been controversial since the automated traffic signal has been in use. Pedestrian safety concerns vs. operational benefits are the primary issues.

2. One extension of the RTOR concept, through-on-red at the unopposed approach of a T-type intersection, was implemented in the State of Indiana, but later repealed. The apparent success of permissive RTOR has also lead to other changes in traffic laws (i.e., LTOR) for the sake of reducing fuel consumption or motorist delay.

3. It is estimated that RTOR maneuvers are permitted at an average of 85 to 90 percent of the signalized intersections nationwide, and this percentage may be expected to increase in the near future.

4. Drivers have apparently readily accepted the concept of turning on red; between 85 and 92 percent of the motorists who have an opportunity to turn on red do so. Between 20 and 45 percent of all right-turning motorists turned on red.

5. There is a need to develop an improved set of nationwide warrants for prohibiting turns on red, especially warrants for improving pedestrian safety.

6. Numerous deficiencies were found in previous RTOR accident studies. No study was found to have successfully isolated and quantified the safety impacts of RTOR; however, the cumulative results indicate that a small detectable problem exists. Pedestrian-related RTOR accidents should be given special attention through countermeasure development.

7. Studies should be conducted to examine trends for motorist noncompliance (not stopping and yielding the right-of-way). Characteristics of noncompliance sites should be identified and appropriate countermeasures developed. Current noncompliance data under the generally permissive RTOR rule are insufficient to identify noncompliance sites or countermeasures.

8. A review of the literature suggests that violations (motorists turn on red at sites where the movement is prohibited) of RTOR

prohibitions occur with a wide variation in frequency by site. Additional violation data should be collected to determine the magnitude of the problem and to identify countermeasures.

9. Substantial operational benefits due to RTOR provide evidence that significant reductions in vehicle delay, fuel consumption, and automobile emissions are achieved. Additional research should be conducted to quantify the effects of RTOR on pedestrian delay and pedestrian conflicts. This research should also be helpful in developing countermeasures to improve pedestrian safety and vehicle operations.

10. The results of economic analysis indicate that the benefits of RTOR far outweigh the estimated RTOR accident costs. Even if RTOR accident countermeasures are used to improve safety, in most cases, the benefits would exceed the costs when applied on an areawide basis.

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