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Observations of Driver Compliance with Dynamic No Right Turn on Red Signs at Signalized Intersections

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Abstract

This paper examines driver compliance with *No Right Turn on Red* (NRTOR) restrictions at eight signalized intersections in Minnesota, where six locations were equipped with pedestrian- or time-of-day-activated dynamic blank-out signs and two locations displayed conventional static signs. High-resolution video observations were used to quantify right-turning driver responses. Compliance was measured using two perspectives: proportion of compliant cycles and proportion of compliant vehicles. The results showed that static signs were generally associated with higher compliance, yielding 80.0% per-cycle and 92.4% per-vehicle compliance, compared with 60.8% and 87.1% for dynamic signs. Logistic regression models were further applied to assess statistical significance and to evaluate how NRTOR effectiveness compares with other geometric and operational factors influencing driver behavior.

Keywords

Signalized Intersections, Right-Turn Movements, Compliance Behavior, Dynamic Blank-Out Signs, Traffic Safety

1. Introduction

Right-turn-on-red (RTOR) maneuvers are widely permitted at signalized intersections across the United States, primarily intended to improve operational efficiency by minimizing delays for right-turning drivers. Despite these benefits, RTOR movements can create safety concerns, particularly for pedestrians. When executing a right turn on red, drivers often concentrate on identifying acceptable gaps in conflicting vehicle traffic, which can reduce their attentiveness to pedestrians. This limited attention is especially problematic for pedestrians crossing from the near-side or stepping into the crosswalk at the onset of the walk interval, where driver awareness may be diminished.

To mitigate such conflicts, agencies have introduced Dynamic No Right Turn on Red (DNRTOR) signs, also referred to as blank-out signs. These devices display the "No Right Turn on Red" restriction selectively, most commonly during pedestrian crossing phases, and remain inactive during other times. By presenting the prohibition in a conspicuous and context-specific manner, DNRTOR signs are expected to discourage illegal RTOR maneuvers and improve pedestrian safety. Given the limited empirical evidence on their effectiveness, this study employs large-scale video-based observations to evaluate driver compliance under both dynamic and conventional static NRTOR treatments.

2. Literature Review

2.1. Safety of RTOR

The Right Turn on Red (RTOR) maneuver has been permitted in the United States for several decades. Prior to the 1970s, individual states applied differing policies: jurisdictions in the western U.S. generally allowed RTOR, while many eastern states prohibited it, largely due to safety concerns. This variation was largely standardized after the Energy Policy and Conservation Act of 1975, which required states to allow RTOR in order to remain eligible for federal highway funds. At present, RTOR is broadly permitted unless explicitly restricted by No Right Turn on Red (NRTOR) signs.

One of the earliest systematic evaluations of RTOR safety was carried out in Indiana in 1976. That study suggested RTOR implementation did not substantially increase crash risk for either motorists or pedestrians, while also reporting measurable reductions in delay for both groups [1]. In contrast, research sponsored by the U.S. Department of Transportation in the 1980s indicated notable safety concerns, estimating that pedestrian crashes increased between 43% and 107% and bicycle crashes rose by 72% to 123% following RTOR implementation [2]. More recent work using Oregon crash records from 2011-2013 found that approximately one-fifth of all statewide crashes occurred at signalized intersections, with right-turn maneuvers comprising about 1.8% of total crashes. This share represented nearly 9% of all intersection-related collisions [3]. Complementary insights from the SHRP 2 Naturalistic Driving Study (NDS) revealed that drivers facing higher levels of conflicting traffic tended to decelerate more sharply before turning, and that under permissive right-turn conditions drivers often showed lower levels of situational awareness combined with faster acceleration. These tendencies contribute to an elevated likelihood of right-turn conflicts involving pedestrians [4].

Several additional studies in the 1980s also raised concerns. For example, one Department of Transportation analysis reported pedestrian crashes increased 43% - 107% and bicycle crashes rose 72% - 123% after RTOR legalization [2], while

Zador observed pedestrian and bicyclist crash increases of roughly 60% and 100%, respectively [5]. Although these percentages appear large, they reflected relatively small absolute increases in crash counts. Chadda and Schonfeld reviewed available evidence and recommended countermeasures such as eliminating unnecessary signals [6], deploying prohibition signage, and providing targeted driver education.

By the mid-1990s, the National Highway Traffic Safety Administration submitted a report to Congress based on the Fatal Accident Reporting System (FARS) and state crash databases [7]. Their findings showed that between 1982 and 1992 only 84 fatal crashes involved right turns at RTOR-permitted intersections, representing a minuscule share of the 485,104 total roadway fatalities during that decade. Overall, RTOR crashes accounted for just 0.05% of total crashes and 0.06% of all fatal and injury collisions. While most RTOR events involving pedestrians or bicyclists resulted in injuries, fatal outcomes were rare (about 1%). Later assessments, including a 2002 study, similarly concluded that RTOR had limited impact on overall safety, as RTOR-related crashes were infrequent and rarely severe. Research conducted at Texas Southern University reinforced this position, emphasizing the minor influence of RTOR on intersection safety outcomes [8].

Taken together, the bulk of prior research has characterized RTOR as presenting only limited safety concerns, primarily because the frequency of serious RTOR crashes is low. However, more recent work has cautioned that pedestrian injury data may be underreported, particularly when no citation is issued to the driver, or when injuries are not immediately apparent [9]. In parallel, the safe system approach, now increasingly adopted by transportation agencies, frames all fatal and injury crashes as unacceptable regardless of their relative frequency. Applying this framework, the Federal Highway Administration has highlighted intersection elements such as exposure, conflict points, and maneuver complexity as critical safety factors [10]. Although not focused exclusively on RTOR, this perspective implies that the maneuver may warrant reevaluation due to its inherent risks to pedestrians and bicyclists [11]. Reflecting this shift in thinking, Washington, D.C. recently moved to implement a citywide ban on RTOR.

While RTOR has historically been considered a relatively safe practice, growing concerns about the safety of nonmotorized users are likely to prompt reconsideration of current policies. Conditional approaches—such as the use of dynamic blank-out NRTOR signs—represent a potential compromise, maintaining operational efficiency for vehicles while enhancing protection for pedestrians and cyclists.

2.2. Effectiveness of Conditional RTOR Treatments

A limited number of studies have evaluated countermeasures that restrict RTOR only under specific conditions. In the 1980s, the Federal Highway Administration conducted one of the earliest assessments of pedestrian safety at intersections with RTOR, including the use of dynamic No Right Turn on Red (DNRTOR) or "blank-out" signs [12]. The Michigan field tests produced several notable observations:

1) At a school zone location with before-and-after measurements, the share of illegal RTOR maneuvers dropped from 1.83% with a conventional sign to just 0.2% once the electronic blank-out display was installed. The authors concluded that the device "virtually eliminated RTOR maneuvers during periods when children were present."

2) At another site where time-of-day activation was applied, 5.1% of drivers made illegal RTORs. Although pedestrian activity was low at this location, no pedestrian conflicts were reported.

3) At a third test location, three operational strategies were compared: a) illumination during the opposing left-turn phase, b) continuous illumination, and c) activation only during the red interval. The corresponding violation rates were 1.9%, 1.9%, and 2.9%, compared with 2.6% for a standard sign. Overall, greater pedestrian presence was associated with higher driver compliance.

That study also benchmarked DNRTOR performance against other countermeasures, such as conventional prohibition signs. The findings suggested that dynamic signs provided modest improvements in compliance and could be particularly beneficial near schools or when left-turn conflicts were a concern. Moreover, the analysis of 110 approaches equipped with static NRTOR signs revealed approximately 2500 violations among 67,347 right turns—a 3.7% violation rate overall. When focusing only on the 12,314 turning movements where RTOR was possible, the violation rate increased to 20.3%.

The Insurance Institute for Highway Safety later examined static NRTOR signs supplemented with conditional text, such as prohibitions applying only when pedestrians were present or during specified times of day [13]. Field observations at 15 intersections—both at treatment and control sites—showed that the "when pedestrians are present" note was associated with roughly three times as many violations as time-of-day restrictions. However, the number of observed RTOR maneuvers was too small to allow for robust statistical testing.

Dynamic blank-out treatments were also part of an FHWA project evaluating pedestrian safety enhancements in Las Vegas. At one intersection, DNRTOR signs were installed alongside other measures such as high-visibility crosswalks and pedestrian countdown signals with animated eyes. The results showed that the proportion of pedestrians scanning for potential conflicts rose from 86% to 96%, and the percentage of drivers coming to a full stop also increased after installation [14].

Complementary research from the University of Massachusetts Amherst examined driver understanding of multiple traffic control devices, including red arrows, flashing yellow arrows, and DNRTOR signs [15] [16]. Survey and simulator experiments with 200 participants revealed that about 80% correctly interpreted the DNRTOR indication, recognizing that RTOR is permitted only when the sign is inactive, while only 7% misunderstood the prohibition. Statistical analysis found no meaningful difference in comprehension between static and dynamic displays.

In Florida, the state DOT tested several pedestrian safety treatments, deploying both static and dynamic NRTOR signs in different regions [17]. At three intersections, dynamic signs with explicit messages instructing drivers to yield to pedestrians improved compliance rates from 59.7% to 73.9%, 81.8% to 87.8%, and 65.2% to 83.4%. In contrast, at one site, a graphical blank-out sign with only a "No Right Turn" symbol proved less effective, with compliance falling from 90.9% to 75.2%. The researchers suggested that drivers were confused about whether the sign denoted a permanent prohibition or a temporary restriction, and recommended adding clarifying text.

In summary, prior investigations have provided only limited field evidence on driver compliance with dynamic NRTOR devices. Two studies in particular have offered key insights:

1) The 1980s Michigan experiments, which indicated potential compliance benefits, especially near schools.

2) The 2019 Florida evaluation, which reported improved compliance at most sites but reduced compliance where only a graphical symbol was displayed.

Despite these promising findings, the long-term effectiveness of DNRTOR signs remains uncertain. Further research is needed to determine whether compliance improvements are sustained over time and across different operational contexts.

3. Assessing Driver Compliance with Dynamic and Static NRTOR

Study Sites

The study was carried out at several intersections in the Minneapolis metropolitan area to evaluate driver compliance with right-turn restrictions. Six of the selected approaches were equipped with dynamic No Right Turn on Red (DNRTOR) blank-out signs. At most of these sites, the signs were activated by pedestrian calls, while one site also employed time-of-day (TOD) activation. For comparison, two additional intersections displaying conventional static NRTOR signs were included in the analysis.

Pedestrian actuations at the DNRTOR sites were relatively infrequent, typically numbering only a few dozen per day. To capture a sufficient sample of intervals when the DNRTOR display was active, data collection therefore extended across multiple weeks. Video detection systems (VDS) installed at the intersections provided the primary dataset, supplemented by high-resolution controller logs that recorded the timing of signal changes, including the onset of pedestrian walk intervals. To verify synchronization, pan-tilt-zoom (PTZ) camera footage was reviewed to confirm that DNRTOR activations coincided with the display of pedestrian indications.

High-resolution signal data consist of a detailed series of timestamped events, documenting changes in vehicular and pedestrian signal states as well as other controller operations [18]. Such data were available at all six DNRTOR study sites and served as a key resource in aligning pedestrian phases with sign activations.

Identifying static-sign locations with roadway characteristics comparable to the DNRTOR intersections proved difficult. Most DNRTOR installations were located at interchanges, whereas static NRTOR signs were uncommon in such contexts because limited sight distance—the primary justification for static prohibitions—was rarely present. Ultimately, two interchange sites with static NRTOR restrictions were identified and incorporated into the study. Across all eight locations, more than 4500 hours of video, amounting to approximately 4 TB of data, were collected. **Table 1** summarizes the study sites and the amount of video captured, while **Figure 1** provides sample views of the approaches from the camera recordings.

The eight study sites were selected in collaboration with MnDOT to represent locations where DNRTOR devices were already deployed, complemented by two static NRTOR sites for baseline comparison. The availability of video detection and controller log data was also a key determinant. Because static NRTOR signs were relatively uncommon at interchange approaches, only two such sites could be included. This imbalance may limit generalizability, as static treatments are underrepresented relative to dynamic sites.

Because the dataset comprised over 4500 hours of video, most collection occurred during AM and PM peak periods under generally clear weather, providing consistency across locations. While isolated deviations occurred, these were rare and not systematically analyzed.

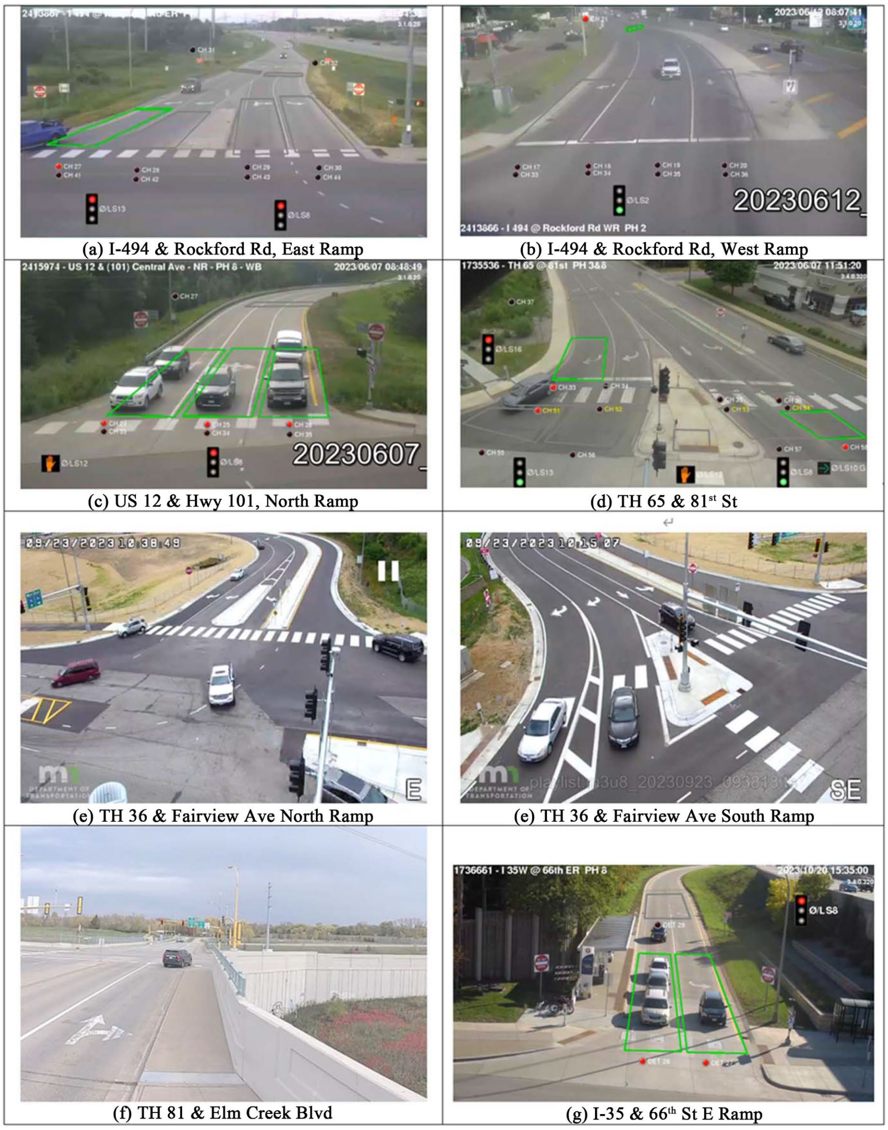
Table 1. Data collection locations.

Location	*Subject Approach*	*Right-Turn Treatment*	*Hours of Video Data*
I-494 *& Rockford Rd., East Ramp*	Northbound	Dynamic NRTOR (ped-activated)	832
I-494 *& Rockford Rd., West Ramp*	Southbound	Dynamic NRTOR (ped-activated)	926
US 12 *& Hwy* 101, *North Ramp*	Westbound	Dynamic NRTOR (ped-activated and TOD)	908
TH 65 *&* 81*st St*	Westbound	DNRTOR (ped-activated)	804
TH 36 *& Fairview Ave., North Ramp*	Westbound	Dynamic NRTOR (ped-activated)	529
TH 36 *& Fairview Ave., South Ramp*	Westbound	DNRTOR (ped-activated)	529
TH 81 *& Elm Creek Blvd.*	Northeastbound	Static	24
I-35 *W &* 66*th St., East Ramp*	Northbound	Static	167

4. Video Data Observations

4.1. Data Validation

The initial stage of analysis involved validating the video data against the high-resolution controller logs to confirm that DNRTOR activations were synchronized with pedestrian signal displays. This was accomplished by comparing event



(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 1. Representative camera views at study approaches.

timestamps from the high-resolution dataset with video frames in which pedestrian indications were clearly visible. Minor discrepancies were occasionally observed between the two sources, but the timing offset rarely exceeded 10 seconds. The Start of Walk event, in particular, was consistently and accurately captured in the high-resolution records, as verified through cross-checking with the corresponding Walk intervals observed in the video. This validation process was applied at all six DNRTOR study sites. In periods when pedestrian signals could not be directly observed in the video footage, other identifiable phase changes were used to infer the DNRTOR interval. Supplemental PTZ camera recordings further confirmed that the NRTOR blank-out message illuminated simultaneously with the Walk indication and extinguished at the conclusion of the Flashing Don't Walk interval.

At pedestrian-activated DNRTOR sites, the indication illuminated only during the Walk and Flashing Don't Walk intervals, rather than the entire red phase. This operational design ensured that the compliance metric reflected driver behavior specifically during pedestrian service, with variation in activation lengths determined by pedestrian clearance times. Cycles outside of these pedestrian phases were not included in the DNRTOR-active dataset.

4.2. Field Observations under Pedestrian-Activated DNRTOR Control

High-resolution event logs were obtained for all six intersections equipped with DNRTOR during the observation period. Because these sites primarily operated under pedestrian-activated control—except for one location that also used time-of-day (TOD) activation—the NRTOR restriction was displayed only when a pedestrian phase was served. Accordingly, the analysis of driver compliance began with the identification of cycles in which the conflicting pedestrian phase included a Walk indication.

The high-resolution records were synchronized with the dates of video collection, and after merging and cleaning the event files, a total of 2274 pedestrian calls were identified. Across the six DNRTOR sites, 4428 hours of VDS video were reviewed, illustrating the infrequency of such events—on average, one pedestrian actuation occurred for every two hours of recorded footage. Because actuations were sparse, it was unlikely that a Walk event from one cycle could be confused with an adjacent cycle. Indeed, among all 2274 Start of Walk events, only a handful (fewer than six) involved more than two consecutive cycles with pedestrian service on the study movement.

For each DNRTOR location, the Start of Walk timestamp in the high-resolution log was used as the reference marker to define relevant cycles. Other pedestrian intervals could then be inferred from this index, given that the durations of Walk and Flashing Don't Walk remained consistent throughout the day. Verification through extensive video review and inspection of timing plans confirmed that none of the sites operated with "Rest in Walk" or "Call to Non-Actuated" settings for through movements.

Video analysis was conducted manually. A team of four trained observers reviewed the pedestrian-activated DNRTOR footage and extracted observations following a structured procedure:

1) Identify the Start of Walk event from the high-resolution data.

2) Retrieve the corresponding video segment and locate the Start of Walk frame.

3) Observe vehicle and pedestrian activity throughout the Walk and subsequent Flashing Don't Walk intervals.

4) Record the number of right-turning vehicles present, note any drivers executing RTOR maneuvers in violation of the restriction, and log the time of the first right-turn movement. Any pedestrian conflicts or other notable behaviors were also documented.

The timing of the first right-turn maneuver was specifically recorded to examine whether drivers tended to delay their turns until pedestrians had cleared the crosswalk. It was hypothesized that RTOR maneuvers would cluster around the onset of the Walk interval and again toward the latter portion of the Flashing Don't Walk phase.

4.3. Video Observations at Static and TOD-Activated NRTOR Sites

In contrast to the pedestrian-activated DNRTOR sites, the location with time-of-day (TOD)-based activation at US 12 & Hwy 101, as well as the control sites with static NRTOR signs, were more amenable to automated data extraction. At these intersections, analysis did not require matching the video with the state of a conflicting pedestrian phase. Instead, entire video segments could be processed directly to identify the relevant right-turning events.

Several rounds of testing were conducted to refine the automated extraction procedure. Early versions of the algorithm faced difficulties in accurately distinguishing between traffic signal states (red, yellow, and green). This limitation was overcome by incorporating video detection system overlays, which consistently displayed the signal indication in a fixed area of the screen. By extracting the red-green-blue (RGB) values of the pixels corresponding to the red aspect of the signal head, the procedure reliably identified whether the signal was displaying red.

5. Overview Of Video-Based Dataset and Findings

Figure 2 presents a summary of the observed signal cycles, including the sources of video data, the number of excluded cycles, and the cycles in which violations of the NRTOR indication were recorded. At the pedestrian-activated DNRTOR sites, high-resolution controller logs identified 2274 cycles in which the DNRTOR display was illuminated in conjunction with pedestrian service. An additional 1103 cycles were obtained from the site with TOD-based DNRTOR operation and from the intersections with static NRTOR signs, resulting in a combined dataset of 3377 cycles. Of these, 777 cycles were discarded because the corresponding video footage was unavailable, primarily due to intermittent recording interruptions or streaming failures during the collection period.

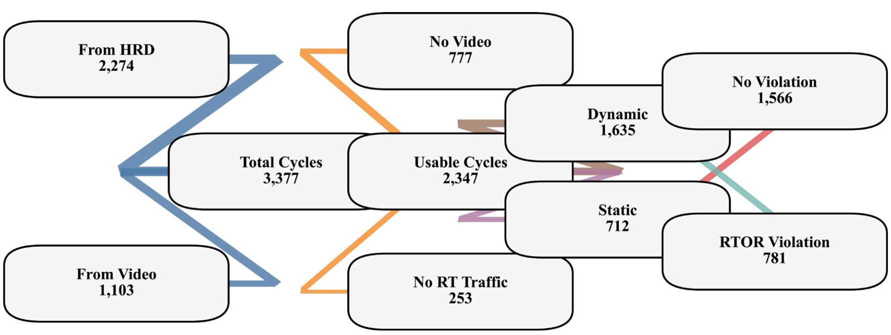


Figure 2. Breakdown of cycles from HRD and video sources (HRD = high-resolution data).

The remaining dataset consisted of 2600 cycles with usable video. Within this set, 253 cycles contained no right-turn vehicles and were therefore excluded from compliance calculations. This group also included cases at approaches with shared through-right lanes where the lead vehicle proceeded through the intersection, preventing an RTOR maneuver. After these exclusions, 2347 cycles with right-turn activity were retained for analysis. Among these, 1566 cycles exhibited full compliance with the NRTOR restriction, while 781 cycles involved at least one violation. The following section provides a more detailed examination of compliance outcomes across treatment types.

6. Compliance Analysis of Right-Turn-On-Red Restrictions

Comparison of Compliance Rates

Table 2 and Table 3 summarize compliance from two complementary vantage points: cycle-based and vehicle-based. In Table 2, a cycle is counted as compliant only if no RTOR occurs while the NRTOR indication is displayed; the appearance of a single turning vehicle renders that cycle non-compliant. Table 3 shifts the denominator to individual right-turning vehicles present during red (*i.e.*, those with an opportunity to turn on red) and reports the share that refrained from RTOR while the message was active. Thus, Table 2 quantifies the likelihood of a violation-free cycle, whereas Table 3 captures driver obedience among eligible right-turn traffic.

Across sites, the two measures diverge in magnitude. Cycle-level compliance spans 38% - 85%, indicating that in 38% - 85% of observed cycles no RTOR occurred during the display. Vehicle-level compliance is higher, at 77% - 93% among

Table 2. Summary of Per-cycle NRTOR compliance results.

Location	*Left-Turn Treatment*		*Cycles with No Violation*	*Cycles with 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	10 am - 6 pm	150	68	68.8%
Dynamic, Total			**993**	**640**	**60.8%**
Static, Total			**571**	**143**	**80.0%**

Table 3. 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	10 am - 6 pm	760	105	87.9%
Dynamic, Total			**7073**	**1048**	**87.1%**
Static, Total			**2324**	**191**	**92.4%**

eligible vehicles. Locations with static NRTOR consistently outperform dynamic installations on both metrics. The treatment gap is more visible at the cycle level, while vehicle-level differences are smaller—an expected pattern because aggregating over many vehicles within a cycle increases the chance that at least one will violate even when most drivers comply.

At US 12 & Hwy 101, where DNRTOR operated in both time-of-day (TOD) and pedestrian-activated modes, results differed by mode. The ped-activated setting produced a larger share of violation-free cycles than TOD, whereas vehicle-level compliance was more similar across the two modes. This is consistent with exposure effects: TOD coincides with peak periods and the sign is illuminated during every red, creating more right-turn opportunities per cycle and, consequently, a higher chance that at least one driver turns on red—despite most individuals still adhering to the indication.

7. Statistical Analysis

7.1. Odds Ratio and Chi-Square Tests

We assessed treatment effects using odds ratios with 95 percent confidence intervals and complemented these estimates with chi-square tests of independence. Results are reported separately for cycle-based and vehicle-based denominators (Table 4(a) and Table 4(b)).

For the cycle-based analysis, the odds that a cycle contained at least one right-turn-on-red (RTOR) under dynamic NRTOR control were 640 to 993, which is approximately 0.645. Under static control, the corresponding odds were 143 to 571, or about 0.250. The implied odds ratio is about 2.6, meaning cycles operating with a dynamic sign had roughly two-point-six times the odds of including a violation compared with cycles operating with a static NRTOR sign.

For the vehicle-based analysis, the odds ratio is approximately 1.8. In other words, for any right-turning vehicle present during the red interval, the odds of executing an RTOR were about one-point-eight times higher with dynamic control than with static control.

The 95 percent confidence intervals in **Table 4** indicate the precision of these estimates; intervals that do not include one imply a statistically meaningful difference between treatments. The accompanying chi-square statistics and p-values further test whether the observed differences between dynamic and static NRTOR are statistically distinguishable for each denominator.

Table 4. Odds ratio and chi-square 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 ($P < 0.001$)	

7.2. Statistical Models

To isolate the effect of sign type while accounting for operational context, we estimated two regression models that incorporate variables reflecting site geometry, traffic exposure, and temporal factors. The covariates were:

- Use of Dynamic Sign—indicator equal to 1 for dynamic blank-out signs and 0 for static signs.
- Time-of-Day (TOD)-based NRTOR—indicator equal to 1 when the restriction was governed by TOD operation (under either sign type) and 0 otherwise.
- Total Right-Turn Vehicles—count of vehicles with an opportunity to perform RTOR.
- Number of Conflicting Through Lanes—lane count on the through movement that conflicts with the subject right turn.
- Presence of a Conflicting Right-Turn-Only Lane—indicator equal to 1 if the opposing through approach also had a right-turn-only lane, 0 otherwise.
- Presence of an Opposing Left-Turn Movement—indicator equal to 1 if a conflicting left-turn phase was present, 0 otherwise.
- Day-of-Week indicators—included as controls; these were not statistically significant in either model.

For the cycle-level analysis, we estimated a logistic regression in which the dependent variable equals 1 if a cycle contained at least one RTOR during red and 0 otherwise. Logistic regression is appropriate here because it models the probability of a binary outcome.

Table 5 reports the coefficient estimates and significance tests for this model. Coefficients can be interpreted in directional terms: positive values indicate a higher likelihood that a cycle includes an RTOR, whereas negative values indicate a lower likelihood. The estimates are consistent with operational expectations:

- Total right-turn vehicles has a positive association with violations: as exposure increases, so does the chance that a cycle contains at least one RTOR.
- More conflicting through lanes is associated with more violations, consistent with greater gap availability across multiple lanes.
- Opposing left-turn present carries a negative sign, reflecting fewer usable gaps when left-turn traffic conflicts with the subject movement.
- TOD operation and static-sign use both have positive coefficients, indicating higher violation likelihood relative to their respective reference categories (non-TOD operation and dynamic signs).

Except for the day-of-week indicators, all covariates were statistically significant in the cycle-level model.

Table 5. Logit model estimated for a dependent variable indicating whether a signal cycle under NRTOR will have one or more RTOR vehicles. (***significant at 99.9%; **significant at 99%; *significant at 95%).

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

We next estimated a Tobit regression with the share of violating vehicles within a cycle as the dependent variable. Because this outcome is bounded between 0 and 100 percent—with mass at the boundaries (e.g., many cycles have zero violations)—the data are censored, making the Tobit specification appropriate. Table 6 reports the estimates. Coefficients are interpreted in directional terms: positive values indicate a higher percentage of RTOR vehicles in a cycle, whereas negative values indicate a lower percentage.

During model refinement, the total number of right-turn vehicles was not statistically significant and was therefore excluded. The effects of the remaining covariates mirror those from the logistic model:

- Dynamic sign use and time-of-day (TOD) operation are associated with a higher percentage of violating vehicles.

- A greater number of conflicting through lanes corresponds to a higher percentage of violations, consistent with increased gap availability.
- The presence of an opposing left-turn movement is associated with a lower percentage of violations, reflecting reduced usable gaps.

All retained variables were statistically significant, although the effect of TOD operation was only weakly significant.

Table 6. Tobit regression model estimated for a dependent variable indicating the percentage of violating vehicles during a cycle under NRTOR (***significant at 99.9%; **significant at 99%; *significant at 95%; †significant at 90%).

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

7.3. Pedestrian-RTOR Vehicle Interactions

Manual reviewers noted, anecdotally, that drivers were more likely to honor DNRTOR indications when a pedestrian or other nonmotorized user was actively occupying the crosswalk; by contrast, RTOR maneuvers typically occurred when no such conflicting users were present. To examine whether pedestrian presence systematically shaped the timing of RTOR relative to the DNRTOR display, observers recorded the time stamp of the first RTOR maneuver in each cycle in which a violation occurred.

Figure 3 plots the empirical distributions of these first-RTOR times for the six DNRTOR sites. The horizontal axis represents elapsed seconds from the Start of Walk, and the vertical axis reports the corresponding frequency of observations. Each cycle contributes at most one observation, namely the first violating vehicle if any occurred. Table 7 summarizes additional statistics computed from the same dataset to contextualize these timing patterns.

During data collection we posited that the timing of the first RTOR within a cycle would dip when pedestrians were most likely to be present in the crosswalk. The site-specific distributions in Figure 3 offer mixed evidence: some panels—e.g., TH 36 & Fairview, North Ramp (Figure 3(a))—appear consistent with this pattern, whereas others—e.g., TH 36 & Fairview, South Ramp (Figure 3(b))—do not. Table 7 lists the counts of first-RTOR occurrences by interval. In raw terms, every intersection shows more first-RTOR events during the Walk interval than

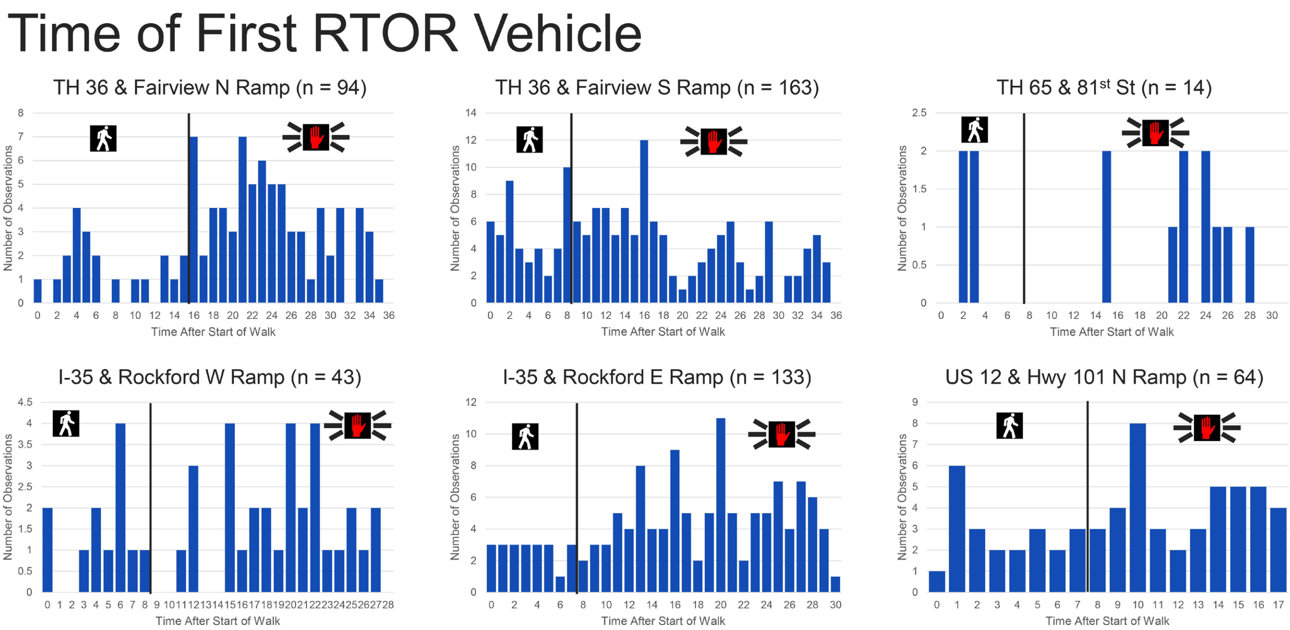


Figure 3. Pedestrian-Activated DNRTOR: Distribution of first RTOR occurrence times.

Table 7. First RTOR occurrence time 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 Flashing Don't Walk (FDW). However, because FDW typically lasts longer, normalizing by interval duration (see the two rightmost columns of Table 7) yields higher rates during FDW at most sites. This suggests some drivers may defer RTORs to later portions of the pedestrian phase, but the pattern is not uniform across intersections, limiting strong conclusions about first-RTOR timing.

Across 849 cycles with RTOR violations at pedestrian-activated DNRTOR locations, only six cycles (0.7%) involved material interference with an actively crossing pedestrian (e.g., a pedestrian was compelled to stop or change path). Although we cannot benchmark these counts against alternative site conditions within this study, the small number of observed conflicts is consistent with the notion that DNRTOR displays improve pedestrian conspicuity.

Although pedestrian conspicuity was assessed qualitatively by manual reviewers, future studies should incorporate quantitative metrics. Potential approaches include coding pedestrian head turns toward traffic, measuring glance frequency toward right-turn lanes, or applying computer-vision methods to track pedestrian gaze direction. Eye-tracking experiments in simulation or controlled field studies could also validate whether DNRTOR illumination improves detectability to drivers. Such measures would provide stronger causal evidence beyond anecdotal notes.

Observers also noted a possible "follow-the-leader" behavior in right-turn queues: once the lead vehicle executed an RTOR, subsequent vehicles sometimes followed with shorter hesitation. The strength of this pattern varied by site—some approaches exhibited multiple RTORs within a cycle, while others typically had only one or two. Because gap availability in the conflicting streams was not measured (beyond the scope of this study), we cannot formally evaluate the mechanism underlying this apparent queuing effect.

Because the analysis emphasized the first RTOR per cycle, subsequent violations within the same cycle were not systematically captured. This approach standardized denominators but may underestimate total non-compliance. Observed 'follow-the-leader' behavior suggests that once an initial violation occurs, trailing drivers may replicate the maneuver. Future work should consider metrics capturing multiple RTORs per cycle to more fully reflect aggregate exposure risk.

8. Conclusions

8.1. Lower Compliance with Dynamic NRTOR than Static Signs

Taken together, the findings show that dynamic NRTOR sites exhibit lower compliance than sites with static signs. This pattern appears in both metrics: the share of cycles with no RTOR (**Table 2**) and the share of right-turning vehicles that refrained from RTOR when given the opportunity (**Table 3**). A chi-square test confirms that these differences are statistically significant (**Table 4**).

In multivariable models, dynamic sign use is associated with more cycles containing a violation (**Table 5**) and with a higher within-cycle percentage of violating vehicles (**Table 6**), after adjusting for geometric and traffic covariates. That said, the estimated effect of sign type is smaller in magnitude than the effects linked to intersection geometry, which exert the stronger influence on observed compliance.

8.2. DNRTOR Displays May Increase Pedestrian Noticeability

At US 12 & Hwy 101 (North Ramp), the DNRTOR display operated in two modes: pedestrian-activated, in which the indication illuminated only when the conflicting pedestrian phase was active, and time-of-day (TOD), in which the indication illuminated during every red interval. At this site, cycle-level compliance was higher under the pedestrian-activated setting—more cycles were free of any RTOR—whereas vehicle-level compliance was broadly similar across the two modes. This divergence between denominators is consistent with exposure effects and user presence: during pedestrian-activated operation, the first eligible right-turning vehicle more often waited until the DNRTOR indication extinguished (*i.e.*, until the pedestrian phase ended), yielding more violation-free cycles; under TOD operation, pedestrians were less likely to be present, yet the indication was active throughout every red, increasing the chance that at least one driver would turn on red within a cycle even if most individual drivers complied.

Manual video review further suggested that most RTOR maneuvers did not conflict with actively crossing pedestrians. Although some drivers violated the DNRTOR blank-out indication, many appeared to delay their turn until the conflicting pedestrian movement had cleared. Among 849 cycles with RTOR violations at pedestrian-activated DNRTOR locations, only six cycles involved substantial pedestrian-vehicle interference (e.g., a pedestrian stopping or altering path). While direct comparison with locations using alternative right-turn controls is beyond this study's scope, the small number of observed conflicts is consistent with improved pedestrian conspicuity under DNRTOR.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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