JTCDR

VOLUME 3
DECEMBER 2025

ON THE COVER

Space for the movement of people takes various forms along this street corridor in central Miami, Florida. Applications of pavement markings and signing are combined with alterations to signal operations in the quest to prioritize movements and modes. Every change alters the balance of risk and delay, a disequilibrium with decades of expectations prompting user responses in an evolving network encumbered by ever-increasing density. Could it be that the collective response to all these changes is very little change?

Such reallocated space in urban street networks remains influenced by the intractable realities of human factors, unchanged in a century, imperceptibly altered in a millennia. All users balance route choice in navigation and speed selection in operations, their behavior being influenced by attitudes, perceptions, capabilities, and the very characteristics of the transportation environment itself. Likewise, a wide variance of conveyance capabilities and limitations molds the journey overall while shaping thousands of interactions along the way. In this particular scenario, discharge of the standing queue will conform to long-standing models describing how road users manipulate vehicle headways. The result of this long queue is higher vehicle speeds attained by moving vehicles released from the back of the queue. As this situation evolves, another headway, namely, that of transit vehicle arrivals, prompts a vulnerable user with experience in failed connections to reverse direction into the path of vehicles standing still mere moments ago. Despite all of the accommodations, this entire traveled way remains aligned to a tangent section, a green ball threatens to become a yellow ball, and the effects of the delay that every user experiences prey on the most intrinsic human traits of all.

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
DECEMBER 2025

J T C D R

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH

VOLUME 3, ISSUE 1
DECEMBER 2025

WHEN USED THROUGHOUT THIS DOCUMENT,
THE ABBREVIATION "TCD" IS INTENDED TO
STAND IN FOR THE TERM "TRAFFIC CONTROL DEVICE"

PUBLISHED BY
**THE NATIONAL COMMITTEE ON UNIFORM
TRAFFIC CONTROL DEVICES**

JOURNAL OF

TRAFFIC CONTROL DEVICE RESEARCH

VOLUME 3

ISSUE NUMBER 1

DECEMBER 2025

VISTA POINTS

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
VOLUME 3, ISSUE 1 | DECEMBER 2025

FOREWORD

Bryan J. Katz, Ph.D., P.E., PTOE, RSP[21]
Vice Chair for Research, NCUTCD
Chair, NCUTCD Research Committee

THE INTRICATE INTERSTATE | PRACTITIONER PERSPECTIVES

Michael J. Tantillo
Secretary, NCUTCD Research Committee

THE STEADY BEACON | PRACTITIONER PERSPECTIVES

Scott O. Kuznicki, P.E.
Chair, *JTCDR* Editorial Board

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
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ACCEPTED SUBMISSIONS

6 PAPERS

RESEARCH & INNOVATION

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
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ACCEPTED SUBMISSIONS

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EDITOR'S WELCOME

Bryan J. Katz, PhD., P.E., PTOE, RSP$_{2I}$
Executive Editor & NCUTCD Vice Chair

It is my pleasure to introduce you to our third volume of the *Journal of Traffic Control Device Research*. This journal is a product of the Research Committee and fulfills our goal to bring practical-based knowledge about traffic control devices to members of the National Committee on Uniform Traffic Control Devices (NCUTCD) as well as the traffic engineering practitioner community at large.

Launching this Journal has been one of my goals as the Research Chair of the National Committee. With the help of an incredible team of people, we have set up a system to receive submissions, review them, assist with formatting, and ultimately publish the Journal itself with posting of the link on the ever-improving NCUTCD website.

You will note that this issue of the journal includes a combination of case studies, state-of-practice information, and research papers. While the contents and formats vary, all contributions to the journal help to disseminate knowledge related to Traffic Control Devices. As we continue the publication of the journal, it is my vision that we will maintain a variety of paper formats. In addition, it is also my vision that we expand our base of authors and that we have more papers that are developed by authors who serve as practitioners in public agencies. You will see that this is already happening to a degree in current and past issues, but I believe there is much benefit to be gained through the publication of the many studies and evaluations conducted by public-sector traffic operations practitioners.

As you read the papers in this issue, I invite you to think about topics that you would like to hear about and encourage colleagues to submit papers for the next edition. In 2026, we will accept submissions beginning in January and expect we can continue to publish this journal annually in the years ahead. The success of the journal comes from our amazing volunteers who take the time to contribute papers and review the submissions. I am very appreciative of the time and effort taken to write papers for publication in our journal. I look forward to being a part of its continued success!

THE INTRICATE INTERSTATE

Michael J. Tantillo
Associate Executive Editor

Spending time with my family this holiday season, I reflected back on a scary experience we had many years ago. It was in the 1990s, and the family was on vacation outside the United States in a place with very similar traffic control devices. I was in the passenger seat helping to navigate in the pre-GPS era.

We were approaching a new city on an undivided two-lane (one per direction) freeway. There was a work zone, it was dark, and there were no pavement markings. There was a cluster of guide signs for some exits, none of which we wanted, so when a roadway diverged off to the right, we kept left. A few seconds later, we reached the end of the work zone, and there were pavement markings.

We were driving down a two-lane roadway, but the edge line to our right was yellow. It took me just a split second to realize that we were driving the wrong way on a freeway. I screamed to the driver “pull over, get off the road, now!” Not ten seconds later, two cars came flying over the crest of a hill in the lane we were in. That could have been the end of the story. Thankfully, seeing that yellow line on the right was quick and decisive confirmation that something was very wrong. It turned out that where the road branched off to the right, it was not an exit, but the beginning of the divided highway.

Two days later, we were on that same road in the daylight. In the work zone, there was a crane lifting a massive “KEEP RIGHT” sign into place at the point where we made our mistake.

Two lessons from this humbling experience. First, be sure temporary traffic control devices are adequate especially in a situation where a divided highway begins. Second, never underestimate the power of the subtle communication of traffic control devices, because it might just save your family’s life one day.


YIELD
SPEED LIMIT
25

THE STEADY BEACON

Scott O. Kuznicki, P.E.
Managing Editor

At a lone intersection with three approaches, a single luminaire spills light onto the roadway forming the stem of the "T". An approaching car rolls into the photonic bath and coasts through a right-hand turn at a speed of roughly 25 feet per second, without stopping, despite the operator facing a well-maintained and duly-erected R1-1.

This happens all the time.

Every day, thousands upon thousands of vehicle operators navigate their vehicles through rolling right turns at locations where the law requires them to come to a complete standstill. In the vast majority of those cases, collisions involving vehicles turning at a reasonable speed are rarely imminent. This reasonable speed happens to correlate to the roadway geometry, road user capabilities *and preferences*, and vehicle limitations. At an intersection in Seattle, a place that exhibits perhaps the foremost juxtaposition of social compliance and disdain for authority, hundreds of bicycle operators disregard intersection traffic control, preferring instead to maintain momentum, awareness, and vehicle control through the art of the rolling stop. Juxtapositions abound.

So what is really happening here? Are all of these people merely crass lawbreakers who deserve the disdain of self-righteous transportation officials? Or are they perhaps inferring some rules from observation of the roadway network configuration and *assuming priority at a node*? Continuous movement of vehicles in turns is common in European countries, a mark of vehicle operator competence and uniform expectations.

Road users infer meaning from the texture of the pavement, the presence of geometric design features such as aprons, curbs, islands, and the marked traveled way. Users indeed react even to the perceived gravity of such control measures. Just as road users infer a 100 mile-per-hour operating speed to be acceptable on a rural motorway, they will likewise infer a 14-mile-per-hour turning speed from a curb radius, signs and restrictions and ordinances notwithstanding. Thus, then, the work of the traffic operations engineer is to design systems that accommodate what we can readily observe. Reality will intervene where the ideal model for system interactions remains in conflict with traffic control devices, indicating disrespect of the road user who respects the design of the road itself.

SUBMISSIONS TO THE
JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH

Submissions to the JTCDR are accepted at the web site of the National Committee on Uniform Traffic Control Devices, http://ncutcd.org on any web browser. Refer to the call for papers and submission guidelines for more information.

Future calls for submissions and papers will address traffic control devices supporting the harmonization of desired characteristics for human drivers, advanced driver automation systems, and highly-automated vehicle systems.

While many journals typically accept research papers summarizing the results of experimentation or describing general methodologies, the Journal of Traffic Control Device Research is also home for a wide variety of technical and philosophical perspectives related to the disciplines of traffic engineering, transportation safety, and human factors engineering in transportation. The list below identifies some of the types of technical materials the editors are seeking for future issues.

- Research Compilation and Syntheses of Practice
- Practices Evaluations and Project Overviews
- Evaluations of Novel and Existing TCDs
- Human Factors Performance Evaluations
- Safety Outcome Evaluations
- Technology Applications and Integration with Automated Driving Systems
- Research Proposals for Innovative and Evolving TCDs
- Historical Perspectives on Traffic Engineering and the Development of TCDs
- Current Perspectives on Issues Related to TCDs and Human Factors Research

The chief goal of this journal is to capture and retain knowledge in an accessible format. The greatest knowledge we can obtain consists of reflections and insights from those who have spent decades learning about this work. These pioneering leaders developed the principles, methodologies, and systematic tools that traffic engineers use today to implement and evaluate the performance of traffic control devices.

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VOLUME 3, ISSUE 1 | DECEMBER 2025

PAPER 008

Quantifying How Much Key Factors Influence Freeway Operational Speeds During Non-Congested Periods

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Key Words:

Freeway operating speed, posted speed limit

Abstract

An evaluation of speeds on Texas freeways used data from 243 roadway sensors located in Fort Worth representing operating speeds during daytime and clear weather conditions from 2015 to 2019. The initial evaluation explored how much average operating speeds increased when the posted speed limit (PSL) was raised from 60 to 65 mph, 60 to 70 mph, or 65 to 70 mph. The average operating speed increased between 2.4 to 4.0 mph for 5-mph increase in PSL or 2.9 mph for the 10-mph increase in PSL. The next evaluation identified variables associated with variations in average freeway speeds. The most significant amount of operating speed variation was associated with unidentified localized factors representing 33.8 percent of variability due to differences between detector locations. Yearly shifts in speeds at a given location were found to be the third most relevant source of speed variation (10.6 percent). Geometry was estimated to explain about 7.5 percent, speed limit 4.1 percent, and citations 3.6 percent of the speed variation in this dataset. Geometry, citations, and PSL represent the range of influence for engineering, law enforcement, and traffic management on operating speed. This study estimates that a strategy that entails modifying geometry, changing the PSL, and varying the level of law enforcement presence within the ranges included in this study may impact freeway operational speeds up to 6.2 mph (depending upon existing conditions along with the changes in the geometry, PSL, and enforcement).

Introduction

A highly complex transportation issue can be determining an appropriate posted speed limit (PSL). Determining the PSL involves engineering, human factors, and political and societal concerns. Drivers' operating speed can be used to set posted speed limits and posted speed limits are assumed to affect the speed selected by a driver. Several roadway-related factors are known or suspected to affect operating speed on freeways, such as vertical alignment, shoulder width, and ramp density. In addition, traffic conditions are a known influence on driver speed choice with slower speeds existing during more congested periods. The influence of the speed limit sign on operating speed, however, is not as well known. The primary goal of the evaluation presented in this paper was to investigate how much impact the posted speed limit sign has on freeway operating speeds including whether operating speeds change after a change in the posted speed limit.

Previous Research

The Transportation Research Board (TRB) *Modeling Operating Speed Synthesis Report* (*1*) documents several studies' findings regarding factors that influence driver's operating speeds with most focusing on two-lane rural highways with horizontal curvature being the prime influence. Much less knowledge is available regarding freeways. The TxDOT project (*2*) that supports the research in this paper investigated this gap.

Operating Speed and Roadway Factor Relationships for Freeways

Roadway geometric design variables with a known relationship to operating speed include access points (negatively associated), horizontal curve radius (positively associated), lane width (positively associated), median width (positively associated), number of lanes (positively associated), paved shoulder width (positively associated), and vertical grade (negatively associated) (*3*). Negatively associated indicates that as the value of the variable increases (e.g., steeper grades), operating speed decreases.

A 2015 TxDOT study (*4*) examined operating speeds on freeways and found an increase of about 2.2 mph for a 12-ft lane as compared to an 11-ft lane. The shoulder width was significant when the adjacent lane is 11 ft wide, but not when it is 12 ft wide which suggests that left shoulder width is more important with a reduced lane width. Operating speeds on Texas freeways are 2 mph lower during nighttime (with roadside lighting present) than during the day. Speeds were higher (by 1.5 mph) on the weekends (Saturday) than on the weekday studied (Wednesday).

The Highway Capacity Manual (HCM), version 6.0 (*5*), states in Exhibit 12-18 that the base free-flow speed under ideal conditions exceeds the speed limit by 5 mph for freeway segments with a PSL range of 55 to 75 mph as well as for multilane highway segments with a PSL of 45 to 70 mph. The HCM also provides additional information in Chapter 12 about adjusting the freeway free-flow speed using adjustment factors for lane width, right-side lateral clearance, and total ramp density.

Robertson et al. (*6*) developed suggested changes to the HCM freeway methodology to be able to consider freeways with free-flow speeds greater than 75 mph. The factors found to influence freeway operating speeds included posted speed limit, ramp density, truck percentage, differences between lanes (i.e., whether the vehicle was in the outside lane or the inside lane), median width, left shoulder width, and vehicle type (passenger car or truck).

Impacts from Increasing Regulatory Posted Speed Limit

Several studies are available regarding the impacts of increasing the regulatory speed limit. Hu (*7*) in 2017 reported that the average speed increased by 3.1 mph for passenger cars (4.1 percent) and 1.7 mph for large trucks (2.5 percent) when the PSL went from 75 to 80 mph on rural interstate roadways in Utah. Souleyrette et al. (*8*) in 2009 reported on implementing a 70-mph speed limit on most rural Iowa Interstates with mean and 85th percentile speed increases of about 2 mph. Utah Department of Transportation (UDOT) in 2009 (*9*) reported that overall, speeds increased between 2 and 3 mph on the sections with a 5-mph speed limit increase. Retting and Cheung (*10*) reported on the 2006 increase in daytime speed limit for passenger vehicles from 75 to 80 mph for West Texas freeways. They found passenger vehicle mean speeds were up by 4 mph on I-10 and 9 mph on I-20 relative to comparison roads.

Dixon et al. (*11*) in 1999 reviewed speed data for 12 rural multilane sites in Georgia in the 1990s to evaluate the effects of repealing the 55-mph national speed limit. They found that operating speeds were higher after the increase in the PSL with observed mean speeds being 3.2 mph higher when the posted speed increased from 55 mph to 65 mph.

The Transportation Research Board (TRB) Special Report 254 (*12*) in 1998 summarized several studies that examined the increase in operating speeds when the National Maximum Speed Limit (NMSL) went from 55 mph to 65 mph. Raising rural Interstate speed limits resulted in the following changes:

- Average speeds increased on the order of 4 mph or less for 10-mph increase in the speed limit.
- 85th percentile speeds also increased on the order of 4 mph or less for the 10-mph increase in the speed limit.

Musicant et al. (*13*) in 2016 analyzed information from several previous research studies where the speed limit in the before period was at least 50 mph. Their database included 108 entries where the speed limit was reduced for 52 locations and the speed limit was raised for 56 locations. Overall, they found that the direction of change in mean driving speed (up or down) is in line with the direction of change in the speed limit; however, the magnitude of change for driving speed is more moderate as compared to the magnitude of change in the PSL.

The magnitude of the change in operating speeds when there is an increase (or decrease) in posted speed is typically only a fraction of the amount of the actual speed limit change. Overall, the previous studies indicate for high-speed rural roadways, mean speeds are generally 3 to 5 mph higher for every 10-mph increase in speed limit above 55 mph, with smaller increases at higher speed limits.

Impacts from Decreasing Regulatory Posted Speed Limit

There are fewer previous research efforts documenting the change in operating speeds when the PSL is reduced for limited-access roads. TRB Special Report 254 (*12)* references a 1984 TRB study (*14*) on the effects of the national 55 mph speed limit and found that the lower limit reduced both travel speeds and fatalities, although driver speed compliance gradually eroded. Parker (*15*) in 1997 examined the effect of changes in speed limits on rural and urban nonlimited-access highways and found generally less than 2 mph change in driving speed regardless of the amount of change in PSL.

Musicant et al. (*13*) in 2016 analyzed information from several previous research studies and reported that when speed limit was reduced, the driving speed was reduced a moderate amount.

Study Approach

Research Questions

The following research questions guided the development and analysis of the freeway database:

- Research Question 1: Do freeway operating speeds change following an increase in PSLs?
- Research Question 2: What is the relationship between daytime operating speeds (average speeds) and the PSL value after accounting for other factors? Within this question is the interest to understand what factors are more influential (e.g., PSL, freeway geometry, other factors).
- Research Question 3: On Texas freeways, are operating speeds increasing over time?

Site Selection / Speed Data

The research team examined recent PSL changes within Tarrant County which includes Fort Worth. Fort Worth previously implemented environmental speed limits (ESL) in 2001 which were replaced in July 2015 based on speed studies conducted by the local TxDOT district. Researchers obtained operating speeds in May 2015 before the speed limits were changed in July. Because researchers also wanted to investigate whether freeway speeds are increasing over time, the data for May of subsequent years 2016-2019 were also gathered. Only one month per year was used to keep the database a manageable size. It was desired to include May 2020 data, but TxDOT lost these data due to a ransomware attack, so April 2020 data were obtained instead.

For the analysis, it was desired to obtain a robust speed dataset that has several locations with speed and volume data where the PSL was changed. TxDOT operates Traffic Management Centers (TMCs) in all large urban areas of Texas, including Fort Worth. The management is accomplished, in part, by roadway smart sensors (*16*). The smart sensors collect speed, volume, and occupancy (SVO) data and their data are stored locally in the field (at 20-second intervals) and then aggregated and archived in a regional data warehouse into five-minute intervals. Typically, two detector links are assigned to one detector (one in each direction).

The researchers reviewed the links and removed several for various reasons such as construction, being on ramps, or data availability. Detectors were also removed that had the following site characteristics because they represented a small number of sites compared to the rest of the database:

- Speed limit was 55 mph.
- The segment had 5 or 6 general-purpose lanes.
- The segment had one or more managed lanes.
- The next upstream or downstream ramp was a left-side ramp.

Ultimately, researchers used 243 detector links for the final dataset.

Developing Study Database

The research team assembled a merged database incorporating several data sources as discussed in the following sections.

Roadway Geometric Data and PSL Data

The roadway dataset included geometric data, PSL, and presence of construction. The geometric data included lane count, lane width, and characteristics of upstream and downstream ramps. The research team used aerial and street-level photographs to identify the locations of PSL signs. Once a PSL sign was identified in a street-level photograph, the historical street view feature was used to review previous years to determine if the PSL value changed in an earlier year. The detector-year was flagged as having construction when, in the opinion of the research team, the level of construction was believed to affect operating speed. Presence of construction was obtained from reviewing historical aerial and street-level photographs.

The PSLs present in the database included detectors that had 60 mph for all years, 65 mph for all years, 70 mph for all years, 60 mph in 2015 and 65 mph in other years, 60 mph in 2015 and 70 mph in other years, and 65 mph in 2015 and 70 mph in other years. A few detectors did not fit in those categories, such as having a speed limit change in 2017, and were removed.

Weather Data

The weather data file consisted of hourly records of precipitation (inches) and visibility (miles) readings at four weather stations in Tarrant County. The research team merged the hourly precipitation and visibility values into the speed database using the latitude and longitude coordinates for the detectors and the weather stations and the date and time variables. Each speed record was matched with the data from the closest weather station, or the next-closest weather station if the closest station was non-functional during the hour of interest.

Speed data were marked for removal if within the hour, more than 0 inches of rain occurred. The research team initially considered including speed data when a small amount of rain was present; however, a study in 2017 (*17*) found that free-flow speed decreased by 4.4 percent when rain between 0 and 0.20 in/h was present. Therefore, any 5-min time slice associated with any rainfall was marked for removal.

Incidents

Because traffic incidents are a major source of nonrecurring congestion (*18*), TMC incidents were compiled from the TxDOT database for the same months as the speed data. This information was used to remove potentially 'abnormal' speeds that could have been influenced by these nonrecurring events. Most of the incidents for the time periods considered in this study were collisions (63 percent) and construction (25 percent). All amber and news alerts, public service announcements, and public emergency incidents were not included because they are more areawide in nature rather than being associated with a specific detector or freeway section.

The research team merged the incident data with the speed data using the latitude and longitude coordinates for the incident and the detector and the date and time variables. The speed record was flagged as being associated with an incident and were removed if the following conditions were met:

- The incident occurred on the same roadway as the speed record.
- The incident started within 10 minutes prior to the 5-minute time slice for the speed record or ended within 20 minutes of the 5-minute time slice.
- The distance between the incident and the detector was less than or equal to 3 miles.
- The incident was not an abandonment. An abandonment is when an unattended vehicle is located and tagged by law enforcement on one of the shoulders. Abandonments were not flagged because they are assumed to cause minimal disruption to traffic flow in the travel lanes.

Light

The research team identified the sunrise for each day represented in the data using archived almanac records (timeanddate.com). Dawn was defined as within 30 minutes before or after sunrise. Dusk was defined as within 30 minutes before or after sunset. The research team combined light condition data with the speed records and designated each record as dawn, day, dusk, or night. Data for only the daytime light condition were used in the analysis.

Citations

The researchers acquired available enforcement speeding citation data from the Department of Public Safety (DPS) and city and county police departments, as the level of enforcement might have an impact on operating speed. Based on local knowledge, the thoughts are that drivers are becoming more familiar with higher operating speeds with the recent opening of several tollways in the area. In addition, drivers may be noticing lower enforcement levels due to a reduction in workforce, caused by higher turnover and lower academy enrollment, or changing enforcement patterns due to recent social issues. Figure 1 shows there was an 11-percent decrease in speeding citations by municipalities and a 25-percent decrease by DPS between 2016 and 2019.

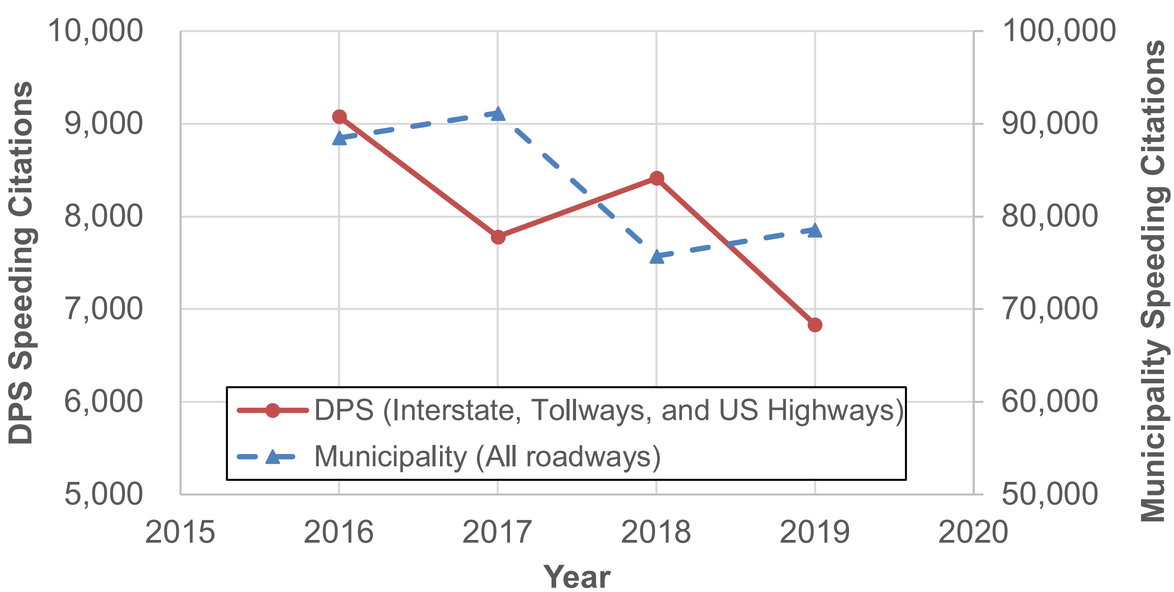


Figure 1. Tarrant County Speeding Citations.

Freeway Database

The research team imported and processed the speed data for the months of May 2015, May 2016, May 2017, May 2018, May 2019, and April 2020. Each record in the speed data represented vehicles at one detector going in the same direction for one 5-minute time slice. The data records included overall time-mean speeds and lane-weighted time-mean speeds per direction. Records were removed for the following reasons:

- Record contained no vehicles or no speed observation.
- Construction was present on the link during the given month and year.
- Precipitation was recorded during the hour that included the 5-minute time slice.

- Record was associated with an incident.
- Speeds (average or lane-weighted) was less than 53 mph (assumed value that indicates that congestion may be beginning) or greater than 90 mph (assumed value for potential sensor error).
- The vehicle count suggested a flow of greater than 3000 veh/hr/lane.
- The light condition was dusk, night, or dawn.

Initial attempts to use the screened sample database with approximately 3 million records resulted in multiple computer failures because of the size of the database. The research team decided to address the database size issue by creating 15-min speed readings based on merging data from three consecutive 5-minute time slices. This approach allowed the research team to use the entire database rather than starting from a sample of the data and then confirming the preliminary findings using the complete database.

The overall average speed per year and PSL is shown in Figure 2. Figure 3 provides the average operating speed by year for each of the control and treated (where PSL changed) groups. Overall, the speeds are fairly similar for 70-mph freeways between 2016 and 2019. The potential impacts of the pandemic stay-at-home restrictions (both businesses and schools), including lower volumes and less enforcement, can be seen in the 2020 data where overage operating speeds are notably higher for each PSL. A recent study conducted by Das et al. (*19*) showed that higher operating speed during COVID-19 is associated with higher fatal and injury crashes on urban freeways. When focusing on 2015 to 2019, the curves for 60 and 65 mph speed limits show an upward trend of higher operating speeds for later years while the data for 70 mph roads show similar average driving speeds for each year.

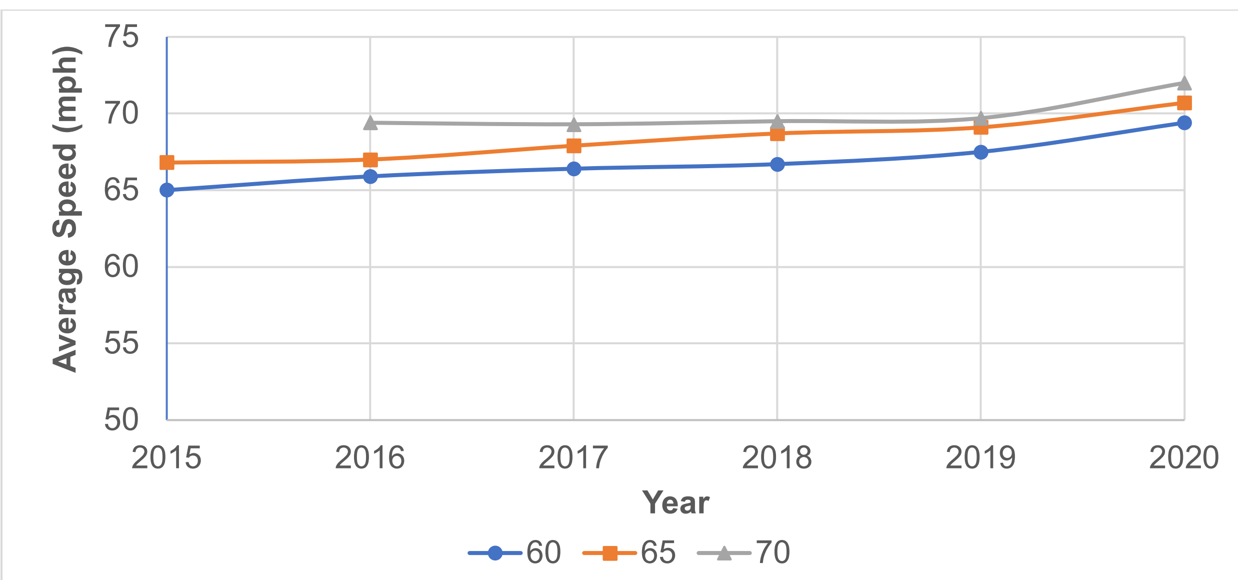
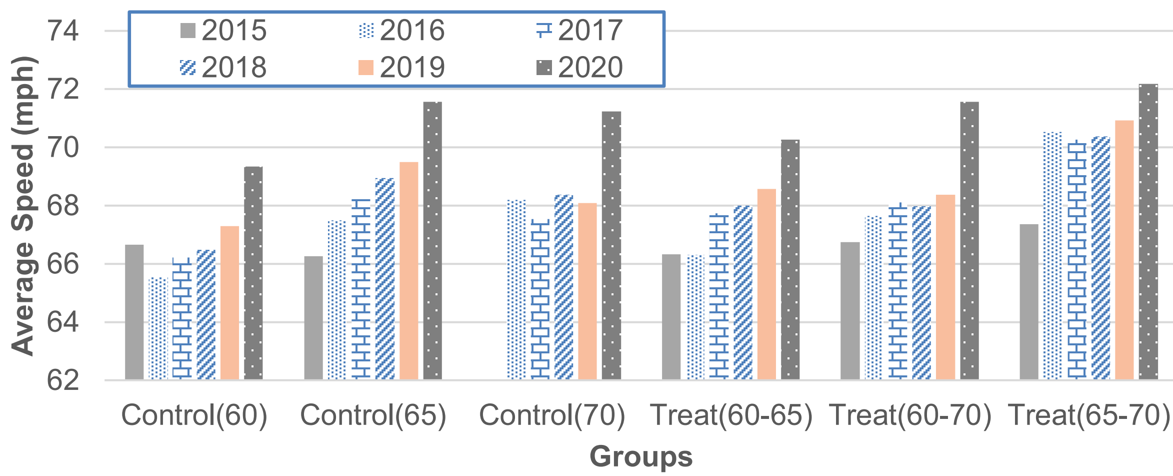


Figure 2. Average Operating Speed by Year and PSL.



Where the groups included the following:

- Control(60) = the detector location had a 60-mph PSL for all years.
- Control(65) = the detector location had a 65-mph PSL for all years.
- Control(70) = the detector location had a 70-mph PSL for 2016 to 2020 (none of the sites in this database had a 70-mph speed limit during 2015).
- Treat(60-65) = the detector location had 60-mph PSL in 2015 and a 65-mph PSL in other years.
- Treat(60-70) = the detector location had 60-mph PSL in 2015 and a 70-mph PSL in other years.
- Treat(65-70) = the detector location had 65-mph PSL in 2015 and a 70-mph PSL in other years.

Figure 3. Average Freeway Operating Speeds by Year for Control or Treated Groups.

Because of the apparent difference in operating speeds for the time period where COVID pandemic stay-at-home restrictions were in place, the research evaluations did not include the 2020 speed data. Descriptive statistics for the site variables are provided in Table 1.

Table 1. Descriptive Statistics for Site Variables for 2015 to 2019 Speed Data

Variable	Measure	60-mph Sites	65-mph Sites	70-mph Sites	All Speed Limit Sites
Number of Sites	Count	147	111	108	366
Number of 15-minute Speed Observations	Count	238,461	220,750	434,922	894,133
Lane Width (ft)	Mean	12	12	11.9	12
	Std. Dev.	0.3	0.3	0.3	0.3
	Range	11.0 to 12.5	11.3 to 12.5	11.2 to 12.5	11.0 to 12.5
Left Shoulder Width (ft)	Mean	9.8	9.4	8.9	9.2
	Std. Dev.	3.6	2.3	2.3	2.7
	Range	4 to 25	4 to 18	4 to 14	4 to 25
Right Shoulder Width (ft)	Mean	10.6	10.2	10.9	10.7
	Std. Dev.	2.4	2.5	2.1	2.3
	Range	4 to 19	4 to 20	6 to 21	4 to 21
Downstream Ramp Distance (ft)	Mean	1241	1115	1902	1530
	Std. Dev.	967	1004	1592	1364
	Range	80 to 6460	80 to 9120	115 to 9120	80 to 9120
Upstream Ramp Distance (ft)	Mean	1333	1313	1989	1646
	Std. Dev.	913	1056	1676	1404
	Range	45 to 6110	55 to 8670	45 to 8670	45 to 8670
Speed (mph)	Mean	67	68.7	70.1	68.9
	Std. Dev.	3.6	3.7	3.8	4.0
	Range	53 to 82	53 to 83	53 to 90	53 to 90
Volume (veh/hr/lane)	Mean	622	647	692	662
	Std. Dev.	426	422	444	435
	Range	2 to 2971	3 to 2976	3 to 2944	3 to 2976

Evaluation – Research Question 1

The change in environmental speed limits can be used to address Research Question 1, "do freeway operating speeds change following an increase in PSLs?." Speed data for May 2015 and May 2016 were compared to identify the amount of operating speed change after the speed limit increase.

Because of construction or data availability for a detector, there could be sites considered in one year but not the other. Table 2 shows the count (sample size) and mean operating speed for each group. For treatment sites with 5-mph PSL increase, all groups experienced higher average operating speed in the after year. For control site groups, while the mean speed is higher the differences are negligible in values (only 0.02 mph for 60-mph control group and 0.04 for the 65-mph control group).

Table 2 provides the statistical comparison between the before and after mean operating speeds. Within the sections with PSL increases (treatment group), the average operating speed increased between 2.4 to 4.0 mph as compared to the 5-mph increase in PSL or 2.9 mph for the 10-mph increase in PSL. These operating speed increases were statistically significant. The control groups – either Group = Control(60-60) or Control(65-65) – saw negligible (in value) increase in average operating speed; and these increases were not statistically significant. The change in average operating speed was only 0.02 to 0.04 mph for those roadway segments with no change in the PSL.

Table 2. Comparison of Mean Speeds by Treatment and Control Groups for Before-After Periods.

Group	**Control (60-60)**	**Control (65-65)**	**Treat (60-65)**	**Treat (60-70)**	**Treat (65-70)**
N 2015	2,782	1,670	4,922	2,531	6,840
N 2016	39,501	6,015	22,853	35,773	39,618
Mean Speed (mph) 2015	65.47	66.2	64.38	64.7	66.83
Mean Speed (mph) 2016	65.49	66.24	66.79	67.62	70.85
Change (mph)	0.02	0.04	2.41	2.92	4.02
Effect Size	0.01	0.01	0.45	0.63	0.91
t-score	0.25	0.41	26.67	27.44	62.95
95% CI	[−0.04, 0.05]	[−0.04, 0.07]	[0.42, 0.48]	[0.58, 0.68]	[0.88, 0.94]
P-value	0.81	0.68	<0.001	<0.001	<0.001

Evaluation – Research Question 2 and Question 3

Panel Model using Binned Freeway Database

The format of the available data fit a panel database structure; therefore, the research team decided to use a mixed effect statistical model with nested random effects. This model specification makes an explicit distinction between variables considered either a fixed feature of the facility (for example, cross-sectional elements) and variables with a more transient nature (for example, hourly fluctuations). Given this distinction, there are variables that fall in a gray area; for example, AADT was treated as a fixed effect even though it is not exactly a fixed feature of the facility, but because it represents a measurable objective systematically defined the same way for each facility under study.

Therefore, in the model specification the research team assigned an initial definition of fixed and random effects for the variables that would clearly fall under each category. A highway corridor variable was initially included in the specification of the random effects to account for spatial proximity, but it was found to correlate with other fixed effects predictors and was thus removed from the model.

Additionally, the research team tested (based on the Akaike Information Criterion or AIC, a measure of model entropy) if additional key variables would be more suitable to be modeled as either a fixed or a random effect. Equation 1 shows the general form of the model specification.

$$Average.Speed_{ijkl} = \boldsymbol{X}' \cdot \boldsymbol{\beta} + Z_i + Z_{ij} + Z_{ijk} + \varepsilon_{ijk} \qquad \text{Equation 1}$$

Where:

$Average.Speed_{ijkl}$	=	Average 15-min binned speed for the ith Link_Name, jth Year, and kth level for GroupDays.
$\boldsymbol{X}$	=	Vector of fixed-effects.
$\boldsymbol{\beta}$	=	Vector of fixed-effects coefficients.
Z_i, Z_{ij}, and Z_{ijk}	=	Random effects (or random parameters), at a given level of aggregation.
ε_{ijk}	=	Residual error.

When handling time series data, it is important to consider explicitly the likely codependence between observations close in time. The mixed-effects framework used in this research allows the implementation of error correlation structures as needed, see Pinheiro and Bates for additional information on the framework (*20*) and the TxDOT project report (*2*) for additional details. After several rounds of model selection within the model structure in Equation 1, the research team arrived at the specification shown in Equation 2. The coefficients were estimated using R, open statistical software and packages. (*21*, *22*)

$$Average.Speed_{ijkl} = \beta_0 + \beta_1 \cdot \ln(AggTotalVol + 0.5) + \beta_2 \cdot SL_{Rf60} + \beta_3 \cdot L_{shld_{wid_{Rf4}}} + \beta_4 \cdot R_{shld_{wid_{Rf10}}} + \beta_4 \cdot \ln(Mun.Citations/78586) + \beta_5 \cdot \ln(DPS.Citations/6833) - \beta_{ramp\_type} \cdot \ln(Ramp\_dist + 0.5) + Z_{0_i} + Z_{0_{ij}} + Z_{0_{ijk}} + \varepsilon_{ijk} \quad \text{Equation 2}$$

Where:

$Average.Speed_{ijkl}$	=	Average 15-min binned speed for the ith Link_Name, jth Year, and kth level for GroupDays.
AggTotalVol	=	15-min volume.
β_n	=	N-th fixed effect coefficient.
β_0	=	Global model intercept (at the fixed-effects level).
β_{ramp_type}	=	One of four coefficients for the different ramp types in the dataset (Upstream Entry, Upstream Exit, Downstream Entry, and Downstream Exit).
$Ramp\_dist$	=	One of four variables in the dataset indicating the distance to one of the four ramp types in the dataset (Upstream Entrance, Upstream Exit, Downstream Entrance, and Downstream Exit).
$R_{shld_{wid_{Rf10}}}$	=	Right shoulder width (ft) with respect to a 10-ft shoulder. A 10-ft shoulder would have a value of 0, while a 11-ft shoulder would have a value of 1, etc. for this variable.
$L_{shld_{wid_{Rf4}}}$	=	Left should width (ft) with respect to a 4-ft shoulder. A 4-ft shoulder would have a value of 0, while a 5-ft shoulder would have a value of 1, etc. for this variable.
SL_{Rf60}	=	Speed limit (mph) with respect to 60 mph (i.e., a 65-mph speed would have a value of 5 mph in this database).
Mun.Citations	=	Total number of yearly citations issued by municipalities within the county on all types of roads
DPS.Citations	=	Total number of yearly citations issued by DPS within the county freeways
Z_{0_i}	=	Local model intercept for i-th Link_Name (level of spatial aggregation).

$Z_{0_{ij}}$ = Local model intercept for j-th Year for i-th Link_Name (first level of temporal aggregation).

$Z_{0_{ijk}}$ = Local model intercept for k-th GroupDays for j-th Year for i-th Link_Name (second level of temporal aggregation).

It should be noted that the number of citations is passed to the model divided by the number in 2019, considered a reference year for the analysis.

Table 3 shows the estimates for the fixed effects part of the model that used the binned database (i.e., 15-min period data where all three consecutive 5-min periods were available). The results have direct implications in understanding the relationships between operational speed and other key variables found relevant in the final model. The following sections describe those implications in more detail.

Table 3. Model Parameter Estimates

Fixed Effects						
Parameter	**Variable**	**Estimate**	**Std. Err**	**DF**	**t-value**	**p-value**
β_0	Base Speed (intercept)	65.3979	1.9216	694010	34.0330	<1e-04
β_1	15-min Volume	-1.0132	0.0079	694010	-127.733	<1e-04
β_2	Speed Limit relative to 60 mph	0.1898	0.0409	587	4.6362	<1e-04
β_3	Left Shoulder relative to 4 ft	0.1232	0.0620	239	1.9885	0.0479
β_4	Right Shoulder relative to 10 ft	0.1146	0.0698	239	1.6417	0.1020
β_5	Number of municipal citations in a year	-4.4433	0.6854	587	-6.4825	<1e-04
β_6	Number of DPS citations in a year	-5.8184	0.5160	587	-11.2758	<1e-04
$\beta_{Down\_Ramp\_typeEN}$	Distance to closest downstream ramp, entrance	-0.6325	0.2001	239	-3.1615	0.0018
$\beta_{Down\_Ramp\_typeEX}$	Distance to closest downstream ramp, exit	-0.5526	0.2139	239	-2.5835	0.0104
$\beta_{Up\_Ramp\_typeEN}$	Distance to closest upstream ramp, entrance	-0.5315	0.1795	239	-2.9610	0.0034
$\beta_{Up\_Ramp\_typeEX}$	Distance to closest upstream ramp, exit	-0.6085	0.1695	239	-3.5893	0.0004
Random Effects and Residuals						
Parameters	Variable	Standard Deviation				
Z_{0_i}	Link_Name	2.478064				
$Z_{0_{ij}}$	Year	1.354728				
$Z_{0_{ijk}}$	GroupDays	1.070744				
$\varepsilon_{0_{ijk}}$	Independent Residual	2.023818				
ρ	Autocorrelation parameter	+0.6412				

Fixed Effects Coefficients

From the fixed-effects coefficient estimates (see Table 3) the model indicates the following:

- Operating speed decreases with increasing 15-min volume in non-congested conditions. A 50 percent increase in volume is associated with a reduction of 0.41 mph (-1.013*ln(1.5)=-0.4108) in average operating speed, or a reduction of 0.70 mph if the volume doubles (-1.013*ln(2)=-0.7023).
- Operating speed increases with increasing speed limit. For each 5 mph increase in the PSL, the average operating speed increases by 0.95 mph (0.1898*5=0.949), or an increase of 1.90 mph for a 10-mph increase in posted speed, say going from a 60-mph freeway to a 70-mph freeway, all other characteristics staying the same (0.1898*10=1.898).
- Operating speed increases with wider left shoulder. For an additional foot of left shoulder, the average operating speed increases by 0.12 mph (0.1232*1.0=0.01232).
- Operating speed increases with wider right shoulder. For an additional foot of right shoulder, the average operating speed increases by 0.11 mph (0.1146*1.0=0.1146).
- Number of yearly citations was found to have an impact on operating speeds. For example, a 20 percent increase in DPS citations is expected to result in a 1.06 mph decrease in operating speed (calculated as -5.818*ln(1.2)=-1.061).

As expected, operating speeds are higher when the distances to upstream and downstream right-side ramps are longer (statistically significant). It should be noted that this finding does not apply to left-side ramps, as this database did not contain locations where the closest upstream or downstream ramp was on the left side. They were removed due to the small number of sites with that geometric feature. Speeds are increasing with greater distances even though the coefficient has a negative sign because the model format as shown in Equation 2 includes a negative sign prior to the coefficient. For example, if the closest downstream ramp is an entrance ramp and the distance is 100 ft, the operating speed is estimated to be higher by 2.92 mph (2.9159 = 0.6325*ln(100+0.5)), compared to a point just at the ramp. If the closest downstream entrance ramp is 1000 ft, the operating speed is estimated to be higher by 4.27 mph (4.3695 = 0.6325*ln(1000+0.5)), compared to a point just at the ramp.

The fixed effects are the part of the model that can be interpreted more directly. The following sections describe the results from other model components and their implications.

Random Effects Coefficients

In the model estimation, the random-effects coefficients are estimated for each unit of nested aggregation as described when defining the model. However, interpreting the individual values of those estimates is generally not relevant as the estimate is specific to a given location or given period at a given location. It is of interest; however, to provide some descriptive statistics on the random-effect estimates as they describe general trends in the data not explicitly captured in the fixed-effects part of the model. The model in this research has nested random effects with one tier of spatial aggregation and two tiers of temporal aggregation as described next.

Spatial Random Effects

The first level of aggregation is spatial by specific detector location within a freeway corridor. Figure 4 shows the histogram of the adjustments per detector location, which the model applies in addition to the fixed effects. It can be seen from Figure 4 that the amount of variation captured by the detector location-specific random effect is significant: the approximate range of these adjustments is [-6 mph, 4 mph].

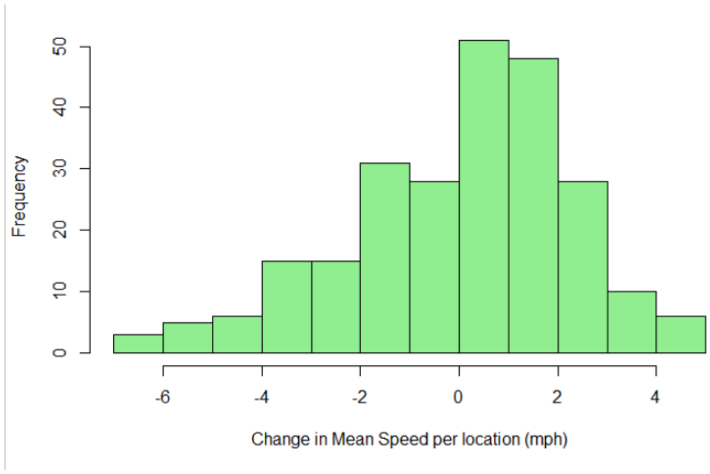
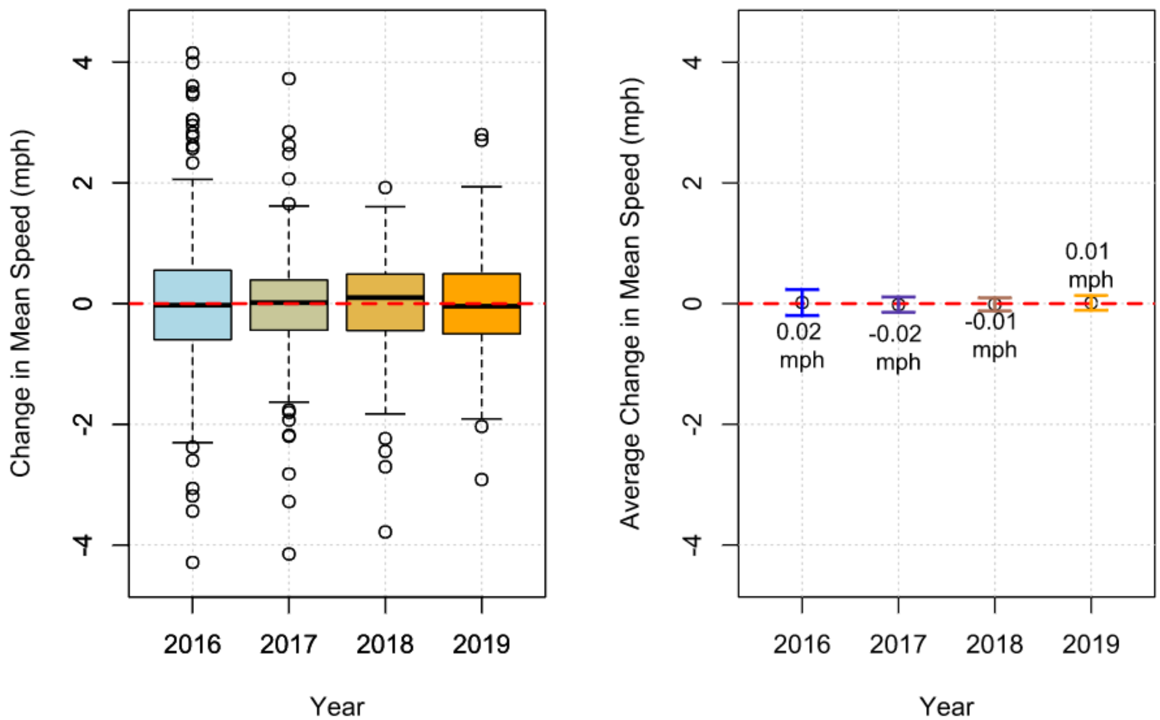


Figure 4. Histogram of Adjustment Per Detector Location.

Temporal Random Effects

In order to capture yearly trends at specific locations, the model provides an adjustment per each year with data at each detector location under study. These yearly adjustments are applied in addition to the spatial adjustment discussed in the prior section. Figure 5 shows boxplots of all yearly adjustments versus year which do not suggest a trend that mean speed varies with increasing year, other things equal. Additionally, when calculating 95 percent confidence intervals around the means of these adjustments, all the intervals contain zero, confirming the absence of a trend by year (see Figure 5).



(a) Yearly Random Effects **(b) Mean of Yearly Effects (with 95% CI)**

Figure 5. Random Effects by Year.

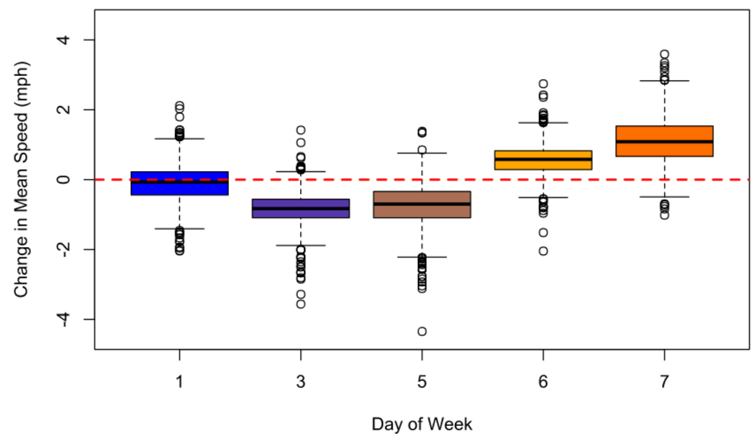
Finally, in the last level of aggregation, the model applies an adjustment per day of the week at each detector location per year of data in the analysis. It can be seen that the speed adjustments drop from the initial baseline on Monday and remain relatively flat for Tuesday through Friday (i.e., comparable baseline speeds) and then it consistently increases from Saturday to Sunday. When plotting all week-day random effects (see Figure 6), a pattern of being relatively similar speeds during weekdays and higher speeds on weekend. Monday tends to have faster speeds compared to Tuesday through Friday. Saturday and Sunday remain the days with fastest speeds, after adjusting for other variables.

The Relative Contribution of Different Factors to the Variability of Operating Speed

To gain perspective of the factors that explain the variability observed in the key variables this section quantifies the contribution of said factors to the operating speed variability, as estimated by the model described in the previous section. This model provides an explicit account of how the factors of interest relate with the operational speed and therefore, it is possible to quantify their systematic variation. The total variability by all explanatory factors in the model, combined with the residual variability that remains unexplained by the model, should amount to the total variability in the response variable.

Table 4 summarizes the breakdown of the variation in the response variable by level of aggregation according to the model. The fourth column of

Table 4 (percent of incremental explained variance) shows the percent of variation in operational speed associated with each explanatory factor in the model. Only 4.4 percent (0.6920 mph^2) of the total variability in the response variable (15.3867 mph^2) can be explained by the variation in 15-min volumes. Although this percentage appears somewhat small, as a reminder, the dataset was based on uncongested traffic conditions as previously described. The finding demonstrates that even in uncongested conditions, speeds are affected by traffic density and proximity to other vehicles.



Note: 1=Monday, 3=either Tuesday, Wednesday, or Thursday, 5=Friday, 6=Saturday, and 7=Sunday (different colors are present; however, they are provided to help the reader to see the differences between the boxplots).

Figure 6. Weekday Random Effects.

Table 4. Variation in Response Variables by Level of Aggregation.

Explanatory Factor (i.e., variables)	**Cumulative Variance (mph^2)**	**Incremental Explained Variance (mph^2)**	**Percent of Incremental Explained Variance (percent)**	**Standard Deviation of Speed (cumulative) (mph)**	**Expected range of variation (95% coverage Interval) (mph)**
15-min Volume	0.6920	0.6920	4.4%	0.8319	+/- 1.63
Speed Limit	1.3322	0.6402	4.1%	1.1542	+/- 2.26
Geometrics	2.5132	1.1810	7.5%	1.5853	+/- 3.11
Citations	3.0845	0.5713	3.6%	1.7563	+/- 3.44
Link_Name	8.4188	5.3343	33.8%	2.9015	+/- 5.69
Year	10.0881	1.6693	10.6%	3.1762	+/- 6.23
GroupDays	11.2243	1.1362	7.2%	3.3503	+/- 6.57
Residuals	15.3867	4.1624	26.4%	3.9226	+/- 7.69

For PSLs, 4.1 percent (1.3322 mph^2) of the total variation in operational speed can be attributed to the operational differences at different speed limits according to the analysis. In other words, the range of variability that can be attributed to PSL and not to other factors is expectedly small. Other variables describing freeway geometric configuration (i.e., shoulder widths and relative location of ramps) are associated with 7.5 percent of the operational speed variation (1.1810 mph^2).

Although Table 3 indicates that the impact of citations on operational speeds is clear, intuitive, and statistically significant, the corresponding share of explained speed variability is smaller than the amount explained by PSL: 3.6 percent or 0.5713 mph^2. This finding, given the relatively robust effects implied by the coefficient estimates, suggests that the amount of variation in the number of citations year by year at the site level is relatively small so that larger changes in future years have large potential to affect operational speeds.

Jointly, the factors in the fixed effects (i.e., 15-min volume, speed limit, geometrics, and citations) explain 20.05 percent of the total variation in operational speed in the dataset (3.0845 mph^2). In contrast, the model attributes a larger amount of variation (5.3343 mph^2 or 33.8 percent) to other unaccounted factors at the detector location (i.e., Link_Name variable) level. This amount of variance is captured as the variation of the Link_Name specific random effects. Because these random effects are gross adjustments of the model to the data per detector location, it follows that a significant amount of variation (33.8 percent) exists from detector location to detector location, such that it is not explained by any of the other variables in the model.

10.6 percent (or 1.6693 mph^2) of variation in operational speed is associated with the differences by year at the Link_Name level. In comparison, 7.2 percent or 1.1362 mph^2 can be attributed to differences in speeds by day of the week.

Finally, 26.4 percent of the variation in the operational speed was captured in the model residuals (4.1624 mph^2) , which means that the remaining 73.6 percent of speed variation is explained by the fixed and random effects combined. Because the residual variation represents variation not explicitly accounted for by any of the model parameters nor the aggregation structure, the interpretation of this result is that operating speed varies by 26.4 percent at each site due to other factors not explicitly considered in this study (e.g., differences in driver speed preference, lane changing behavior, etc.).

Conclusions and Recommendations

An evaluation of speeds on Texas freeways used data from 243 sensors located in Fort Worth representing operating speeds during daytime and clear weather conditions from 2015 to 2019. The initial evaluation explored how much average operating speeds increased when the posted speed limit was raised from 60 to 65 mph, 60 to 70 mph, or 65 to 70 mph. The average operating speed increased between 2.4 to 4.0 mph for 5-mph increase in PSL or 2.9 mph for the 10-mph increase in PSL.

The next evaluation identified the variables associated with variations in average freeway operating speeds during daytime without rain or incidents, and in uncongested periods. The range of posted speed limits represented in the database was 60, 65, or 70 mph. Following are the key conclusions and recommendations from the evaluation:

1. The most significant amount of operating speed variation was found to be unidentified localized factors representing 33.8 percent of variability due to differences from detector location to detector location. The researchers theorize that possible sources could be local attractors, traffic generators including those associated with heavy truck traffic, facility types connecting to and from the nearby ramps, or driver’s familiarity or trip purpose.
2. The next most important source of speed variation was found at the speed location (26.4 percent of total variation represented in the residuals). Differences between driver speed preferences, vehicle types, and number and characteristics of lane changing maneuvers are examples of transient events that were not identified nor explicitly accounted for in the model that should affect the speed measured from period of analysis to period of analysis and thus captured in this source of variation.
3. Yearly shifts in speeds at a given location was found the third most relevant source of speed variation (10.6 percent). These yearly shifts could be explained by economic fluctuations and other factors that might change from year to year, including, perhaps, the local population being more willing to operate at higher speeds or drivers becoming more familiar with the area.
4. Geometry was found as the fourth most influential factor affecting operating speed, as it was estimated that it explains about 7.5 percent of the speed variation in this dataset.

5. Weekly patterns at specific sites were found as the fifth most influential factor on operating speed, accounting for 7.2 percent of the total speed variation.
6. Differences in volume between 15-min periods only accounted for 4.4 percent of total speed variation. The research team expected this variable to have minimal impact as periods with high volume were removed from the dataset.
7. Second to last, varying posted speed limit values was found to affect the operating speed only by 4.1 percent. The range of posted speed limits included in the dataset was 60, 65, and 70 mph.
8. Finally, the level of enforcement was found to impact operating speeds significantly with more citations being associated with lower expected speeds. However, the size of that effect and the range of citation levels represented in the data only account for 3.6 percent of the total variation in operational speed.

Citations together with PSL and geometry represent the range of influence that engineering, law enforcement, and traffic management can influence operating speed. This study estimates that a strategy that entails modifying geometry, changing the PSL, and varying the level of law enforcement presence within the ranges included in this study may impact freeway operational speeds up to 6.2 mph (depending upon existing conditions along with the changes in the geometry, PSL, and enforcement).

Comparing the amount of influence between points 1 and 7, a recommendation would be that design and area-wide traffic management are important, but that a significant amount of effort needs to be devoted to looking at localized factors at specific sites, which can be more influential than design and operations management.

Another recommendation would be to examine what other factors by location and by year within location might be systematic and could be explicitly measured with additional variables in the analysis. Factors associated with location or years at a given location amount to 40.4 percent of speed variation in the dataset, but the researchers were unable to identify these specific factors with the resources available in the project.

Regarding point 8 above, it should be noted that the account for law enforcement presence in the current analysis was as yearly levels of citations for the overall study area, both in all municipal roads and in all freeways by DPS. Future work should consider additional efforts to account for law enforcement with more sensitivity to the locations and periods of time with law enforcement presence. Expectedly, an analysis with such an account of this important factor could help explain some of the variability currently found as uncharacterized operational differences from location to location and from year to year (points 1 and 3, which combined currently account for 47.2 percent of the total variability in the speed data).

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: this research was sponsored by Texas Department of Transportation (TxDOT) as part of TxDOT research project 0-7049 (Improving and Communicating Speed Management Practices).

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JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
VOLUME 3, ISSUE 1 | DECEMBER 2025

PAPER 009

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH | VOLUME 3, ISSUE 1 | DECEMBER 2025 | PAPER 009

Keeping Drivers Right:
Iowa's Low-Cost Strategy to Prevent Wrong-Way Entries

November 2025

Submitted to:
The Journal of Traffic Control Device Research (JTCDR)

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Abstract

Wrong-way driving (WWD) crashes, though infrequent, carry a high risk of fatal and severe outcomes. The Iowa Department of Transportation (Iowa DOT) identified recurring WWD movements at partial cloverleaf (Parclo B) interchanges and implemented a series of low-cost, human-factor-based signing and marking countermeasures. The “gateway treatment” approach emphasized driver guidance through enhanced “Do Not Enter” and “Keep Right” signing and improved pavement markings. Evaluation across multiple sites showed an 88 percent reduction in WWD events per month and no crashes at treated locations since implementation. The results demonstrate that simple, data-driven strategies can deliver substantial safety benefits and serve as a practical model for other agencies addressing WWD risks.

Introduction

Over the last decade, Willy Sorenson, a longtime Iowa Department of Transportation (Iowa DOT) Traffic and Safety Engineer, has become one of the leading voices in understanding and preventing wrong-way driving (WWD).

What began as a personal initiative, a single engineer tracking a handful of puzzling wrong-way entries on one corridor, slowly grew into a statewide effort built on curiosity, persistence, and a willingness to test every idea that might make a difference. Mr. Sorenson evaluated nearly every WWD detection technology available, pored over crashes and near misses, and partnered with colleagues across disciplines to uncover patterns hidden in the data.

Wrong-way driving remains one of the most difficult roadway safety challenges to grasp. WWD events are rare, unpredictable, and scattered across the entire network. They can happen anywhere, at any time, for reasons that are often impossible to pinpoint, making them feel like finding a needle in a haystack the size of a state. Because of this unpredictability, it is neither practical nor cost-effective to deploy advanced ITS detection systems everywhere.

Yet the rarity of WWD events does not diminish their danger. A single wrong-way entry can lead to catastrophic head-on collisions, and some roadway configurations quietly raise the odds that a driver will make a path-choice error. Understanding how geometry, signage, pavement markings, and even lighting contribute to these mistakes is essential for identifying where physical changes can truly make a difference.

This combination of rare events, dispersed locations, severe consequences, and subtle human-factor triggers underscores why agencies need strategies that can detect patterns, prioritize locations, and apply practical, affordable countermeasures. This paper tells the story of how the Iowa DOT moved beyond standard guidance to develop a low-cost, human-centered approach that has dramatically reduced wrong-way entries across the state.

Statewide Screening and Site Prioritization

By the time the Iowa DOT began digging into its wrong-way driving (WWD) records, one thing had already become clear: the data alone did not tell the full story. Since 2010, the agency had been cataloging WWD events by frequency, location, and crash history, but the patterns were incomplete, and many incidents were not reported. Others were recorded only after a near miss or a driver's panicked call to 911. Understanding "when, where, and why" quickly proved far more complicated than the numbers suggested.

As the team reviewed national practices, they found a variety of ranking systems used by other agencies. Each offered pieces of the puzzle, but none fully captured the nuances the Iowa DOT saw in its own system. If Iowa was going to truly understand where the highest risks existed, it needed a way to see the network through a new lens—one that blended data, geometry, and human factors.

With this in mind, the DOT developed a modified scoring system to evaluate 129 interchanges and thirty-six at-grade intersections across the state. Rather than relying on a single metric, the system weighed six factors together: the number of wrong-way crashes, mainline traffic volume, side-road volume, interchange type, the number of non-crash WWD events, and whether the site was urban or rural. When the scoring was complete, a clearer picture emerged. Iowa's interchanges are clustered into three main configuration types: at-grade intersections, standard diamonds, and folded diamonds, each with its own tendencies and risks.

Among them, the folded diamond (or partial cloverleaf) interchanges stood out. Their geometry, turning paths, and visual cues created just enough opportunity for a driver to make the wrong choice at the wrong moment. These were the locations where small errors could turn into serious consequences.

This paper focuses on the Iowa DOT's efforts to understand and mitigate WWD at these folded diamond interchanges, where thoughtful design changes could have the greatest impact.

Problem Definition and Context

Geometry and Driver Behavior at Parclo Interchanges

Among Iowa's many interchange designs, the folded diamond, also known as a partial cloverleaf or "Parclo," presents a unique set of challenges for drivers. These interchanges appear frequently across the state, and although they function well under typical conditions, their geometry can create moments of hesitation or confusion, particularly for drivers who are unfamiliar with the area.

A Parclo interchange consists of several ramps, each identified by a letter and arranged to connect the major roadway with the minor road in a compact looping pattern. These partial cloverleaf ramps, known as Parclos, are labelled by letter designation. Figure 1 provides an example. The aerial view highlights the intended travel paths, and the accompanying photograph shows how those same movements appear from the driver's perspective. The photo (left) also shows the typical signage provided up through roughly 2013, with an additional R5-1A not shown.

Mr. Sorenson refers to the inherent risk for drivers making wrong-way movements as "Parclo A is OK, but Parclo B is Bad". In practice, this means that the configuration of the "A" ramps tends to guide drivers correctly with little confusion, while the "B" ramps, depending on turning angles, sight distance, and driver conditions, appear more susceptible to wrong-way entries and fatal consequences.

Understanding how these geometric factors influence driver behavior became a critical step in identifying where low-cost treatments could provide meaningful improvements.

Figure 1. Typical Folded Diamond interchange. Aerial image source: Story County Assessor. Photo Source: Google StreetView (2013)

Observed Wrong-Way Driving Trends

When Iowa DOT reviewed ten years of data from 55 Parclo interchanges, a clear pattern emerged. Over that period, 36 wrong-way crashes were recorded, and most were the result of simple driver mistakes rather than intentional or reckless behavior. In many cases, drivers overlooked or misunderstood the cues intended to guide them into the correct lane. Figure 2 illustrates this with three examples where a driver failed to stay to the right, passing by standard signs and pavement marking arrows that were in place but did not prevent the wrong-way entry.

Figure 2. Images of wrong-way drivers at 3 Parclo B ramp locations

Gateway Treatment Concept and Design

The Iowa DOT set out to develop treatments that were simple, affordable, and grounded in human factors, rather than relying on costly Intelligent Transportation System (ITS) technologies. Their first step was to revisit the standard signing and pavement marking practices already in place. The goal was to strengthen the visual cues that guide drivers to stay on the correct path and to create a clear sense of a gateway at the decision point, where a wrong-way movement could occur.

Enhanced Signing and Pavement Marking Details

To begin addressing the persistent wrong-way entries on Parclo B ramps, the team examined the standard signing shown on the left side of Figure 3. This signing typically included the R4-7 “Keep Right” symbol sign, the R5-1 “Do Not Enter”, and the R5-1a “Wrong Way” sign, which is not shown in the image.

As the team explored options to better influence driver decisions, they developed the idea of creating a visual red “Do Not Enter” gateway that would be perceived by the driver about to go the wrong direction while still providing a clear and intuitive path for drivers to keep right. To support this concept, the team positioned the signing at the same point as the R4-7 “Keep Right” sign so that drivers were presented with a strong and unified set of cues. They also enhanced the pavement markings by widening the gore area and adding horizontal pavement marking lane arrows in each lane.

Figure 3 shows an example of these enhanced gateway treatments on the right, compared with the standard signing arrangement on the left. Some additional signs are not shown in the images but were part of the treatment package.

Figure 3. Same location showing before and after, where the standard Parclo B signage is shown on the left and the enhanced gateway treatment is shown on the right.

Implementation Approach and Cost Summary

In 2021, the Iowa DOT implemented gateway treatments at 43 of the 55 Parclo B interchanges identified statewide. Each location required an investment of roughly five thousand dollars, which is only a small portion of the cost of advanced ITS detection and warning systems. The treatments were installed efficiently, with minimal impact on traffic, and relied solely on standard signing and pavement marking materials that maintenance crews already use daily. Each enhancement included the following elements:

- Dual R5-1 “Do Not Enter” Signs: These were placed side by side at the ramp entrance to create a strong visual gateway and provide a clear and immediate cue to discourage wrong-way entry.
- Pavement Markings: Directional arrows were added along with a wider gore median.

Evaluation and Results

The effectiveness of the gateway treatments was assessed using a combination of field-based observations and a review of crash and event data.

Methodology

During the summer of 2021, the Iowa DOT installed cameras capable of detecting wrong-way driving at seven Parclo B ramp locations scheduled to receive the gateway treatment. The cameras operated continuously, capturing wrong-way movements both before and after installation. Each recorded event was reviewed in detail and categorized, and any movements associated with work zones, emergency responders, or law enforcement activity were excluded from the analysis to ensure accuracy. Figure 4 presents a map of the seven study locations. The red arrows indicate the wrong-way movements that were detected by the cameras and included in the evaluation.

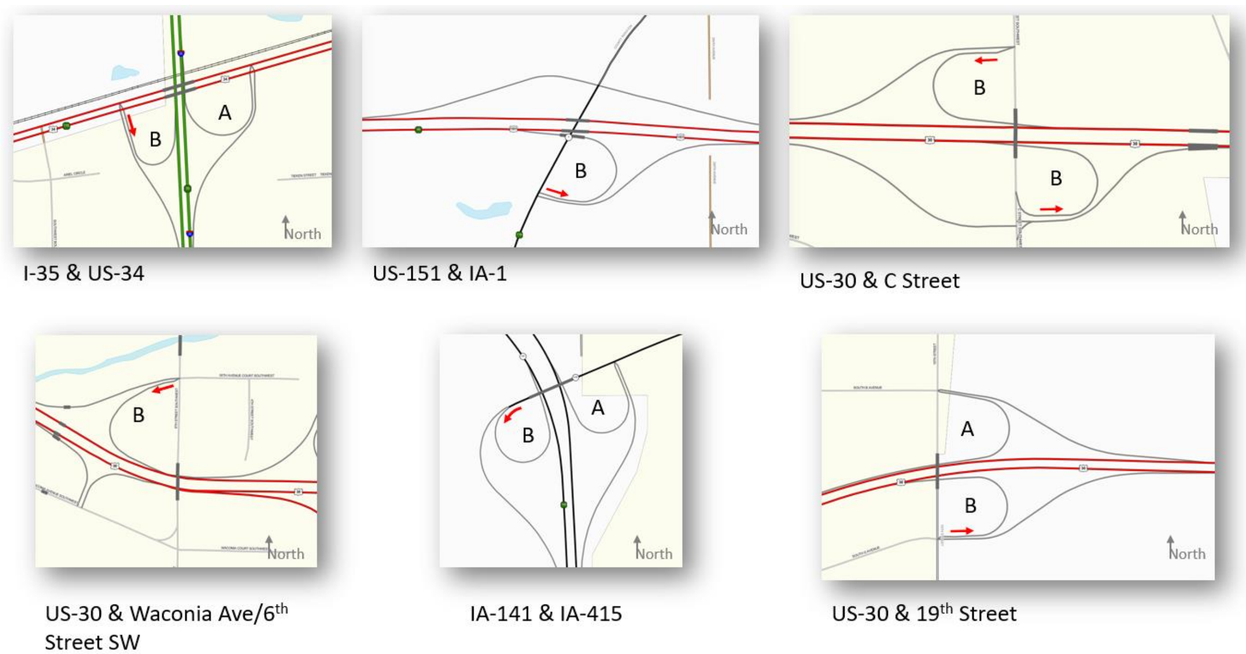


Figure 4. WWD camera locations used in the before-and-after analysis.

Results

The wrong-way events recorded by the cameras were used to compare conditions before and after installation of the gateway treatments at each study location. The summary of these observations, reported through July 13, 2025, is provided in Table 1.

Table 1. WWD events before and after the installation of the gateway treatments as of July 13, 2025

Interchange Location	Type	Camera	# Months Before Treatment	# WWD Events Before Treatment	# Months After Treatment	# WWD Events After Treatment
I-35 & US-34	Parc-Lo "AB"	WWD55	1	1	29	0
US-151 & IA-1	Parc-Lo "B"	WWD04	1	1	13	1
US-30 & C St (WB Exit loop)	Parc-Lo "B"	WWD18	2	1	38	4
US-30 & C St (EB Exit Loop)	Parc-Lo "B"	WWD19	2	0	38	0
US-30 & Waconia Ave/6TH St SW	Parc-Lo "AB"	WWD09	3	4	37	8
IA-141 & IA-415	Parc-Lo "AB"	WWD40	1	2	38	4
US-30 & 19th St	Parc-Lo "AB"	WWD62	6	1	43	1

Findings and Interpretation

While having only one month of "before" data is not ideal from an analytical standpoint, many agency studies lack comparable data either before or after implementation. In this case, the Iowa DOT demonstrated considerable foresight by installing wrong-way detection cameras in advance of the gateway treatments, creating an opportunity for a meaningful before-and-after comparison that is rarely possible in real-world field conditions. The authors acknowledge the study limitations due to the brief before installation monitoring period, the site and exposure variations, and a lack of control sites. Even with these constraints, an aggregate comparison provides a clear indication of the treatment's effectiveness.

Across all monitored locations, the gateway treatments resulted in a reduction of approximately 88 percent in the average number of WWD events per month based on the following:

- Before Treatment: 0.63 WWD events per month (10 WWD events over 16 months)
- After Treatment: 0.08 WWD events per month (18 WWD events over 236 months)

To determine whether this reduction was statistically significant, a Poisson rate ratio test was conducted. The analysis compared the total number of WWD events and the total observation time before and after installation at all sites. The post-treatment event rate of 0.08 events per month was roughly 12 percent of the pre-treatment rate of 0.63 events per month, representing an 88 percent decrease. The estimated rate ratio of 0.12, with a 95 percent confidence interval of 0.07 to 0.21, was highly statistically significant ($p < 0.001$).

These results provide strong statistical evidence that the gateway treatments meaningfully reduce wrong-way events across the study locations. The findings reinforce the value of these treatments as a practical and cost-effective safety countermeasure supported by data and field performance.

Ongoing Refinements and Lessons Learned

As Mr. Sorenson shared the gateway treatment concepts with staff and with non-technical audiences, he became increasingly interested in understanding why wrong-way decisions occur in the first place. The R4-7 “Keep Right” symbol sign emerged as a key point of curiosity. He wanted to know how quickly and accurately people recognized its meaning compared with the R4-7b “Keep Right” word legend sign.

To explore this question, he incorporated an informal “pop quiz” into his presentations over several years, using the two slides shown in Figure 5. The process was simple. He first displayed Slide 1 and asked the audience to identify the meaning of the symbol sign, offering no hints or guidance. He then revealed Slide 2 and again asked for responses, allowing participants to answer freely before any explanation was provided.

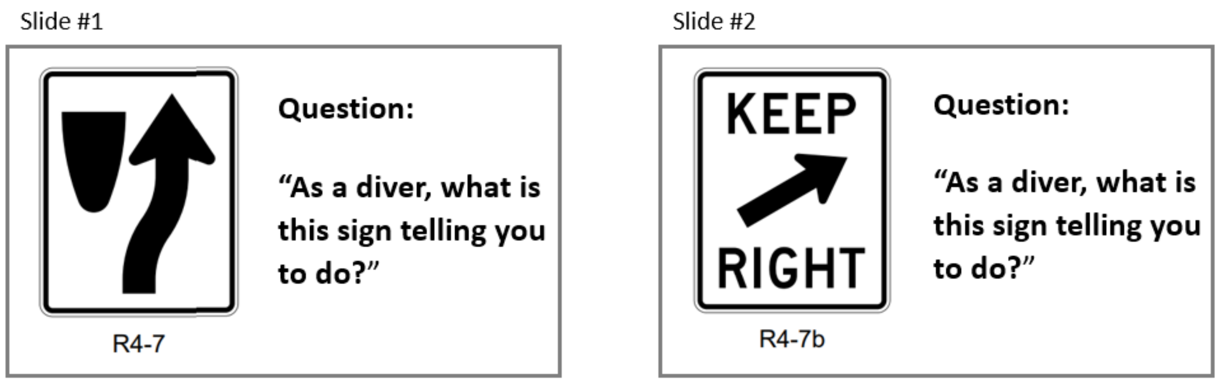


Figure 5. Slides that were used to gather input on the meaning of each sign.

Although the exercise was not a formal study, the responses revealed a consistent pattern. Many participants hesitated when interpreting the R4-7 symbol sign. Their answers were often hesitant, unsure, and sometimes creative but incorrect. In contrast, the R4-7b word legend sign was immediately understood. Responses were quick, confident, and with a few people adding “duh” to their answer.

This insight prompted the Iowa DOT to replace the R4-7 symbol sign with the R4-7b word legend at most Parclo B locations. Records indicating the exact timing of each replacement were not available, but the observations clearly influenced the evolution of the Parclo B treatment, as shown in Figure 6.

Future enhancements under consideration include:

- Rumble strips: Suggested as a tactile and audible deterrent for vehicles drifting toward incorrect entry paths.
- Channelization islands/raised pavement markers: Potential additions to further emphasize correct routing.

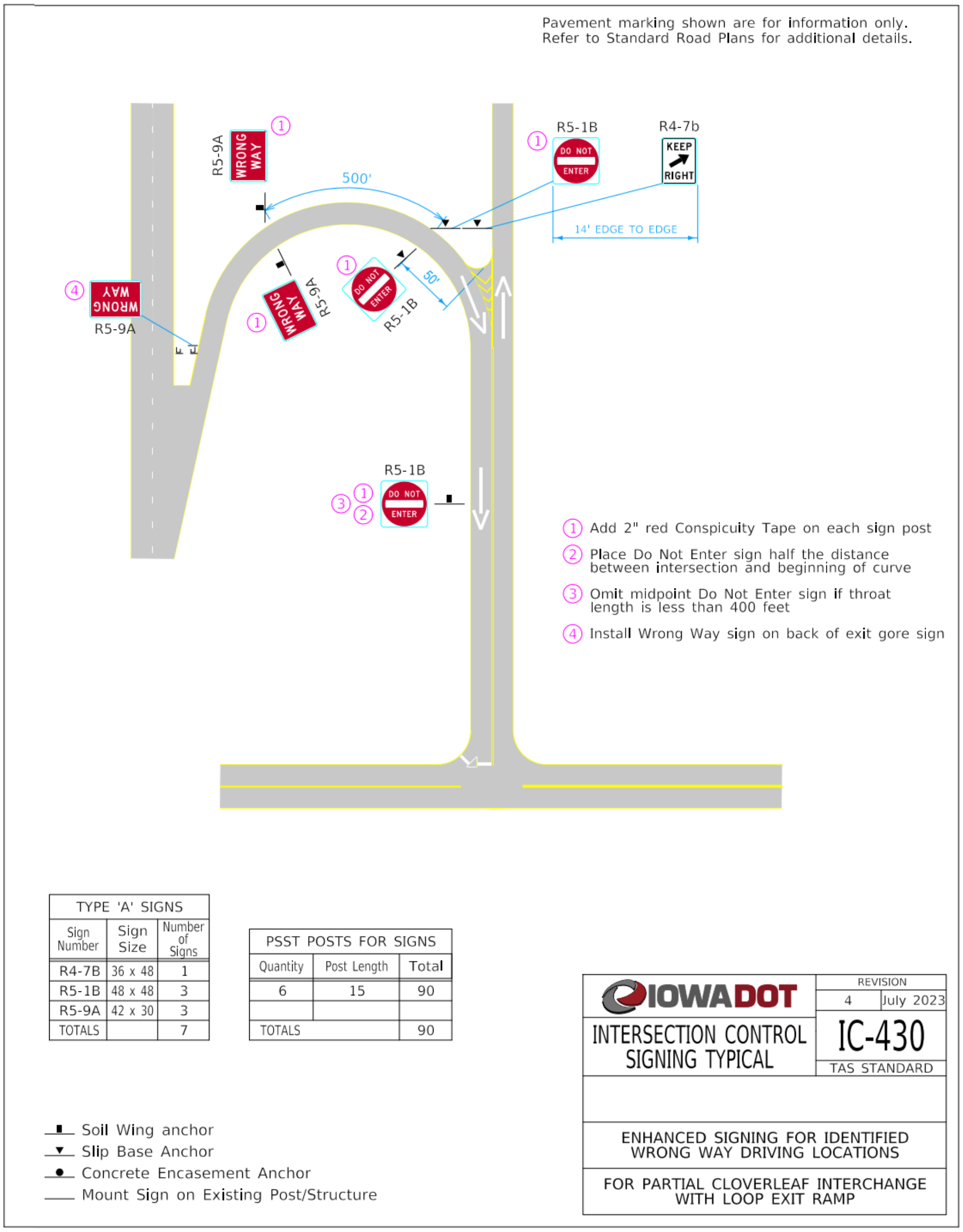


Figure 6. Gateway treatment details

Emerging Technology

The Institute for Transportation (InTrans) at Iowa State University has advanced a new method for identifying wrong-way driving patterns across the state by combining roadway network data with connected vehicle (CV) trajectory data at a three-second resolution. This approach examines statewide vehicle paths at three-second resolution and compares each trajectory to the roadway direction of travel for every segment. Although connected vehicle data represent only a subset of all drivers, the method provides a valuable window into wrong-way movements that have not been available through traditional crash reports or occasional field observations. It reveals when and where they recognize their mistakes and where and how they self-correct, if at all.

Figure 7 highlights an example from one location where, on two different occasions, eastbound drivers on a minor road turned too quickly, ending up as a WWD on the I-80 exit ramp instead of on their desired road (256th Street).

This data-driven methodology offers new insights into wrong-way driver behavior and gives the Iowa DOT the ability to monitor their entire roadway network with far greater context and precision than was possible in the past.

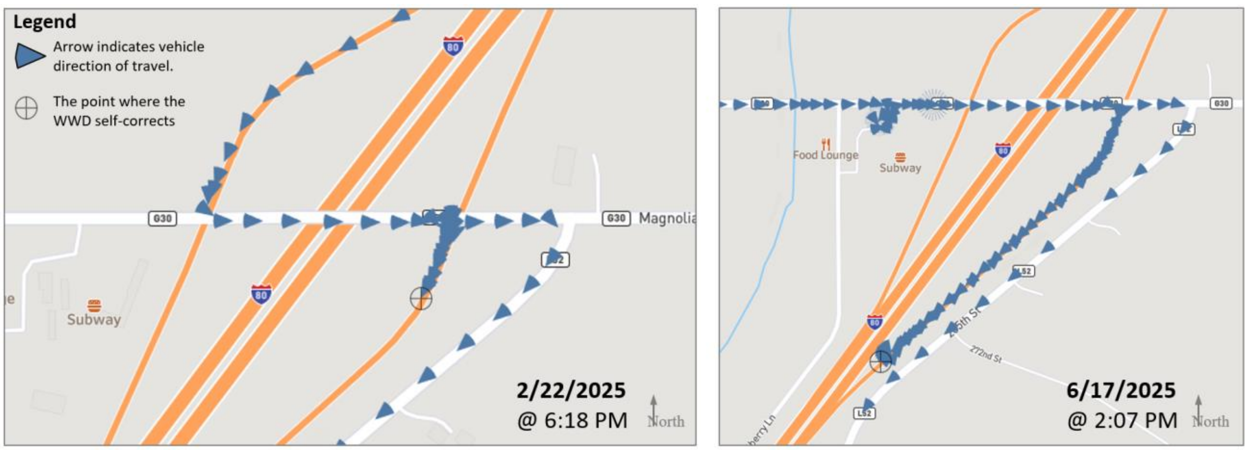
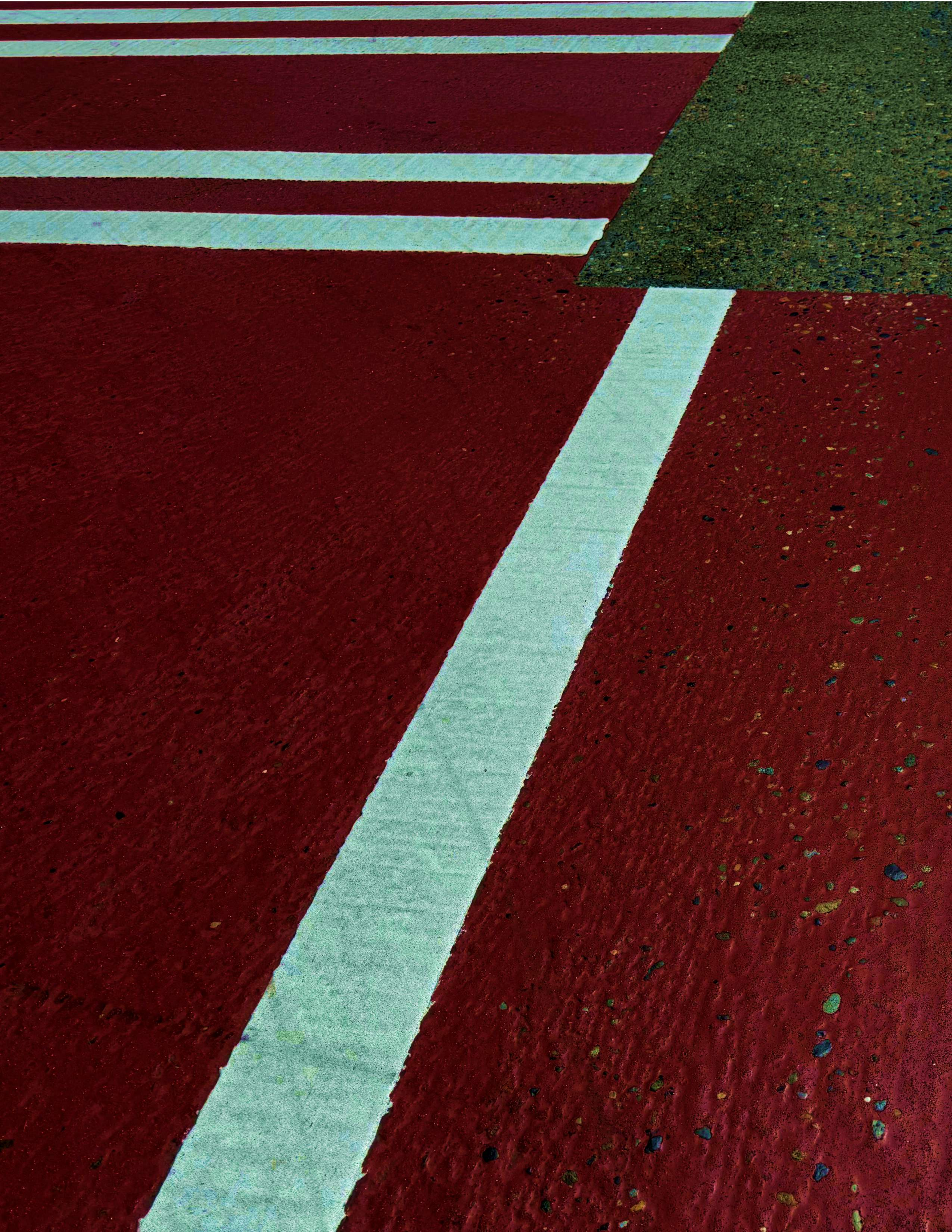


Figure 7. Detection of two wrong-way driving incidents at the same location using InTrans CV data-based methodology.

Conclusion and Implications

The Iowa DOT's experience shows that simple and thoughtful countermeasures rooted in human factors can produce significant improvements in roadway safety. Through close observation, ongoing refinement, and careful field evaluation, the agency achieved an eighty-eight percent reduction in wrong-way entries at Parclo B ramps. It is also notable that no wrong-way driving crashes have been documented at the treated locations since the treatments were installed.

This work demonstrates that even small, thoughtful improvements can reshape driver behavior and reduce the risk of severe crashes statewide.



JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH

VOLUME 3, ISSUE 1 | DECEMBER 2025

PAPER 010

A New Method to Assess Pavement Marking Retroreflectivity for Compliance with the MUTCD Minimum Pavement Marking Retroreflectivity Levels

July 11, 2025

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Introduction

Pavement markings are an important element of the roadway infrastructure providing delineation and safety for human drivers as well as machine visions systems used in automated vehicles, making up larger portions of the vehicle fleet in the US each year. The Federal Highway Administration (FHWA) has published minimum retroreflectivity requirements in the Manual on Uniform Traffic Control Devices (MUTCD). Support documents provided by the FHWA describe methods that can be used to manage pavement marking retroreflectivity. This paper describes the requirements set forth by FHWA and also describes a new tool that agencies can use to manage pavement marking retroreflectivity so that they can be in compliance with the National minimum retroreflectivity requirements.

Background

In Edition 3 of the 2009 MUTCD, the FHWA published minimum pavement marking retroreflectivity levels for longitudinal lines. The language remains the same in the 11th Edition

Section 3A.03 Maintaining Minimum Retroreflectivity

Standard:

01 Except as provided in Paragraph 5, a method designed to maintain retroreflectivity at or above 50 mcd/m2 /lx under dry conditions shall be used for longitudinal markings on roadways with speed limits of 35 mph or greater.

Guidance:

02 Except as provided in Paragraph 5, a method designed to maintain retroreflectivity at or above 100 mcd/m2 /lx under dry conditions should be used for longitudinal markings on roadways with speed limits of 70 mph or greater.

03 The method used to maintain retroreflectivity should be one or more of those described in "Methods for Maintaining Pavement Marking Retroreflectivity" (see Section 1A.11) or developed from an engineering study based on the values in Paragraphs 1 and 2. Talk about compliance dates and deadline of August 2026.

of the MUTCD (the most recent MUTCD). Some of the critical MUTCD language is shown below.

The MUTCD minimum maintained retroreflectivity levels apply to all longitudinal pavement markings (i.e., center lines, lane lines, and edge lines) on roadways with posted speed limits of 35 mph or greater. This includes both temporary and permanent pavement markings. Agencies have the option to exclude markings where ambient illumination assures markings are adequately visible from their method. Also, markings on streets or highways that have an average daily traffic (ADT) of less than 6,000 vehicles per day may be excluded. In addition, dotted extension lines (per MUTCD Section 3B.08), curve markings, parking space markings, and shared-use path markings may be excluded from an agency's method.

Along with Edition 3 of the 2009 MUTCD, the FHWA also published a supporting document that describes acceptable retroreflectivity maintenance methods that, when implemented as intended, provide agencies with flexible means of being in conformance with the standard. These methods were developed specifically for longitudinal pavement markings (i.e., center lines, lane lines, and edge lines) although some of the methods could also be applicable to other types of markings. Agencies are supposed to use the methods that best suit their needs to satisfy compliance of the MUTCD's minimum retroreflectivity levels. The acceptable methods are listed and briefly described below.

Measured Retroreflectivity Method – In this method, pavement marking retroreflectivity is measured and directly compared to the MUTCD minimum levels. The retroreflectivity measurements can be made with either handheld or mobile instruments using the standard 30-meter geometry. Inspectors must follow the instructions provided by the manufacturer to obtain reliable retroreflectivity readings, including periodically calibrating the equipment.

Nighttime Visual Inspection Methods – There are two wo types of nighttime visual inspections that can be implemented to maintain pavement marking retroreflectivity Consistent Parameters Nighttime Visual Inspection and Calibrated Pavement Markings Nighttime Visual Inspection). Both methods are meant to be conducted during dry nighttime conditions. These two methods have common elements such as:

- The use of low-beam headlamp illumination.
- Inspections conducted at prevailing nighttime speeds.
- The use of trained inspectors.
- The dependence on subjective evaluations.

Service Life Based on Historical Data Method – Using this method, an agency documents pavement marking installation dates and, using historical data or research results, establishes a schedule for replacing the markings. The schedule to replace the markings is designed to prevent the pavement marking retroreflectivity from falling below the MUTCD minimum levels.

Pavement marking replacement schedules can be set for similar markings in similar conditions (considering factors such as pavement marking type, retroreflective optics, pavement type, pavement condition, and traffic volumes).

Service Life Based on Monitored Markings Method – Using this method, an agency documents pavement marking installation dates and periodically monitors the retroreflectivity of a subset of the markings as a way to track their durability (retroreflectivity). The monitored markings represent a larger group of similar markings in similar conditions. When the monitored markings degrade and approach the MUTCD minimum levels, the entire group of markings (both monitored and the larger group they represent) are restriped. This is an alternative method for agencies that want to use a service life type of method but do not have historical data or specific research supporting service life estimates for their region and specific conditions.

Other Methods – An effective approach may be to combine one or more of these methods or to develop other methods based on engineering studies. If an agency develops a different method, however, it is important that the method be based on an engineering study and tied to the MUTCD minimum levels.

Road Marking Assessment Device

A new AI technology tool has been developed that uses a traditional phone (iPhone or Android). The tool is called the Road Marking Assessment Device (or RMAD). With an app installed and the phone mounted in the windshield of a vehicle, the driver turns on the app to record and conducts a daytime drive of the roadway of interest. The app uses AI technology to locate markings on both sides of the road and tracks them. By default, assessments are made at 30-meter intervals but can be customized by the user. The app then uses a 1-meter section of the markings to determine the presence of the markings. The results are mapped using different colors to show the condition of markings using presence. CSV files are available to further analyze the results as well.

Figure 1. RMAD Collecting Data

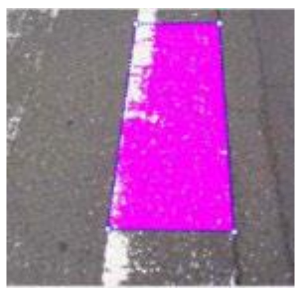

Figure 2. Assessment of a Worn Marking

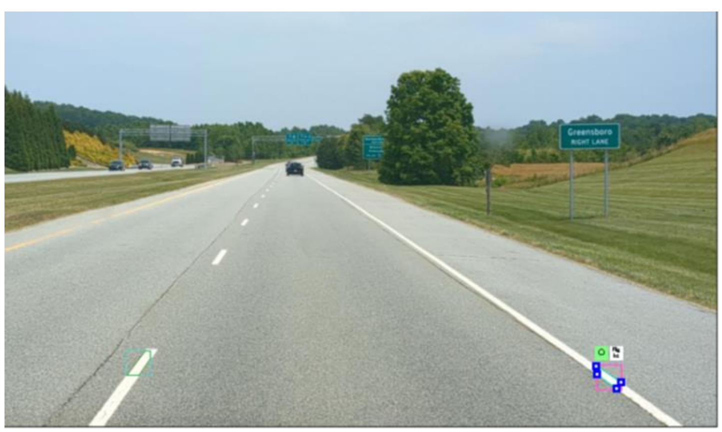

Figure 3. Green Boxed on Lane Line and Edge Line Show Area of Assessment

Figure 4. Results Mapped Using Color to Show Categories of Condition

Retroreflectivity Analysis

The RMAD tool was developed and tested in Japan and had shown strong correlations between presence and retroreflectivity. The research described in this paper was conducted to determine if US markings would also produce a strong correlation between presence and retroreflectivity.

The RMAD tool and mobile retroreflectivity were simultaneously used to collect data on 848 miles of roadways in the US. The data were collected in Texas, California, Kansas, North Carolina, and Nebraska in 2024. The roadways included a variety of multilane roadways and two-lane roadways. Statistics of the retroreflectivity data are provided in Table 1.

Table 1. Retroreflectivity Data Summary

Marking Color	Min (mcd)	Avg (mcd)	Max (mcd)
Yellow	28.1	203.7	1174.8
White	51.2	348.3	981.9

Figure 5 shows the mobile retroreflectivity equipment used during the data collection efforts. The marking materials included a variety as well such as paint, thermoplastic, and epoxy. There was no information availability about the age of the markings or the type of beads or their application rates.

Figure 5. LaserLux G7 Mobile Retroreflectivity Equipment

To inspect the data visually, both sets of data were plotted against the distance traveled. Figure 6 shows an example of the measured data plotted against the distance traveled (x-axis).

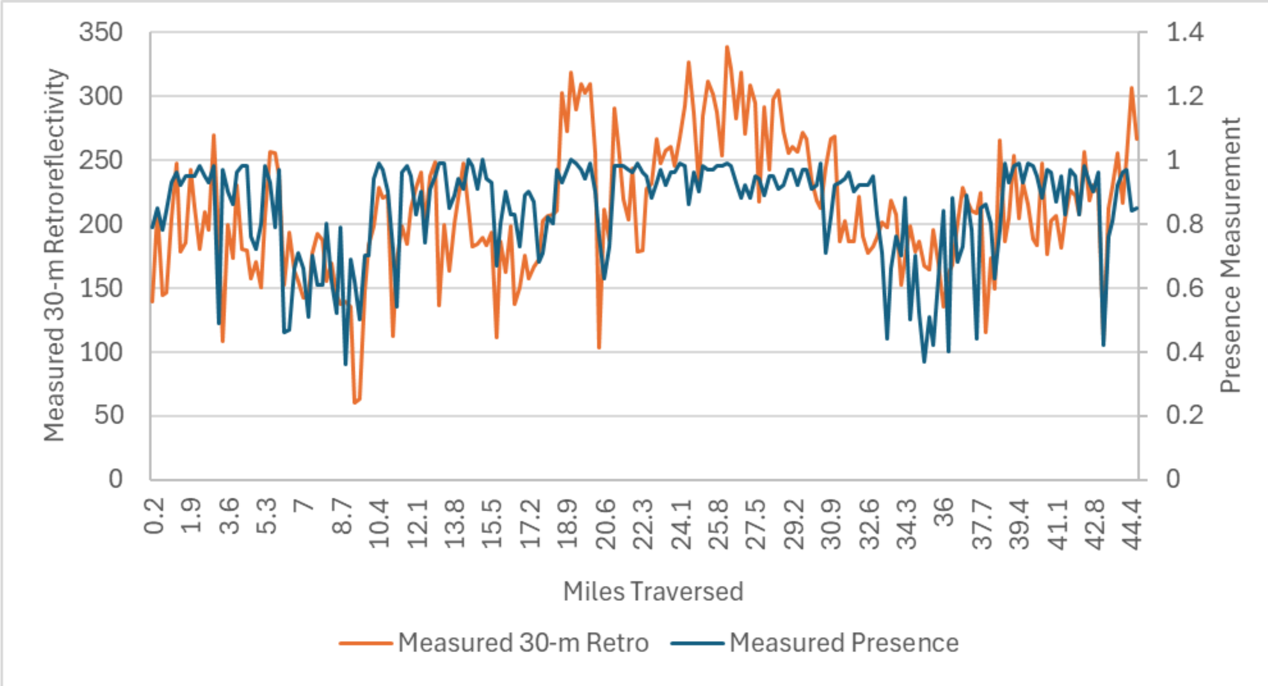

Figure 6. Simple Comparison of Measured Retroreflectivity and Presence

The data were then analyzed by running linear correlations between the measured presence and measured 30-m retroreflectivity readings. The results for the yellow markings are shown in Figure 7 and the results for the white markings are shown in Figure 8.

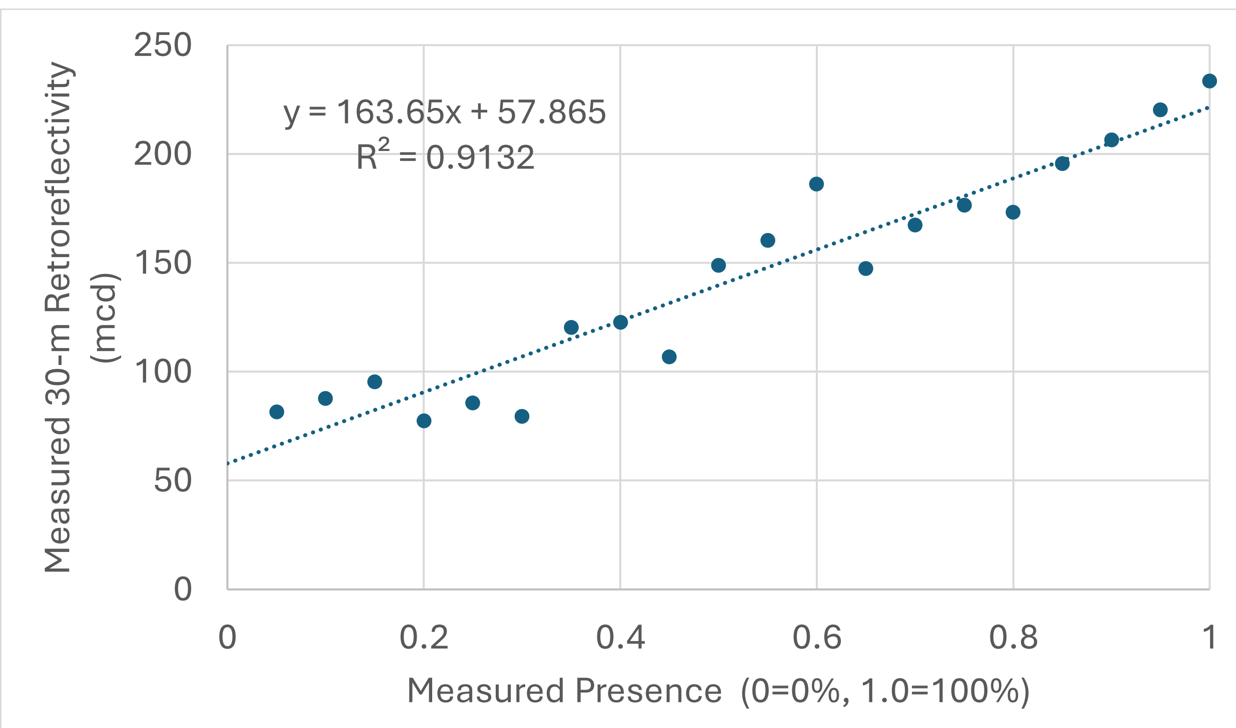

Figure 7. Correlation of Yellow Markings

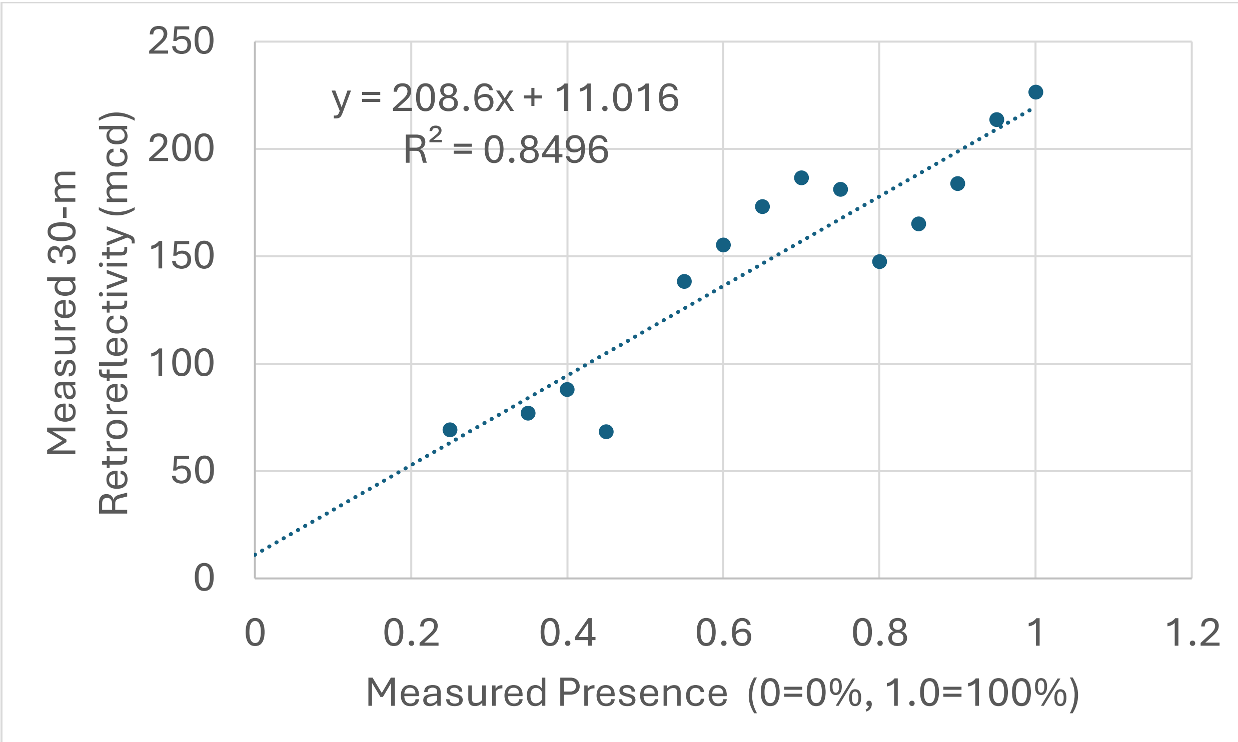

Figure 8. Correlation of White Markings

Both colored markings show a strong correlation that indicate that the results of the RMAD tool can be used to assess not only the presence of the markings, but also the retroreflectivity level. Compared to visual inspection methods, the RMAD device removes the subjectivity from the rating by the human observer. It is also considerably less costly than buying mobile retroreflectivity devices. The RMAD tool could be used on its own by an agency to manage pavement marking retroreflectivity or can be used in combination with methods such as Expected Service Life to help agencies refine their estimated service life based on materials, traffic, etc.

Discussion

It is interesting that the RMAD results correlate well with retroreflectivity given that the RMAD tool collects daytime images. While this work did not have the resources to test different theories, one theory is related to bead loss. As markings wear, they tend to lose the drop on beads that are applied before the marking cures. These drop on beads provide retroreflectivity and nighttime visibility. As the markings wear, the beads can pop out of the markings, leaving small craters. They can also crack or get sheared off by plows. All of these failures tend to leave the marking looking dingy or even dirty, which then cause the RMAD tool to rate the presence lower. See Figure 9 for an example of how bead loss tends to create pockets where road dirt and grime tends to fill the empty craters leaving the marking dirty and darker looking than it would without the bead loss. Obviously, the retroreflectivity would also be lower in these cases too. Therefore, this might be one way to explain the strong correlation between the RMAD tool results and retroreflectivity.

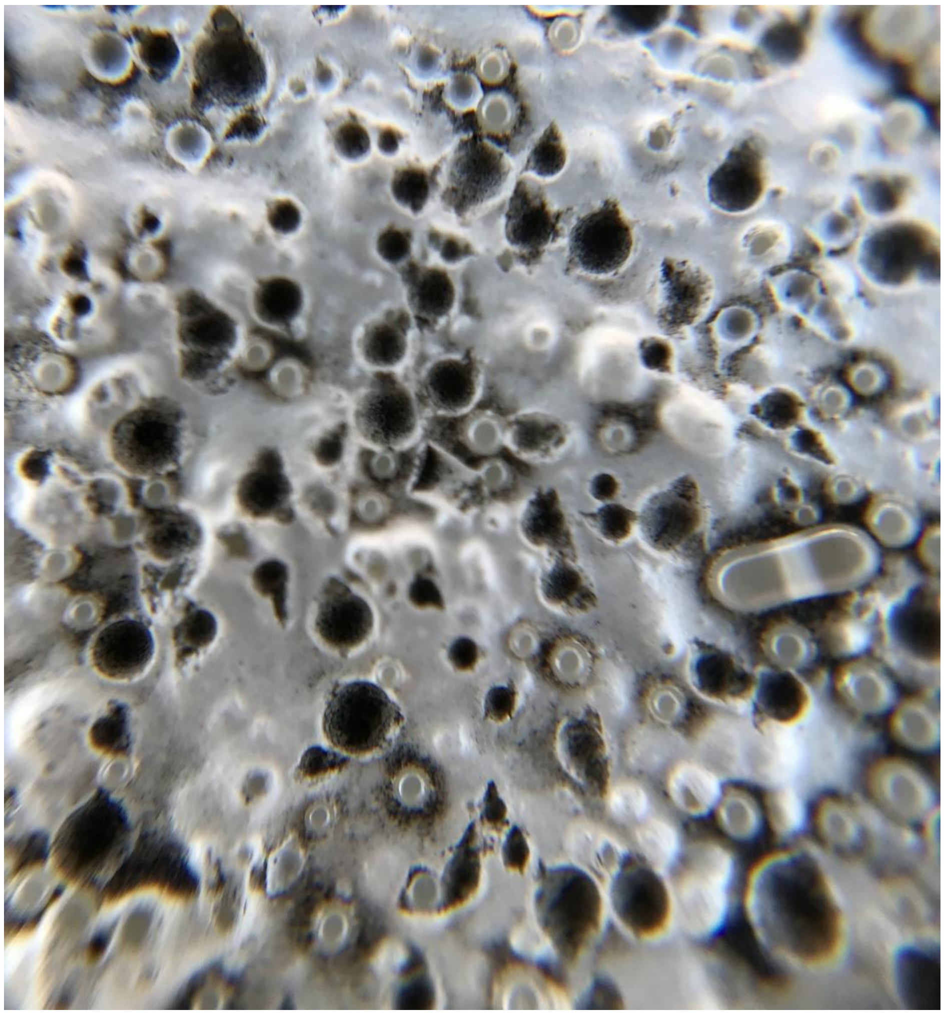

Figure 9. Bead Loss and Dirt Collection

Conclusion

The results of this paper show that the RMAD tool can be used by agencies to complement their existing pavement markings retroreflectivity management program or even be used on its own to meet the MUTCD requirements of maintaining minimum retroreflectivity levels. Technically, this tool would fall under the "Other Methods" as described in the FHWA's report (Methods for Maintaining Pavement Marking Retroreflectivity, FHWA-SA-22-028, July 2022). It can be used on its own or combined with other methods. In many places where measured retroreflectivity is used, the mobile equipment does not generally measure ramps or frontage roads. In these cases, the RMAD tool would be a good complement. It could also be used for those using the expected service life method. RMAD would most likely be a better method than visual inspections, taking the subjectivity out of the visual inspection method.

Acknowledgement

This paper is based on data collected by Potters Industries. Potters Industries collected both the retroreflectivity data (using a calibrated LaserLux G7 Mobile Retroreflectometer) and smart phone data with the RMAD software loaded and running. We would like to express our sincere gratitude to all those involved for their valuable time and cooperation in collecting and providing the data; and assisting in the analysis and compilation of this paper. Contact Potters Industries for more information about the RMAD, setting up a demonstration, and understanding pricing options.

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
VOLUME 3, ISSUE 1 | DECEMBER 2025

PAPER 011

STATE OF THE PRACTICE REVIEW

STATE OF THE PRACTICE REVIEW

Human Factors Considerations for LED-Enhanced Static Traffic Signs

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Introduction

Traffic signs communicate important information that drivers rely on to safely perform driving tasks. Because of their critical role, it's crucial that drivers are able to detect, recognize, and respond to signs with sufficient time and distance to do so safely. When signs are difficult to detect or not easily distinguishable within a visually complex environment, drivers may miss critical information, which can compromise safe driving performance. As a result, enhancing sign visibility and conspicuity are key components in roadway and traffic control design.

There are a variety of treatments that can be implemented to improve sign conspicuity, including the use of retroreflective materials, the removal of unnecessary or redundant signs, and increases in sign size. In the early 2000s, light-emitting diodes (LEDs) were first introduced within static traffic signs to draw drivers' attention to particularly important information (Bert, 2021).

From a human factors perspective, the effectiveness of LED-enhanced static signs depends on how drivers perceive, interpret, and respond to these visual stimuli under real-world driving conditions. This report explores literature on the use of LEDs within static signs, examines how their use relates to human factors principles, and describes current guidance and state practices regarding their implementation.

Background

Traditional traffic signs provide crucial information that drivers must be able to detect, read, and interpret in a timely manner to support safe driving behavior. In visually complex roadway environments, signs may be overlooked, increasing the risk that important information is missed. To address this challenge, conspicuity-enhancing treatments, such as LEDs within static signs, have been implemented, with their use first introduced in the 2003 Edition of the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) and more substantial provisions on their appropriate use incorporated in the 2009 Edition.

The MUTCD establishes uniform national criteria for the use of traffic control devices to promote consistency nationwide. The MUTCD provides extensive provisions on the placement, color, size, location, and spacing of static signs, as well as proven treatments to enhance conspicuity. However, because the use of LEDs within static signs is still relatively new within the MUTCD, existing guidance is limited with respect to key design and operational factors such as LED color, spacing along the border, luminance, flash patterns, and frequency of use. This highlights the need for additional research to identify optimal and effective LED design characteristics.

MUTCD Specifications

Within the MUTCD, provisions related to roadway signs are addressed in Part 2. Most provisions related to the use of LED enhancements within static signs are located in Chapter 2A, which provides general criteria for signs, including size, placement, and other general provisions.

Within Chapter 2A, Section 2A.12 (LEDs Used for Conspicuity Enhancement on Standard Signs) establishes conditions under which LEDs may be used to enhance the conspicuity of static signs. The section clarifies that LEDs are intended to supplement, not replace, the sign legend and that their use does not convert a static sign into a changeable message sign.

When LEDs are used, the sign is still required to meet all applicable retroreflectivity and illumination requirements for nighttime viewing. The MUTCD places several constraints on LED application to preserve uniformity and driver comprehension, including limitations on where LEDs may be placed (e.g., within legends, symbols, or borders rather than sign backgrounds), restrictions on LED size and spacing, and requirements for appropriate color based on sign type.

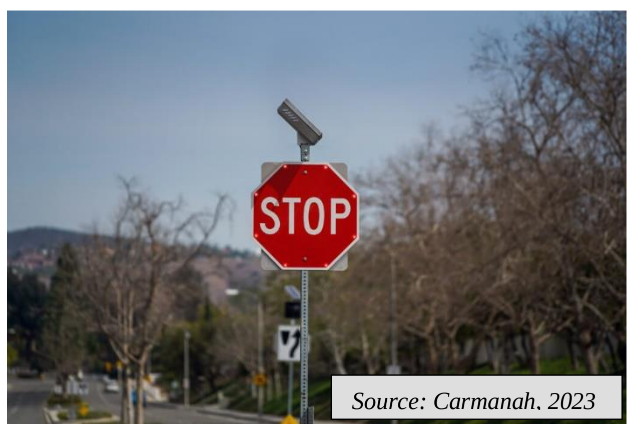
Provisions further specify that LEDs, if flashed, must flash simultaneously at a steady rate and that certain sign types (such as STOP and YIELD signs) require continuous operation without actuation.

Additional provisions specify that when used along the border, LEDs must be positioned along each edge and corner to ensure the sign shape is visible during nighttime conditions. For LEDs being used in the border of circular signs, the number of LEDs used must be enough to clearly form the appearance of a circle, to not be confused with a different shape.

Although the MUTCD establishes baseline standards for the use of LEDs within static signs, questions remain regarding the most effective application of this enhancement under varying conditions and sign types. Additional research could expand on the current MUTCD provisions by offering evidence-based recommendations to support decisions regarding when, where, and how to deploy LEDs within static signs.

State-of-Practice Review

This section summarizes the current state of practice regarding the use of LEDs within traffic signs. A number of state and local agencies across the United States utilize embedded LEDs within static signs to enhance visibility and conspicuity. Common applications include regulatory and warning signs such as STOP, WRONG WAY, DO NOT ENTER, YIELD, Pedestrian Crossing, STOP AHEAD, Speed Limit, and Chevron Alignment signs (U.S. DOT, 2009; Institute for Transportation, 2025; Carmanah Technologies, 2023; Institute of Transportation Engineers, 2015).



Source: Carmanah, 2023

Given the critical role these signs play in supporting safe driving behavior, supplementing them with LEDs is appropriate given their importance; failure to detect or respond to these signs could have severe consequences, including failure to stop at an intersection, wrong-way driving, pedestrian collisions, or roadway departures on curves. Enhancing the conspicuity of these signs through LED treatments is therefore intended to reduce the likelihood that drivers will miss essential information.

However, it is important that LEDs are used sparingly so drivers do not become accustomed to their presence and stop adhering to them (Institute of Transportation Engineers, 2015). Because of this, existing guidance and agency practice identify situations in which LEDs may be appropriate, including (U.S. DOT, 2009; Institute for Transportation, 2025; Minnesota DOT, 2017; FHWA, 2010):

- Locations with limited sight distance (horizontal curves, glare, etc.),
- Locations where drivers may fail to recognize an intersection,
- Intersections with a high crash rate history, and
- Intersections where a STOP sign may be unexpected.

There are currently no provisions in the MUTCD that provide a minimum or maximum value of brightness levels of LEDs embedded within static signs. One distributor of LED-embedded signs offers an optical light intensity of a minimum of 1,000,000 millicandela (mcd) during the daytime and is able to dim the daytime intensity between 10 and 100 percent for nighttime conditions (Carmanah, n.d.). Another distributor of LED-embedded signs offers a maximum of 5,200 lumens and their systems can automatically dim based on the amount of surrounding light in the environment (TAPCO, n.d.). Texas Department of Transportation (TxDOT) published specifications for LEDs embedded on curve warning signs and specified that the LEDs must output a minimum of 550,000 mcd during daytime peak and be able to automatically adjust the brightness to the surrounding environment (Texas DOT, 2024).

The cost of these systems and installation varies slightly. Pennsylvania installed a number of LED embedded signs around the state. The cost ranged from approximately $37,100 to $682,100, but all locations saw a positive benefit-cost ratio (U.S. DOT, 2023). Minnesota Department of Transportation (MnDOT) and North Dakota DOT reported a minimum cost per intersection between $2,000 and $3,000 and a maximum cost of $6,000, which included two LED-enhanced STOP signs and solar charging equipment (Minnesota DOT, 2017; North Dakota DOT, 2017). MnDOT also published a report that compared the cost of a passive LED STOP sign system, $2,000, and an activated LED STOP sign system, $20,000 (Minnesota DOT, 2016).

Literature Review

This section reviews and summarizes research on the human factors considerations related to the use of LEDs within static signs. Because prior studies use overlapping or inconsistent terminology to describe how drivers interact with signs, key terms are clarified to establish a consistent framework for this review.

In this paper, a driver's ability to detect a sign is described in terms of visibility and conspicuity. Visibility refers to how easily the sign can be seen, while *conspicuity* refers to how readily the sign attracts attention relative to its surrounding environment. A driver's ability to comprehend a sign is based on both recognition and legibility, where *recognition* refers to correctly identifying the sign and *legibility* is how easily the sign's text or symbols can be read. Finally, *compliance* refers to whether and how drivers modify their behavior after viewing the sign.

The literature reviewed in this section examines the extent to which LEDs influence each of these stages of driver interaction with static signs: detection (visibility and conspicuity), comprehension (recognition and legibility), and compliance. Literature was reviewed to see how LEDs impacted each of these factors.

Detection of Signs

In practice, traffic signs are meant to be both visible and conspicuous, meaning drivers can both see the sign and notice it quickly, regardless of the environment or conditions. LED enhancements can help achieve this; however, there are certain situations under which the visibility or conspicuity of LED-enhanced signs may be reduced. How visible or conspicuous a sign is can vary depending on the time of day or condition of the roadway, even for the same sign. For instance, LEDs within a static sign where there is an abundance of light from the sun may have limited impact on visibility as the sun can diminish their relative contrast (Bullough, 2017; Theiss et al., 2022). In comparison, LED enhancements tend to be more effective during lower lighting situations such as fog, rain, snow, or nighttime conditions, where additional luminance can improve sign detectability (Dulebenets et al., 2021).

However, differing lighting conditions may not necessarily produce the same results in achieving conspicuity. If a driver is on a rural road and sees a static sign with LEDs, there is a greater possibility that the sign will be visible and conspicuous since there are fewer competing background visuals. In contrast, if a driver was in a city with lots of lights, people, cars, and buildings, LEDs may be less effective, even if they improve visibility, due to increased visual clutter (Inman & Philips, 2013; McPhee et al., 2004; National Academies of Sciences, Engineering, and Medicine, 2024; Shoptaugh & Whitaker, 1984). Generally, the more complex or cluttered the roadway environment, the more difficult it becomes to extract information from signs (Lerner et al., 2003) and the time it takes to locate and respond to sign information increases (Shoptaugh & Whitaker, 1984).

There are a number of factors that impact the effectiveness of LED enhancements on conspicuity, two of which being brightness and flash characteristics. The brightness levels of the LEDs are one of the more impactful characteristics when it comes to visibility and conspicuity as it can help draw the driver's attention to the device (Bullough, 2017; Bullough et al., 2000; Fitzpatrick, Avelar, & Robertson, 2015; Freyssinier et al., 2006). However, excessive brightness can have negative impacts, including visual discomfort, glare, and reduced ability to view other crucial roadway elements (Chrysler et al., 2017; Freyssinier et al., 2006; Fitzpatrick, Avelar, Potts, et al., 2015; Fitzpatrick et al., 2011; Sunkari & Institute, 2014). A study on LED-enhanced STOP signs found that that signs were most detected on the lowest brightness setting during nighttime conditions and the highest brightness setting during daytime conditions (Fitzpatrick et al., 2011). This finding suggests that LED brightness does not uniformly improve sign visibility or conspicuity across all lighting conditions.

Source: Fitzpatrick et al., 2015

Flash patterns of the LEDs can also impact the visibility and conspicuity of the sign. Several studies have reported that flashing LEDs increased the sign's visibility and conspicuity compared to steady LEDs (Bullough, 2017; Fitzpatrick, Avelar, & Robertson, 2015). A study conducted by Texas Transportation Institute (TTI) evaluated various flash patterns by having participants view simulated beacons with five different flash patterns (Hawkins & Young, 2010). There were no significant findings across the different flash patterns, making it difficult for the researchers to recommend one flash pattern over another for implementation within static signs.

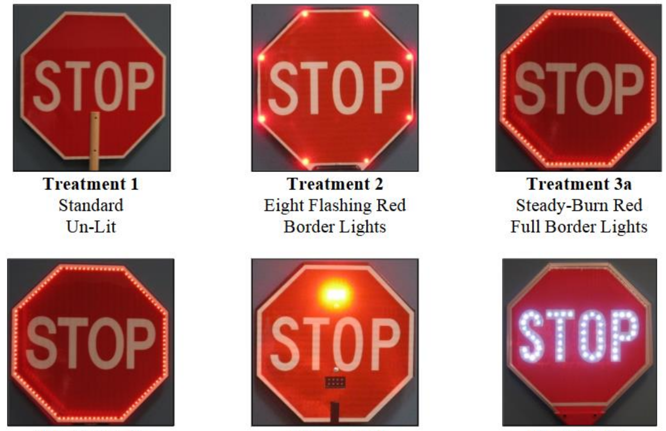
While LEDs can be a useful tool for increasing conspicuity and visibility, overusing them can lead to a decrease in effectiveness as people may stop paying as much attention to them (Institute of Transportation Engineers, 2015; Fitzpatrick et al., 2011; Forbes, 2011). This highlights the importance for the MUTCD to provide guidance on what situations warrant LED enhancements to avoid their overuse.

Comprehension of Signs

The ability to detect a sign and notice it with sufficient time to respond is important; however, detection alone is insufficient if drivers cannot recognize key characteristics of the sign, read its information, or comprehend its meaning. Recognition and legibility are therefore key factors that must be established regardless of any improvements in visibility or conspicuity provided by LED enhancements.

TxDOT conducted a laboratory study evaluating the impact of LEDs on recognition of a sign's shape, color, or type (Fitzpatrick et al., 2011). The study compared a number of different signs, including STOP (R1-1), YIELD (R1-2), PEDESTRIAN CROSSING (W11-2), Do Not Enter symbol (variation of an MUTCD sign), SPEED LIMIT (R2-1), Intersection Ahead (W2-1), Two-Direction Large Arrow (W1-7), and a circular STOP sign. The signs were tested with different LED configurations, colors, flash rates, and flash patterns. Overall, the study found that the inclusion of embedded LEDs decreased sign recognition time. During the lab portion of the study, participants perceived signs with LEDs enhancements as smaller than the standard unlit signs. When comparing the impact of different LED colors, seven LED arrangements were used on STOP signs. The seven variations included an un-lit, eight red dots in the border, 8 white bars flashing simultaneously in the border, 8 white bars with 4 bars flashing alternatively in the border, 8 red bars flashing simultaneously in the border, 8 red bars with 4 bars flashing alternatively in the border, and 4 red dots in the background of the sign. The results showed that the alternating flashing bars had the worse color recognition and the red simultaneous flashing bars had the best color recognition. For sign recognition, simultaneous flashing performed better an alternating flashing and red bars performed better than white bars. The researchers concluded that LEDs embedded in the border of signs can help with recognition, but as shown in the laboratory study, at greater distances, the LEDs have a greater potential to distort the shape of a sign. The research also found that using LED colors that match the sign background, such as red LEDs for STOP signs, can help distinguish the sign type.

TTI performed a study to evaluate the impact of LED configuration and color on the recognition of STOP paddles (Finley et al., 2012). The configurations tested included a standard un-lit sign, eight flashing red LEDs embedded in the corner, steady red LEDs around the full border, flashing red LEDs around the full border, vertically centered flashing red LEDs, and steady white LEDs within the sign legend. The findings showed that the vertically centered flashing red LEDs and the steady white LEDs within the legend had a negative impact on driver's recognition of the sign compared to the un-lit paddle. In a post-task assessment, participants indicated that the vertical flashing lights were blinding and distracting, and the steady white LEDs made it more difficult to distinguish the red background color on the paddle. The study also found that none of the light configurations impacted the driver's ability to recognize the sign shape compared to the un-lit paddle, but the three red LED configurations along the border of the sign showed further recognition distances. Researchers suggested that this may be due to the over-glow of the white LEDs, making it more difficult to see the background color or shape.



Treatment 1 Standard Un-Lit

Treatment 2 Eight Flashing Red Border Lights

Treatment 3a Steady-Burn Red Full Border Lights

Treatment 3b Flashing Red Full Border Lights

Treatment 4 Flashing Red Vertically Centered

Treatment 5 Steady-Burn White STOP Legend

Source: Finley et al., 2012

The same TTI study also evaluated the legibility of the word "STOP" using the same LED colors and configurations (Finley et al., 2012). The results showed that the embedded LEDs did not impact the driver's ability to read the STOP legend of the sign compared to the un-lit paddle. For the paddle with the white LEDs within the legend, the legibility distance was further in the evening than during the day, and the legibility distance was further in the evening for this treatment compared to the flashing red LED borders or the vertical red LEDs. However, the post-task assessment indicated that participants found both the vertical red LEDs and the white LEDs within the legend difficult to read.

Another TTI study evaluated the legibility of WRONG WAY signs with different treatments (Finley, et al., 2014). The study was conducted on a closed course during nighttime conditions, and participants were impaired by alcohol. They were asked to indicate when they could read the legends of different signs placed along the roadway. The results showed that the legend of WRONG WAY signs with flashing red LEDs around the border were more difficult for the participant to read compared to other treatments. However, researchers indicated that additional research is needed to determine the optimal brightness of LEDs during different conditions that increase conspicuity without compromising legibility.

Recognizing color and shape can be extremely useful for signs such as STOP and YIELD, as those signs have a unique color and shape associated with them, so identifying that alone can provide drivers with clues to what to expect coming up. However, for signs such as warning signs that all have the same shape and color, being able to read the information on the sign is extremely important.

Compliance with Signs

The ultimate goal of enhanced conspicuity treatments is to influence driver behavior in a manner that improves roadway safety. While improving a driver's ability to see and detect a sign is a necessary first step, increased visibility alone does not guarantee that drivers will modify their behavior or comply with the sign's message (Katz et al., 2022; Theiss et al., 2022). Enhanced conspicuity is generally intended to draw drivers' attention to critical signs and, in doing so, increase the likelihood of appropriate behavioral response. All studies reviewed in this section were field studies.

Studies consistently demonstrate that enhanced conspicuity may increase compliance. MnDOT reported a 41.5 percent reduction in angle crashes after replacing a standard STOP sign with a flashing LED STOP sign (Davis et al., 2014). Another analysis conducted by MnDOT found that a flashing STOP sign that activated when a vehicle passed a STOP AHEAD sign, reduced approach speeds, increased stop duration, and eliminated rolling stops when another vehicle was in the intersection (Kwon & Ismail, 2014). Other studies similarly observed increases in the proportion of vehicles coming to a complete stop when there is an LED-enhanced STOP sign (Davis et al., 2014; Foomani et al., 2015; Gates et al., 2004; Van Houten & Retting, 2001), with some studies noting greater compliance during nighttime conditions (Arnold & Lantz, 2007; Li et al., 2020).

LED enhancements have also been associated with improved compliance for other regulatory signs. One study found a significant reduction in vehicle speeds approaching a railroad crossing after embedding LEDs within a Grade Crossing Crossbuck and DO NOT STOP ON TRACKS signs (Hellman & Lamplugh, 2016). Another study observed a decrease in the number of vehicles stopping within the grade crossing after embedding LEDs within the border of a DO NOT STOP ON TRACKS sign (Hellman, 2020).

Source: Hellman & Lamplugh, 2016

Findings for warning signs were less consistent. Warning signs are intended to alert drivers to upcoming conditions rather than mandate a specific action at the sign location, and compliance is often assessed indirectly through measures such as speed or yielding behavior. Several studies found increased driver yielding at pedestrian (W11-2), school (S1-1), and trail crossing (W11-15) warning signs when enhanced with LEDs (Ellis & Tremblay, 2014; Fitzpatrick et al., 2023). However, one study found no significant change in average vehicle speeds before and after the installation of a BE PREPARED TO STOP (W3-4) sign with LEDs within the border (Theiss et al., 2022).

Importantly, the absence of behavioral changes does not necessarily indicate that LED enhancements were ineffective. In some cases, baseline speeds or compliance rates at the study sites may have already been within acceptable ranges, limiting the potential for measurable improvements. Additionally, for warning signs in particular, it may not be reasonable to expect a consistent or immediate change in driver behavior, especially when the condition being warned of does not require a definitive response or when drivers are already behaving appropriately. The effectiveness of LED enhancements on compliance is likely context-dependent and influenced by both baseline conditions and the intent of the sign.

Conclusion

The selective integration of LEDs within static traffic signs represents an important advancement in enhancing road safety and communication where increased conspicuity it necessary. This review outlined real-world applications of LED-embedded signs, existing research on these devices, and current provisions on the use of LEDs within static signs. Together, the state of practice review and literature review highlight the continued technological advancement and the continued commitment to improving roadway safety through targeted conspicuity treatments.

This review highlighted research pertaining to the impacts of LEDs on the visibility, conspicuity, recognition, legibility, and compliance of roadway signs. While many studies demonstrate that LEDs can enhance visibility and conspicuity, the findings also indicate potential tradeoffs that agencies must consider when implementing these treatments. For example, some research showed that the inclusion of LEDs can obscure key sign characteristics, such as sign shape, or introduce excessive glare that can negatively impact legibility. These findings emphasize the importance of carefully balancing the attention-grabbing features with the need to preserve the essential visual information integral to sign comprehension and roadway safety.

Many field studies reported seeing an improvement in driver compliance following the installation of LED-embedded signs, particularly for STOP signs and selected warning signs. However, the magnitude and consistency of these behavioral changes varied by sign type, roadway context, baseline conditions, and LED configuration, and not all studies observed measurable improvements in compliance. These findings suggest that the effectiveness of LED enhancements depends on appropriate application and design.

As LED technology continues to evolve, ongoing research will be essential to refine best practices and inform future guidance. Addressing remaining gaps in knowledge will help inform appropriate deployment of LED-enhanced signs in a manner that increases safety, supports human factors principles, and meets the needs of all road users.

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JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
VOLUME 3, ISSUE 1 | DECEMBER 2025

PAPER 012

Technology Solutions for Temporary Traffic Control Operations

Automated Flagger Assistance Device, Portable Traffic Signal, and Residential Driveway Temporary Signal Applications

AFAD (Image: Michigan DOT)

Portable Signal (Image: Horizon Signal)

August 2025

American Traffic Safety Services Association

ATSSA
Safer Roads Save Lives

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Introduction

Transportation agencies, contractors, traffic control services companies, and a broad range of other stakeholders desire efficiency and safety in implementing temporary traffic control (TTC) for a variety of situations. Vendors are continuously researching, prototyping, and engineering devices that can improve operations and safety. For devices to gain adequate use, they need to be simple, straightforward, easily moved to the site—or remobilized to another location—and cost effective to use.

Temporary traffic control applies to work zones, planned special events, and traffic incident management. Each situation is different and requires planning to ensure adequate levels of safety. While incident management planning focuses on proactive verification and response, work zones and planned special events both benefit from the use of devices within the traffic control plan that can improve safety.

Fatalities and serious injuries at or near temporary traffic control setups remain problematic. In 2023, 39,345 fatalities occurred on highways in the United States.[1] In the same year, 818 fatal crashes occurred in work zones, resulting in 899 work zone fatalities.[2] In addition, nearly 38% of the 156 fatalities coded as non-motorist deaths are individuals working at the project site. In 2024, eight flaggers were struck and killed by approaching vehicles.[3] Regardless of the number of advanced warning signs installed, distracted drivers often do not lower their speeds accordingly when approaching typical temporary traffic control configurations.

> In 2024, eight struck-by incidents resulted in eight flagger fatalities. All of these fatalities were the result of individuals being struck by an approaching motorist.

The American Traffic Safety Services Association (ATSSA) is committed to reducing work zone injuries and fatalities through promotion of safe work zone traffic control practices. ATSSA members research, develop, and manufacture devices and technologies that provide greater levels of efficiency and safety in and around work zones. Of particular focus is moderate- to high-speed two-lane rural work zones where traffic is controlled by stopping one lane at a time and alternating traffic through the work zone.

Depending on conditions at project sites, there are several options for managing traffic flow through work zones on two-lane highways. These techniques are outlined in the *Manual on Uniform Traffic Control Devices* (MUTCD), in existing ATSSA publications, and in transportation agency standards and specifications. Two devices with significant safety, mobility, and efficiency benefits include automated flagger assistance devices (AFAD) and portable traffic

[1] National Highway Traffic Safety Administration, "NHTSA Estimates 39,345 Traffic Fatalities in 2024," news release, April 8, 2025, NHTSA Releases 2023 Traffic Deaths, 2024 Estimates.
[2] "Work Zone Data," National Work Zone Safety Information Clearinghouse, accessed August 1, 2025, http://www.workzonesafety.org/work-zone-data/.
[3] "Fatality and Catastrophe Investigation Summaries," Occupational Safety and Health Administration, accessed August 1, 2025, https://www.osha.gov/ords/imis/accidentsearch.html.

signals (PTS). In addition, the Federal Highway Administration recently granted interim approval for the Residential Driveway Temporary Signal (RDTS) that provides guidance to motorists entering a one-lane, two-way work zone configuration from a driveway.

Practitioners have a need for information on proven, tested techniques that can improve work zone safety. This need includes examples of requirements and accepted practices for use of the AFAD, PTS, and RDTS on two-lane roadways. This case study outlines some examples of proper application of the devices, along with example agency requirements and traffic control plan standard drawings. These case study examples will benefit interested transportation agencies and private sector representatives.

Automated Flagger Assistance Devices

AFADs provide enhanced safety for flaggers by allowing them to control the flagging devices from a safe location off the shoulder of the roadway. AFADs can be mounted on a trailer, cart, or tripod and are operated by a trained flagger to control traffic in one or both directions. AFADs typically have a gate arm, which is used to control the flow of traffic into a one-lane, two-way work zone.

Portable Traffic Signals

PTS are trailer- or cart-mounted devices that may include multiple signal heads and control traffic at the approach to a one-lane, two-way taper or open lane. PTS control each traffic approach to a project site on a two-lane road without the need for flaggers. These devices can use pre-determined or customized timing plans.

Differences and Similarities in the AFAD and PTS

AFADs are controlled by one or more individuals from within the work zone and are designed for use with short- and intermediate-term operations (typically one work shift). Some agencies limit AFAD use to three days. AFADs can be equipped with a red and flashing yellow indicator or a stop/slow indicator.

Figure 1. Closed Lane AFAD Application in Michigan (Image Courtesy Michigan Department of Transportation)

The MUTCD outlines several requirements and recommendations for applying AFADs, including the following condition information:

- AFADs shall only be used in situations where there is only one lane of approaching traffic in the direction to be controlled.

- When used at night, the AFAD location shall be illuminated in accordance with Section 6D.06.
- Because AFADs are not traffic control signals, they shall not be used as a substitute for or a replacement for a continuously operating temporary traffic control signal as described in Section 6L.01.
- AFADs shall meet the crashworthy (see definition in Section 1C.02) performance criteria contained in Section 6A.04.
- If used, an AFAD shall be operated only by a flagger (see Section 6D.01) who has been trained on the operation of the AFAD. The flagger(s) operating the AFAD(s) shall not leave the AFAD(s) unattended at any time while the AFAD(s) is being used. The owner-agency may also require operators to have manufacturer training for operation.
- Traffic control using AFADs must either include an AFAD at each end of the work zone, or an AFAD at one end and a flagger at the opposite end.
- AFADs must be operated by qualified flagger(s) with unobstructed views of the AFADs and traffic approaching in both directions. Check with your state department of transportation (DOT) on the requirements for AFAD operation.
- Proper training related to the specific device in use may be required by the owner-agency and should be provided to operators prior to use.
- AFADs may include a stop/slow indication or a red/yellow signal lens, along with an actuated gate arm.

Some AFAD systems link portable camera technology to portable electronic devices in the field for closer monitoring of the approaches by appropriate personnel. Additional personnel may monitor the operation using a connected device while the flagger controls the AFAD from a nearby location. This application has also been used with multiple flaggers and with pilot car operations, where the pilot vehicle leads traffic through more complicated routes. In this example, the operation used two flaggers near the AFAD to control each device along with one pilot car operator. In addition, AFADs support traffic rerouting through third-party app connectivity.

The following map indicates the states that permit the use of AFADs and PTS.[4]

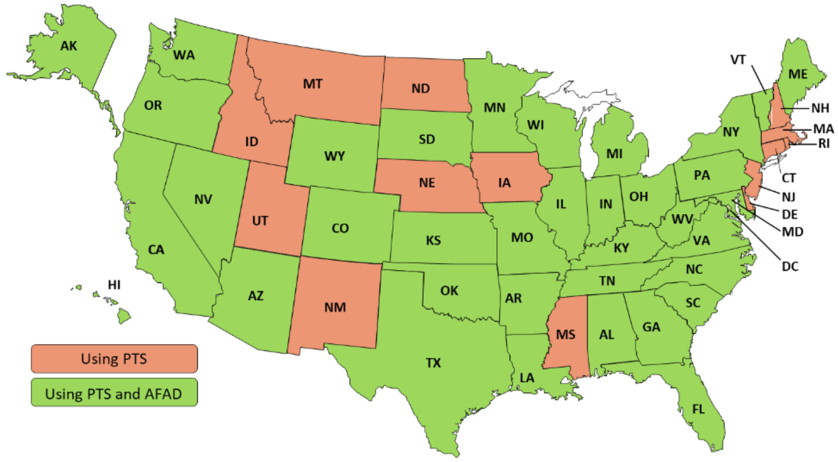

Figure 2. AFAD/PTS Use by State (As of December 2022)

Figure 3. Pedestal-mounted PTS (Image Courtesy Branz Technologies)

PTS allow more efficient traffic flow compared with traditional flagging operations because they use detection system components that allow signal timing to be adjusted in real-time based on traffic conditions. PTS have a variety of applications depending on the duration of the project and can also be used on two-lane roadways and bridges where traffic must alternate in the long-term. One agency uses PTS for daytime work on high-volume, two-lane roadways and for all nighttime work on two-lane roadways. PTS can be mounted on a trailer or smaller pedestal for ease of maneuvering. Trailer-mounted PTS can be used to control both vehicular and pedestrian traffic.

Part 4 of the MUTCD outlines requirements for using temporary traffic signals as noted in the following list.

- Advance signing shall be used when employing a temporary traffic control signal.
- A temporary traffic control signal shall:
    A. Meet the physical display and operational requirements of a conventional traffic control signal;
    B. Be removed when no longer needed; and
    C. Except as provided in Paragraph 5 of this Section, be placed in the flashing mode during periods when it is not desirable to operate the signal in the steady mode, or

[4] Usage statistics determined based on the presence of a standard drawing, specification, verbal or written agency confirmation, or the device is included on the agency's approved products list. In some cases, information may not have been readily available.

the signal heads shall be covered, turned, or taken down to indicate that the signal is not in operation.

Residential Driveway Temporary Signal

In addition to managing two-lane traffic approaching the work area, another challenge in effectively managing traffic in and around work zones is traffic entering from driveways and side streets. For a long section of one-way flow on a two-lane road with one lane closed, driveway entry into the traffic space can be confusing for motorists unless they are able to follow a mainline vehicle or platoon of vehicles. To alleviate this issue, FHWA released an interim approval to allow the RDTS.

RDTS—formerly referred to as Driveway Assistance Devices—are trailer-mounted traffic control units engineered to manage driveway ingress and egress within extended one-lane, two-way operations on two-lane roadways. These systems interface with Portable Traffic Signals (PTS) located at each terminus of the work zone to coordinate traffic flow.

RDTS utilize flashing yellow arrow indicators to inform driveway users of the current direction of travel on the mainline, thereby reducing the risk of wrong-way entries. By providing clear, real-time directional guidance, RDTS enhance safety and operational efficiency within the TTC zone, particularly in areas with frequent driveway access points. Recent evaluations have shown positive benefits from the application, including one statistic citing a safe side-street traffic-movement rate of 93 percent.[5]

FHWA issued Interim Approval for the use of RDTS, authorizing specific signal indications to support safe driveway and side street operations within one-lane, two-way TTC zones. Approved signal indications include flashing and solid yellow arrows, as well as a circular red lens to denote a stop condition. These visual cues are critical for guiding vehicles entering the mainline from driveways or side streets.

[5] Iowa State University Institute for Transportation, "Research studies driveway assistance devices (DADs) as potential work zone option," news release, May 16, 2022, https://intrans.iastate.edu/news/research-studies-driveway-assistance-devices-dads-as-potential-work-zone-option/.

To reinforce proper turning behavior, RDTS installations must include regulatory signage such as:

NO TURN ON RED

TURN ONLY IN DIRECTION OF ARROW

These signs work in conjunction with the signal indications to prevent wrong-way entries and improve compliance with temporary traffic patterns.

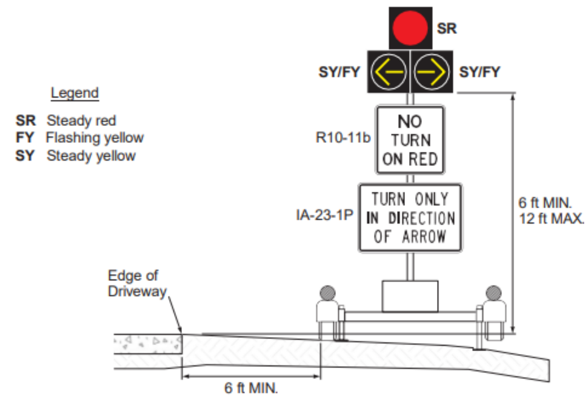

Figure 4. RDTS Device configuration (Image: FHWA)

RDTS units are trailer-mounted and feature a 360-degree rotating mast, allowing flexible orientation during deployment to accommodate varying site conditions. The system is designed for interconnectivity, enabling multiple RDTS units to operate in coordination with Portable Traffic Signals (PTS) located at each end of the work zone. This networked configuration ensures synchronized traffic control across the entire TTC zone.

Each RDTS is powered by an onboard battery system, supplemented by solar panels to extend operational duration and reduce maintenance needs. The device actively manages traffic from side streets and driveways by displaying either a STOP indication or a directional arrow, depending on the current flow of mainline traffic.

Per FHWA guidance, jurisdictions seeking to deploy RDTS must submit a written request to the Office of Transportation Operations. Additionally, a State Department of Transportation may request blanket Interim Approval on behalf of all jurisdictions within the state, streamlining the adoption process and promoting uniformity in work zone safety practices.

Strengths, Benefits, and Challenges to Using AFAD and PTS Technologies

In addition to several other strategies that can be used, both AFAD and PTS devices are components of a practitioner’s work zone safety and mobility toolbox. Each strategy must be used appropriately and in appropriate situations for maximum effectiveness.

Table 1 outlines some common types of TTC operations and their associated benefits.

Table 1. Types of Flagging Operations: Differences, Benefits, and Requirements

Example Strategy	Benefits, Uses, Challenges, and Requirements
Two flagger operation	• Allows monitoring of traffic delays and queues • Requires two individuals with potential exposure to traffic
Single flagger operation	• Flagger is positioned to be visible to road users approaching from both directions • Appropriate in low-volume, low-speed situations with adequate sight distance
Pilot car operation	• A pilot car leads traffic through a more complex work zone • Flaggers control both approaches to the work zone
Automated Flagger Assistance Device (AFAD)	• Designed for short- and intermediate-term activities • Allows the flagger(s) to stand in a safer position off the shoulder (requires trained flaggers) • May include red/yellow indicator lights or stop/slow indicator • Typically trailer-mounted devices or portable units with gate arms and manual control • Must be controlled remotely by an appropriately trained individual with unobstructed views of the AFAD and approaching traffic (in both directions for a single operator) • May include one or two flaggers – AFAD shall not be left unattended • Requires signing similar to traditional flagging operations and may be supplemented with additional traffic control devices
Portable Traffic Signal (PTS)	• Designed for short- to long-term work zones with one-lane, two-way tapers that remain in place while no workers are present • No need to position a flagger on the shoulder near the path of oncoming traffic • Requires signing similar to traditional flagging operations, although flaggers should not be used to control these devices. PTS use should be based on state/local municipality requirements for traffic signals, and authorization may be required in the jurisdiction.
Residential Driveway Temporary Signal (RDTS)	• Controls driveway traffic entering a one-lane, two-way TTC zone • Provides an indication of the direction of turn by communicating with PTS at each end of the work zone • Received FHWA Interim Approval in January 2025

Summary and Conclusions

The benefits of using AFAD and PTS devices are readily apparent. Table 2 summarizes these benefits based on the type of device used and typical situations.

Table 2. Summary AFAD and PTS Benefits and Applications

Type of Device	Typical Situations and Benefits
AFAD	Allows the flagger to stand in a safer position off the shoulder; applicable to short-term work zones where one or more flaggers are present
Pedestal-Mounted PTS	Smaller footprint where widths may be limited; removes the need for the flagger(s); allows flexibility in positioning devices in work zones on bridges or narrow shoulders where a flagger would not have a safe position on the bridge or an adequate escape route; common applications include maintenance and utility work, parking garages, and side roads
Trailer-Mounted PTS	Applicable to long-term work zones with one-lane, two-way tapers that remain in place while no workers are present; removes the need for the flagger(s); broad application including temporarily signalizing a two-or four-way stop-controlled intersection, use with bridge repair, emergency knockdowns, and haul roads
RDTS	Programmed to work in conjunction with the PTS at each end of the work zone; provides guidance to driveway traffic entering a one-lane, two-way constriction on which direction the vehicle platoon is traveling

Temporary traffic control for work zones and planned special events requires careful planning and consideration of innovative approaches to minimize impacts. The temporary traffic control approaches highlighted in this document provide work zone safety and mobility benefits when implemented by agencies, contractors, and private sector representatives. The American Traffic Safety Services Association is committed to improving work zone safety and reducing injuries and fatalities through outreach on innovative practices.

Resources for Practitioners

Caltrans Flagging Instruction Handbook, 2020. https://dot.ca.gov/-/media/dot-media/programs/construction/documents/construction-safety-and-insurance/safety-traffic/flagging-instruction-handbook.pdf

Flagger Force brochure, 2019. https://www.flaggerforce.com/newsletters/OnTheMove-newsletter_Feb-2019/inc/html/11.html?page=10

National Highway Traffic Safety Administration Press Release, 2020. https://www.nhtsa.gov/press-releases/2020-traffic-crash-data-fatalities

Tennessee Department of Transportation Work Zone Field Manual, 2019. https://www.tn.gov/content/dam/tn/tdot/traffic-engineering/Work%20Zone%20Field%20Manual%20-%20Final%204-29-2019.pdf

Virginia Department of Transportation Work Area Protection Manual Revision 2.1. http://www.vdot.virginia.gov/business/resources/traffic_engineering/workzone/wapm/2011_WAPM_REV_2_1.pdf

Wisconsin Department of Transportation Work Zone Field Manual, 2021. https://wisconsindot.gov/dtsdManuals/traffic-ops/manuals-and-standards/wzfm/wzfm.pdf

Work Zone Safety Information Clearinghouse. http://www.workzonesafety.org/work-zone-data/ https://workzonesafety.org/work-zone-devices/

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
VOLUME 3, ISSUE 1 | DECEMBER 2025

PAPER 013

CASE STUDY

CASE STUDY

Conversion of Solar-Powered Rectangular Rapid Flash Beacon (RRFB) to a Solar-Powered HAWK Signal or Pedestrian Hybrid Beacon (PHB)

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Sergeant Tadeo, Town of Sahuarita, Police Department

Case Study Background

In April 2024, a meeting was held with the town of Sahuarita, Arizona concerning pedestrian crossing safety at a marked crossing with an (RRFB) Rectangular Rapid Flash Beacon on a four-lane divided street. The meeting was attended by the town's public works operations manager and signal technician personnel along with the traffic enforcement sergeant.

Sahuarita is a town in Pima County, Arizona, United States. Sahuarita is located south of the Tohono O'odham Indian Nation and abuts the north end of Green Valley, 15 miles south of Tucson. The 2022 population estimate was 35,638. Sahuarita is one of Arizona's fastest-growing communities and is located roughly 20 minutes south of Central Tucson on Interstate 19 and was incorporated in 1994.

S. Rancho Sahuarita Blvd and S. Avenida Mitla is today an intersection with a marked RRFB pedestrian crossing on the northeast side that originally had low AADT and pedestrian crossing activity. However, the area is growing significantly with the addition of Parque del Rio/Safari Park, expanded housing, business and schools serving the area. The roadway is posted at 30 mph with a properly designed horizontal and vertical curve however, which leaves little leeway for crossing pedestrians to be seen by approaching drivers in order to stop, especially if they are traveling above the posted 30mph speed limit. The crosswalk is also used as a school bus loading/stopping point in the morning and afternoon and parents wait for the children on the side streets for the bus to arrive.

The town had installed an RRFB flashing yellow crossing warning system a number of years ago to assist pedestrians in crossing the roadway, as well as an advance RRFB warning beacon. The YELLOW beacons have been working only just at a satisfactory level up to the present day in attempting to get drivers to yield to the crossing pedestrians. The town officials reported receiving several citizen complaints recently expressing their concerns regarding drivers frequently failing to stop for crossing pedestrians, especially under the current higher traffic volumes, and increased crossing demands.

Comments from city staff:

"… residents have told me that they will not use this crossing because of perceived safety issues." *City of Sahuarita, Operations Division Manager*

Fortunately, there have been minimal (3) motor vehicle crashes and no pedestrian crashes over the last five years, the majority being run off the road type crashes due to high speed and or drivers under the influence, most likely. However, the town examined the intersection for the need for a full traffic signal at the public's request. The warrant study noted the traffic, and pedestrian conditions were nowhere near the national and state warranting levels. Further, the warrant studies noted a full signal could be expected to increase crashes such as angle, rear-end and/or side-swipe type crashes, rather than improve the total safety performance at the intersection.

The citizen concerns and the observation of conflicts along with the ADOT pedestrian crossing countermeasures guidance has led to the consideration of upgrading the RRFB pedestrian crossing to a HAWK beacon type operation. A HAWK crossing device provides drivers with a significant indication of a requirement to stop for the crossing pedestrian with a RED stop light indication, rather than the existing flashing YELLOW warning light indication. The citizens seemed to have felt the RED meant STOP, while the flashing YELLOW does not.

Since the traffic conditions have changed significantly, the town had desired to consider an alternative crossing device called a (PHB) Pedestrian Crossing Hybrid Beacon or HAWK and still use the existing RRFB equipment as much as possible. The town reviewed the concept of using a solar powered HAWK operation to replace the solar powered RRFB operation.

The study found that the two traffic control devices are technically interchangeable on identical foundations and poles. New solar and signal LED technology helped make the conversion possible. In addition, the HAWK RED lights increased the driver's yielding to the crossing pedestrians with minimal increase in operational and installation costs when compared to a traditional commercially powered PHB traffic control device. Further the LED pedestrian signal gave a positive indication to the pedestrians when to cross.

Observations

The intersection was viewed by both Gabe Thum, PAG Transportation Safety Program Manager and Richard Nassi, PAG Consulting Services, the morning and afternoon of April 16, 2024, and again on September 14, 2024, two weeks after the HAWK beacon was installed. The initial and matching after-viewing times were selected by the town since it was felt that that time would provide the heaviest traffic and pedestrian movements on S. Rancho Sahuarita and S. Avenida Mitla. In addition, the intersection was videoed for two weeks before a after the traffic control modifications.

Crosswalk and Driver Observations with RRFB: See Appendix Pictures B1-6 Intersection Observations.

As previously mentioned, the town installed a video camera to study and record the driver and pedestrian behaviors before and after at the crossing with an RRFB, Rectangular Rapid Flash Beacon, YELLOW light and then the HAWK RED light operation.

The "before" videos generally showed a large variation in the yielding behavior of the drivers. Of particular significance and concern with the RRFB showed young children attempting to cross, then running to clear the crosswalk to get away from a very hard breaking vehicle trying to stop.

The reviewers noted that RRFB traffic control devices were:

a) Properly designed, well timed and maintained
b) Signs and Markings were well maintained and visible
c) An advance RRFB warning flasher with the crosswalk warning sign was properly placed and was activated when the RRFB units were in operation

d) Roadway Lighting is present, seems adequate (owned by another authority), see Appendix Photos C6, 7
e) Traffic conditions have changed significantly since the installation of the RRFB constituting the need for other higher level traffic control devices to be considered
f) Speed limit signs are installed at frequent intervals and visible. However, drivers were still observed traveling above the posted 30 mph speed limit, though not to a level that would meet enforcement policy/court levels, but could be to a level that may begin to reach the upper limit of the horizontal and vertical curve design levels

Pedestrian Observations with RRFB

a) Pedestrians crossing at the intersection activated the RRFB flashers consistently during observations times and crossed in the crosswalk area
b) There were no violations by the pedestrians noted during the review times
c) Several observations were made of the drivers stopping very late to avoid multiple -threat type conflicts with crossing pedestrians: there were some observations of pedestrians turning back or running to avoid conflicts with vehicles

Driver Observations after Conversion to a HAWK Beacon: See Appendix C-1 through C7

The HAWK beacon was installed on the existing poles that once supported the RRFB units. The review noted that the new TCD was:

a) Properly designed and installed
b) Signs and marking were present and very visible
c) The advance RRFB warning flasher with the crosswalk warning sign was still in position and was still activated when the HAWK units were in operation
d) Roadway lighting was still present
e) The HAWK beacon was operated with a "HOT" button operation giving an immediate response to the pedestrian call and was well obeyed by the pedestrians.

The Federal Highway Administration (FHWA) notes the prime objective of a HAWK is to provide pedestrians with safer crossing opportunities using a RED signal. As such, a reduction in pedestrian crash risk would be expected to be associated with the HAWK, since a statistically significant reduction in pedestrian crashes was found in nationwide studies, even better than traditional traffic signals. The installation of the HAWK was also found to be associated with a statistically significant reduction in total crashes. The driver's behavior at this location matched the national study's findings.

The before-after evaluation by FHWA was as follows:

- 29 percent reduction in total crashes
- 69 percent reduction in pedestrian crashes
- There was a 15 percent reduction in severe crashes

https://www.fhwa.dot.gov/publications/research/safety/10045/

The "after" HAWK videos show the orderly and consistent stopping for the crossing children with no multiple-threat type conflict behavior recorded.

Application in town of Sahuarita, AZ

ADOT has developed an interactive guide to assist agencies in selecting the most appropriate pedestrian crossing assistance measures given the condition at a particular location. In this case, given the past and current conditions, the ADOT recommendation would historically support the RRFB and now the HAWK beacon. The current levels of AADT (greater than 15,000) and considering the actual speed (not the posted speed) of 35mph, the guidelines no longer recommend the RRFB for consideration but recommend **only** the HAWK installation which the town had taken steps to install.

https://azdot.gov/business/tsmo/operational-and-traffic-safety/az-step/four-lanes-with-raised-median

Recommendations for Conversion to HAWK Crossing Beacon

- Attached are the Pima County/ City of Tucson Guidelines, Appendix Figure A,
- The drivers approaching the new HAWK beacon were observed to be stopping properly without signs at the new stop bars. Appendix Photo D. (If the town considers R1-5b STOP HERE FOR PEDESTRIANS (Symbolic) on both the median and side of the road due to the horizontal and vertical elements of the road, it is critical to ensure the placement of the signs do not block the view of the curb side HAWK beacons as a vehicle approaches in the curb lane.)
- Consider lengthening the solid white wide lane lines to the longer distances
- Consideration may be given to modifying the existing advance activated flasher to normal round signal heads to further improve visibility, if necessary, in follow-up reviews
- Legally close the southern unmarked crosswalk area and guide all pedestrians to the HAWK.
- If the roadway remains at two lanes in each direction, mast arms may be considered for beacon(s) over the roadway. Observations of the driver's response indicate the side mount units are quite adequate.

  MUTCD 4J.02 Design of Pedestrian Hybrid Beacons
  "On multi-lane approaches having posted or statutory speed limits or 85th-percentile speeds of 35 mph or less, either a pedestrian hybrid beacon face should be installed on each side of the approach (if a median of sufficient width exists) or at least one of the pedestrian hybrid beacon faces should be installed over the roadway."

Solar HAWK Installation Notes

A solar HAWK installation is a very unique concept and the Tempe, Arizona manufacturer of solar traffic control equipment that installed the RRFB years earlier was contacted to design and install the solar HAWK conversion equipment. PHB or HAWK installations are generally considered to be significantly more expensive (frequently in the $150,000+ range) than the traditional RRFB flasher units. However, the town chose a technique of using a solar powered HAWK operation that directly fits on the exact same foundation and support equipment as the current RRBF installation.

Comparative Safety Benefits

Driver Yielding Rate: FHWA comparison studies of flashing beacon done by Texas A & M University, Texas Transportation Institute, for FHWA, have shown that the existing yellow flashers (RRFB) only have an average of a **57% driver yielding rate, with an extremely large variation in driver compliance**, some yielding rates as low as in the teens. Further, RRFBs do not provide a pedestrian signal indication when they are in operation and this particular crossing is a school bus stop. In comparison, the HAWK beacons have a consistent average always in the **97% driver yielding rate with minimal variation** and are frequently at higher yielding levels on higher speed streets. Further, the HAWK beacon provides pedestrian signaling thus, providing the pedestrian with a clear indication of when to cross in greater potential safety, which is an MUTCD for consideration for school signaling crossings.

***Cost Conversion Comparison*:** The town provided the comparison costs of the two systems in current-day 2024 dollars. The additional initial cost for the upgraded HAWK crossing compared to an RRFB crossing was only **$13,712** more using the new technology on existing support equipment.

The initial cost for the RRFB was calculated to be $15,558 in 2024 dollars, excluding the existing poles and foundations. The additional cost for the upgrade to a HAWK beacon operation was only $13,712 in 2024 dollars. The manufactured has a controller, called "Micro-HAWK" made specifically for HAWK operations, not requiring a more expensive controller that is mainly designed to operate a normal traffic signal. The HAWK controller has the standard controller type fail-safe type monitor so the WALK indication would not be displayed unless the RED units were illuminated and a fail-safe system that would place the unit into the flashing YELLOW mode if there was a problem with the equipment as the MUTCD requires. Further, the manufacturer has available alerting equipment that could be installed in the solar equipment, if the client desired, to place a call to the traffic operations group alerting the technician to an equipment failure.

More important than the cost of the installation is the fact that drivers' yielding rate has now increased from a large variation range averaging only 57% to a consistent average of 97%, thus providing a significant increase in potential pedestrian safety for only a slight increase in equipment cost. A recent article in Florida Today, February 28, 2020, questioned whether *Flashing Yellow Crosswalks give a False Sense of Security* especially to children.

Flashing yellow crosswalks give a false sense of security; why are we still using them? | Rangel

Isadora Rangel
Florida Today

Published 10:08 a.m. ET Feb. 28, 2020

Sophia Nelson did what she was instructed to do: She activated the flashing yellow light on SR A1A in what was supposed to be a command for drivers to stop and let pedestrians cross. She waited for cars to pass and stepped into the crosswalk in Satellite Beach.

The 83-year-old driver in this incident didn't stop. And I have a feeling she's not the first and won't be the last one to fail to do so at these confusing flashing-beacon crosswalks. For many drivers, including yours truly, a flashing yellow means "slow down" — not "come to a full stop."

BEFORE: RRFB Crossing installation (cost $15,558 in 2024 dollars) excluding poles and foundations

AFTER: Conversion to a HAWK Crossing (cost $29,270 in 2024 dollars) using existing poles and foundations from original RRFB installation

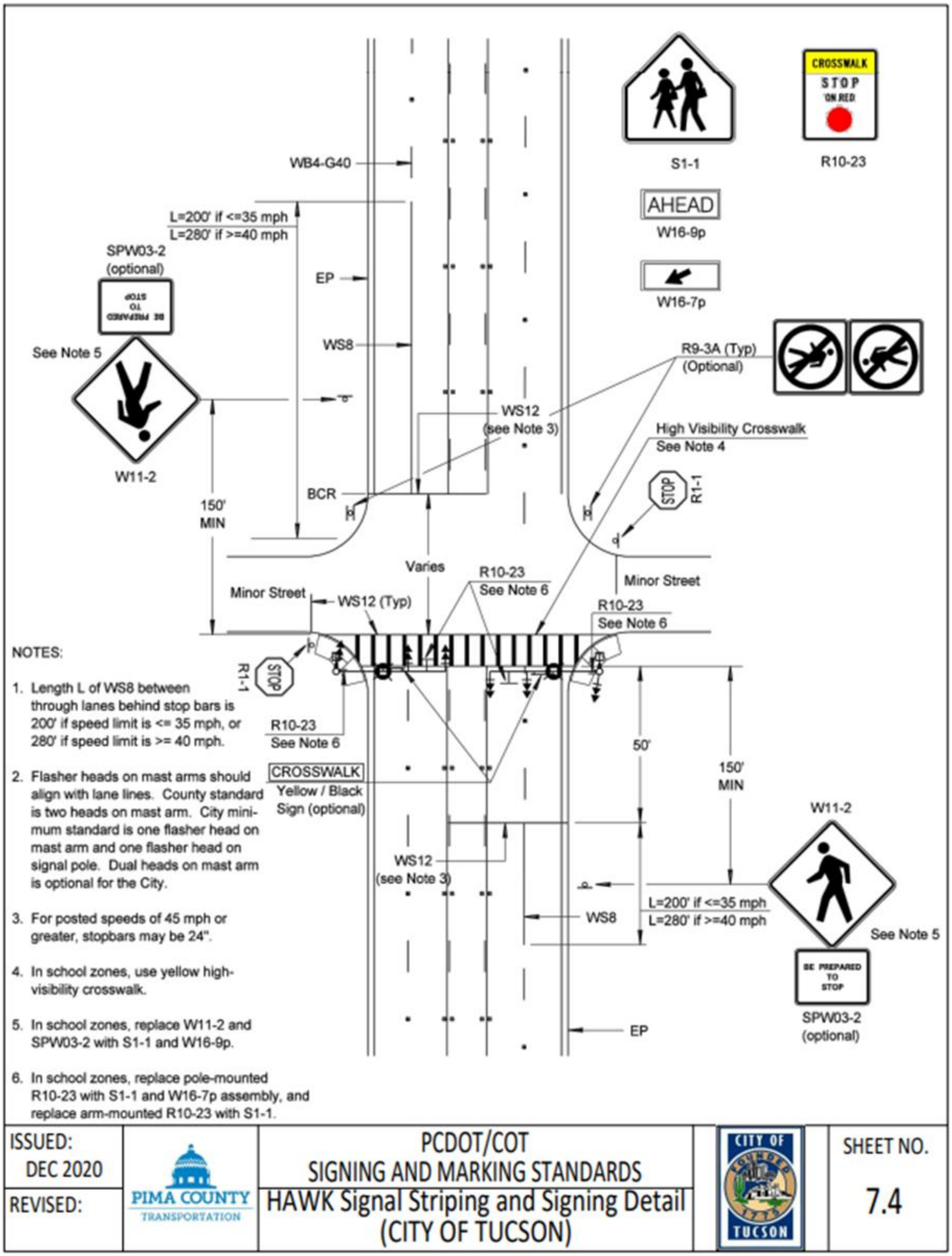
SUMMARY

The town not only improved the safety at this crosswalk, but also at another school crosswalk in the town on a narrow street with lower speeds by relocating the RRFB equipment (onto new supports) which was more suitable for that particular location and traffic conditions. This project provided a total gain in crosswalk safely townwide. This traffic control change was done more efficiently than typical installations due to utilizing a solar-powered operation as opposed to a traditional utility installation.

The town's selection of a solar crosswalk traffic control system allows the traffic control devices to be independent of the power grid and associated electrical power boxes, meters, conduits or blackouts which can become a problem during the sever desert summer storms. The children's safety continues even when the power goes out.

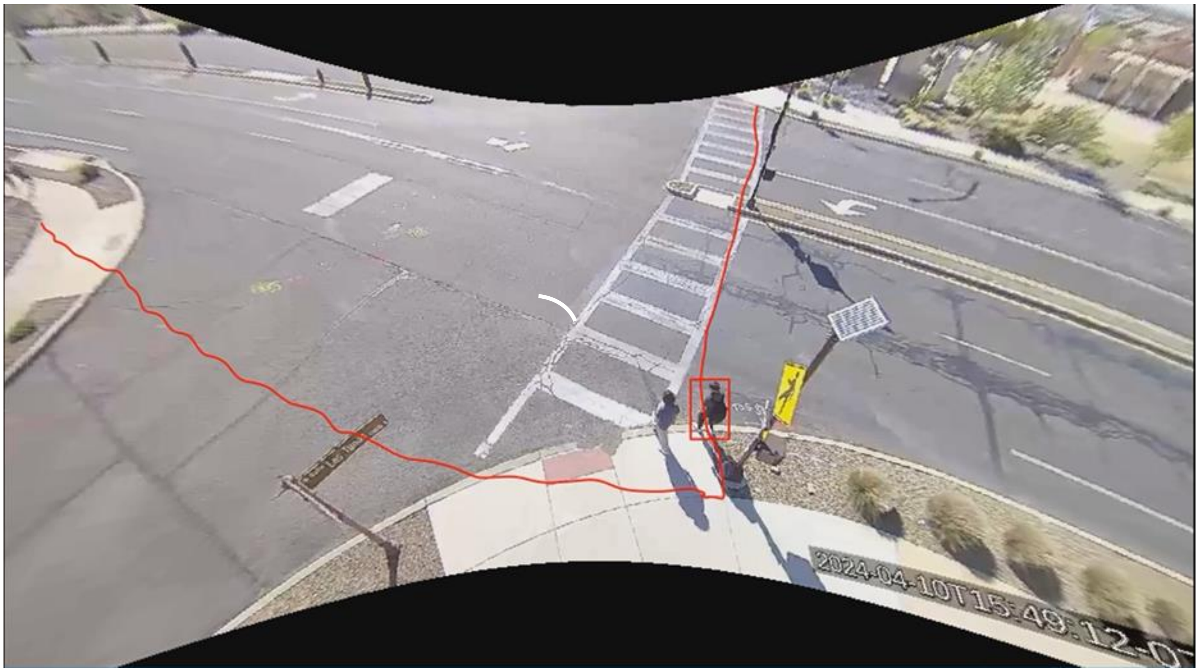
Another saving factor is that there can be less maintenance because modern electronics, batteries and LED technology are becoming highly reliable, and a properly designed system will run by itself for years. There are a few items that need to be checked periodically. You will need to check the batteries every three to five years and check the height of trees around the site for as they grow, they could impair a system's full functioning by casting shade on the solar module(s). Basically, routine tree and sign/signal maintenance is like what the town needs to do with any other traditional traffic sign and signal installation to ensure the (TCD) traffic control device is not blocked by vegetation.

APPENDIX

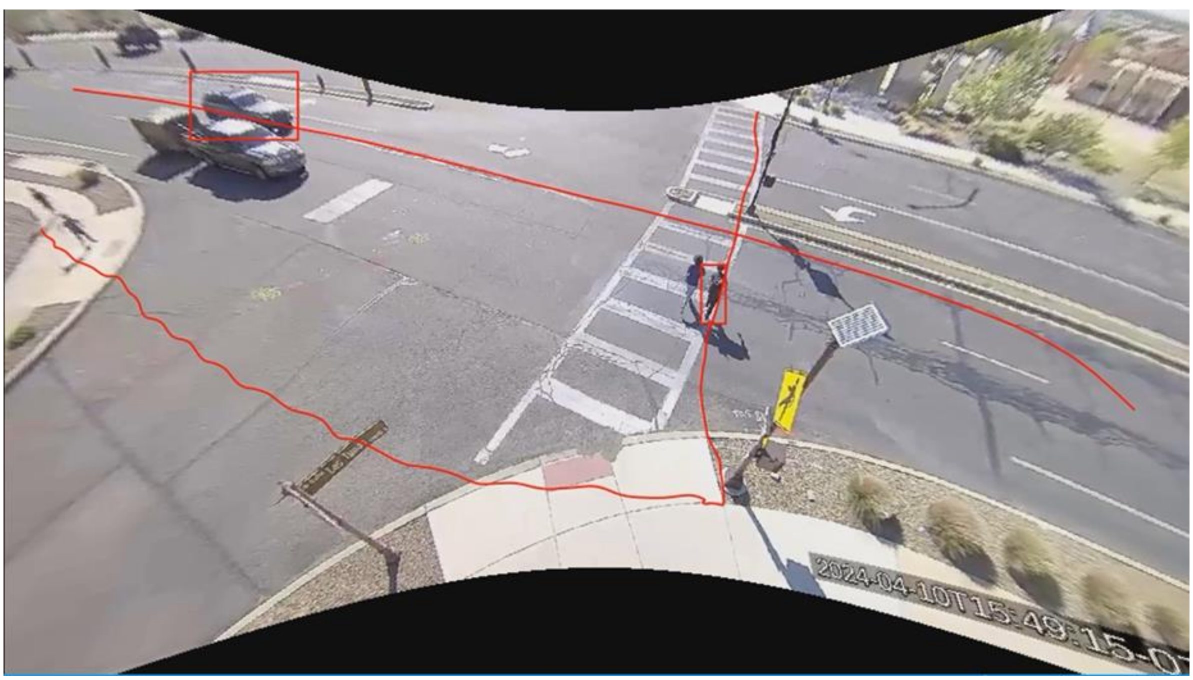

S1-1
CROSSWALK
STOP
ON RED
R10-23
AHEAD
W16-9p
W16-7p
WB4-G40
L=200' if <=35 mph
L=280' if >=40 mph
SPW03-2
(optional)
BE PREPARED TO STOP
EP
WS8
See Note 5
R9-3A (Typ)
(Optional)
WS12
(see Note 3)
High Visibility Crosswalk
See Note 4
W11-2
BCR
150'
MIN
STOP
R1-1
Varies
R10-23
See Note 6
Minor Street
WS12 (Typ)
Minor Street
R10-23
See Note 6
NOTES:
1. Length L of WS8 between through lanes behind stop bars is 200' if speed limit is <= 35 mph, or 280' if speed limit is >= 40 mph.
2. Flasher heads on mast arms should align with lane lines. County standard is two heads on mast arm. City minimum standard is one flasher head on mast arm and one flasher head on signal pole. Dual heads on mast arm is optional for the City.
3. For posted speeds of 45 mph or greater, stopbars may be 24".
4. In school zones, use yellow high-visibility crosswalk.
5. In school zones, replace W11-2 and SPW03-2 with S1-1 and W16-9p.
6. In school zones, replace pole-mounted R10-23 with S1-1 and W16-7p assembly, and replace arm-mounted R10-23 with S1-1.
R10-23
See Note 6
CROSSWALK
Yellow / Black
Sign (optional)
50'
150'
MIN
W11-2
WS12
(see Note 3)
WS8
L=200' if <=35 mph
L=280' if >=40 mph
See Note 5
BE PREPARED TO STOP
SPW03-2
(optional)
EP
ISSUED:
DEC 2020
REVISED:
PIMA COUNTY
TRANSPORTATION
PCDOT/COT
SIGNING AND MARKING STANDARDS
HAWK Signal Striping and Signing Detail
(CITY OF TUCSON)
CITY OF
TUCSON
SHEET NO.
7.4

Appendix Figure A: Notes 2,4,5,6 are not applicable. Lighting is under the responsibility of another agency other than the town

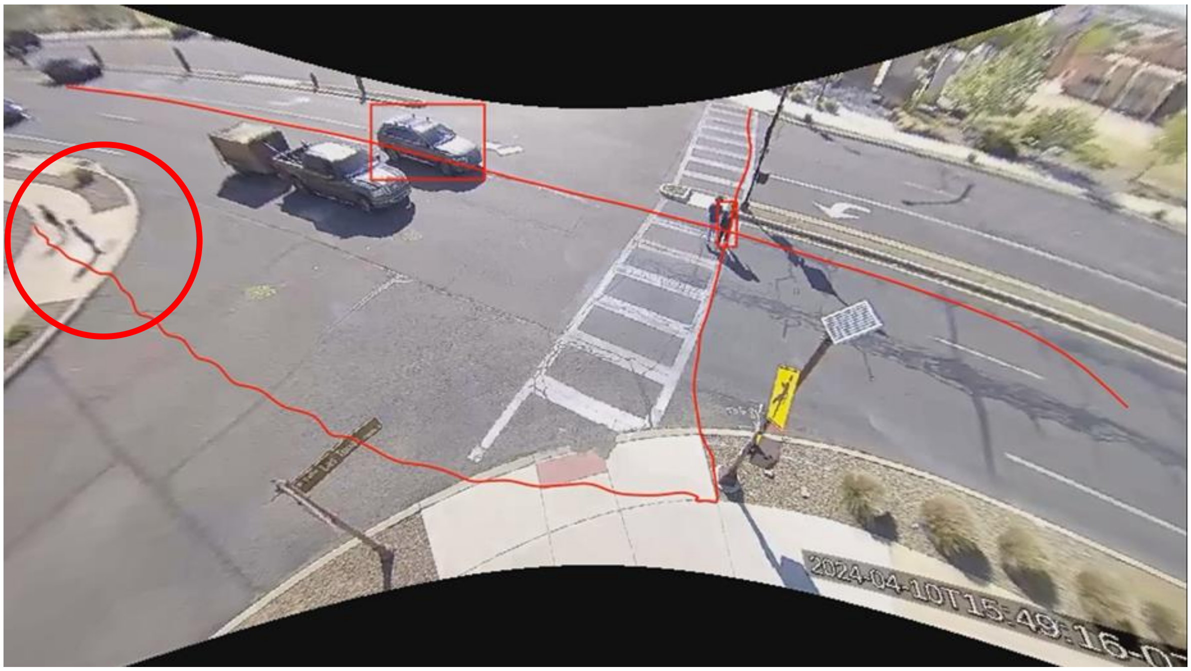
Appendix B: BEFORE Study with RRFB Crossing YELLOW Flasher



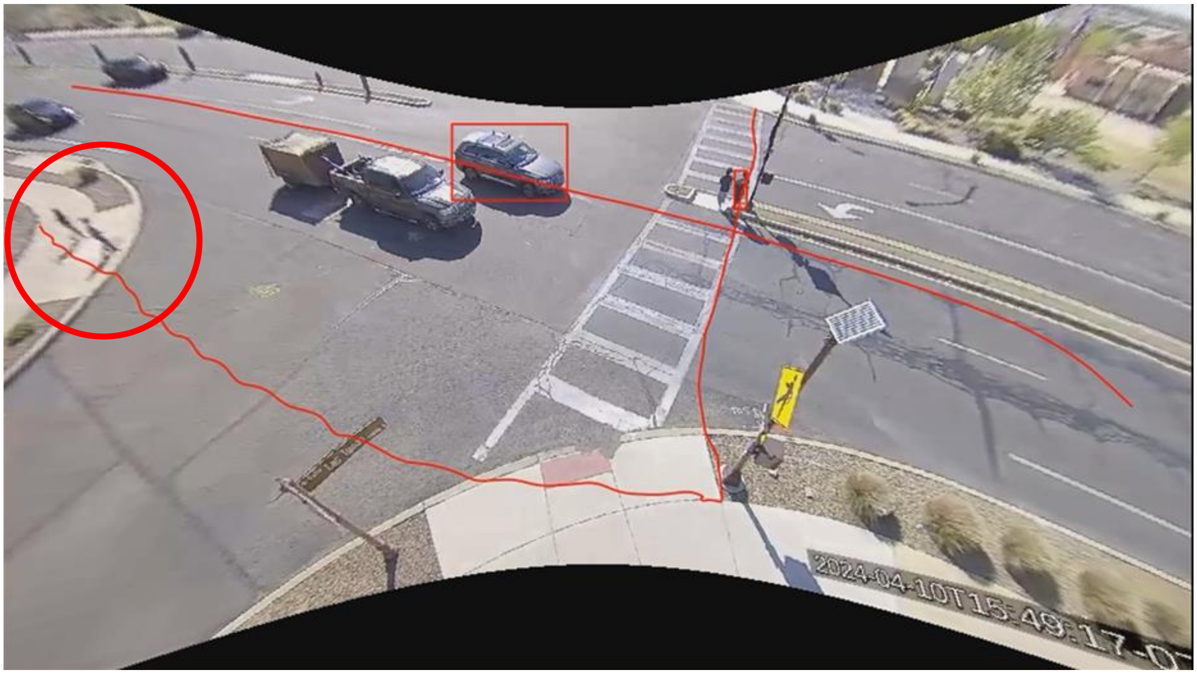
Appendix Photo B1: Children activate YELLOW flashers



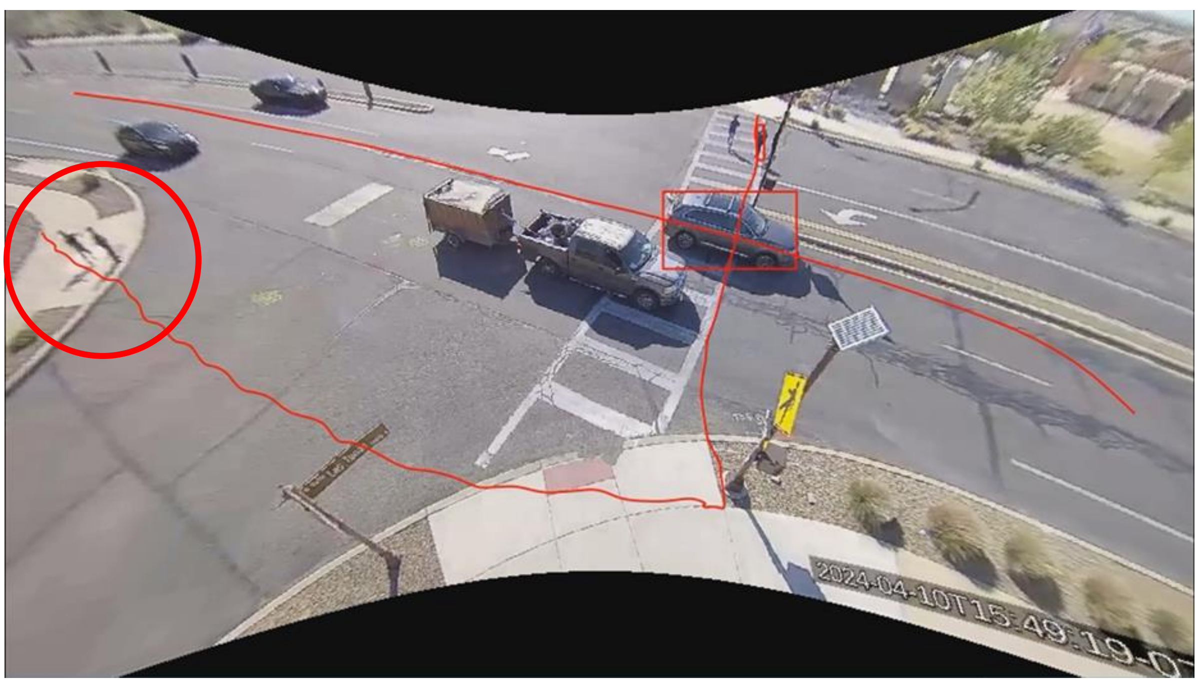
Appendix Photo B2: Children begin crossing. The curb lane driver sees and yields to children on the crosswalk. The median driver seems to fail to see the crossing children and proceeds to pass the yielding vehicle illegally and then begins hard braking so as to not strike the children.



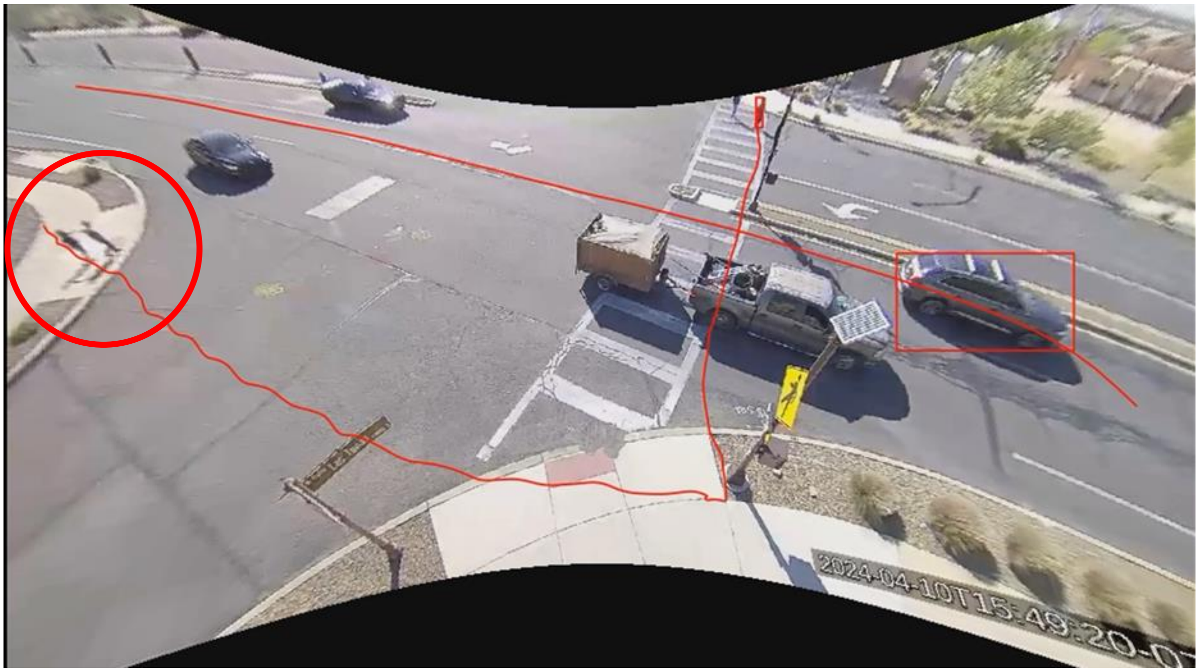
Appendix Photo B3: Median driver sees children and attempts to stop immediately. Children run to the median to get out of the street and to a point of greater safety. Notice the children in the southeast corner seeing and most likely hearing the traffic commotion and looking toward the vehicles



Appendix Photo B4: Crossing children leave island and run across the other half of the crossing to get away. The median lane driver is still trying to stop. Children on the southeast corner, realizing the danger, react to the situation and one friend begins to pull the other back from the curb.

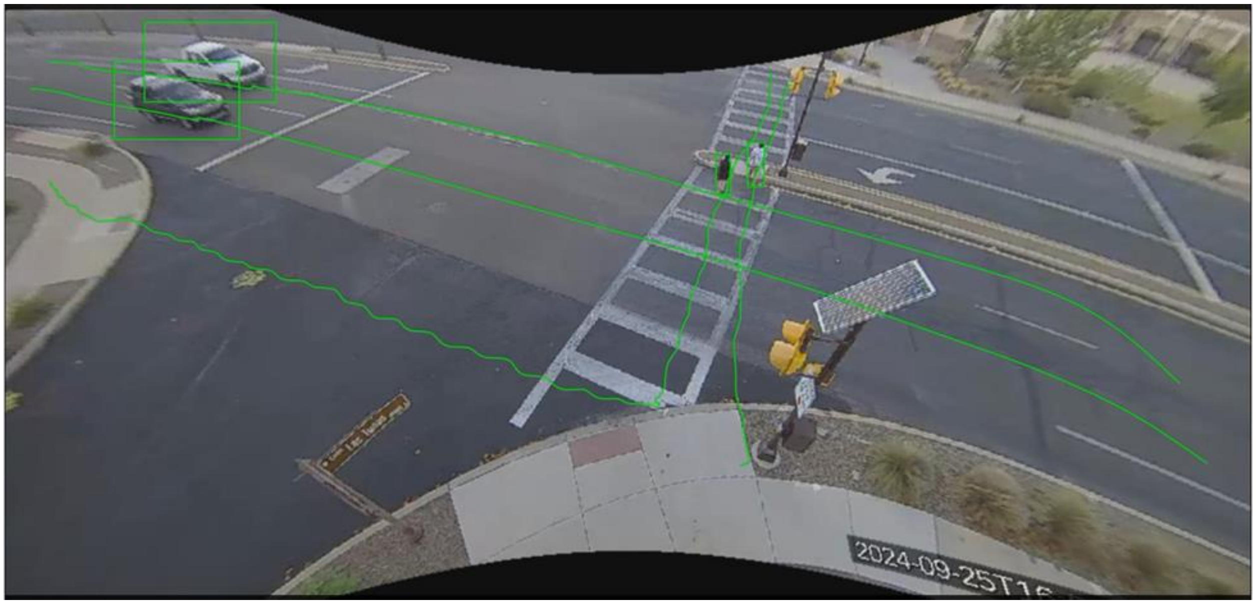


Appendix Photo B5: Crossing children run to the far curb to safety. The median driver is not able to come to a complete stop and passes through the crosswalk. The concerned child friend on the southeast curb was still holding on to his friend pulling him back from traffic.

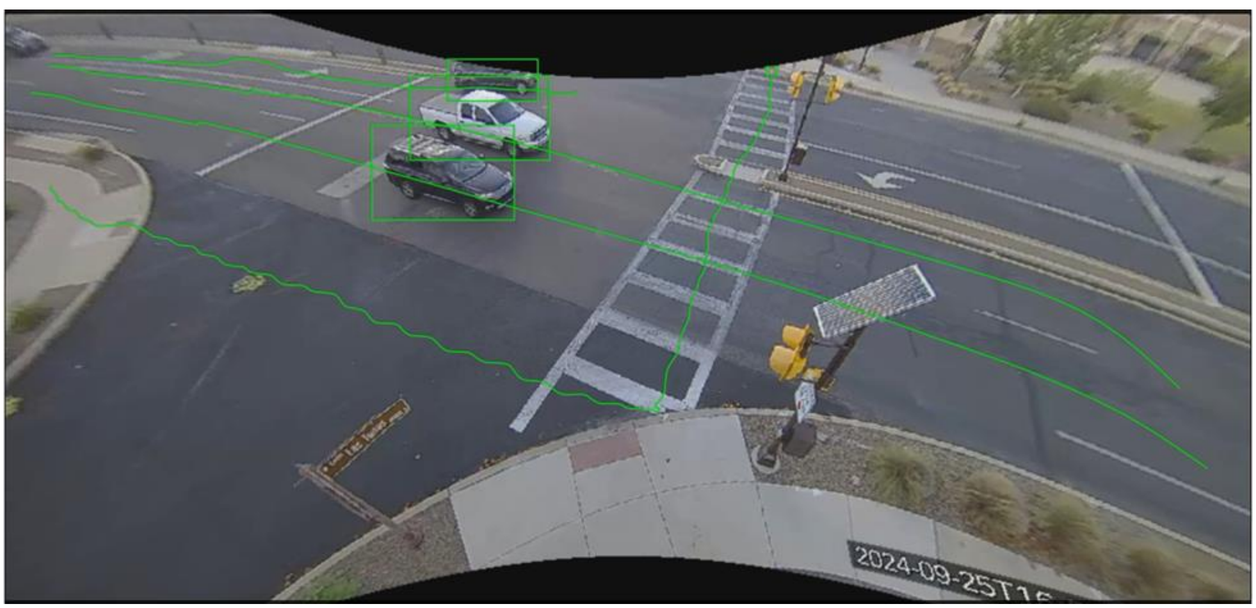


Appendix Photo B6: The median driver never fully stops. Crossing children are now completely safe on the far side of the street. The traffic is moving through or past the crosswalk and the friend is still holding onto the other's shirt still continuing to pull him back from the street

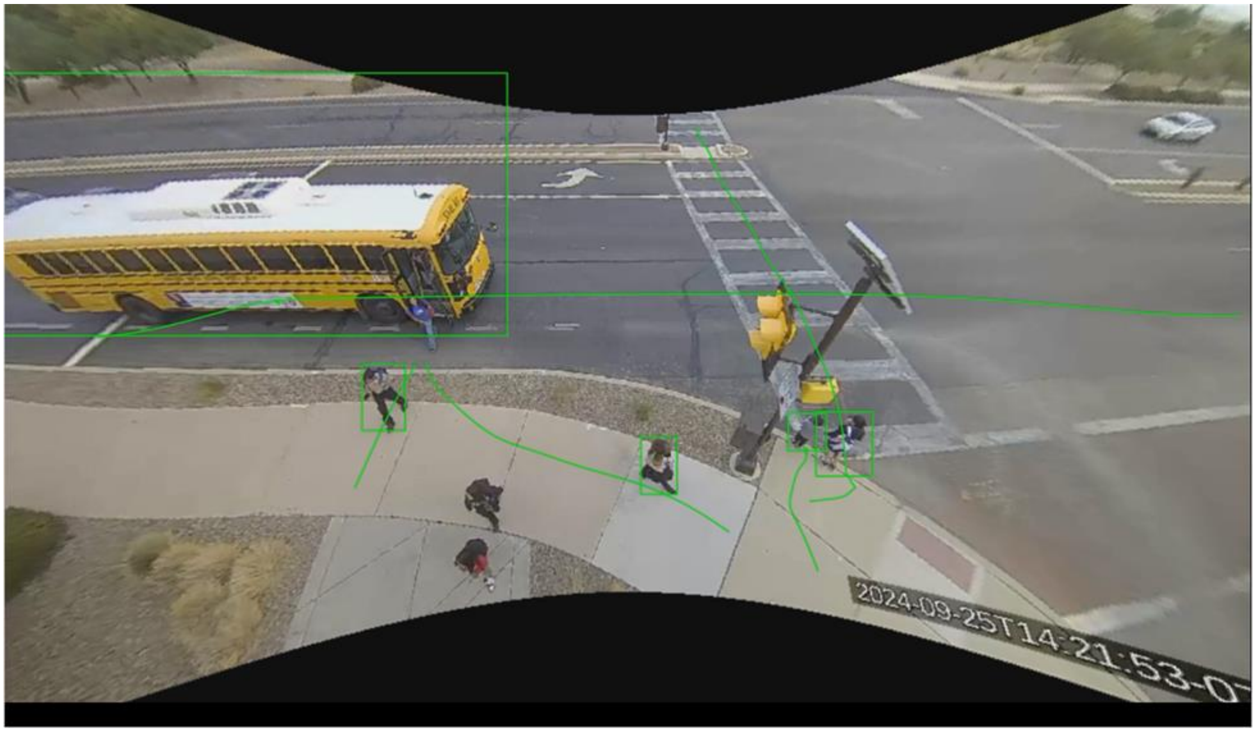
APPENDIX C: AFTER STUDY with HAWK Crossing



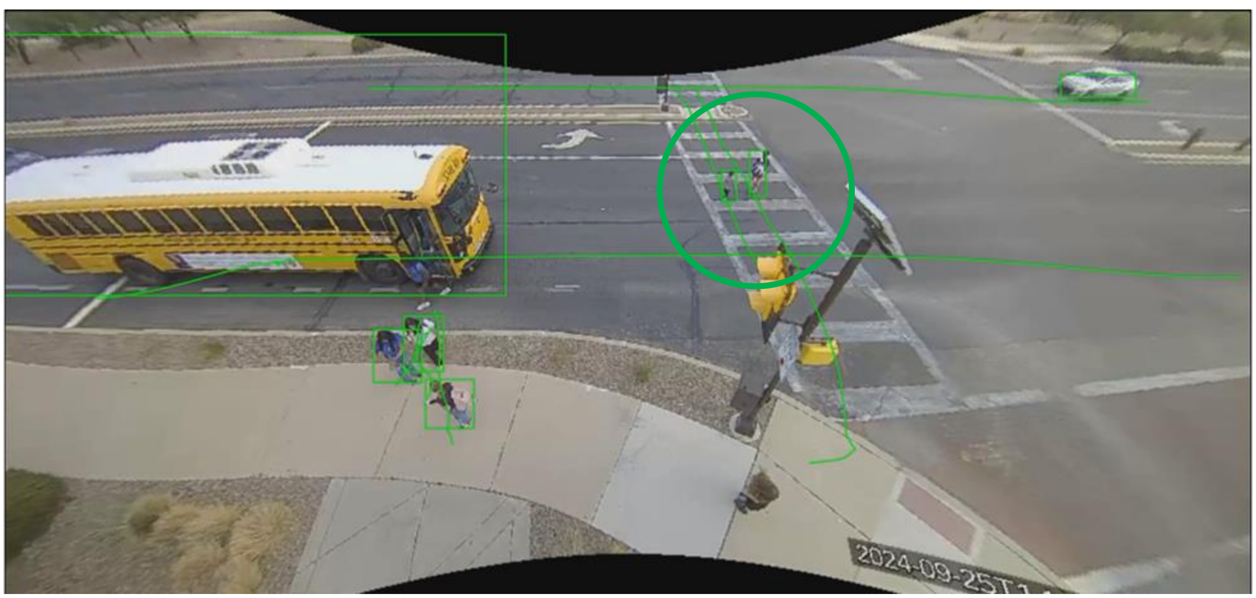
Appendix Photo C1: Both drivers are shown a HAWK Beacon solid RED indication and stop properly at the stop bar, allowing the children to cross in relative safely. This positive driver behavior is quite evident when compared to the RRFB Appendix yield B1 through 5 which shows a failure to yield to the crossing children and the driver in the median lane shows the most reluctant yielding and dangerous conflict behavior.



Appendix Photo C2: The children have now completed their crossing, and the drivers now are proceeding through the crosswalk during the flashing RED indication when it is safe to proceed. Further it is critical to note that there were no conflicts, or “close calls” noted during the video study.

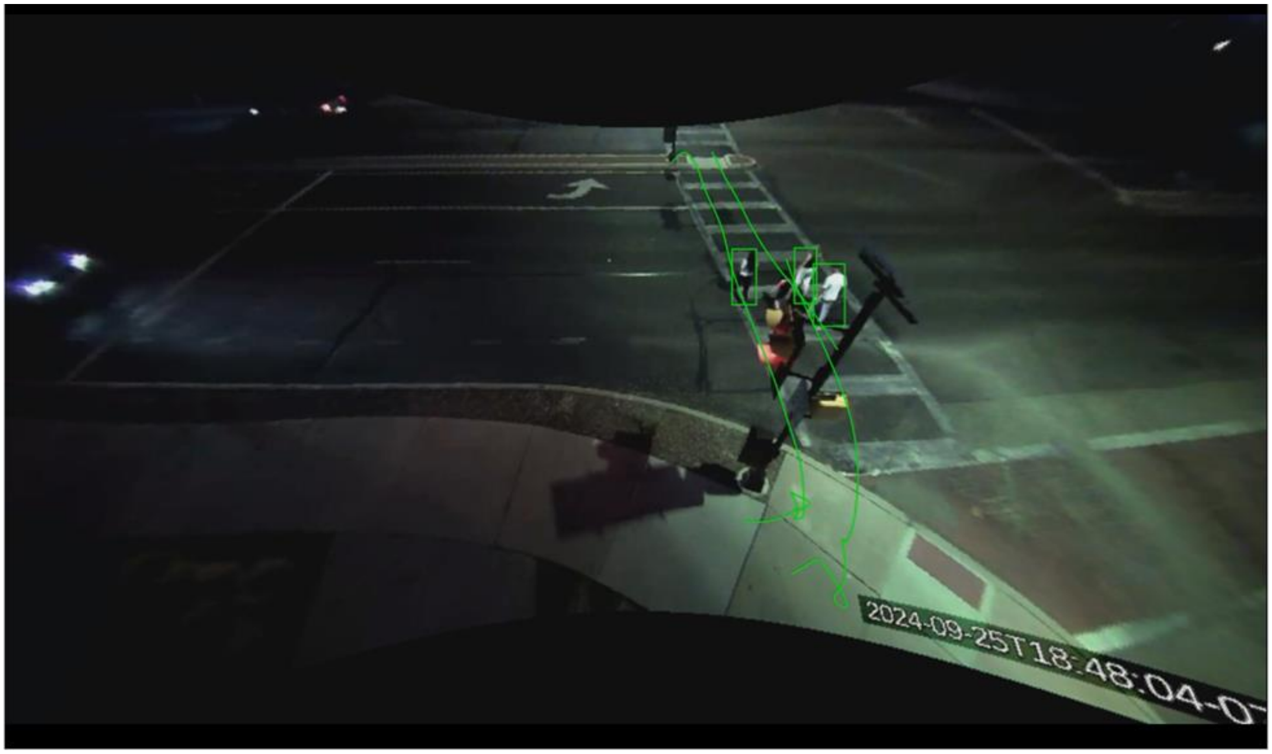


Appendix Photo C3: School Bus operations are greatly facilitated with the new HAWK crossing operation over the RRFB. The children alight/disembark and cross the street to or from their homes in greater security. The school bus lights are RED as well as the HAWK's RED lights, <u>but</u> as the children cross with the flashing RED lights on the school bus they do not provide protection while crossing the other half of the divided roadway. Since the roadway is divided, only the HAWK crossing beacon protects the crossing children all the way across the road. As can be seen in photos C4 and C5



Appendix Photo C4: The school bus lights are on. The west to south traffic stops at the back of the bus. However, since the road is divided, the north to east traffic is not required to stop for the bus's RED flasher. (see the white vehicle still waiting for the crossing children).

Appendix Photo C5: As the children prepare to cross the second half of the roadway, they are further protected by the HAWK RED beacon as they prepare to cross the second half of the street, since the state school bus law does not require a stop for the school bus RED lights on a divided highway under this condition. (note the white vehicle is still waiting)



Appendix Photo C6: Drivers wait at the stop bars during the RED indication. Lighting is adequate

Appendix Photo C7: Drivers pass through the crossing during the FLASHING RED indication after the crossing family has moved to a position not in conflict with the vehicle(s).

Appendix Photo D: Drivers wait at the proper location without the need for signing


TO MONTOUR FALLS
WEST
224
YOU ARE HERE
– 7%
– 3%
2.3 MILES
CHECK YOUR BRAKES

ABOUT THE IMAGERY

Full-page imagery exhibited apart from the research papers in this publication is intended to highlight useful, innovative, unusual, unique, archaic, or even nostalgic traffic control devices. A description of the images in this edition is provided below.

> *Contrasting approaches to markings highlight the value of delineation devices in a world where costs constrain maintenance cycles.*
>
> *A new system interchange taking shape in Fife, Washington State, appears to provide a crash course in value engineering and network topology even before a single traffic control device is installed.*
>
> *A sequence of compact roundabouts on Via Linda in Scottsdale, Arizona, virtually eliminates delay while encouraging the free-flow of calmed traffic.*
>
> *Members of an NCUTCD sponsoring organization were sent to the doghouse at the FDOT Regional Transportation Management Center in Sanford, Florida, home of a signal equipment testing facility.*
>
> *You've probably never seen a transit bus crosswalk before.*
>
> *Volcanic activity near the Blue Lagoon in Iceland has reshaped the road network, leading to long-term temporary signing of link closures.*
>
> *Variations in visor size recall a bygone era for many agencies, with these trust traffic signal heads in Phoenix, Arizona, serving up displays in the sun.*
>
> *Heavy vehicles navigate numerous short and steep grades in the hills of western New York, typical of Appalachian topography.*
>
> *Up ahead, a[n] RR crossing of sorts.*

All photos outside of the research papers in this edition are courtesy of Scott O. Kuznicki, from a personal collection of 1.6 million photos and videos spanning 25 years of travel in countries around the globe. Visit transportationpixels.com to learn more about how this collection and others like it will be launched in an crowd-sourced format featuring billions of photographs, for the benefit of practitioners and researchers.

Photograph submissions for future issues of the Journal may be made directly to the editors or by addressing @scottokuznicki on social media.

THE

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH

IS A PUBLICATION OF THE

National Committee on
Uniform Traffic Control Devices

13236 N. 7th St., Suite 4-259
Phoenix, AZ 85022

www.ncutcd.org

J T C D R

PUBLISHED BY

The National Committee on Uniform Traffic Control Devices