DEPARTMENT OF TRANSPORTATION

Evaluation of static and dynamic no right turn on red signs at traffic signals

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16. Abstract (Limit: 250 words)

This study examined the operation of static and dynamic no right turn on red (NRTOR) signs at eight signalized intersections in Minnesota (six dynamic and two static). Driver compliance with the NRTOR indications were measured using video data. Most dynamic NRTOR sign locations were pedestrian-activated, with one location having additional time-of-day activation of the NRTOR indication. Compliance rates were calculated per signal cycle and per vehicle. Per-cycle compliance rates were 60.8% for dynamic and 80.0% for static sign locations, while per-vehicle compliance rates were 87.1% for dynamic and 92.4% for static sign locations. Statistical models were further developed to confirm the statistical significance of the results and to explore the strength of the effect compared to other intersection characteristics. A survey of practitioners was included to identify the installation and maintenance costs of DNRTOR devices. The report concludes with recommendations on uses of DNRTOR.

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Evaluation of Static and Dynamic No Right Turn on Red Signs at Traffic Signals

Final Report

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Executive Summary

The right turn on red (RTOR) movement is commonly used at signalized intersections in the United States and has the benefit of improving efficiency by allowing right turning vehicles to proceed when a gap exists in crossing traffic. However, RTOR can lead to conflicts between right turning vehicles and pedestrian traffic. Drivers making the RTOR movement are typically looking in one direction to identify gaps and may not always look carefully in both directions for pedestrian traffic before proceeding. To reduce these conflicts, one potential treatment is the use of a dynamic No Right Turn on Red (DNRTOR) sign, also called a blank-out sign, which can conditionally show the No Right Turn on Red (NRTOR) indication when a pedestrian phase is being served and blank out the message at other times. This contrasts with the use of a static sign, which shows the NRTOR message at all times. It is thought that DNRTOR signs could reduce the number of RTOR violations by adding conspicuity to NRTOR messaging. However, little previous guidance on the use of DNRTOR signs has been developed to date.

This study explores the use of DNRTOR signs, with the following objectives: (1) measure compliance rates for both dynamic and static NRTOR signs; (2) develop information about maintenance requirements with a practitioner survey; and (3) develop recommendations from this information in conjunction with a literature review.

Driver compliance rates were measured by collection of video data from eight intersections, including six with DNRTOR signs and two with static signs. The DNRTOR sign locations all operated with pedestrian-activated NRTOR indications, except for one location where time-of-day (TOD) operation was also used. One static sign location used a “No Turn on Red” sign with no conditions, while the other static location had NRTOR by time of day. More than 4,500 hours of video were collected in total during two separate data collection periods in June and September/October 2023, from which about 2,347 individual signal cycles were selected for analysis. The controlling factor was the relative rarity of pedestrian activations that caused the DNRTOR indication to be illuminated; about 2 hours of video data for every individual pedestrian indication at the DNRTOR locations was collected.

Compliance rates were tabulated on a per-cycle and per-vehicle basis. For per-cycle compliance, if one or more NRTOR violations occurred during a cycle, that cycle was counted as non-compliant. For per-vehicle compliance, the number of NRTOR violations was compared against the total number of right turning vehicles during the same cycle. Per-cycle compliance rates ranging from 37.8% to 79.3% were observed at the DNRTOR locations, with an overall compliance rate of 60.8%. This indicated the percentage of observed cycles without NRTOR violations and compares to an 80.0% per-cycle compliance rate for the static sign locations. Per-vehicle compliance rates were higher, ranging from 77.7% to 92.9%, with an overall compliance rate of 87.1%, compared to 92.4% for static sign locations. These compliance rates indicated the percentage of right turning vehicles arriving on red that obeyed the NRTOR indication (including those that were queued behind other vehicles). Overall, driver compliance was lower at the DNRTOR locations compared to the static NRTOR sign locations. The measured compliance rates were similar to those reported in the literature.

At the same time, however, some observations suggested that the DNRTOR signs could help contribute to greater driver awareness of the presence of pedestrians. At one study location where both TOD and pedestrian-activated DNRTOR indications were used, there were fewer cycles under pedestrian-activated control having RTOR violations compared to TOD operation, although there was a similar per-vehicle compliance rate. This suggested that during pedestrian-activated DNRTOR operation, some drivers may be more likely to obey the NRTOR indication than when pedestrian traffic was less likely to be present. Also, manual observations found that among the 849 RTOR violations, six involved substantial vehicle-pedestrian conflicts (or 0.7% of the violations) where pedestrians were forced to adjust their movement across the intersection because of vehicle movement into their intended path.

A practitioner survey was also undertaken as part of this study to gather information about sign deployment and maintenance. There were 27 responses from transportation agencies. Most respondents indicated that the DNRTOR signs were generally found to reliable, with many more respondents indicating reliable than unreliable operation. A few agencies (but not all) in locations with winter weather reported having issues during extreme weather conditions. Routine maintenance costs were found to be small while non-routine maintenance was rarely required by most respondents. Installation costs were found to be on the order of thousands of dollars, while maintenance costs were generally quite low (less than $300 per year). Information about Underwriters Laboratories (UL) or Nationally Recognized Testing Laboratory (NRTL) listed signs were sought during the study, but little information was obtained. Some survey respondents indicated requiring UL listing, but those who responded to follow-up inquiries indicated that they did not in fact require UL listing.

Given that DNRTOR installation and maintenance was not found to be especially challenging according to the practitioner survey, recommendations on use of DNRTOR were developed largely based on the synthesis of the measurement results and previous studies. The main recommendations are as follows.

For an objective of purely reducing the number of NRTOR violations, the DNRTOR treatment does not appear to be the best option. Dynamic sign compliance rates were lower than static sign compliance rates, when measured per cycle as well as per vehicle. For locations where the objective was to avoid any RTOR movement, such as where a sight distance challenge exists, a DNRTOR sign seemed unlikely to offer much benefit beyond a static sign. The lack of sight distance likely reinforced the need for the NRTOR indication.

For an objective of improving pedestrian visibility (i.e., making drivers more aware that pedestrians were present), the DNRTOR treatment appeared to be helpful. The literature included two before-after studies showing improvements of compliance, although one location in a prior study showed a lower compliance rate with the use of a sign with less clear meaning. In this study, one location under both pedestrian-activated and TOD control had higher per-cycle compliance rates during pedestrian-activated operation although the per-vehicle compliance rates were similar for both types of operation. This suggested that the first vehicle with the opportunity to make the RTOR was more likely to wait until after the NRTOR indication blanked out when pedestrians were present. In addition, during manual observations, it was found that most RTOR maneuvers, although violating the NRTOR indication, rarely led to substantial vehicle-pedestrian conflicts.

Chapter 1: Introduction

1.1 Problem Statement

The right turn on red (RTOR) movement improves the operational efficiency of signalized intersections by allowing drivers to carry out the right turn movement without having to wait for the green interval. Permission of RTOR has been the default intersection treatment in the United States since the mid-1970s, with a No Right Turn on Red (NRTOR) sign being used to indicate where RTOR is prohibited.

The RTOR maneuver is a source of conflict between vehicles and pedestrians (and other vulnerable road users) because RTOR drivers must cross the path of crossing pedestrians while also looking for gaps in conflicting vehicle flow. One potential treatment to reduce these conflicts is to use a dynamic No Right Turn on Red (DNRTOR) sign, which provides an illuminated message to the driver when RTOR is prohibited. The signs can be blanked out during other times, such as when there are no pedestrians present. Because an electronically illuminated sign is more conspicuous than a static sign, the use of DNRTOR is anticipated to increase driver compliance with NRTOR compared to a static sign. The ability to permit RTOR at other times should permit the intersection to retain the efficiency benefit from RTOR when there are no conflicts. However, at present there is very little guidance regarding the use of blank-out NRTOR signs, and few studies of their potential effects.

1.2 Study Objectives

This study has three objectives:

1. Measure compliance rates for static and dynamic NRTOR signs. At present, there are few existing sources of information reporting compliance rates. This study examines these for intersections operated by Minnesota DOT.
2. Better understand maintenance requirements for operating DNRTOR signs. A practitioner survey is used to develop this information.
3. Develop recommendations on the use of DNRTOR signs, considering the potential operational objectives and outcomes from measurement of compliance rates and other field observations.

The results of the study should help signal operators make better informed decisions about the use of DNRTOR by better understanding the likely range of outcomes for future DNRTOR deployments and consider the potential effects in light of deployment and maintenance costs.

1.3 Report Organization

The second chapter of this report presents results of a literature review on RTOR and DNRTOR, including results from some previous studies that examined DNRTOR operation. The third chapter presents the details of the analysis undertaken in this study, including the data collection process, analysis of the data, and conclusions about compliance rates obtained from that data. The fourth chapter presents results of a survey on blank-out sign maintenance. The fifth chapter concludes the report by synthesizing the previous material and presenting recommendations from these results based on probable agency objectives.

Chapter 2: Literature Review

This chapter presents the results of a literature search on RTOR. At the time of the review, there were very few studies in the literature on DNRTOR signs specifically. However, there have been some studies on other strategies intended to serve similar purposes, including other conditional NRTOR treatments such as flashing yellow arrow (FYA) or leading pedestrian intervals (LPIs). This review examines the literature to gather insights on how the effectiveness of these treatments have been evaluated and what factors may have influenced their effectiveness.

2.1 Safety Impacts of Right Turn on Red

RTOR has been used in the US for many years. Prior to the 1970s, the status of the permissive right turn varied considerably by jurisdiction, with western states often allowing RTOR and eastern states prohibiting it. Many jurisdictions prohibited RTOR because of safety concerns (Jaleel, 1984). The oil crisis of the 1970s led to policy changes intended to reduce fuel consumption. In the Energy Policy and Conservation Act of 1975, Congress required states to change their traffic laws to allow RTOR to receive federal funds. Today, it is common for RTOR to be allowed by default at most intersections except where NRTOR signs are in use. Only a few locations in the US have areawide prohibitions of RTOR. New York City has had a RTOR prohibition for many years, and Washington, DC is currently implementing a citywide ban on RTOR after a recent city council decision.

Several studies have examined the impact of RTOR. One of the earliest was published by Mamlouk et al. (1976), who examined RTOR operation in Indiana. The authors concluded that RTOR had little adverse impact on motorist and pedestrian safety, while reporting reductions in both vehicle and pedestrian delays. The population of the community where the intersection was located, the number of lanes on the subject approach, and the existence of right turn only lane on the subject approach were found to be significant. The authors suggested criteria for prohibiting RTOR including sight distance, signal phasing, duration of red, the number of legs at the intersection, vehicular and pedestrian volume, among others. Some of the criteria mentioned in this early study may seem cautious in comparison to the widespread deployment of RTOR currently in effect.

In the 1980s, a DOT study (Preusser et al. 1981) estimated that RTOR led to an increase in pedestrian crashes from 43–107% while bicycle crashes increased by 72–123%. Another study by Zador (1984) estimated that allowing RTOR increased pedestrian and bicyclist crashes by about 60 and 100 percent respectively. These large percentage values are associated with small numerical increases in the crash counts. Chadda and Schonfeld (1985) performed a review and analysis of pedestrian safety problems resulting from allowing RTOR and suggested countermeasures. Numerous potential causes of pedestrian-RTOR vehicle crashes were examined in the study. Removal of unwarranted traffic signals, use of RTOR prohibition signs and angled stop bars, incorporating RTOR regulations in driver education curriculum and driver licensing tests, and developing and implementing school safety education programs were countermeasures suggested in this study.

In the mid-90s, NHTSA (1995) produced a report to congress that examined the impact of allowing RTOR, making use of the Fatal Accident Reporting System (FARS) data as well as crash report data from four states where a code for RTOR was available. The principal findings of the study are as follows:

- According to the FARS data, from 1982-1992, 84 fatal crashes involving right turn vehicles occurred at intersections where RTOR is allowed. However, the data does not reveal whether the crash occurred because of RTOR (i.e., it is not known whether the crash occurred because the vehicle was carrying out a RTOR maneuver). Over the same time period, 485,104 fatalities occurred in total in all crashes, so the number of potential RTOR fatal crashes was relatively small.
- The state crash data showed that RTOR crashes represent about 0.05% of all crashes and 0.06 of all fatal and injury crashes. However, according to the NHTSA summary, 93% of reported RTOR crashes involving pedestrians or bicyclists resulted in injury. About 1% of these resulted in fatal injuries, representing 0.2% of all fatal pedestrian and bicyclist crashes involving RTOR.

A 2002 study (Lord, 2002) on the safety of RTOR in the US and Canada concluded that, when examined broadly, the allowance of RTOR has little impact on motorist or pedestrian safety. The proportion of crashes resulting from RTOR is usually very low and such crashes are usually not severe. The study did not explore site-specific conditions where crashes were more frequent or severe, nor did the study examine countermeasures.

Researchers at Texas Southern University (Yi et al., 2012) investigated RTOR and concluded, based on a synthesis of the literature, that RTOR has a minor impact on intersection safety. This report also mentioned a 2005 document prepared by the City of Minneapolis entitled *No Turn on Red Implementation Guideline* that reportedly stated that RTOR was responsible for 0.1% of fatal pedestrian crashes and about 0.6% of all crashes at intersections in total, and that implementation of RTOR was associated with a slight increase in pedestrian crashes. However, a document produced by the City of Minneapolis having this title could not be found with a web search in December 2022.

A study of naturalistic driving data obtained in the Second Strategic Highway Research Program (SHRP 2) examined details of ten drivers' behavior at six intersections using records from 300 trips (Wu and Xu 2017). It was observed that RTOR drivers used more acceleration than those turning during green, although their average speeds were lower. The presence of pedestrians was associated with lower acceleration.

Overall, the consensus of the previous research would tend to lead the reader to conclude that RTOR presents a minimal safety issue, from there having been relatively few fatal/injury crashes associated with RTOR, compared to the total numbers of fatal/injury crashes.

Nevertheless, relative fatal/injury crash rates are not necessarily the only pertinent information from which the safety of RTOR operation can be evaluated. Although RTOR crashes are not associated with large numbers of fatalities, it is possible that the number of injuries may be underreported. Recent research (Oxley et al., 2018) has identified discrepancies between numbers of pedestrian injuries reported by law enforcement compared to the number of injuries treated by hospitals. Relevant crash reports are unlikely to be generated if the driver of the vehicle is not cited for a violation. Also, pedestrians involved in crashes may not realize that they are injured immediately after the crash and may not seek treatment until later.

Recently, the safe system approach has been increasingly adopted by transportation agencies. From this perspective, any number of fatal/injury crashes are considered unacceptable, even if they are relatively rare (USDOT, 2022). Recent FHWA research (Porter et al., 2021) applied the safe system approach to intersections, leading to development of a methodology that considers factors such as exposure, conflict points, conflict severity, and movement complexity. This research did not look at RTOR specifically, but it is clear that following the methodology would portray RTOR less favorably than previous studies which emphasized the relative rarity of RTOR crashes with severe outcomes. At the time of writing, an evaluation of RTOR using a safe system analysis has not yet been published. However, as the safe system approach continues to gain traction, it seems likely that a perspective which rejects the potential reduction in nonmotorized user safety associated with RTOR, no matter how small its effects, will become increasingly important. The recent city council decision of Washington, DC to eliminate most RTOR within the jurisdiction illustrates how this shift in perspective could influence policies on traffic control devices.

Some elements of the safe system approach represent a substantial divergence from current practice. For example, one core safe systems concept is that it is not considered acceptable to "tradeoff" safety for mobility or other benefits. However, agencies operate within constrained resources and with many stakeholders, and must ultimately achieve designs that are implementable and effective. The effect of adopting the safe systems approach on agency policies and practices has yet to be seen. This research helps provide recommendations on where to use dynamic blank-out NRTOR signs by identifying the amount of benefit that is likely to be yielded by their use. From there, decision makers may decide whether that benefit is reasonable (for which the "traditional" approach or the safe systems approach may lead to a different conclusion).

Although historically RTOR has not been considered problematic because of the relative infrequency of severe RTOR crashes, recent concerns about nonmotorized user safety seem likely to lead to reevaluations of RTOR. In this context, it is important to explore options besides unconditional permission or prohibition of RTOR. Different traffic control devices may be used to establish conditional RTOR, which may be able to better balance the need to protect nonmotorized road users while also preventing unnecessary delays to motor vehicle traffic when such users are not present at the intersection. The present research project takes on this problem by examining dynamic blank-out NRTOR signs in particular. The next section examines options available for configuring right turns at signalized intersections and reviews existing literature on the effectiveness of conditional RTOR treatments, including dynamic blank-out NRTOR signs.

2.2 Effectiveness of Conditional RTOR Treatments

Several options for configuring right turn movements at signalized intersections are possible, varying with the lane configuration, presence of islands and channelization, signal indication, and method of traffic control (Dixon et al., 2004). Possible right-turn lane configurations include shared, single, and dual right-turn lanes (more is possible, but rare). Channelization may enable separation of the right-turn movement from the rest of the intersection and, in some cases, using yield control or merging (i.e., the right turn might not be signalized). For right turns that are not channelized or where the degree of channelization does not permit separation from the rest of the signal, a decision must be made whether to always permit RTOR, conditionally permit RTOR, or always prohibit RTOR. A list of traffic control devices that can be used for these conditions is presented in Table 2.1.

Some previous studies have examined the effectiveness of some treatments that conditionally permit RTOR. However, there are relatively few studies that have examined dynamic NRTOR signs in detail, and very little information on cost and maintenance of the devices has been published. The remainder of this section presents studies were found in the literature search. Some discussion of previous study results on compliance with static signs is also included, to provide some additional perspective on overall driver NRTOR sign compliance.

In the 1980s, a FHWA study examined pedestrian safety at intersections with RTOR (Zegeer and Cynecki, 1985; Zegeer et al. 1985). The use of a dynamic blank-out NRTOR sign was one of the treatments tested. Blank-out signs were tested at several intersections in Michigan, with the following results:

1. At one intersection in a school zone where the authors had before and after data, the authors observed that 1.83% of motorists illegally made a RTOR when a standard RTOR sign was in place at the intersections, whereas only 0.2% were observed to do so when the blank-out sign was in use. The authors concluded that the electronic signs “virtually eliminated RTOR maneuvers during periods when children were present.”
2. At another intersection, 5.1% of drivers carried out illegal RTORs. The signs were illuminated by time of day. There seem to have been fewer pedestrians at this test location, and the authors report that no pedestrian interactions occurred.
3. At a third location, three different options were used with the blank-out sign, including (1) cyclic use when the opposing left turn phase was green; (2) continuous illumination of the sign; and (3) illumination of the sign only during the red interval. The rates of illegal RTOR maneuvers were 1.9%, 1.9%, and 2.9% for the three options respectively, with the standard RTOR sign having a rate of 2.6%. There tended to be more pedestrians during the times when compliance was higher.

This study also compared several other countermeasures, including the standard NRTOR sign as mentioned, along with several other options. The authors concluded that the dynamic NRTOR sign performed “slightly better” than the standard sign and suggest that it could be used to protect pedestrians during certain times of day or for preventing conflicts with opposing left turns during the relevant portion of the cycle. In addition to these specific countermeasures, the study also examined 110 signal approaches with ordinary NRTOR signs. About 2500 violations were observed from 67,347 right turn movements observed in the study, an overall violation rate of 3.7% per right turn vehicle. When considering only the right turns with an opportunity for RTOR (12,314 movements), the violation rate increases to 20.3% per right turn vehicle that had the opportunity to execute a RTOR.

Table 2.1 Options for controlling right turn movements

RTOR Policy	Right Turn Signal Head Configuration	Additional Traffic Control Devices	Description
Prohibit RTOR	3-section, circular red 5-section, circular red	NRTOR sign	RTOR is permitted when the red circular indication is displayed, unless a NRTOR sign is present.
		Enhanced NRTOR signs	Use of larger, multiple, or more conspicuous NRTOR signs.
	3-section, steady red right arrow	(None)	In Minnesota, RTOR is permitted where a red arrow display is present, when signed*. The laws of other states vary with regard to this.
Only allow RTOR from one lane (dual right turn)	(any)	Sign indicating RTOR from specified lane only	For locations with dual right turn lanes, it may be desired to only allow RTOR from one of the two lanes.
Conditionally Allow RTOR	(any)	Dynamic blank-out NRTOR sign	Right turns are prohibited when the sign is illuminated.
		NRTOR sign with supplemental sign about presence of pedestrians (Figure 2.1a)	Drivers are instructed to avoid executing the RTOR if there are pedestrians at the intersection.
		NRTOR sign with supplemental sign about time of day (Figure 2.1b)	Drivers are advised that RTOR is not permitted during certain times of day.
Allow RTOR (including methods intended to improve safety)	(any)	(None)	The default situation. In absence of a NRTOR sign, it is usually assumed that RTOR is allowed.
		Crosswalk relocation	Locate crosswalk where pedestrians are more visible to drivers and vice versa. May include added markings to increase pedestrian visibility.
		Stop bar relocation	Locate right turn stop bar in front of other traffic lanes on approach to permit driver to more easily view conflicting vehicular traffic.
		Signs indicating: RTOR must yield to U-turn, Yield to Pedestrians, etc.	Increase driver awareness of conflicting demands.
		Sign indicating RTOR allowed after stop	Remind drivers that they are supposed to stop before executing RTOR.
Enhanced right turn signaling (RTOR may or may not be allowed)	3-section, 4-section, or 5-section with flashing yellow right arrow	"Right Turn Signal" sign is recommended by MUTCD (FHWA, 2009)	The right-turn movement is permitted without stopping when the flashing yellow arrow (FYA) is displayed.
	3-section or 5-section with green right arrow		The right-turn movement is protected when the green right arrow is displayed.
	Flashing red arrow		Intended to inform drivers that RTOR is allowed (Zegeer et al., 1985)

*From Minnesota State Statute 169.06 (emphasis added): "*Vehicular traffic facing a steady red arrow signal*, with the intention of making a movement indicated by the arrow, *must stop* at a clearly marked stop line… and must remain standing until a permissive signal indication permitting the movement indicated by the red arrow is displayed, except as follows: *when an official sign has been erected permitting a turn on a red arrow signal*, *the vehicular traffic facing a red arrow signal indication is permitted to enter the intersection to turn right*, or to turn left from a one-way street into a one-way street on which traffic moves to the left, *after stopping*, but must yield the right-of-way to pedestrians and other traffic lawfully proceeding as directed by the signal at that intersection."

(a) Reminder for drivers to yield to pedestrians.

(b) Time-of-day prohibition.

Figure 2.1 Examples of "NO TURN ON RED" signs with supplemental signage

A study by Insurance Institute of Highway Safety researchers examined effects of static NRTOR signs that included a note that the maneuver is prohibited when pedestrians are present, or by time of day (Retting et al., 2002). Field observations were made at 15 intersections, with different types of signs used at different sites ("control" sites, which appear to be locations where RTOR is allowed, and NRTOR signs with supplemental signs). Observations were made before and after the installation of the NRTOR signs. The researchers found that the "when pedestrians are present" NRTOR sign had about three times the number of RTORs compared to time-of-day prohibitions. The number of RTOR observations was not adequate to perform a statistical comparison.

Dynamic NRTOR signs (called "ITS No Turn on Red" signs) were included in a FHWA-sponsored study on pedestrian safety improvements in the Las Vegas area. The signs were installed at one intersection along with others (high visibility crosswalk and a pedestrian countdown signal modified to show animated eyes) in staged deployments. The addition of the dynamic NRTOR signs was observed to increase the proportion of pedestrians looking for conflicting vehicles from 86% to 96%. In addition, the percent of drivers making complete stops increased (Nambisan et al., 2008).

Researchers at University of Massachusetts Amherst investigated driver comprehension of various traffic control devices, including red arrows, flashing yellow arrow (FYA), and dynamic NRTOR signs (Knodler et al., 2017; Casola 2018; Ryan et al., 2019). This study included two hundred participants and included survey and driving simulation studies. The participants were first asked to indicate the meaning of traffic control devices given a variety of scenarios. Most participants clearly understood the illuminated dynamic NRTOR sign, with about 80% correctly identifying that the RTOR is permitted when the sign is not active and only 7% incorrectly responded that RTOR is permitted when the message was visible. A statistical comparison of responses for different device types found no significant statistical difference between the static and dynamic NRTOR signs in terms of driver comprehension (Knodler et al., 2017). The driving simulator component of the study had drivers do ten passes through an intersection with FYA and dynamic NRTOR signs. Vehicle speeds were found to significantly decrease with the use of FYA (Casola 2018). A similar test does not appear to have been done using dynamic NRTOR signs.

A Florida DOT study (Lin et al., 2019) investigated driver responses to pedestrian treatments at intersections, including a variety of options including various messages implemented as both static and blank-out signs. These were tested in several different regions of Florida. Several messages for both static and dynamic signs were tested. For the dynamic NRTOR signs, a message stating that drivers must yield to pedestrians increased driver compliance at three different locations, with percentage compliance increasing at these locations from 59.7% to 73.9%, 81.8% to 87.8%, and from 65.2% to 83.4%. On the other hand, at a different location, the use of the graphical symbol for "No Right Turn" with no accompanying text on a blank-out sign was found to be less effective than the use of a static NRTOR sign. Driver compliance decreased from 90.9% to 75.2% at the location where this sign was used. Images of the tested blank-out signs are included in Figure 2.2. The study concluded that more driver education was needed to improve comprehension of the "No Right Turn" sign. It could probably also be speculated that drivers may have been confused about whether the indication means that right turns are always prohibited or if they are supposed to wait until the sign blanks out before executing the movement. Addition of a clarifying message might have increased compliance.

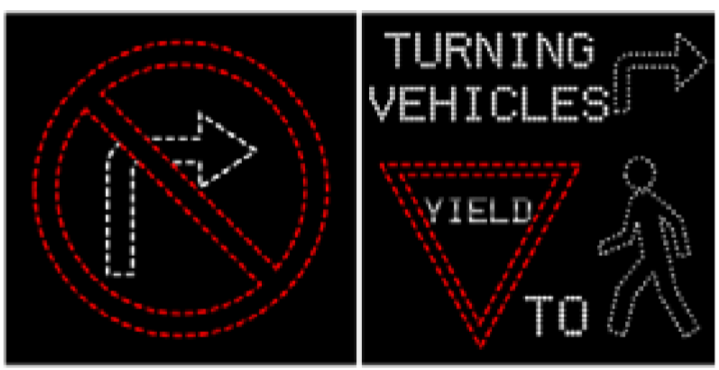


Figure 2.2 Dynamic blank-out signs tested by Florida DOT (Lin et al., 2019).

NCHRP study 15-63 developed guidance on pedestrian and bicycle safety treatments, which included geometric improvements and use of traffic control devices (Sanders et al., 2020). The guidance includes several 2-page information sheets on a variety of treatments. Static and dynamic NRTOR signs are included together as one of the potential treatments. The authors mention that "preliminary research" found increased driver compliance with the use of dynamic signs; this remark is accompanied by a citation of NCHRP Synthesis 498 (Thomas et al. 2016). This may be referring to anecdotal reports from agencies surveyed for that synthesis, since the cited synthesis report does not include data to substantiate the claim of increased driver NRTOR compliance.

In summary, six studies were found in the literature that included an examination of some aspect of dynamic NRTOR signs. However, only two of these studies included field results on right-turn driver compliance with the NRTOR indication. Both of these studies included before-after comparisons. One of these was carried out in Michigan in the 1980s and suggested that the blank-out signs may provide better compliance, especially near school zones. A 2019 Florida study examined before-after treatments at four locations; three of these saw improved compliance rates while another location had a lower compliance rate. Reduced compliance at this location was attributed to poor driver comprehension of the use of a graphical "No Right Turn" symbol (Figure 2.2, left image) at that location, whereas the other locations used textual messages. Since these were both before-after comparisons, it is not clear whether the improvements in driver compliance after the installation of a dynamic NRTOR sign are sustained over long periods of time. That is, it is unclear whether such devices retain their effectiveness after they have been used at a location for a long time.

2.3 Conclusion

This chapter presented a literature review on dynamic NRTOR signs. First, a brief review was presented on the impacts of RTOR, highlighting several studies on the safety of RTOR which have established the prevailing consensus about the maneuver being relatively unhazardous because it is associated with relatively few fatal/injury crashes, and how recent initiatives such as the adoption of the safe system approach may change this consensus.

Next, papers specific to the effectiveness of dynamic blank-out NRTOR signs were reviewed. Although there are several additional papers which mention that dynamic NRTOR signs are an option for controlling right turn movements, a total of six studies that included a substantial analysis or at least some statement of the effectiveness of dynamic NRTOR signs were included. Most of these studies indicate that the devices can increase compliance, but only two studies presented compliance data. One study reported a decrease in driver compliance at one location, which was attributed to driver miscomprehension. The existing studies on compliance were before-after evaluations and it is not clear whether the improvements in driver compliance may be due in part to the novelty of a recently installed dynamic NRTOR sign.

From this review it may be concluded that more research on the effectiveness of dynamic NRTOR signs is needed. The present research project contributes to this area of study by performing a comparison of driver compliance between different right-turn treatments at similar intersections where the signs have been installed and in place for a relatively long time. In addition, the literature review did not uncover previous reports of the cost-effectiveness or maintenance requirements specific to dynamic NRTOR signs. Results of a survey on DNRTOR sign maintenance is presented in the fourth chapter of this report.

Chapter 3: Evaluation of Driver Compliance with Dynamic and Static NRTOR Signs

This chapter presents results of a field evaluation of driver compliance with dynamic and static DNRTOR signs. Data were collected at eight signalized intersections in the greater Minneapolis-St. Paul area, including six with DNRTOR signs and two with static signs. Video was collected at the intersections. Most of the DNRTOR sign locations used pedestrian-activated display of the NRTOR indication, so high-resolution traffic signal event data was used to help identify time periods of interest. A combination of manual and automated analysis was used to reduce the data and calculate compliance rates. The rates are presented, followed by a statistical analysis to identify the significance and effects of different factors on compliance. Compliance rates are explored in terms of per-cycle and per-vehicle analyses. The chapter concludes with a summary of the main findings.

3.1 Video Data Collection

3.1.1 Selection of Study Sites

Study sites were selected in consultation with the technical advisory panel. The selection of DNRTOR locations was relatively straightforward, because such locations were easily located from intersections operated by Minnesota DOT. Most of these locations were pedestrian-activated, with one location also having the DNRTOR signs active by time of day (TOD). In addition to six DNRTOR locations, two other locations with static signs were included.

The relative rarity of conflicting pedestrian actuations influenced the data collection methodology. Because conflicting pedestrian actuations were relatively rare, with a few dozen actuations per day occurring at the DNRTOR intersections, it was not feasible to use field data collection equipment, since battery life limited its use to no more than 24 hours at a time. To observe a sufficient number of ped-activated NRTOR intervals, data would need to be collected over several weeks. Initially, it was attempted to use the network of pan-tilt-zoom (PTZ) cameras deployed at intersections and at freeway locations near some of the intersections of interest. However, this strategy proved to be challenging to implement for two reasons. First, the freeway cameras were often required to monitor developing conditions on the freeway system, and thus consequently would be moved away from the study intersections without prior notice. Secondly, the PTZ cameras deployed at the intersections were mounted directly above the right-turn movement of interest, so the relevant movement could not be captured in the field of view.

A solution to this problem was to use streaming video from the video detection systems (VDS) available at the intersections. Although the DNRTOR sign itself was not included in the field of view, its operation could be identified with the use of high-resolution data, which logged the times when the Walk indication came on. This proved not only to be convenient but essential for finding the video times when the DNRTOR was active. The PTZ camera video available from some of the sites was used to validate the assumption about the active DNRTOR indication being coincident with the display of the Walk indication. High-resolution data is a set of timestamped signal changes, including when the vehicular and pedestrian indications change, among other events (Smaglik et al., 2007). This data is primarily used for performance measures (Day et al., 2014). Minnesota DOT was one of the first agencies to collect this data (Liu et al., 2009). In recent years, the performance measurement methodology has become packaged into open-source and commercial software packages under the name "Automated Traffic Signal Performance Measures" (ATSPM). The supporting high-resolution data was available for all six DNRTOR locations included in the study, and was logged by the controllers at the intersection.

It was challenging to find static sign locations with similar road geometry as the DNRTOR locations. Most of the DNRTOR locations were interchanges, but there were few interchanges having static NRTOR signing, mostly because of the lack of sight distance restrictions at most interchanges that would have required NRTOR. Ultimately, two locations were identified that featured static NRTOR signs.

The eight selected study locations are listed in Table 3.1.

Table 3.1 Data collection locations.

Location	Subject Approach	Right-Turn Treatment	GPS Coordinates
I-494 & Rockford Rd., East Ramp	Northbound	Dynamic NRTOR (ped-activated)	45.02821, -93.45143
I-494 & Rockford Rd., West Ramp	Southbound	Dynamic NRTOR (ped-activated)	45.02895, -93.45387
US 12 & Hwy 101, North Ramp	Westbound	Dynamic NRTOR (ped-activated and TOD)	44.97603, -93.50208
TH 65 & 81st St	Westbound	DNRTOR (ped-activated)	45.11503, -93.24159
TH 36 & Fairview Ave North Ramp	Westbound	Dynamic NRTOR (ped-activated)	45.01129, -93.17649
TH 36 & Fairview Ave South Ramp	Westbound	DNRTOR (ped-activated)	45.00915, -93.17664
TH 81 & Elm Creek Blvd	Northeastbound	Dynamic NRTOR (ped-activated)	45.13114, -93.44289
I-35W & 66th St East Ramp	Northbound	Dynamic NRTOR (ped-activated)	44.88343, -93.29540

3.1.2 Video Data Collection

At six of the eight intersections listed in Table 3.1, streaming video from the VDS were recorded by the research team. It proved to be possible to record video at all locations in parallel using a single PC. The free video software package "PotPlayer" was used for this purpose because it was able to automatically truncate the recorded video clips into clips of a predefined length while continuing to record. Individual video recordings were 1 hour in length, and there was no loss of video in transitioning from one recording to the next.

Streaming VDS video was collected from four intersections with DNRTOR signs for approximately two weeks in June 2023. Additional video was recorded in September-October 2023 for the same locations, along with two additional intersections with DNRTOR signs (the TH 36 & Fairview Ave ramps). Finally, data was obtained from the two locations with static NRTOR signs. At I-35W & 66th St, the VDS video could not be streamed, so an external hard drive was placed on site to record locally. At TH 81 & Elm

Creek Blvd, a field data collection setup was used. This consisted of an Insta360 X3 camera mounted on a pole temporarily mounted to a local sign, as shown in Figure 3.1. With the use of a portable battery, data were collected for approximately 24 hours from this location with the use of this setup. One battery changeout was required.

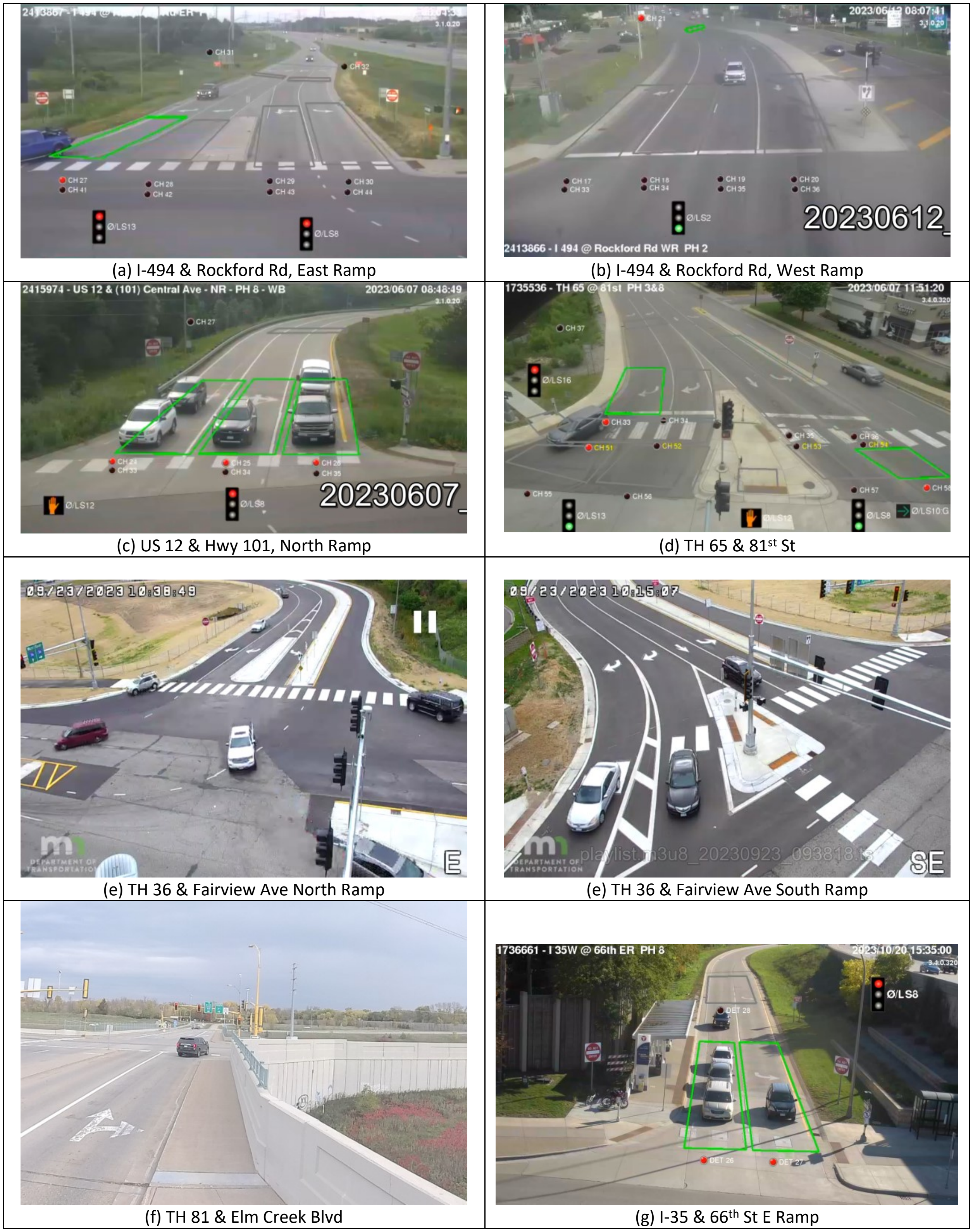
Figure 3.1 Example view of field data collection setup used at TH 81 & Elm Creek Blvd.

Table 1 shows a summary of the data collected during Task 3, including the locations, the type of right-turn control, type of video data collected, and the amounts of video data obtained from each site. Example views from the VDS video are shown in Figure 3.2. Altogether, over 4500 hours of video (approximately 4 TB of data) were obtained from all locations.

Table 3.2 Summary of data collected during this study.

Location	Right-Turn Treatment	Type of Video Data Collected	Data Collection Times	Hours of Video Data
I-494 & Rockford Rd, East Ramp	Dynamic NRTOR (ped-activated)	VDS	6/12/23–6/24/23 9/21/23–10/13/23	832
I-494 & Rockford Rd, West Ramp	Dynamic NRTOR (ped-activated)	VDS	6/12/23–6/24/23 9/21/23–10/13/23	826
US 12 & Hwy 101, North Ramp	Dynamic NRTOR (ped-activated and TOD)	VDS	6/7/23–6/24/23 9/21/23–10/13/23	908
		PTZ*	6/21/23–6/24/23	86
TH 65 & 81st St	Dynamic NRTOR (ped-activated)	VDS	6/12/23–6/24/23 9/21/23–10/13/23	804
		PTZ*	6/21/23–6/24/23	89
TH 36 & Fairview Ave North Ramp	Dynamic NRTOR (ped-activated)	PTZ	9/21/23–10/14/23	529
TH 36 & Fairview Ave South Ramp	Dynamic NRTOR (ped-activated)	PTZ	9/21/23–10/14/23	529
TH 81 & Elm Creek Blvd	Static NRTOR (24 hours)	Field Camera	10/17/23–10/18/23	24
I-35W & 66th St East Ramp	Static NRTOR (6 am – 10 pm)	VDS	9/21/23–10/14/23	167

* PTZ views were not continuously pointed at the intersection. The field of view was occasionally moved to the freeway. The video collected with the PTZ cameras is redundant with the VDS video and was used to validate the blank-out sign operation.



(a) I-494 & Rockford Rd, East Ramp

(b) I-494 & Rockford Rd, West Ramp

(c) US 12 & Hwy 101, North Ramp

(d) TH 65 & 81st St

(e) TH 36 & Fairview Ave North Ramp

(e) TH 36 & Fairview Ave South Ramp

(f) TH 81 & Elm Creek Blvd

(g) I-35 & 66th St E Ramp

Figure 3.2 Example views from video data. Multiplexed VDS images have been cropped to show the subject right turn only.

3.2 Video Data Observations

3.2.1 Data Validation

The first step in evaluating the video data was to ensure that the video record of events aligned with the high-resolution data, and to check that the DNRTOR operation followed assumptions that the display of the NRTOR message was coincident with the display of the Walk and Flashing Don't Walk indications for the pedestrian movement conflicting with the right-turn movement of interest. The high-resolution data was checked by comparing the event data with times of day where the pedestrian signal indications could be clearly seen in the video (i.e., when lighting conditions did not preclude direct visual observation).

It was found that although the high-resolution data timestamps and video timestamps did experience some drift, usually the amount of clock drift was less than 10 seconds. Additionally, the Start of Walk event was found to be reliably recorded in the high-resolution data. Numerous instances of the Start of Walk times were cross-referenced against video where the Walk indication could be clearly seen to confirm that the event timestamp correlated to a time when the phase actually came on in the field. This was done for all six DNRTOR locations. During other times of day when the pedestrian indications could not always be clearly seen in the video, there was usually evidence of pedestrian demand, and other observable phase events could be used to identify the start and end of the DNRTOR interval. Observations of the limited amounts of PTZ video available from selected locations where it was coincident with VDS collection confirmed that the NRTOR message turned on at the same time as Walk started, and the sign blanked out at the same time that the Flashing Don't Walk interval came to an end.

3.2.2 Observations of Pedestrian-Activated DNRTOR Sign Operation

High-resolution data was obtained for the data collection periods of interest for the six intersections with DNRTOR. Because these were mostly under ped-activated control (with the exception of one intersection that also used TOD control), the only times when the NRTOR indications were active was when the conflicting pedestrian phase was active. Thus, the starting point for evaluating driver compliance was to find the signal cycles where the conflicting pedestrian phase showed a Walk indication.

High-resolution data was obtained from the same dates as video collection for the six DNRTOR locations (see Table 3.2). After merging and filtering the event data, a total of 2,274 pedestrian actuations were identified. A total of 4428 hours of VDS video were recorded from the six DNRTOR locations, which demonstrates the relative rarity of the events; there was one actuation for every two hours of video, approximately. Because these events were relatively rare among the many hours of video collected, it was unlikely that the Walk event in one cycle could have been mistaken for one in a preceding or subsequent cycle. Of the 2274 start of Walk events recorded, there were less than 90 occurrences where two relevant Walk events occurred within 120 seconds of each other, and less than six occurrences where more than two start of Walk events occurred in subsequent cycles.

For the DNRTOR locations, the start of Walk time from the high-resolution data became the key index time for indicating cycles of interest. Other pedestrian events could be deduced from this event time, because the duration of the Walk and subsequent Flashing Don't Walk intervals were constant throughout all times of day. This initially assumed operation was confirmed by extensive observation of video from various times of day, as well as examination of the signal timing plans. These plans indicated that a "Rest in Walk" arrangement was not used at the sites. Furthermore, the through movements at the intersections were not configured as "Call to Non-Actuated" phases. Such a configuration would have caused the duration of the Walk interval to have been automatically extended (as "Walk Hold") during coordinated operation. This was fortunate, because it was found that some other events in the high-resolution data, including the end of the Walk interval, were not always recorded reliably.

Because the high-resolution data issue indicated that care would be needed in each cycle to visually confirm the events, and because the relevant events were distributed across hundreds of separate video files comprising several terabytes of video data, the research team decided to proceed with the analysis of the DNRTOR video data using a manual process. A team of four observers was organized to manually extract the relevant observations from the locations where ped-activated DNRTOR indications were used. The observation process is described below:

1. Identify the start of Walk from the high-resolution data.
2. Open the relevant video file and go to the time of interest. Identify the start of Walk in the video.
3. Watch the video during the subsequent Walk and Flashing Don't Walk intervals.
4. Count the number of right-turn vehicles present on the movement during the Walk and Flashing Don't Walk intervals and note any vehicles that execute the right turn (i.e., NRTOR violations). Record the time when the first right turn movement takes place. Note any conflicts with pedestrians or other notable occurrences.

The reason for recording the time of the first right turn movement was to determine whether an analysis of that data would agree with a preliminary anecdotal observation that the RTOR drivers seemed to at least wait until the conflicting pedestrian traffic was out of the way. It was hypothesized that the RTOR movement times might be concentrated around the start of Walk and later in the Flashing Don't Walk intervals.

3.2.3 Observations of Static NRTOR and TOD-based DNRTOR Sign Operation

In contrast with the ped-activated DNRTOR locations, the location with DNRTOR activation by TOD (US 12 & Hwy 101) and the control locations with static NRTOR signs could more readily be adapted to automated extraction of the event data. The reason for this was that because there were not supposed to be any RTOR vehicles during any cycle, and the red indication was easily identified in the video views (either as an overlay, or because it was in the field of view at TH 81 & Elm Creek Blvd), meaning that there was no need to cross-reference the video with the state of a conflicting pedestrian phase. Thus, a single video could be processed in its entirety in order to extract as much data as desired. Enough video for these locations were

One of the locations used video recorded in the field by the research team. While the right turn traffic and the signal heads controlling the right turn movement are both clearly visible in the field of view, because of the smaller amount of data from this location and the fact that the signal head is rather small and consequently its state was difficult to be automatically extracted, it was decided to manually process the video recorded at that location using the same method as for the other locations.

Several iterations of the automated process were tested before a working procedure that yielded all required data could be fully developed. One limitation of existing packages is that the object identification method was not initially able to correctly differentiate between different signal states (i.e., red, yellow, or green). It was found that this could be accomplished using the video detection system data, which contained overlays showing the signal state that were always in the same position on screen, and for which the red/green/blue values of the pixels corresponding to the red aspect of the signal head could be extracted to determine whether the signal was red or not. By the time this process was finalized, the project timeline was approaching the deadline for final deliverables. Because the automated process requires extensive processing time, to complete data reduction in a timely manner, the automated process was ultimately used for data from US 12 & Hwy 101 during TOD operation, while data from the final location (I-35 & 66th St) was evaluated by manual observation.

3.2.4 Summary of Video Data Observations

Table 3.3 presents a summary of the amounts of data for the study locations, in terms of the number of signal cycles containing an interval where NRTOR was in effect, either because of a pedestrian phase actuation that would have caused the DNRTOR sign to be lighted, or because of a red interval with a static NRTOR sign or TOD operation of a DNRTOR sign. For the locations with ped-activated DNRTOR, the cycles were identified from the high-resolution data, while for other locations the cycles were identified directly from the video.

There were some cycles that had to be excluded for reasons explained below. To better illustrate this breakdown, Figure 3.3 shows the numbers of cycles pertaining to these categories.

1. To begin, there were 2,274 cycles identified in the high-resolution data corresponding to relevant pedestrian phase actuations. There were 1,103 cycles from the locations with TOD-based DNRTOR operation or static NRTOR signs. Therefore, there were 3,377 cycles among all the data processed to date.
2. About 777 cycles did not have usable video data. For some locations, the streaming video intermittently became unavailable. At one location (TH 65 & 81st St), one of the four multiplexed screens containing the subject right-turn movement would intermittently become frozen. This location accounted for most of the cycles without usable video. The other cycles without video were due to temporary issues with data recording or differences in the start/end times of video data collection and the high-resolution data.
3. Of the 2,600 remaining cycles having available video, there were 253 cycles that had no right-turn traffic, so there was no contribution to the compliance rates. This number also includes cycles at locations with shared through-right lanes where the first vehicle in that lane was a through

vehicle, so there was no opportunity for RTOR. All such cycles were excluded from subsequent analysis.

Compliance rates were calculated only for the remaining 2,347 cycles where there was right-turn traffic. Among these, there were 1,566 cycles in which no violation of the NRTOR sign took place, while there were 781 cycles in which a violation did take place. The next section explores the compliance results in greater detail.

Table 3.3 Summary of video data (number of signal cycles; HRD = high-resolution data).

Location	Left-Turn Treatment		Cycles From HRD	Cycles From Video	No Video	No RT Traffic	Usable Cycles
TH 36 & Fairview N Ramp	Dynamic	Ped-Activated	346	-	38	47	261
TH 36 & Fairview S Ramp	Dynamic	Ped-Activated	288	-	21	8	259
TH 65 & 81st St	Dynamic	Ped-Activated	616	-	547	18	51
I-35 & Rockford Rd W Ramp	Dynamic	Ped-Activated	314	-	111	13	190
I-35 & Rockford Rd E Ramp	Dynamic	Ped-Activated	266	-	0	27	239
US 12 & Hwy 101 N Ramp	Dynamic	Ped-Activated	444	-	60	75	309
		TOD	-	329	0	5	324
TH 81 & Hwy 610 (Elm Creek Blvd)	Static	24-hours	-	555	0	59	496
I-35 & 66th St E Ramp	Static	10am-6pm	-	219	0	1	218
		Total	**2274**	**1103**	**777**	**253**	**2347**

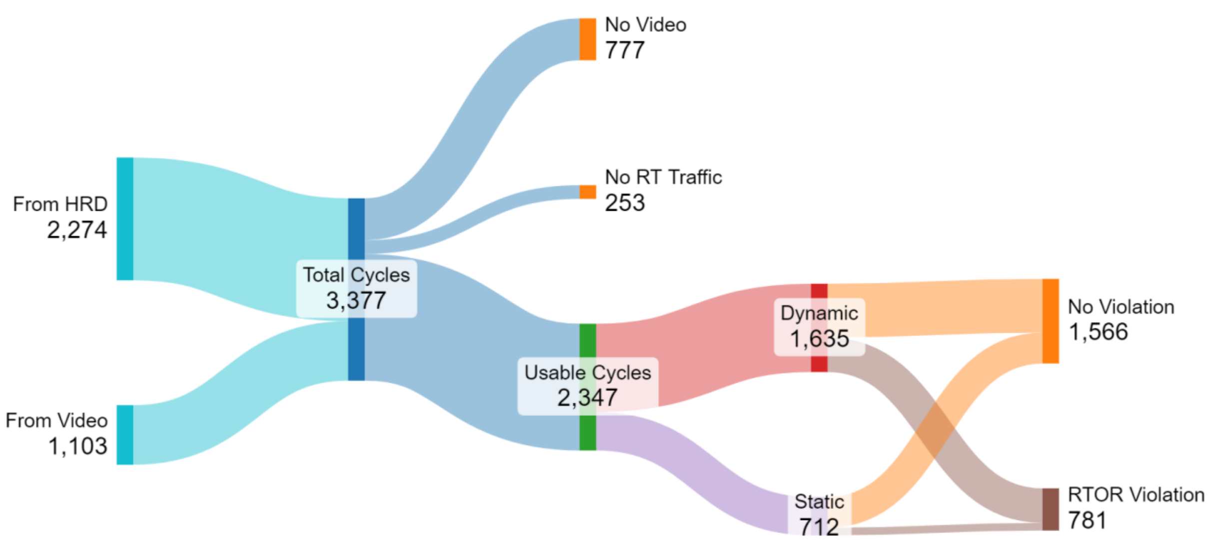


Figure 3.3 Diagram showing the breakdown of data (HRD = high-resolution data).

3.3 Evaluation of Driver Compliance

3.3.1 Comparison of Compliance Rates

Driver compliance rates are shown in Table 3.4 and Table 3.5 respectively for per-cycle and per-vehicle calculations. The per-cycle compliance results show whether any given signal cycle contains at least one vehicle that executed the RTOR in violation of the NRTOR indication. The "percent compliance" data in Table 3.4 shows the likelihood that a signal cycle at the listed location was free of any RTOR violation from the subject movement during the analyzed time periods. The per-vehicle results show the compliance rates in terms of the amounts of right-turning traffic that were present during the red intervals. Thus, these percentage compliance rates reflect the compliance among traffic that had an opportunity to execute a RTOR movement.

Table 3.4 Summary of per-cycle NRTOR compliance results.

Location	Left-Turn Treatment		No Violation	Violation	Percent Compliance
TH 36 & Fairview N Ramp	Dynamic	Ped-Activated	167	94	64.0%
TH 36 & Fairview S Ramp	Dynamic	Ped-Activated	98	161	37.8%
TH 65 & 81st St	Dynamic	Ped-Activated	37	14	72.5%
I-35 & Rockford Rd W Ramp	Dynamic	Ped-Activated	143	47	75.3%
I-35 & Rockford Rd E Ramp	Dynamic	Ped-Activated	104	135	43.5%
US 12 & Hwy 101 N Ramp	Dynamic	Ped-Activated	245	64	79.3%
		TOD	199	125	61.4%
TH 81 & Hwy 610 (Elm Creek Blvd)	Static	24-hours	421	75	84.9%
I-35 & 66th St E Ramp	Static	10am-6pm	150	68	68.8%
Dynamic, Total			**993**	**640**	**60.8%**
Static, Total			**571**	**143**	**80.0%**

Table 3.5 Summary of per-vehicle NRTOR compliance results.

Location	Left-Turn Treatment		Total RT Vehicles*	Violating Vehicles	Percent Compliance
TH 36 & Fairview N Ramp	Dynamic	Ped-Activated	855	123	87.4%
TH 36 & Fairview S Ramp	Dynamic	Ped-Activated	1265	343	78.7%
TH 65 & 81st St	Dynamic	Ped-Activated	142	17	89.3%
I-35 & Rockford Rd W Ramp	Dynamic	Ped-Activated	610	70	89.7%
I-35 & Rockford Rd E Ramp	Dynamic	Ped-Activated	775	222	77.7%
US 12 & Hwy 101 N Ramp	Dynamic	Ped-Activated	840	74	91.9%
		TOD	2586	199	92.9%
TH 81 & Hwy 610 (Elm Creek Blvd)	Static	24-hours	1564	86	94.8%
I-35 & 66th St E Ramp	Static	10am-6pm	760	105	87.9%
Dynamic, Total			**7073**	**1048**	**87.1%**
Static, Total			**2324**	**191**	**92.4%**

*During the red interval.

Overall compliance rates are as follows: 38–85% of cycles were free of NRTOR violations, while 77–93% of right-turn vehicles with the opportunity for RTOR did not execute a RTOR movement and therefore complied with the NRTOR indication. The static sign locations had higher compliance rates for both per-cycle and per-vehicle tabulations. There was a greater difference in the per-cycle numbers, while per-vehicle numbers were more similar.

At the US 12 & Hwy 101 location, which had both TOD-based and ped-activated DNRTOR, the compliance rates differed with respect to the type of operation depending on how it was tabulated. There was a greater percent of cycles without violations with ped-activated control compared to TOD control, but there were slightly fewer violating vehicles during ped-activated control. The reason for this disparity may be because TOD operation coincided with peak hours, whereas ped-activated operation was distributed throughout other times of day. Thus, whereas a cycle would be marked as containing a violation even if only one vehicle in a given cycle executed the RTOR, so the higher amounts of traffic during TOD operation may have increased the likelihood that at least one vehicle would turn right on red, even though most of the vehicles complied with the NRTOR sign.

3.3.2 Statistical Analysis

To determine the significance of the observed differences, and to better understand the relative strength of the effect on compliance due to the type of sign used compared to other intersection features, some statistical analysis of the data was undertaken, as described in this section.

3.3.2.1 Odds Ratio and Chi-Square Tests

Odds ratio and chi-square tests were used to evaluate the results. Table 3.6 presents the outcomes of the tests for the per-cycle (Table 3.6a) and per-vehicle (Table 3.6b) data. The odds ratio focuses on the ratio of the odds that RTOR took place under the two different treatments. For example, with the per-cycle data, the odds of any cycle under dynamic NRTOR control having a RTOR versus not having a RTOR is 640 to 993, or 64.5%, whereas for static control the odds are 143 to 571, or 25.0%. Thus the odds ratio is equal to 64.5 / 25.0 = 2.8. This indicates that the odds are 2.6 times greater for a cycle to have at least one RTOR vehicle with a dynamic sign when compared to use of a static NRTOR sign. Similarly, an odds ratio of 1.8 for per-vehicle data means that the odds are 1.8 times greater for any given vehicle to execute a RTOR for dynamic versus static sign use. The 95% confidence intervals are also presented, showing the likely range of values of the odds ratio.

The statistical significance of the results was tested using the chi-square test. Both per-cycle and per-vehicle data yielded chi-square test values greater than the critical value of 3.84 for a 2×2 contingency table with one degree of freedom and 95% confidence level, indicating that the results are statistically significant.

Table 3.6 Odds ratio and chi-square test results.

Observations	(a) Per-Cycle Test		(b) Per-Vehicle Test	
	Dynamic NRTOR	Static NRTOR	Dynamic NRTOR	Static NRTOR
RTOR	640	143	1048	191
No RTOR	993	571	7073	2324
Odds	64.5%	25.0%	14.8%	8.2%
Odds Ratio	2.6		1.8	
Odds Ratio 95% Confidence Interval	[2.08, 3.19]		[1.53, 2.13]	
Chi-Square Test Value	81.205 (P < 0.001)		52.101 (P < 0.001)	

3.3.2.2 Statistical Models

Two regression models were estimated to derive some additional insights about the effect of the type of NRTOR sign used, along with other variables reflecting other site conditions, the overall amount of traffic, and day-of-week effects:

- Use of Dynamic Sign: Indicator variable equal to 1 if a dynamic sign was used, or 0 if a static sign was used
- Time-of-Day-based NRTOR: Indicator variable equal to 1 if TOD operation was used (either under dynamic or static sign), and 0 if not
- Total RT vehicles: The total number of vehicles having an opportunity for RTOR
- Number of Conflicting Approach Through Lanes: The total number of through lanes on the vehicular through movement that conflicts with the subject right-turn movement
- Presence of Conflicting approach Right-Turn Lane: An indicator variable equal to 1 if the conflicting vehicular through movement also contained a right-turn-only lane, or 0 if not
- Presence of Opposing Left-Turn Movement: An indicator variable equal to 1 if there was a conflicting left turn movement, and 0 if not.
- Day-of-week indicator variables were not found to be significant in either model.

A logistic regression model was estimated to predict whether a signal cycle will have at least one RTOR vehicle. That is, the dependent variable was the indicator variable equal to 1 if there was at least one RTOR vehicle during red, and 0 if there were none. Logistic regression is used to estimate probability, making it appropriate for such an indicator variable. Table 3.7 shows the results of this model. The coefficient estimates are helpful to examine. A positive coefficient indicates that the variable is associated with a greater likelihood of RTOR while a negative coefficient indicates that it is associated with a smaller likelihood of RTOR. Overall, the results appear to be reasonable. As the amount of right-turn traffic increases, the likelihood of having at least one RTOR in a cycle should also increase, while a greater number of lanes on a conflicting movement also yields more RTOR, since the conflicting traffic is spread out into more lanes, increasing the number of gaps for the RTOR movement. The presence of another movement (in this case, the opposing left) would reduce the number of gaps, and the negative coefficient shows this effect in the model. Use of TOD operation and use of a static sign both have positive coefficients and are therefore associated with a greater likelihood of RTOR. All of the variables were significant.

Table 3.7 Logit model estimated for a dependent variable indicating whether a signal cycle under NRTOR will have one or more RTOR vehicles.

Independent Variable	Coefficient	Std. Err.	Z-value	P-value
(Intercept)	–2.75038	0.41103	–5.839	*** < 0.001
Use of Dynamic Sign	0.83561	0.16033	5.212	*** < 0.001
Time-of-Day-based NRTOR	0.40851	0.19466	2.099	*0.036
Total right turn Vehicles	0.06331	0.01783	3.551	*** < 0.001
Number of Conflicting Approach Through Lanes	0.39548	0.14059	2.813	**0.005
Presence of Conflicting Approach Right-Turn Only Lane	1.31447	0.17924	7.334	*** < 0.001
Presence of Opposing Left-Turn Movement	–1.36607	0.17358	–7.870	*** < 0.001

***significant at 99.9%; **significant at 99%; *significant at 95%

Next, a Tobit regression model was estimated that used a dependent variable equal to the percentage of violating vehicles in a cycle. This dependent variable has a possible range of [0%, 100%], meaning that the data is "censored" in that certain ranges are not possible. Tobit regression can be used with this type of dependent variable. Table 3.8 shows the results of this model. Again, a positive coefficient is associated with a greater number of RTOR vehicles while a negative coefficient is associated with fewer RTOR vehicles. While estimating this model, the total amount of right-turn traffic was not found to be significant, so that variable was removed. The effects of the remaining variables are quite similar to the logistic regression model. The use of a dynamic sign and TOD operation are both associated with a greater percentage of violating vehicles. More lanes on the conflicting through movement approach are associated with a greater percentage of violating vehicles while the presence of an opposing left-turn movement is associated with a smaller percentage. All of the variables were significant although the use of time-of-day NRTOR indications was only weakly significant.

Table 3.8 Tobit regression model estimated for a dependent variable indicating the percentage of violating vehicles during a cycle under NRTOR.

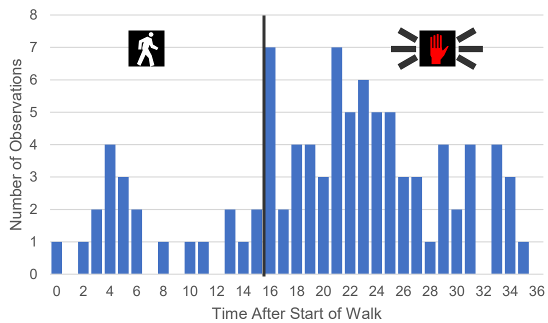
Independent Variable	Coefficient	Std. Err.	Z-value	P-value
(Intercept)	–0.98243	0.21444	–4.581	*** < 0.001
Use of Dynamic Sign	0.34653	0.06831	5.073	*** < 0.001
Time-of-Day-based NRTOR	0.13195	0.07870	1.677	†0.0936
Number of Conflicting Approach Through Lanes	0.12766	0.06250	2.042	*0.0411
Presence of Conflicting Approach Right-Turn Only Lane	0.54725	0.07731	7.079	*** < 0.001
Presence of Opposing Left-Turn Movement	–0.62707	0.07628	–8.221	*** < 0.001
log(sigma)	–0.21747	0.03439	–6.323	*** < 0.001

***significant at 99.9%; **significant at 99%; *significant at 95%; †significant at 90%

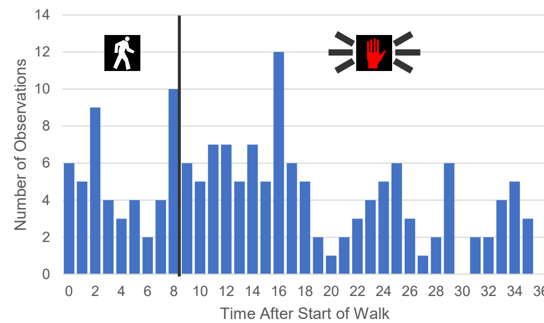
The results from the two models further suggest that the use of dynamic NRTOR signs were associated with more RTOR maneuvers compared to the use of a static sign, when some other site-specific factors are also considered. The relative magnitude of the coefficients among indicator variables provides some insights as to the strength of the effect. The use of a dynamic sign did not have as strong of an effect as the use of TOD-based NRTOR in both models. The presence of a right-turn lane in the conflicting through traffic and the presence of an opposing left turn movement both had a stronger effect than the use of a dynamic sign in both models.

3.3.3 Additional Observations

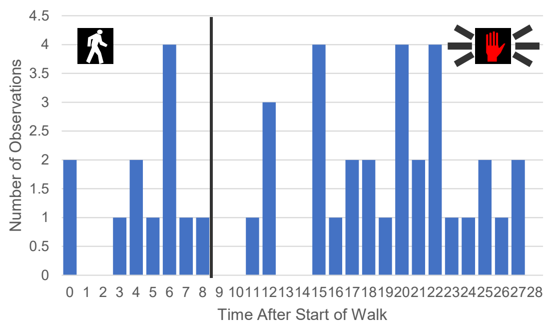
An anecdotal observation reported by the manual video observers for the DNRTOR locations was that the RTOR vehicles tended to obey the DNRTOR signs when a pedestrian or other nonmotorized road user was actively traversing the crosswalk. That is, the RTOR vehicles tended to execute the movement at times when there was no longer any conflicting nonmotorized traffic at the intersection. To explore whether the presence of pedestrians might be associated with a systematic difference in the tendency for RTOR vehicles to execute the movement early or late relative to the display of the DNRTOR indication, observers wrote down the time of the first RTOR vehicle (if RTOR took place). Figure 3.4 shows these distributions for the six DNRTOR locations. In these charts, the horizontal axes show the time elapsed since the start of the Walk interval, and the vertical axis shows the number of observations. Only the times of the first RTOR vehicle are included. Table 3.9 provides further calculations based on the same data.



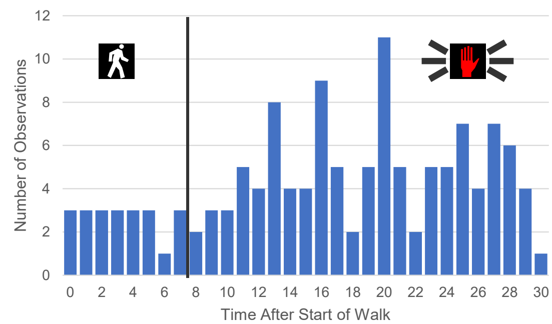
(a) TH 36 & Fairview N Ramp (n = 94)



(b) TH 36 & Fairview S Ramp (n = 161)

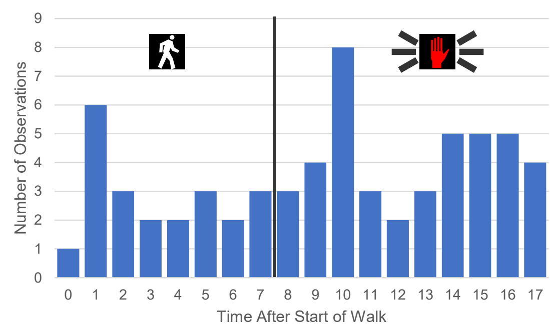


(c) I-35 & Rockford Rd W Ramp (n = 47)



(d) I-35 & Rockford Rd E Ramp (n = 135)

(e) TH 65 & 81st St (n = 14)



(f) US 12 & Hwy 101 N Ramp (n = 64)

Figure 3.4 Distribution of the times during ped-activated blank-out sign operation when the first vehicle violated the NRTOR indication.

Table 3.9 Time of first RTOR violation by location (FDW = flashing don't walk).

Location	Cycles with RTOR Violation	Walk interval duration (s)	FDW interval duration (s)	Cycles with First RTOR in Walk	Cycles with First RTOR in FDW	First RTOR per Walk interval duration	First RTOR per FDW interval duration
TH 36 & Fairview N Ramp	94	15	21	21	73	1.4	3.5
TH 36 & Fairview S Ramp	161	8	28	47	114	5.9	4.1
I 35 & Rockford Rd W Ramp	47	8	20	12	35	1.5	1.8
I-35 & Rockford Rd E Ramp	135	7	23	22	113	3.1	4.9
TH 65 & 81st	14	7	24	4	10	0.6	0.4
US 12 & Hwy 101 N Ramp	64	7	10	22	42	3.1	4.2

During data collection, it was hypothesized that a distribution of the times of the first RTOR movement in a cycle might exhibit a valley during the region where most conflicting traffic is likely to be present in the crosswalk. Some distributions in Figure 3.4 seem to exhibit this, such as TH 36 & Fairview North Ramp (Figure 3.4a), but others do not, such as the TH 36 & Fairview South Ramp (Figure 3.4b). Table 3.9 shows the number of first RTOR times occurring in each interval. At each intersection, the first RTOR maneuver in a cycle occurs more frequently during Walk than the Flashing Don't Walk (FDW) interval. To some degree this is true because the FDW intervals are longer, but if the numbers of occurrences are divided by the interval duration (as shown in the two rightmost columns of Table 3.9), the rates are higher during the FDW interval at most but not all intersections. This suggests that vehicles may tend to wait until later in the ped intervals, but the results are not consistent across all intersections. Altogether, it is difficult to draw conclusions from the time of the first RTOR movement.

Of 849 observed cycles at locations with ped-activated DNRTOR in which RTOR violations took place, only six cycles (or 0.7%) had vehicle-pedestrian conflicts where a RTOR vehicle forced pedestrian traffic to stop, wait, adjust their crossing path, or where physical contact appeared to take place (this happened in two cycles). While this observation is difficult to fully assess without making similar observations with other right-turn treatments, the relatively small number of conflicts may support the assertation that DNRTOR signs improve pedestrian visibility.

A second anecdotal observation from the observers was that a "follow-the-leader" effect was sometimes seen in the right-turn traffic. That is, after the driver of the first vehicle in the queue executed the RTOR movement, following vehicles would sometimes follow suit. A pattern was sometimes seen where the first vehicle to make the RTOR would sometimes appear to hesitate for some amount of time, before finally deciding to turn right on red, and the next vehicle in line would not wait for as long of a time. This observation was difficult to confirm with data. While some locations were more likely to have multiple RTOR vehicles within one cycle, other locations tended to have only one or two RTOR vehicles in most cycles. However, without also gathering further information about the presence of gaps in conflicting traffic, which was beyond the scope of the present study, it is difficult to further evaluate the presence of such an effect.

3.4 Conclusions

3.4.1 DNRTOR Compliance Rates Lower than Static Sign Compliance Rates

Overall, the results show that the dynamic NRTOR sign locations have lower rates of compliance than the locations with static sign operation. This is true both in terms of the percentage of cycles with any RTOR movement (Table 3.4) as well as the total number of right-turn vehicles with the opportunity to execute a RTOR movement (Table 3.5). These differences were shown to be significant using a chi-square test (Table 3.6).

Further statistical analysis showed that the use of a dynamic sign tended to be associated with more cycles with violations (Table 3.7) or a higher percentage of violating vehicles within a cycle (Table 3.8), after taking a few other geometric and traffic variables into account. The effect was weaker than that of intersection geometric characteristics.

3.4.2 DNRTOR May Improve Pedestrian Visibility

One location (US 12 & Hwy 101 North Ramp) included two types of DNRTOR operation: pedestrian-activated and TOD-based. During TOD-based operation, the NRTOR indication was lighted during every red interval, while during pedestrian-activated operation, the indication appeared only when the conflicting pedestrian movements were active. At this location, the pedestrian-activated operation had a higher per-cycle compliance rate, meaning that there were more cycles free of RTOR during ped-activated operation. Per-vehicle compliance rates were similar. This may indicate that the DNRTOR signs may help improve pedestrian visibility, since the divergence of per-cycle and per-vehicle results shows that there are more cycles during pedestrian-activated operation where the first vehicle with the opportunity to execute the RTOR waits until after the NRTOR indication has blanked out, whereas under TOD operation it is much less likely that pedestrians are present.

During manual video analysis, observers anecdotally reported that most of the RTOR movements that took place without conflicting with pedestrian movements. Although some drivers turned right on red in violation of the DNRTOR blank-out signs, most appeared to wait until the conflicting pedestrian movement completed before proceeding. Of 849 cycles at DNRTOR locations with RTOR violations, only six cycles had substantial pedestrian-vehicle conflicts. While this is difficult to assess without making similar observations at locations with different right-turn treatments, the small number of conflicts suggests that DNRTOR signs may help improve pedestrian visibility.

3.4.3 DNRTOR and Arterial Operation

At one location (US 12 and Hwy 101 North Ramp), the TOD-based DNRTOR operation is used to reduce the amount of traffic executing the RTOR movement during peak hours. The purpose of this operation is to respond to a request by drivers at a downstream unsignalized intersection who had previously reported that they are unable to exit the intersection due to a large amount of conflicting traffic. During TOD operation, this intersection had a compliance rate of 92.9% of vehicles that arrived on the right-turn movement during the red interval, indicating that the restriction is effective at reducing the amount of RTOR traffic entering the arterial during these times of day.

Chapter 4: Maintenance Requirements for DNRTOR Signs

4.1 Practitioner Survey

One of the objectives of the present research study is to obtain better information about sign reliability and cost performance to assist with decision making about whether to implement DNRTOR signs. No such information was uncovered in the previous literature review. Thus, to obtain this information, a survey was distributed to State DOT traffic engineers, through the TRB Committee on Traffic Control Devices, the ITE Members Forum, and directly to cities that were known to have DNRTOR signs in operation. A total of 27 responses were received. Location information was provided by 11 respondents and represented nine states, a map of which can be seen in Figure 4.1. A copy of the survey questions is included in Appendix A.

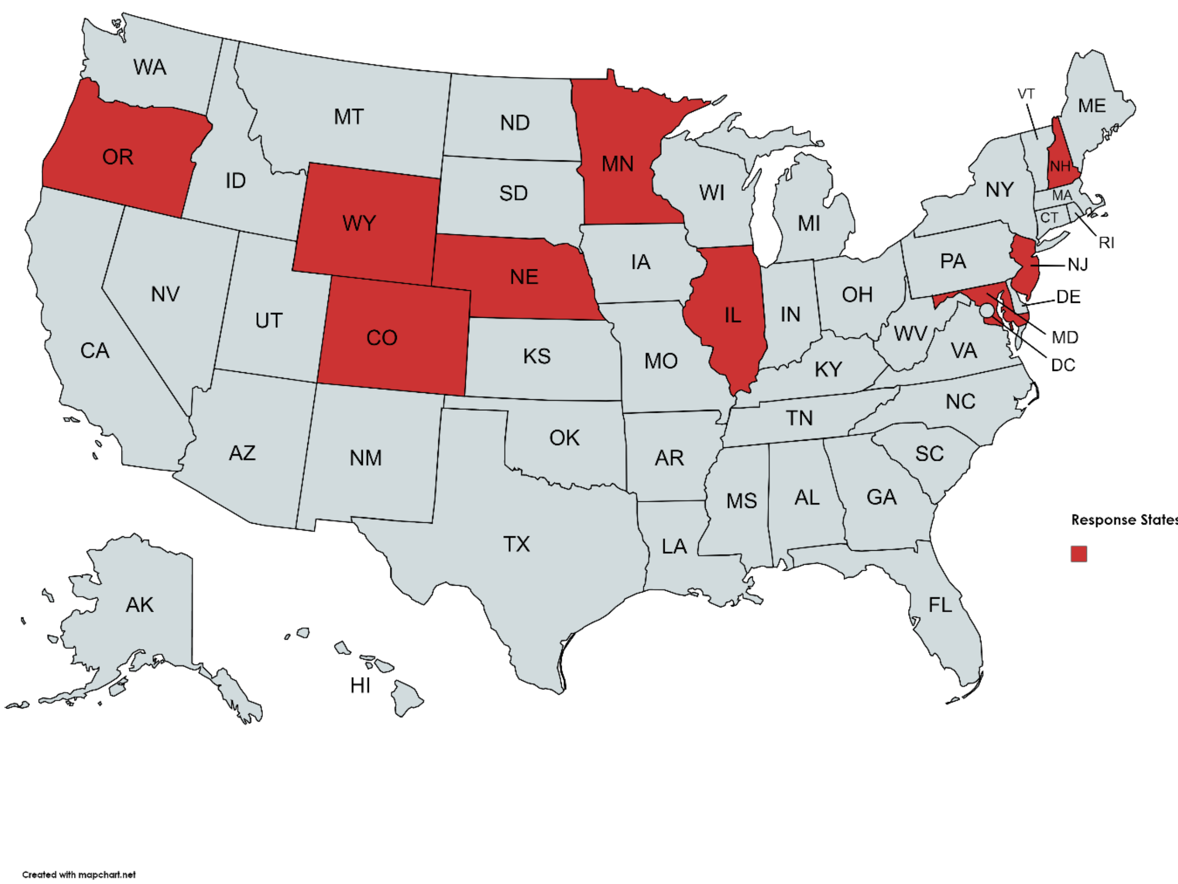


Figure 4.1 Map of Responding States

Of the 27 responses received, 22 responded that their agency operated these signs. The other five responses indicated that they do not have experience with these signs. The respondents who provided agency location information all had experience with the signs. The respondents who provided agency information were from DOTs (3), counties (4), cities (2), and city or state utilities (2). The role of the respondents ranged from Traffic Engineers (5) including state and chief, county engineer (1), Traffic Operations Division Manager, Deputy Director of Public Safety (1), lead Maintenance Electrician (1), Director of Transportation (1) and Traffic Signal Standards (1).

4.2 Reliability

4.2.1 Overall Reliability

The respondents were first asked to rate the reliability of the signs. Eight respondents did not provide a response. Of those who did respond, three called them extremely reliable, six as reliable, one as somewhat reliable, and one as not so reliable. The three respondents who rated the signs as extremely reliable were from agencies across the US. Two of them stated that they had not had issues with operation in over 10 years. Some of the respondents who said the signs were reliable stated that there were occasional misfires/malfunctions, or that the signs stay on longer due to train activation, while another noted some minor issues due to signal equipment or weather failures. The other three respondents who rated the signs as reliable stated that they have not had any issues with the signs. One of these respondents had only had the sign installed for approximately two months. The respondent who noted that their sign was somewhat reliable had issues with some of the LEDs burning out over time and switched to static signs for their application. The respondent from the City of St. Paul rated the signs as being not so reliable because of issues with flickering and inconsistent flash.

4.2.2 Reliability in Extreme Weather

Three of the respondents from Midwestern states (Illinois, Minnesota, and Nebraska) mentioned having issues with the signs during weather extremes. As mentioned earlier, the City of St. Paul noted problems with flickering and inconsistent flash rates. The City of Lincoln, NE noted that they have a wide range of weather extremes which they felt could be the cause of failures they experienced although they were not certain. Finally, the City of Schaumburg, IL noted having issues with the signs becoming covered during severe weather events where a combination of wind and snow would lead to the signs becoming covered with snow. It may be worth noting that this issue can also affect static signs. Other survey respondents who were located in states that experience winter weather, including New Hampshire, Colorado, Wyoming, and other agencies in Minnesota, did not note any such issues.

4.2.3 UL or NRTL Listed Signs

Seven of the respondents (four of whom included their contact information) noted that their agency requires that blank-out signs be Underwriters Laboratories (UL) or Nationally Recognized Testing Laboratory (NRTL) listed. Eight respondents (six of which included contact information) were unsure, and one respondent (located in Oregon) noted that they do not require signs to be UL or NRTL listed.

The four respondents who indicated that UL listing was required were contacted by email to inquire about the specific models in use, but those who responded to the email inquiry replied that their signs were not in fact UL listed after all.

4.3 Maintenance

4.3.1 Routine Maintenance

Thirteen respondents included a response to a question relating to the routine maintenance activities they perform on their signs. One respondent noted they do monthly monitoring. Four respondents noted that they do an annual check for proper operation. Two respondents noted that DNRTOR sign maintenance is done as part of routine maintenance of their traffic signal systems. One respondent noted that their primary maintenance concern was bulb failures, but after switching to LEDs they reported that the signs last much longer. Five respondents said that they do not perform any routine maintenance, but instead address issues as they come up.

4.3.2 Non-Routine Maintenance

The survey respondents were then asked about non-routine maintenance activities. Three respondents noted they have dealt with screens diming. Three respondents noted occasions where the signs would not light up (all three of these noted at least one other issue with the signs). One respondent noted the signs did not blank out. Five respondents noted that they had other non-routine issues that were not included in the list included in the survey. These other issues have included equipment failures relatively soon after installation due to bad components, inconsistent flashing behavior, signal phasing issues including unexpected “gotcha” concerns related to permitted left turns (during the green ball on the opposing approach), and partial LED failures with signs that use a symbol display (as opposed to a text display). Table 4.1 includes a summary of how often these issues were reported to have occurred. None of the respondents noted issues with non-scheduled software upgrades, loose connections, or signs overheating.

Table 4.1 Summary of Non-Routine Maintenance Issues and their Occurrence

Issue	Number of Respondents	Occurrence of Issue
Screen dims	3	Rarely (2), Very Rarely (1)
Sign not lighting up	3	Frequently (1), Occasionally (1), Rarely (1)
Sign not blanking out	1	Rarely
Other	5	Frequently (2), Occasionally (1), Rarely (1), Very Rarely (1)

4.4 Costs Related to the Installation and Operation of Signs

The initial cost of installing the DNRTOR signs varied from $1,500 to approximately $5,000. Six of the respondents were unable to estimate their initial costs, with some mentioning that it was included with the installation of other signal equipment, so they did not have a price for the DNRTOR sign alone. The average operational costs varied across the respondents but were generally relatively inexpensive. Four respondents noted that they were unsure of the average operating cost, was while one noted it was minimal, while another stated that the cost was less than $100 per year. Three respondents noted that their only costs were due to set-up. Two others responded that their only cost was electricity usage, which they do not track separately from the overall usage by the signal.

Routine annual maintenance costs were noted by most respondents as being very small. Six respondents stated their costs were $0 or not applicable. One specified that there were no additional costs for the DNRTOR signs in their existing signal maintenance contract. One respondent noted their cost was less than $100 per year. Four respondents did not know what their routine maintenance costs were.

Non-routine maintenance costs were more varied. Two respondents noted that they had no such costs. Another noted that their cost was under $100 per year. Another respondent estimated their cost at $300 per year. Another noted that they were implementing signing, striping, and signal indication changes to address phasing concerns, at a cost of $5000 altogether. Four respondents were unsure of their non-routine maintenance costs.

A question was asked related to the costs associated with removing and disposing of one of these DNRTOR signs. Two respondents provided cost numbers, which were $200 and $500. Seven respondents were unsure what the cost would be, and one noted they have not had to remove any signs yet, so they did not have a cost.

4.5 Other Concerns

An open-ended question was included about any other concerns the agency may have with these signs. One of the respondents stated that their main issues are related to drivers' understanding of the signs. Drivers often do not know when to stop or whether they can go when the message is blanked out. This suggests an education campaign might be beneficial when installing the signs in an area where they have not been used before, and that it may be helpful to include such information in driver's education curricula.

The other response received for this open-ended question noted that the signs sometimes get water in them, but that with functional weep holes at the bottom, water is able to exit the housing. Sun exposure can also damage the lens which can affect its clarity and require the sign to be replaced more frequently. A similar issue is seen with static signs, which also tend to fade in proportion to their exposure to sun.

4.6 Conclusion

The survey received 27 responses, with 21 responding to most of the survey, and with 11 including providing agency information. These responses were from 9 states. The signs were found to have varying levels of reliability, but overall were found to be generally reliable. Nine respondents stated they were reliable or extremely reliable and two noted they were somewhat or not reliable. Some agencies located within midwestern states noted they had issues with the signs in extreme weather conditions, including one noting an issue also seen with static signs where they become covered with snow. Other agencies within states that see extreme weather did not note any issues. Routine maintenance was found to be minimal and generally conducted yearly, while non-routine maintenance varied by agency. Overall, the non-routine maintenance was found to be rarely or very rarely needed. The City of St. Paul reported frequent issues with the signs not lighting up or having an inconsistent flash, while the City of Lincoln, Nebraska had occasional issues with signs not lighting up, and frequently experienced issues with partial LED failures. Hennepin County, Minnesota reported having occasional signal phasing issues which they are trying to address by making some signing, striping, and signal indication changes. Costs related to the installation of the signs were found to be in the low to mid thousands of dollars while operational and maintenance costs were found to be generally very low.

Chapter 5: Conclusions and Recommendations

This report examined the impact of using blank-out DNRTOR signs at intersections on driver compliance by comparing rates of compliance at six intersections with pedestrian-activated DNRTOR signs and two intersections with static NRTOR signs. One location used a DNRTOR sign under pedestrian-activated control during all times, with TOD-based activation during peak hours. This study is, to the authors' knowledge, the first to examine NRTOR compliance rates at intersections where the DNRTOR treatment has been in use for a long time. Two previous studies found in the literature that reported compliance rates were before-after studies. In addition to driver compliance, the study also examined maintenance requirements for DNRTOR.

5.1 Maintenance Requirements for DNRTOR

A survey of practitioners was carried out to assess maintenance requirements. This survey received 27 responses from transportation agencies. Respondents were not required to provide location information, but those who did were distributed from across nine states. The survey included several questions aimed at developing information about costs of deploying and maintaining DNRTOR.

Overall, the survey responses indicated that DNRTOR signs are generally found to be reliable. Nine respondents indicated that the signs were reliable or extremely reliable compared to two reporting that they were somewhat unreliable or not reliable. Some (but not all) agencies in states with winter weather reported issues during extreme weather conditions. Routine maintenance costs were found to be small and generally conducted yearly. Responses on non-routine maintenance requirements were more varied, but overall, non-routine maintenance was rarely needed by most respondents. Costs related to the installation of the signs were found to be in the range of thousands of dollars, while operational and maintenance costs were found to be generally very low by most respondents (less than $300 per year).

Information about UL/NRTL listed DNRTOR signs were sought from respondents. While four respondents who provided contact information indicated that they required UL/NRTL listing, follow up inquiries about the signs did not uncover which signs the agencies were using. Those who responded to the follow up inquiry reported that their signs were not in fact UL listed.

5.2 Observations from Field Data

5.2.1 Driver Compliance

Driver compliance rates were measured from the field at eight locations as described in Chapter 3. A combination of manual and automated techniques were used to extract driver compliance observations from the data, and these were used to tabulate compliance rates per cycle and per vehicle for the eight locations, as shown in Table 3.4 and Table 3.5, respectively. Overall, the compliance rates were higher at the static sign locations compared to the dynamic sign locations, when calculated either per cycle or per vehicle. These results were further examined by statistical testing, which showed that the result was significant, according to a chi-square test (Table 3.6). When combined with other variables in regression models, the use of a dynamic blank-out sign was found to be associated with a greater number of RTOR maneuvers, when predicting the probability of a cycle having one or more RTOR vehicles, or when predicting the percent of complying vehicles in a cycle. The effect was not as strong as attributes of the intersection geometry in these models.

Overall, the locations with DNRTOR signs showed greater numbers of RTOR maneuvers in violation of the NRTOR indication compared to static signs. These results may seem surprising given the lighted NRTOR indication provided by blank-out signs should be more conspicuous than a static sign and more likely to command driver attention, which should induce greater compliance. This, however, was not supported by the data obtained in this study, which showed overall lower rates of compliance at the DNRTOR sign locations compared to the static sign locations.

There are some potential reasons for there to be lower compliance at the DNRTOR locations. One reason may be that drivers are more used to the static signs, whereas the dynamic signs have more variability in the type of display. Another potential reason is that static signs were typically used at locations where sight distance is not available, so drivers were additionally encouraged to comply with the NRTOR sign by the fact that they were unable to see conflicting traffic. It was challenging to find locations with similar geometry as the DNRTOR locations that also had static NRTOR signs. Many different interchange intersections were examined during site selection, and only two were found that included static NRTOR indications. One of these (I-35 and 66th St East Ramp) had a NRTOR restriction by time of day (6am—10pm), indicating that sight distance issues did not preclude RTOR during all times of day. The compliance rate at this location was lower than the location with a 24-hour restriction; in fact, the per-vehicle compliance rate was similar to the average compliance rate across the dynamic locations. This supports the idea that some drivers may be likely to ignore NRTOR indications if there are no sight distance limitations.

Overall compliance rates across the DNRTOR locations were similar to those reported in the literature. The average compliance rate in this study was 87.1% of right turning vehicles present during the red interval (i.e., vehicles that had an opportunity to execute the RTOR movement). Individual locations varied from 77.7% to 91.9%. Prior research by Zegeer et al. (1985) showed 2,500 RTOR violations per 12,314 right-turn movements where the vehicle had the opportunity to execute a RTOR, which implies a compliance rate of 79.7%. Prior research by Lin et al. (2019) showed compliance rates ranging from 73.9% to 87.8% for locations where DNRTOR signs were used.

5.2.2 Pedestrian Visibility

Although DNRTOR compliance rates are not lower than static signs, there is some evidence that the use of DNRTOR may improve the visibility of pedestrians. One location (US 12 & Hwy 101 N Ramp) used both TOD-based and pedestrian-activated operation. The pedestrian-activated operation had fewer cycles with RTOR violations compared to TOD operation, although the percentage of complying vehicles were similar under both types of operation. This means that there were more cycles during ped-activated operation compared to TOD operation in which the first driver having the opportunity to make the RTOR movement decided to wait until after the NRTOR indication blanked out. Manual observations of the cycles at the DNRTOR locations found that most drivers who executed RTOR waited until after the conflicting pedestrian traffic was out of the way. Among 849 observed RTOR violations, there were six substantial vehicle-pedestrian conflicts.

5.3 Recommendations for RTOR Treatments

To conclude this report, recommendations are provided regarding use of DNRTOR signs based on the observations made from data during this study, synthesis of the literature review, maintenance requirements, and potential objectives.

Overall maintenance requirements for DNRTOR do not appear to be burdensome, with few survey respondents noting significant requirements for non-routine maintenance. From a maintenance perspective, the static sign is the easier option, yet DNRTOR signs do not seem to be especially problematic to install or operate according to results of the practitioner survey. The recommendations are therefore built around the potential effectiveness of DNRTOR as a treatment.

For an objective of purely reducing the number of NRTOR violations, the DNRTOR treatment does not appear to be the best option. Dynamic sign compliance rates were lower than static sign compliance rates, when measured per cycle as well as per vehicle. For locations where the objective is to avoid any RTOR movement, such as where a sight distance challenge exists, a DNRTOR sign seems unlikely to offer much benefit beyond a static sign. The lack of sight distance likely reinforces the need for the NRTOR indication.

For an objective of improving pedestrian visibility (i.e., making drivers more aware that pedestrians are present), the DNRTOR treatment appears to be helpful. The literature includes two before-after studies showing improvements of compliance, although one location in a prior study showed a lower compliance rate with the use of a sign with less clear meaning. In the present study, one location under both pedestrian-activated and TOD control had higher per-cycle compliance rates during pedestrian-activated operation although the per-vehicle compliance rates were similar for both types of operation. This suggests that the first vehicle with the opportunity to make the RTOR is more likely to wait until after the NRTOR indication blanks out when pedestrians are present. In addition, during manual observations it was found that most RTOR maneuvers, although violating the NRTOR indication, rarely lead to substantial vehicle-pedestrian conflicts.

For an objective of creating gaps on the crossing street, the overall high compliance rates of drivers with the NRTOR indication indicate that DNRTOR is effective at preventing a high percentage of right turning traffic from executing the RTOR.

One advantage of using DNRTOR to help protect pedestrian phases is that the conditional display of the NRTOR indication means that it is not necessary to prohibit the movement when there are no conflicts. This improves intersection efficiency by allowing right-turning traffic to proceed when there is a gap in cross street traffic. For this reason, the option to retain the possibility of DNRTOR while drawing some attention to the presence of pedestrians seems a reason to retain DNRTOR as a potential tool. However, it needs careful consideration to assess whether compliance rates similar to those reported with DNRTOR treatments in this study are sufficient.

Where DNRTOR indications are used, the use of messaging that reduces ambiguity is more likely to achieve the desired result. The DNRTOR signs at locations considered in this study included the supplemental text “ON RED” underneath a graphical No Right Turn symbol. The continued use of this additional message for other DNRTOR signs would seem to be sensible. At locations where DNRTOR is considered for use solely to protect pedestrians, designs that call greater attention to the presence of pedestrians could potentially help support that objective.

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Appendix A: Survey Questions

1) Has your agency had experience with dynamic blank-out no right turn on red (NRTOR) signs which are blank until triggered (e.g. time of day, pedestrian activation, other event)?
   a) Yes
   b) No
2) How would you rate the reliability dynamic blank-out no right turn on red (NRTOR) signs?
   a) Extremely reliable
   b) Reliable
   c) Somewhat reliable
   d) Not so reliable
   e) Not at all reliable
3) Why did you choose this reliability rating?
4) Have you had reliability issues with the signs during extreme weather conditions (i.e. high heat and humidity or extreme cold)?
   a) Yes (please describe)
   b) No
   c) Unknown
5) Does your agency require that blank-out signs be Underwriters Laboratories (UL) or Nationally Recognized Testing Laboratory(NRTL) listed?
   a) Yes
   b) No
   c) Unknown
6) What routine maintenance activities do you perform on dynamic blank-out NRTOR signs and at what interval do you perform each activity?
7) What non-routine maintenance issues have you had with dynamic blank-out NRTOR signs (select all that apply)?
   a) Screen dims
   b) Non-scheduled software upgrades
   c) Loose connections
   d) Overheating
   e) Sign not blanking out
   f) Sign not lighting up

9) How often have you had problems with the screen dimming?
   a) Frequently
   b) Occasionally
   c) Rarely
   d) Very rarely
10) How often have you had problems with non-scheduled software upgrades?
   a) Frequently
   b) Occasionally
   c) Rarely
   d) Very rarely
11) How often have you had problems with loose connections?
   a) Frequently
   b) Occasionally
   c) Rarely
   d) Very rarely
12) How often have you had problems with the sign overheating?
   a) Frequently
   b) Occasionally
   c) Rarely
   d) Very rarely
13) How often have you had problems with the sign not blanking out?
   a) Frequently
   b) Occasionally
   c) Rarely
   d) Very rarely
14) How often have you had problems with the sign not lighting up?
   a) Frequently
   b) Occasionally
   c) Rarely
   d) Very rarely

16) How often have you had other problems?
    a) Frequently
    b) Occasionally
    c) Rarely
    d) Very rarely
17) What was your initial purchase cost of one of these dynamic blank-out NRTOR signs?
18) What were the average operational costs associated with these dynamic blank-out NRTOR signs (e.g. set up costs, electrical costs, etc.)?
19) What was the average cost of routine maintenance for one of these signs on an annual basis?
20) What was the average cost of non-routine maintenance for one of these signs on an annual basis?
21) What was the cost (or is the expected cost) associated with removal and disposal of the dynamic blank-out NRTOR signs?
22) Do you have any other comments on the cost, maintenance requirements or reliability of dynamic blank-out NRTOR signs?
23) What is the name of the agency you work for?
24) What is your role within the agency?