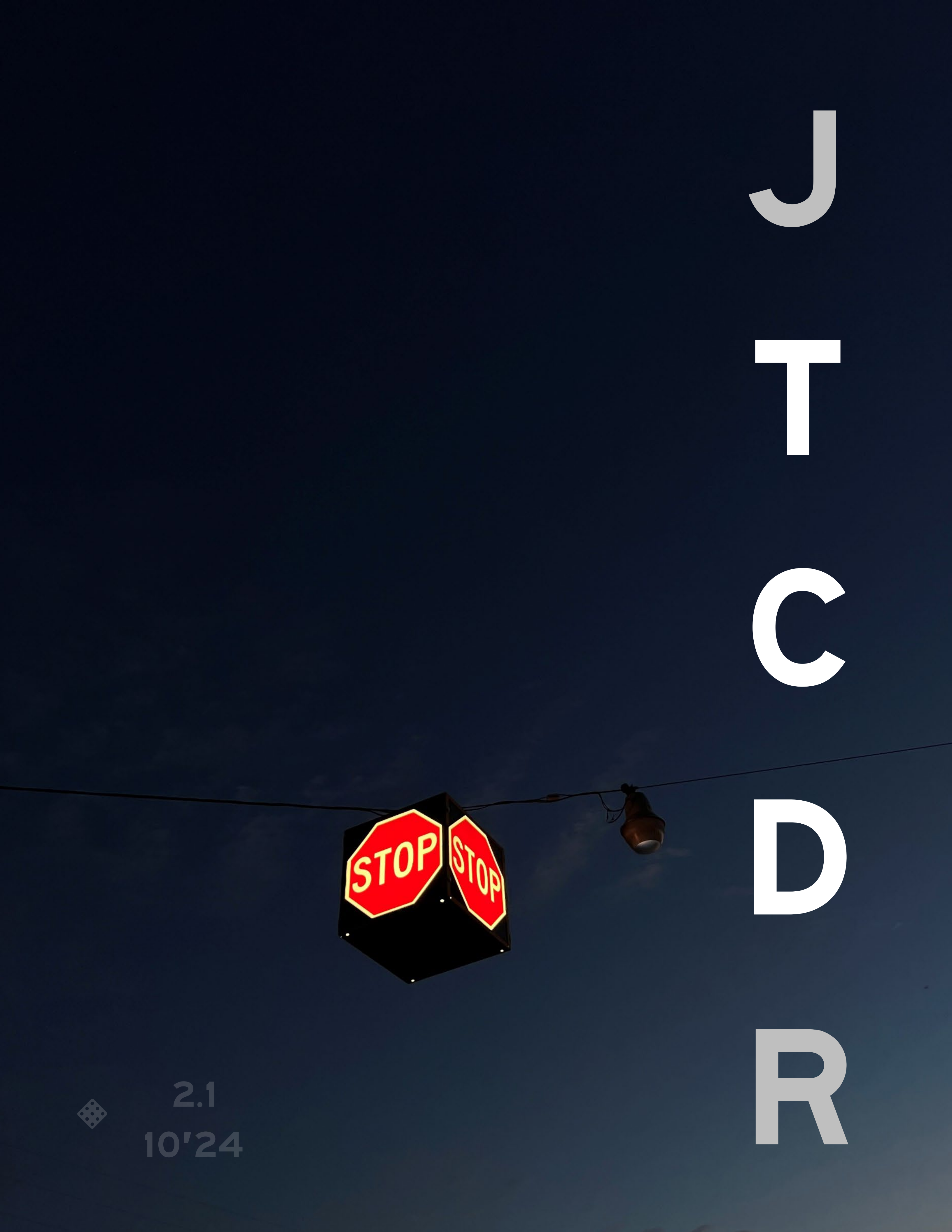

JTCDR

2.1

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ON THE COVER

Illuminated overhead signs at this intersection in Saginaw Township, Michigan, display supplemental STOP signs on two orthogonal approaches of the three approaches to this intersection. Translucent panels provide visibility in a wide variety of ambient lighting conditions and the overhead location is aligned near the center of vehicle operator's cone of vision, being particularly suited for conspicuity at higher approach speeds.

In Michigan, overhead span-wire mounting of illuminated regulatory signs is common at intersections throughout both the Upper and Lower Peninsulas. In addition to STOP and YIELD signs, DO NOT ENTER, Lane Use Control, ONE WAY, and the unique LEFT signs above left turn signals are routinely mounted overhead. These signs are uniformly specified for numerous intersections of varying geometry, including intersections with curvilinear and non-orthogonal high-speed approaches. These signs also command attention at many of the displaced left turns along divided highways in urban and rural areas, for both signalized and unsignalized u-turns, clearly indicating the location of the turning movement. During inclement weather and where significant snow accumulation exists, illuminated overhead signs with heat-producing illumination fixtures improve the ability of approaching vehicle operators to locate the traveled way and location of conflicts at intersections, incurring safety and operational benefits alike.

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
OCTOBER 2024

J T C D R

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH

VOLUME 2, ISSUE 1
OCTOBER 2024

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

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VOLUME 2

ISSUE NUMBER 1

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VISTA POINTS

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
VOLUME 2, ISSUE 1 | OCTOBER 2024

FOREWORD

Timothy Gates, Ph.D., P.E.
Editorial Partner, *JTCDR*

THE INTRICATE INTERSTATE | PRACTITIONER PERSPECTIVES

Michael J. Tantillo
Secretary, Research Committee

THE STEADY BEACON | PRACTITIONER PERSPECTIVES

Scott O. Kuznicki, P.E.
Vice Chair, Research Committee

RESEARCH & INNOVATION

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH

VOLUME 2, ISSUE 1 | OCTOBER 2024

PAPERS 001 THRU 003 ARE PUBLISHED IN VOLUME 1, ISSUE 1

FOREWORD

Timothy Gates, PhD., P.E.
JTCDR Editorial Partner

Welcome to the second issue of the NUTCD's Journal of Traffic Control Device Research (JTCDR). As you may be aware, the current mission of the JTCDR is to increase the dissemination of findings from traffic control device research and evaluations to inform recommendations for changes to the MUTCD. Within this issue of the JTCDR, you'll find papers that are written by practitioners and researchers that are intended to advance traffic control device practices in the United States. Not surprisingly, the style and scope of our papers will differ from those found within a typical academic journal, with an increased emphasis on results. The editors will ensure that these papers are readable and understandable by a broad practitioner audience.

The JTCDR editorial board is currently preparing a strategic plan to help guide development of future issues. This plan will consider the Journal's mission and will identify the goals of the Journal, publication schedule, review process, and distribution plan. The editorial board understands the challenges associated with producing a high-quality journal. Journals are competitive, and we have no intentions of competing with the Transportation Research Record (TRR) and other journals designed for academic-style papers. However, as several editorial board members serve in various leadership capacities within the TRB Standing Committee on Traffic Control Devices (ACP55), there is likely an opportunity for liaison.

Most importantly, in order for the JTCDR to be successful, we would like to see more NCUTCD members involved in the journal development. Our organization is collaborative, which makes it easy to reach out to leadership on the Research Committee, the Executive Board, or any Technical Committee Chair with your ideas and questions.

In closing, I'd like to thank the efforts of the three original members of the editorial board: Bryan Katz, Scott Kuznicki, and Mike Tantillo. Without their efforts, neither the first nor second issues of this journal would have happened. And I would be remiss if I didn't acknowledge that the Journal exists today thanks to the vision and leadership of NCUTCD Chair, Gene Hawkins. As a newcomer to both the NCUTCD and the JTCDR editorial board, I look forward to working with these talented folks as we shape the plan for future issues.


EXIT 7C
80th Ave SE
LEFT 1 MILE

THE INTRICATE INTERSTATE

Michael J. Tantillo
Associate Executive Editor

The year 2024 has been quite a whirlwind of activity in the traffic control device community! Everyone is excited about the new 11th Edition of the *Manual on Uniform Traffic Control Devices* (*MUTCD*) and is ready to put it into practice. The most common question I've received from practitioners is, "When can I start using the new MUTCD?"

The correct answer, for now anyway is, "it depends." Public agencies are in the midst of a transitional two-year period wherein some jurisdictions have already adopted and are using the 11th Edition while others are still using the 2009 *MUTCD* and associated state MUTCDs and Supplements for the time being. If in doubt, ask someone at the agency to confirm which set of traffic control device standards are in effect for a given project.

A significant amount of effort goes into a state's adoption of an *MUTCD*. First, the Final Rule content must be evaluated to determine the impact to a State DOT's operations in the context of the following considerations:

- State laws
- Fiscal and budgeting aspects
- DOT internal policies and practices

These impacts will closely drive how a State DOT achieves the required substantial conformance with the Federal *MUTCD*. Internal agency practices can be updated with leadership buy-in and some training. More complicated, however, is the process of budgeting and updated state laws, a time-consuming process. That is part of the reason why FHWA allows a full two years for transitioning to and adopting a new *MUTCD*. Best practice is to start as early as possible and develop a plan of action for each item or document that needs to be updated.

For states with a state Supplement or state *MUTCD*, new and conforming content can be drafted based on state transition plans. New for the 11th Edition of the *MUTCD* is a requirement that other state documents, such as standard drawings, specifications, and other agency policies, be in substantial conformance with the *MUTCD*, as they are considered supplements to the *MUTCD* by FHWA. Once all of those documents have been produced or modified, there are various approvals that take place, including substantial conformance reviews by FHWA Division offices andand formal adoption by officials. In some states, a state-level rulemaking process may also exist.

Sometimes non-critical items require a level of additional research and analysis before they are ready to be published in a state Supplement or state MUTCD. Often these are optional practices from the *MUTCD* governed by, "If used…" Standard statements where the decision to utilize or not use is left up to a state DOT, and the state desires more concrete guidance. Other times, they are new devices that a state wishes to use but were not adopted into the *MUTCD* by FHWA. These circumstances may result in small research projects conducted by a state in cooperation with FHWA through the Request for Experimentation process. If the evaluation involves a new traffic control device not currently in the *MUTCD*, the FHWA *MUTCD* Team is wiling and prepared to collaborate on research development and successful completion of an evaluation so that functional experimental devices can be provisionally approved for limited use and possibly included in future revisions of the *MUTCD*. Even if not related to a new device and an official experiment, any research or best practices on a traffic control device that may be beneficial to other practitioners can be readily and easily shared within our community: Simply submit a short (or long) research summary or other research paper to the *JTCDR*!

The above is what typically happens at the state level during the adoption period and why a two-year transition period is necessary. Our NCUTCD membership remains a crucial and competent resource for information sharing during *MUTCD* adoption. We all look forward to January 2026 when the transition period is over and everyone is using the 11th Edition of the *MUTCD*.

THE STEADY BEACON

Scott O. Kuznicki, P.E.
Managing Editor

Speed! It thrills. It kills. This assumed universal enemy of safety appears to be an afterthought on crash reports even as a simple variance between two numbers is used to justify a massive and unending revenue stream. In the free market, where value is created, speed is the foundation of a robust economy, being the selling point for drive-thru and delivery and even featured in the tagline of a High Plains motorway operator. Speed is measured, managed, and monetized, often marginalized, and most assuredly misunderstood.

On urban streets and in areas where vulnerable users are prevalent or even expected, managing speed is the chief goal of the traffic operations engineer. Such an art must recognize that geometric design speaks volumes more than traffic control devices. Five graceful radii in the modern roundabout induce speed harmonization, ensuring adequate sight distance for the widest variety of users. Performing under yield control, modern roundabouts allow for the selection of any adequate gap by any entering vehicle. Attention to the circulating roadway, the priority roadway, reduces task saturation and induces compliance and coordination while preserving priority according to vehicle position and presence. A stunning contradiction manifests in the ability of roundabouts to reduce travel speeds while correspondingly reducing delay and travel time.

While desirable in a roundabout, speed harmonization on motorways often represents a failure to assign and respect priority by position. While roundabouts normalize the performance vehicles and operators, the magic of the motorway ensues in the promotion of order through unconstrained accommodation of diverse capabilities and limitations.

The benefits of order are evident when slower and heavier vehicles keep right while the left lane is reserved for the most flexible and capable combinations of vehicles users, affording priority by position *and* performance. Where roundabouts calm and coordinate traffic by inducing larger and heavier vehicles to obtain the same speed as a bicycle, well-policed motorways promote safety by releasing the user to perform at speed and thereby at attention, conferring convenience to all on the safest and most flexible roads in the world. Accommodating speed and promoting order on the motorway is the key to a safe system and the pathway to a world where the courteous are quick to yield.

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.


SIGNAL

JOURNAL OF TRAFFIC CONTROL DEVICE RESEARCH
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PAPER 004

Tucson BikeHAWK: Adapting the Pedestrian Hybrid Beacon to Assist Bicyclists in Crossing Arterial Streets

2024 Update

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EXECUTIVE SUMMARY:

The operation of the Tucson BikeHAWK, crash history, usage, and compliance:

*• There have been **NO** cyclists related crashes over the last 6 years (even during the pandemic times) and 96% of the riders use the BikeHAWK as intended.*

• Basically, 100% of family riders with children or children alone use the BikeHAWK as intended.

• 94% of the crossers were bicyclists and 6% were pedestrians generally at Bike Boulevard crossings.

• The device was found to be easily understood by all users and bicyclists who followed the designated paths with ease. The high level of understanding was most likely because the BikeHAWK was designed based upon their natural behavior that was observed while crossing at HAWK controlled crosswalks.

• There continues to be the normal high level of driver compliance to the HAWK crossing device, especially at the higher-speed crossings. Driver yielding compliance still consistently remains within the range from 97% to 100% yielding at HAWKs and BikeHAWKs. A new technique has dramatically increased pedestrian compliance which increased from approximately 70% to over 90% with the "HOT" button operation with minimal loss in arterial LOS. "HOT" button operations have been recommended by FHWA at such pedestrian crossings that respond promptly to the pedestrian's or cyclist's call button for service. (Automated pedestrian activation was experimented with, however there were many missed or false calls. It was found, especially true during the hot Tucson summers, pedestrians do not wait at the curb, but in the nearest shade to wait for the HAWK beacon to activate when in coordination mode.)

• 50% of riders using the BikeHAWK were males, 46% were females, and 6% were children. (This level of female ridership is significantly higher than the historical Tucson average regional percentage of 26%. The higher percentage is considered an indication of perceived safety by cycling experts)

The key elements of the BikeHAWK design include:

• A short, separated green protected two-way contra-flow bike lane to position bicyclists into an area delineated by flexible posts associated with the HAWK controlled pedestrian crossing.

• Placement of curbside signal detection buttons within easy reach of bicyclists and "HOT" button operation.

• Use of green pavement markings in a high-visibility crosswalk pattern adjacent to the high-visibility white crosswalk.

• Supplemental (CMS) illuminated sign to support the (R9-5) sign's understanding and enforcement.

• MUTCD-approved signs and pavement markings reminding bicyclists to ride with traffic after the crossing has been completed and it is safe to make the maneuver (R5-1b and R9-3cP).

One of the first BikeHAWKs serving Pima Community College and Medical/Social Services Facility at W. Speedway and N. 10th Avenue

HISTORY LEADING UP TO THE TUCSON BIKEHAWK

The Pedestrian Hybrid Beacon (PHB) or HAWK has been successfully used by communities around the nation to facilitate safe, convenient crossings of busy, high-speed roadways by pedestrians since its inclusion in the 2009 edition of the Manual on Uniform Traffic Control Devices (MUTCD). While not excluding their use, standard PHBs or HAWKs have never explicitly accommodated another vulnerable large user group in need of the same facilitation to cross arterials: bicyclists. In 2012, as part of the bicycle boulevard program, the City of Tucson began efforts to modify selected PHBs or HAWKs to allow for the clear and safe crossing of both user groups.

Starting in the 1980s, the City of Tucson shifted its focus from simply providing bike lanes along arterial and collector roadways to identifying existing residential streets that could be enhanced to provide a network of calm, low-stress bikeways. Having identified these routes (now termed bike boulevards), the city endeavored to improve this network by reducing intruding automobile traffic, encouraging bicyclist use, and most critically, addressing how to safely and conveniently cross major streets where they intersect these bike boulevards.

BACKGROUND OF TUCSON BIKEHAWK

The HAWK crossing was instituted by the city of Tucson as a pedestrian safety program of "Watching Over the Pedestrian Like a Hawk." The hawk is part of local Indian lore that watches over the children and mother earth. The beacon light was developed to protect the pedestrian crosswalk, not operate an intersection. The first HAWK beacon pedestrian crossing was installed in early 2000. Later as bicycle boulevards were developed city wide, we found that cyclists were traveling along these residential streets using the HAWKs to cross the major streets, so the city developed modifications at the HAWKs to facilitate the bicycle crossings that matched their natural behavior patterns. Thus, the first BikeHAWK design modification in 2012 was in conformance with the 2009 MUTCD's guidance and was connected to the HAWK's controller's pedestrian crossing's signals. The BikeHAWK is a HAWK with an added two-way protected contra-flow bike lane, curb-side push buttons within easy reach to call the pedestrian phase along with MUTCD R9-5 signs and GREEN pavement high visibility stripes adjacent to the WHITE high visibility pedestrian crosswalk. Thus, the BikeHAWK facilitates the crossing of both cyclists and pedestrians. There are over two dozen currently in operation and more scheduled for installation.

MUTCD TEAM, RSA REVIEW and LEGAL OPINION

A MUTCD Team Member came to Tucson in June of 2015 to view the operation and examined one of the first BikeHAWK installations. There was an agreement that the design modifications were in substantial conformance with the 2009 MUTCD's guidance. He also had further recommendations for consideration regarding a supplemental (CMS) illuminated bike informational sign, to supplement the R9-5 sign's meaning to the crossing public.

As you know, late entries by pedestrians happen with the current pedestrian and countdown signals at traditional traffic signals as well as PHBs. We were concerned about the same late entries during the flashing red phase of the HAWK with bicycles. The city had spent extensive time monitoring bicycle activity at the existing HAWK crossings and bicycle usage. The cyclists were already crossing at HAWKs safely. There was a desire to try to further encourage safe crossings as part of the cyclist's natural behavior with the BikeHAWK modifications. We considered additional signing, doubling up on pedestrian signal heads, and/or bike signals. Additional oversize signing was installed. The doubling-up of pedestrian signals did not provide further explanation of the cyclists' responsibilities and the supplemental illuminated (CMS) sign focused upon that need. Bicycle signals were problematic. The FHWA Bicycle Facilities and the MUTCD, summary table in 2012-3 noted that FHWA has discontinued the approval of experiments with bicycle signals at PHBs and further noted that: *"Bikes can be assisted in crossing a roadway by a pedestrian hybrid beacon type of device at the present time."* [i]

The city then examined supplemental illuminated (CMS) sign design for the bicycle crossing in addition to the MUTCD pedestrian signals, that further explained the R9-5 sign's legal responsibilities upon cyclists. It was noted that the 2009 MUTCD allowed local jurisdictions to provide signs with special word messages to assist in enforcement and understanding of regulations. The 2009 MUTCD further provided guidance that (CMS) signs may be used as a supplement to conventional signs. The MUTCD Team Member suggested consideration of an illuminated one color (WHITE) expanded verbiage message for the supplemental CMS sign. The city considered the recommendation, hired and expert traffic engineering firm to complete an RSA, Road Safety Audit of the Tucson BikeHAWK technique.[ii]

The engineering study noted that the use of a two-color supplemental illuminated sign that would indicate when bikes must "WAIT" or when it was "OK" to proceed would be better understood than the suggested single (WHITE) color expanded message. There was a danger of a potential human factors failure by showing the "proceed" message and "wait" message in the same white color. It was felt that the two colors from the approved pedestrian signal would be better understood by the public. The MUTCD R9-5 sign says "BIKES (SYMBOL) USE PEDESTRIAN SIGNAL", The pedestrian signal displays an ORANGE indication for the wait message and WHITE indication for the proceed message thus the supplemental illuminated sign with the same colors will further emphasize the MUTCD R9-5 message. The RSA [iii] further recommended that, to accommodate bicyclists, the supplemental bicyclist changeable message sign (CMS) should be required, and the supplemental sign was powered in parallel with the pedestrian signal circuit insuring full coordination between all the traffic control devices.

o "A changeable message sign for bicyclists at the BikeHAWK should display a different color during the crossing or "go" time and the bicycle clearance interval (the displays both should not both be white – otherwise a bicyclist may confuse one message with the other or may not distinguish the two different messages. The use of different colors for different messages would also be a benefit for those who are proficient in English and for those with vision limitations."

- *“The amount of words on the changeable message sign should be minimized to make the sign more readable and minimize the size of the housing. The word message recommended by the FHWA Team Representative (“BIKES USE PED SIGNAL” during the WALK interval and a “BIKES WAIT AT CURB” message during the pedestrian clearance interval) may make a changeable message sign rather large or result in the words being too small to distinguish. Fewer words are better to see and comprehend.”*

- *“A bicycle signal is contraindicated for this BikeHAWK since it is located at an intersection crossing be the best option at an intersection crossing and there is a concern that a side street motorist may inadvertently confuse a red/yellow/green bicycle signal with a motor vehicle signal. The FHWA Interim Approval IA-16 (and current MUTCD) for bicycle signal faces prohibits the use of a bicycle signal face at a Pedestrian Hybrid Beacon, which is the design that a BikeHAWK is based upon. Since the BikeHAWK is used at a local street intersection where motorists approach from the side street, the FHWA prohibition in 1A-16 has merit.” (It was noted that there can be an unintended consequence of side street driver violations of the STOP sign, conflicts with crossing pedestrians and cyclists when the GREEN light is seen by drivers on the residential street.)*

The flashing of the BIKES WAIT change interval was considered for the supplemental illuminated (CMS) sign and engineering judgement/human factors supported the use of the MUTCD approved flashing interval to call attention to the change interval just as is done with the pedestrian signal to further supplement and support the R9-5 sign’s meaning.

Review by the Tucson City Attorney’s Office reaffirmed the engineering study’s recommendations supporting the supplemental illuminated (CMS) sign to explain and enforce the regulatory sign. The police department’s review indicated they needed the regulatory supplemental (CMS) sign to enforce the R-5 sign in accordance with state law,[iv] since cyclists’ responsibilities are silent in the statutes regarding pedestrian signals.

11th Edition MUTCD (2023)

The language in the new 11th Edition of the MUTCD further supports the concept of a supplemental illuminated TCD to educate the cyclists as to the R9-5 sign’s meaning and assist in the enforcement the crossing since pedestrian indications are silent concerning cyclists’ legal responsibilities.

The need for the additional supplemental illuminated sign traffic control device has been further emphasized in the MUTCD Bicycle part. Section 9E.08 discusses Counter-Flow Lanes and has a standard that requires appropriate traffic signaling oriented toward the cyclists in the counter-flow lane, including a method for cyclists to actuate the phase for the counter-flow movement. However, in section 4H.02 bicycle signals are specifically prohibited from use at PHB or HAWK crossing beacons.

Thus, the next possible alternative presents itself in section 2A.02 Design of Signs, where state and local agencies may develop special word legends signs in situations where engineering judgement determines roadway conditions make it necessary to provide additional regulatory or warning information about a situation that might not be readily apparent. Part 2L, Changeable Message Signs notes, users of (CMS) are expected to consult the other chapters in this Manual for criteria on how to develop effective messages that comply with this Manual and that meet the expectancy and limitations of the road user. The 11th Edition of the MUTCD further lists under a support section that the purpose of the (CMS) is to provide real-time traffic regulatory, warning, or guidance messages as clearly identified under letters G and H. The development of the supplemental illuminated sign (CMS) at the Tucson BikeHAWK falls well within the concepts in the new MUTCD and the need to educate and enforce the safe use of the crossing, especially the MUTCD R9-5 sign regulations.

CRASH EXPERIENCE

The city of Tucson recently forwarded a crash summary for HAWKs, and BikeHAWKs, covering 2018 to 2023, including the meteoric rise in crashes during the pandemic. There has only been one fatal crash at a BikeHAWK crossing**. It is critical to note that the pedestrian failed to activate the signal beacon, was crossing against the light, NO cyclist was involved, and the driver complied with his legal duties.**

Witnesses told the police the pedestrian was attempting to cross a six-lane divided arterial (posted at 40 mph) at night. Unfortunately, the pedestrian **did not activate** the PHB or HAWK beacon system and entered the crossing against all of the traffic control devices. Even though the street was lit, the approaching driver did not notice the pedestrian in time to avoid a crash. See the following crash summary table from the city with the specific crash highlighted.

Thus, the most recent crash records show the design is very safe and there have been **(0) zero** cyclist related crashes over the last 6 years at the Tucson BikeHAWKs, even including the unprecedented spike in pedestrian and bike crashes nationwide during the pandemic years as well as Tucson.

The Pima County medical examiner noted an abnormal increase in drugs or alcohol involved in the region's pedestrian crashes.[v] Pima County just like other regions of the nation encountered a significant increase in traffic crashes. The County Medical Examiner noted: homelessness, gender, time of day and substance abuse were all factors involved in many, if not all of the crashes.

There.have.been. ZERO.cyclist. related.crashes. over.the.last.❷. years.at.the. BikeHAWKs

At.one.BikeHAWK.crossing. a.fatal.pedestrian.crash. occurred¡.No.cyclist.was. involved.™ .the.signal. beacon.had.not.been. activated.by.the.crossing. pedestrian.who.crossed. against.the.light.at.night¡.

City of Tucson Fatal and Injury Crashes at HAWK and BikeHAWK Locations 2018 - 2023

Year	Location	Manner*	Activated
2018	NONE	N/A	NA
2019	3333 N Flowing Wells Rd	In crosswalk. **HAWK not activated**	**NO**
2020	8111 E. Broadway Blvd	Family of three crossing in activated HAWK. Two children struck. One dies.	YES
2021	S Sahuara Av & E 22nd St	Pedestrian crossing in activated HAWK struck and killed	YES
2021	N Alvernon Wy & E Flower St	Pedestrian crossing in activated HAWK struck and killed	YES
2021	W Valencia Rd & S San Fernando Ave	Pedestrian crossing in diagonal green bike marking portion of crossing stuck and killed. **BikeHAWK not activated**	**NO**
2022	E Grant Rd & N Palo Verde Av	In crosswalk. **HAWK not activated**	**NO**
2022	E Broadway Bl & E Old Spanish Tr	Pedestrian crossing in activated HAWK struck and killed	YES
2022	E 26th St & S Craycroft Rd	Pedestrian crossing 20-feet north of **HAWK not activated** struck and killed	**NO**
2023	E Speedway Bl & N Dodge Bl	Pedestrian (70 y/o Female) crossing south to north in activated HAWK crossing struck and killed	YES

**Most of the fatal crashers at activated HAWKs involve hit and run crashes*

If the HAWK and BikeHAWKs are properly installed to manage a crossing and <u>not</u> a full intersection they can be a very successful traffic safety tool when they are activated by the crossers and drivers obey the RED beacon lights.

PROFESSIONAL PUBLICATIONS and OUTREACH

The city continues to provide outreach to the profession concerning the success of this project. For your informational files, the Tucson BikeHAWK has been published for the transportation professions' information in the:

- FHWA and UNC Highway Safety Research Center's, Pedestrian and Bicycle Information Center, https://www.pedbikeinfo.org/resources/resources_details.cfm?id=4950

- Rob Sanders, the creator, and host of Road Guy Rob, prepares a video series in which he strives to show "today's cutting-edge developments in transportation engineering." The BikeHAWK operation can be seen in, *"Stop Lights can .... Ruin the street for bicycles"* https://www.google.com/search?q=BikeHAWK+and+TOUCAN+stop+light+can+ruin+a+street&rlz=1C1ONGR_enUS1087US1088&oq=BikeHAWK+and+TOUCAN+stop+light+can+ruin+a+street&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIJCAEQIRgKGKABMgkIAhAhGAoYoAEyCQgDECEYChigATIJCAQQIRgKGKAB0gEKNjA5NTRqMGoxNagCALACAA&sourceid=chrome&ie=UTF-8#fpstate=ive&vld=cid:38ee1019,vid:Dk8uhfFCtM0,st:0

- The BikeHAWK was recently again recognized in the NCUTCD, Journal of Traffic Control Device Research, in 2023. https://ncutcdjournal.org/index.php/jtcdr

- The Mountain Section of ITE and ISMA has the Tucson BikeHAWK and TOUCAN presentation scheduled for the 2024 Spring session.

[i] Bicycle Facilities and the Manual on Uniform Traffic Control Devices 2009, Tabular summary of bicycle and pedestrian projects, www.fhwa.dot.gov/bicycle_pedestrian guidance/design

[ii] Pima Association of Governments, Mini-RSA Broadway Blvd at Treat Avenue BikeHAWK Crossing, Final Report, January 22, 2016, by Lee Engineering, Phoenix, Arizona

[iii] Ibid page 23-24

[iv] Legal Opinion Re: HAWK Bicycle Signing, City of Tucson Attorney's Office, A0117558

[v] Arizona Daily Star, Pima County, Medical Examiner: An in-depth look at fatal pedestrian accidents in 2022, https://www.kold.com/2022/12/31/medical-examiner-an-in-depth-look-fatal-pedestrian-accidents-2022/

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PAPER 005

Field Evaluation of Methods for Enhancing Sign Conspicuity

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INTRODUCTION

The 2009 Manual on Uniform Traffic Control Devices (MUTCD) outlines various strategies to enhance the conspicuity of traffic signs, defined as a traffic sign's ability to stand out and attract attention. Improving sign conspicuity is believed to directly and indirectly impact safety by promoting compliance, reducing speeds, and decreasing accidents. However, despite these enhancements, there is a lack of comprehensive research on their actual effectiveness on driver behavior. This study aims to fill that gap by evaluating the effectiveness of these conspicuity treatments, focusing on methods currently endorsed by the MUTCD rather than exploring novel treatments.

To conduct this evaluation, the research team reviewed existing literature and practices, consulting with members of the Traffic Control Devices Pooled Fund Study (TCD PFS) to identify which MUTCD treatments were being effectively utilized across states. Given that conspicuity, especially retroreflectivity, cannot be effectively replicated in laboratory settings, the researchers employed field experiments to gather data. They utilized a two-part approach, combining observational field data and eye-tracking studies, to assess how these conspicuity treatments influence driver behavior. This methodology allowed for a nuanced understanding of whether these enhancements lead to increased attention to signs and subsequent changes in driving behavior.

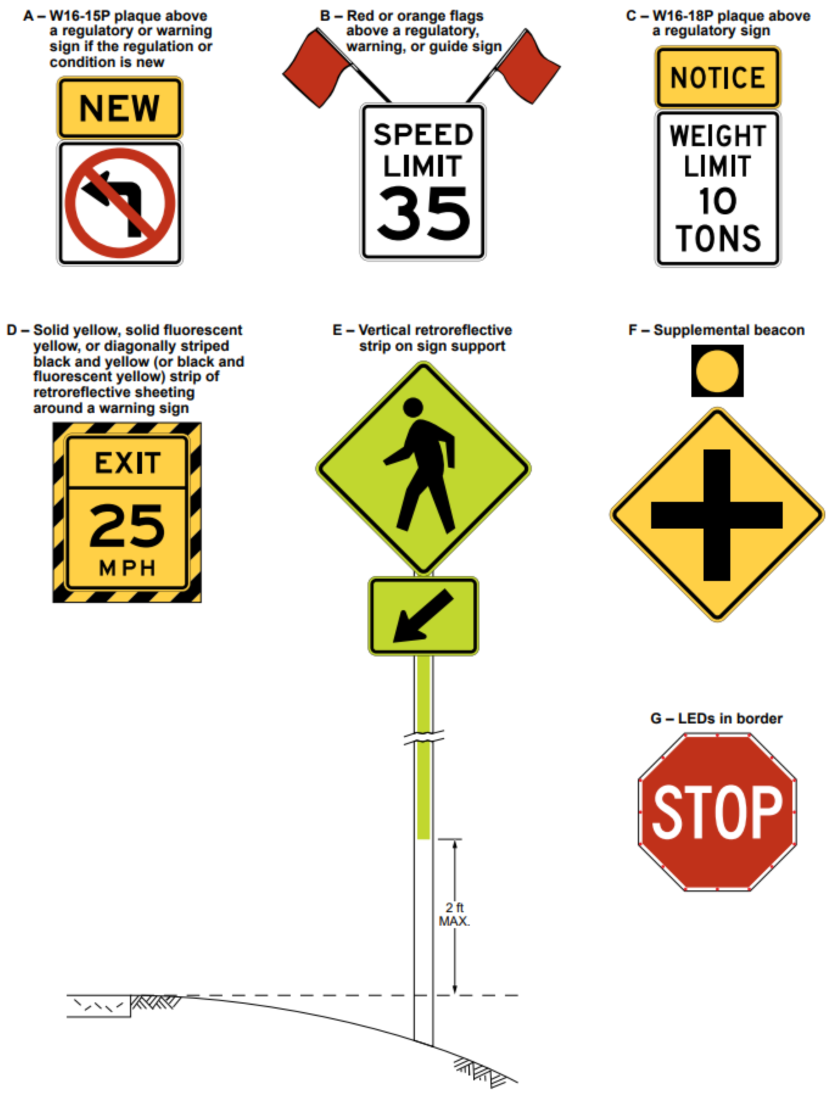

Figure 1: 11th Edition MUTCD Figure 2A-1. Examples of Enhanced Conspicuity for Signs

LITERATURE REVIEW

Enhancing the conspicuity of traffic signs is essential for improving road safety. Various studies have explored the effectiveness of materials and designs aimed at increasing sign visibility. This literature review examines these approaches and their implications for traffic sign conspicuity.

One study by Gates and Hawkins conducted before-and-after evaluations of various high-conspicuity sign materials.[1] One key application was the addition of a 3-inch red microprismatic border around a Speed Limit sign at the entrance of a speed zone. The study reported approximately 2 mph decreases in mean and 85th percentile speed at the entry point to the speed zone, as well as 500 feet after entering the zone, for daytime passenger vehicles. The study also

[1] Gates, T.J., and Hawkins, H.G., Effect of Higher-Conspicuity Warning and Regulatory Signs on Driver Behavior, Texas Transportation Institute, Project Summary Report 0-4271S, 2004.

found an 18.4 percent reduction in the number of vehicles exceeding the speed limit. Additionally, the study examined the installation of red flashing light-emitting diodes (LEDs) on STOP signs, which led to a 28.9 percent decrease in the number of vehicles not fully stopping at the sign.

According to the synthesis in Castro and Horberry's *The Human Factors of Transport Signs*, other studies have indicated that colored borders can enhance the visibility of traffic signs.[2] However, they caution that such borders should be used judiciously, particularly on warning signs, as they may reduce legibility if positioned too close to the text.[3] A separate study by Arnold and Lantz in Virginia assessed the effects of adding red flashing LEDs to STOP signs, yielding somewhat inconclusive results; while speeds did decrease slightly, the presence of additional measures like "Stop Ahead" signs and rumble strips likely influenced the outcomes.[4]

Further research has explored treatments such as increasing sign size and duplicating signs on the left side of the roadway. A case study by the FHWA in Winston-Salem, NC, showed a reduction in crashes and injuries from a combination of measures, including larger signs and added markings.[5] However, when multiple enhancements are made at the same time, it is difficult to determine which countermeasure (or combination of countermeasures) is responsible for the increased safety benefits, or if a single countermeasure could produce the same benefits on its own.

Similarly, Pour-Rouholamin et al. conducted a survey and discussed multiple case studies regarding WRONG WAY signs, DO NOT ENTER signs, and wrong way driving.[6] Participants in the survey represented sixteen states. One of the survey questions focused on conspicuity methods that states implement on WRONG WAY and DO NOT ENTER signs. The results revealed that over half of the respondents used specific treatments: adding a second identical sign on the left side of the roadway, increasing the sign size, and adding a retroreflective strip to the sign support. Additionally, nearly half of the states mounted their signs at the minimum height allowed by the MUTCD instead of the standard height. While the survey highlighted the impacts of these conspicuity treatments, the case studies offered deeper insights. For instance, Caltrans reported a significant drop in wrong way driving incidents by lowering sign mounting heights to align with vehicle headlights, reducing incidents from 50-60 per month to just 2-6 in some areas. Similarly, TexDOT observed a 30% reduction in incidents following the installation of WRONG WAY signs with flashing LED borders in a San Antonio study. The authors also referenced several other studies that implemented larger signs and placed identical signs on the left side of the road. Although these measures led to incident reductions, it's important to note that changes in driver behavior cannot be attributed to any single countermeasure, as multiple strategies were often employed together.

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[2] Castro, C., & Horberry, T. (2004). *The Human Factors of Transport Signs*. CRC Press.

[3] Young, S.L. (1991). Increasing the noticeability of warnings: effects of pictorial, color, signal icon and border. *Proc. Hum. Factor Soc. 35th Annu. Meet.* 580-584 San Francisco: Human Factors Society.

[4] Arnold, E. D., Jr., & Lantz, K. E., Jr. (2007). *Evaluation of Best Practices in Traffic Operations and Safety: Phase I: Flashing LED Stop Sign and Optical Speed Bars* (Rep. No. FHWA/VTRC 07-R34). Charlottesville, VA: VTRC

[5] Federal Highway Administration (FHWA), 2009. Stop Sign-Controlled Intersections: Enhanced Signs and Markings, A Winston-Salem Success Story. FHWA-SA-09-010.

[6] Pour-Rouholamin, M., Zhou, H., Shaw, J., & Tobias, P. (2015). Current Practices of Safety Countermeasures for Wrong-Way Driving Crashes. In Transportation Research Board 94th Annual Meeting.

Research into flashing beacons has also been conducted, with Janoff and Hill summarizing previous findings on their effectiveness. They noted that the presence of flashing beacons at curve warnings led to reduced speeds and fewer crashes related to loss of control.[7] A study by Pant et al. compared intersections with only STOP signs to those equipped with Intersection Control Beacons, finding speed reductions but no significant changes in compliance or crash rates.[8] An FHWA pooled fund study examined three types of flashing beacons and found an overall reduction in crashes, although sample sizes were insufficient to draw statistically significant conclusions for each type.[9] Notably, flashing beacons on stop signs showed potential for greater effectiveness, but a cost-benefit analysis indicated that actuated beacons might not be a worthwhile investment in most stop-controlled locations.

Table 1: Angle Crash Reduction (Srinivasan, 2007)

Group (# of Sites)	Estimate of Percent Reduction
Rural Sites in NC and SC (76)	15.7%
Suburban Sites in NC (14)	11.8%
Urban Sites in NC and SC (16)	-12.3%
Two-way stop in NC and SC (95)	12.7%
Two-way stop in SC (31)	-10.4%
Four-way stop in SC (11)	27.8%
Standard Overhead in NC and SC (84)	11.9%
Standard STOP sign mounted in NC and SC (5)	58.2%
All Standard in NC and SC (89)	13.3%
Actuated in NC (17)	14.0%

METHODOLOGY

The methodology for this research involved two key components: an observational field study conducted in Virginia and New Hampshire, and an eye-tracking study carried out in Virginia. In collaboration with State Departments of Transportation (DOTs), the research team focused on gathering observational data at selected high-traffic sign locations, implementing specific conspicuity treatments to assess their effects on driver behavior. Simultaneously, the eye-tracking study in Virginia provided insights into drivers' visual attention patterns in relation to these treatments. Together, these approaches aimed to evaluate the effectiveness of various enhancements to traffic sign visibility and compliance, offering a comprehensive understanding of their impact on road safety.

[7] Janoff, M. S., & Hill, J. G. (1986). Effectiveness of Flashing Beacons in Reducing Accidents at a Hazardous Rural Curve (Abridgment). Traffic Control Device and Rail-Highway Crossings, (1069), 80-82 Transportation Research Board.
[8] Pant, P. D., Park, Y., Neti, S. V., & Hossain, A. B. (1999). Comparative Study of Rural Stop-Controlled and Beacon-Controlled Intersections. Traffic Control Device and Rail-Highway Crossings, (1692), 164-172 Washington, D.C.: Transportation Research Board.
[9] Srinivasan, R., Carter, D., Eccles, K., Persaud, B., Lefler, N., Lyon, C., & Amjadi, R. (2007). *Safety Evaluation of Flashing Beacons at STOP-Controlled Intersections* (Rep. No. FHWA-HRT-08-044). Washington, DC: FHWA.

Observational Field Data Collection

The research team collaborated with two State DOTs in New Hampshire and Virginia to gather observational field data. These States were chosen based on their participation in the TCD PFS and their proximity to the research team, facilitating efficient travel to various research sites. The team worked closely with state officials to identify specific locations where enhanced conspicuity treatments could be applied, implementing only one treatment per sign location. Signs were selected in heavily traveled areas to ensure robust data collection, focusing on those designed to elicit specific driver behaviors (e.g., STOP signs, Speed Limit signs) for more quantifiable outcomes. While some signs were included at the request of the states due to problematic driver behavior, most were selected based on their strategic locations and proximity to other relevant signs.

To assess the impact of the treatments, the research team evaluated criteria such as driver speed, stopping behavior, and turning behavior at each sign location. They collected mean speed and 85th percentile speed data, classifying vehicles as small, medium, or large based on their length. In Virginia, the signs and treatments used for observational data were consistent with those in the accompanying eye-tracking study. The literature review indicated that novelty effects could influence results, prompting the team to establish three data collection periods in each State: before (before treatments were installed); initial-after (immediately following installation); and second-after (approximately 2–4 mo after installation). New Hampshire was an exception, with only before and initial-after data collection due to the need to remove treatments before winter tourist season. The timing of data collection varied among the States due to differences in tourism, weather patterns, and delays related to the COVID-19 pandemic, as well as variations in environmental factors and DOT availability for installation.

New Hampshire Observational Field Data Collection

Table 2 outlines the signs, conspicuity treatments, and data collection devices utilized in New Hampshire. The research team employed speed radar devices at all Speed Limit sign locations to assess average driver speeds, while cameras were used at all other sign locations.

Table 2: Summary of Data Collection Placement and Equipment for New Hampshire

Sign	Conspicuity Treatment	Data Collection Device	Data Collected
Railroad signing	Add yellow retroreflective strip (westbound direction only)	Camera	Count of vehicles stopped on tracks
SPEED LIMIT 30	Add additional sign in the median on a U-channel sign support duplicating the size and message of the existing Speed Limit sign.	Speed radar devices	Driver speeds
NO RIGHT TURN ON RED*	Add fluorescent-yellow rectangular header panel at the top of the sign with the word NOTICE	Camera	Count of vehicles that turned right on red
SPEED LIMIT 30	Add white retroreflective strip on signpost	Speed radar devices	Driver speeds
Pedestrian warning sign with RRFB	Add yellow retroreflective strip on both sides of both signposts (four strips total)	Two cameras	Count of vehicles that did and did not stop properly for pedestrians at ramps and in crosswalks
Pedestrian warning sign without RRFB	Add yellow retroreflective strip on both sides of both signposts (four strips total)	Two cameras	Count of vehicles that did and did not stop properly for pedestrians at ramps and in crosswalks

*Note: The standard MUTCD sign to prohibit all turns on a red signal indication is the “NO TURN ON RED” sign.
**RRFB = rectangular rapid-flashing beacon.

Figure 2 through Figure 9 show some examples of signs before and after the conspicuity treatments were applied.

Figure 2. Photo. Before and After treatment: retroreflective 2.5-inch yellow strip.

Figure 3. Photo. Before and After treatment: header panel.

Figure 4. Photo. Before and After treatment: retroreflective white strip.

Figure 5. Photo. Before and After treatment: retroreflective 2.5-inch yellow strip.

During both the before- and after-data collection periods, the research team gathered data on a Friday and Saturday. These days were chosen in collaboration with the New Hampshire DOT to ensure that both a weekday and a weekend day with higher traffic volumes were included. The treatment locations were along routes frequented by tourists, meaning many drivers would likely encounter the signs for the first time.

Virginia Observational Field Data Collection
In Virginia, the research team applied conspicuity treatments to six different signs, as outlined in Table 3.

Table 3: Summary of Data Collection Placement and Equipment for Virginia

Sign	Conspicuity Treatment	Data Collection Device	Data Collected
STOP	Add red retroreflective strip on signpost	Camera	Count of vehicles that did and did not come to a complete stop
Curve Warning sign with 50-mph advisory speed plaque (duplicate signs on both sides of road)*	Replace sign with oversized sign (increased to 48×48 inches) for both sides of the road	Speed radar devices	Driver speeds
SPEED LIMIT 45 (duplicate signs on both sides of road)*	Add fluorescent yellow NOTICE header panel on both signs**	Speed radar devices	Driver speeds
SPEED LIMIT 45 (duplicate signs on both sides of road)*	Replace sign with increased size (increased to 48×60)	Speed radar devices	Driver speeds
SPEED LIMIT 55 (duplicate signs on both sides of road)*	Add white retroreflective strip on post	Speed radar devices	Driver speeds
Curve Warning sign with advisory speed (40 mph)	Replace sign with oversized sign (increased to 36×36)	Speed radar devices	Driver speeds

*Duplicate signs were already in place before the study began.
**The NOTICE header panels are not compliant with the MUTCD. The MUTCD only allows for a header panel that is the full width of the sign.

Figure 10 through Figure 12 show examples of signs before and after treatments were installed (Note: The NOTICE header panels shown in Figure 12 are not compliant with the MUTCD. The MUTCD allows for only a header panel that is the full width of the sign).

Figure 6. Photo. After treatment: oversized sign.

Figure 7. Photo. After treatment: red retroreflective strip.

Figure 8. Photo. After treatment: fluorescent yellow NOTICE header panel.

Eye Tracking Study

For the eye-tracking field study, participants drove along a predetermined 24-mi route in Elliston, VA. The research team installed three Speed Limit sign treatments along the test route and used one control Speed Limit sign. The study examined driver eye-glance behavior toward each of the test signs and the control sign.

Virginia Eye Tracking Study

Sixty-three participants drove a field research vehicle along a predetermined 24-mi route in Elliston, VA. Among them, 28 were female and 35 were male, with ages ranging from 18 to 69 years (mean age = 25). The field research vehicle was a medium-sized sports utility vehicle. Each participant wore a head-mounted, mobile eye-tracking system that resembled a pair of glasses to collect visual-attention data. After calibrating the glasses, each participant completed a practice drive before starting the test route. A researcher was always present in the vehicle with them. During the test drive, participants received verbal navigational instructions and were told to drive as they normally would, despite the new elements (e.g., different vehicle, headset, additional passenger). The research team installed three sign treatments along the test route:

- Sign 1—a duplicate SPEED LIMIT 55 sign.
- Sign 2—fluorescent yellow NOTICE header panels on two SPEED LIMIT 45 signs.
- Sign 3—white retroreflective strip on SPEED LIMIT 55 signpost.

The research team also used these signs and treatments in an observational portion of the data collection for Virginia. Figure 13 through Figure 15 display the three treatments. A single SPEED LIMIT 55 sign was used as a control.

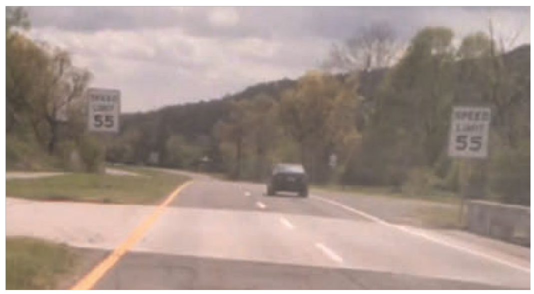

Figure 9. Photo. Conspicuity treatment: duplicate signs.

Figure 10. Photo. Conspicuity treatment : fluorescent yellow NOTICE header panels.

Figure 11. Photo. Conspicuity treatment: white retroreflective strip on signpost.

RESULTS

This section presents the results from the observational field studies conducted in New Hampshire and Virginia, along with findings from the eye-tracking study performed in Virginia. The outcomes highlight the effectiveness of various conspicuity treatments on driver behavior and compliance at selected traffic sign locations, providing insights into their impact on road safety. Each study component details specific interventions and their associated effects, offering a comprehensive overview of the research findings.

New Hampshire Observational Field Data Collection

The following presents the results of the observational field data collection in New Hampshire, organized by specific traffic sign categories.

Railroad Signing

The research team applied a yellow retroreflective strip to the signpost facing westbound. To assess noncompliance at the railroad crossing, the team counted the number of vehicles that were stopped on the tracks, provided that the queue was long enough to extend to the crossing. Data analysis showed that noncompliance significantly decreased after the treatments were installed compared to before (p_before = 0.54, p_after = 0.37, chi-squared = 6.44, degrees of freedom (*df*) = 1, p = 0.01).

No Right Turn on Red

The research team placed a fluorescent yellow NOTICE panel at the top of the sign. However, there was no statistically significant change in the number of vehicles making right turns on red before and after the treatment was implemented.

Pedestrian Warning Sign with RRFB

The research team applied a yellow retroreflective strip to both sides of the signposts. However, there were no statistically significant differences in the number of vehicles that did not stop for pedestrians at ramps (pedestrians who were waiting to cross, i.e., not in the crosswalk) or for pedestrians in crosswalks after the treatments were installed compared to before.

Pedestrian Warning Sign without RRFB

The research team applied a yellow retroreflective strip to both sides of the signposts. The proportion of vehicles that failed to stop for pedestrians at ramps was statistically significantly higher after the installation of the treatments compared to before (p_before = 0.57, p_after = 0.66, chi-squared = 3.88, df = 1, p = 0.05). In contrast, the proportion of vehicles not stopping for pedestrians in the crosswalk showed no statistically significant difference after the treatment was implemented (p_before = 0.34, p_after = 0.28, chi-squared = 0.32, df = 1, p = 0.57).

Speed Limit Signing
The research team compared mean speeds before and immediately after treatment installations. Three Speed Limit signs received conspicuity treatments, as listed below:

- SPEED LIMIT 30—NH–112 Eastbound—added retroreflective white strip to signpost.
- SPEED LIMIT 30—NH–112 Eastbound by I–93 overpass—added sign in median to match the existing sign.
- SPEED LIMIT 35—Route 3 Northbound—increased sign size to one size larger using MUTCD dimensions.

There were no significant differences in speeds before and after the installation of treatments at any of the three locations (Table 4). Additionally, the 85th-percentile speeds showed no significant changes before and after treatment installation at any of the sites (Table 5).

Table 4. Change in Mean Speeds (mph) for All Vehicles for New Hampshire.

Sign	Before Mean Speed (mph)	Initial-After Mean Speed (mph)	Change in Speed, Before to First-After Difference (mph)	Change in Speed, Before to First-After (*p*-value)	Change in Speed, Before to First-After (Cohen's *D* [SE])
SPEED LIMIT 30—add sign and oversize	36.02	37.00	0.98	1.00	0.18 (0.02)
SPEED LIMIT 30—add retroreflective white strip	39.16	39.53	0.37	1.00	0.08 (0.03)
SPEED LIMIT 35—increase sign size	39.53	39.73	0.20	0.97	0.05 (0.02)

SE = standard error.
Note: The p-value corresponds to t-test with one-sided alternative hypothesis. Small values suggest that speeds fell over time, and large values suggest that speeds did not fall over time.

Table 5. Change in Mean Speeds (mph) for All Vehicles for New Hampshire.

Sign	Statistic	Before	First-After
Speed Limit—add sign and oversize (SPEED LIMIT 30)	Q85	41.00	42.00
Speed Limit—add sign and oversize (SPEED LIMIT 30)	SD	5.74	4.95
Speed Limit—add retroreflective white strip (SPEED LIMIT 30)	Q85	44.00	44.00

Sign	Statistic	Before	First-After
Speed Limit—add retroreflective white strip (SPEED LIMIT 30)	SD	4.32	4.73
Speed Limit—increase sign size (SPEED LIMIT 35)	Q85	44.00	44.00
Speed Limit—increase sign size (SPEED LIMIT 35)	SD	4.37	4.50

Q85 = 85th-percentile speeds; SD = standard deviation.

The research team also analyzed mean speeds by vehicle classification (e.g., small, medium, large). However, there were no significant differences in average speeds before and after the installation of treatments based on vehicle size, and the number of small vehicles observed during the study periods was limited.

Virginia Observational Field Data Collection

The following subsection outlines the results of the observational field data collection in Virginia, including the stopping data and speed data.

Stopping Data

For the STOP sign, the research team utilized a camera to record the number of vehicles that came to a complete stop versus those that did not, both before and after the installation of the red retroreflective strip on the signpost. They focused on observing drivers making right and left turns at the STOP signs. As illustrated in Figure 16, there was no statistically significant change in the rate of complete stops during the initial-after period; however, the second-after period showed a significant increase in complete stops for both turning directions.

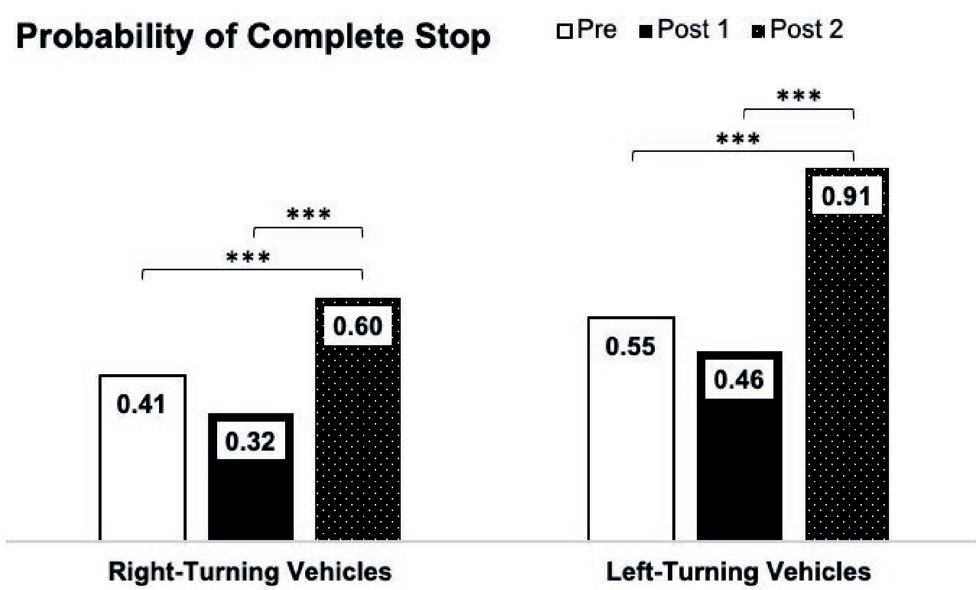

Figure 12. Graph. Probability of a complete stop by data collection period—Virginia.

***Statistically significant difference at the $p = 0.01$ level.

Two limitations affected the stopping data. First, there was variability in the data collection days across the before, initial-after, and second-after periods. The research team collected data for the following:

- Before treatment installation on a Friday, Saturday, and Sunday.
- Initial-after period on a Wednesday, Thursday, and Friday.
- Second-after period on a Monday, Tuesday, and Wednesday.

Variations in traffic volume (e.g., weekdays versus weekends) may have affected stopping behavior. For instance, drivers might have been more inclined to come to a complete stop when there was a higher volume of cross traffic. This ties into the second limitation of the data: due to the camera's positioning, the research team could not determine whether any cross traffic was present when vehicles approached the STOP sign. As a result, they were unable to ascertain whether drivers chose to stop or were compelled to do so because of cross traffic.

Speed Data

The research team compared mean speeds before and after the installation of treatments. Table 6 presents the results for the five signs for which speed data was collected. A negative value indicates a decrease in speed after treatment installation, while a positive value signifies an increase. The table also includes *p*-values, with bold numbers denoting statistically significant changes at a 95-percent confidence level.

There were some notable but small decreases in speeds following treatment installation. The most significant initial speed reduction was observed for the oversized Curve Warning sign, where mean speeds were approximately 1.5 mph slower in the initial-after period compared to the before period. However, in the second-after period, speeds returned to levels seen before the treatments were applied.

For the Speed Limit sign featuring the fluorescent yellow NOTICE panel, mean speeds decreased by 0.46 mph in the initial-after period and by 1.39 mph in the second-after period compared to the pre-treatment speeds. The larger Speed Limit sign showed a mean speed reduction of about 0.94 mph in the second-after period relative to before treatment installation. Additionally, the Speed Limit sign with the white retroreflective strip and the second oversized Curve Warning sign experienced mean speed reductions of 0.47 mph (initial-after) and 0.54 mph (second-after), respectively.

Table 6. Change in Mean Speeds for All Vehicles for Virginia.

Sign	Posted/ Advisory Speed (mph)	Before Mean Speed (mph)	Initial-After Mean Speed (mph)	Second-After Mean Speed (mph)	Change in Speed, Before o Initial-After (Mph)	Change in Speed, Initial-After to Second-After mph)	Change in Speed, Before to Second-After (mph)
Used oversized Curve Warning sign (1)	55/40	54.8	53.3	55.23	**–1.50 ($p < 0.01$)**	1.58 ($p = 1.00$)	0.08 ($p = 0.87$)
Added yellow NOTICE header to	45	50.89	50.44	49.7	**–0.46 ($p < 0.01$)**	**–0.93 ($p < 0.01$)**	**–1.39 ($p < 0.01$)**

Sign	Posted/ Advisory Speed (mph)	Before Mean Speed (mph)	Initial-After Mean Speed (mph)	Second-After Mean Speed (mph)	Change in Speed, Before o Initial-After (Mph)	Change in Speed, Initial-After to Second-After mph)	Change in Speed, Before to Second-After (mph)
Speed Limit sign							
Increased Speed Limit sign size	45	49.68	49.78	49.12	0.10 ($p = 0.94$)	**–1.04 ($p < 0.01$)**	**–0.94 ($p < 0.01$)**
Added white retroreflective strip on Speed Limit sign	55	58.31	57.84	59.14	**–0.47 ($p < 0.01$)**	1.07 ($p = 1.00$)	0.60 ($p = 1.00$)
Used oversized Curve Warning sign (2)	55/40	45.73	—	45.19	—	—	**–0.54 ($p = 0.05$**

—No data.
Note: The *p*-value corresponds to *t*-test with one-sided alternative hypothesis. Small values suggest that speeds fell over time, and large values suggest that speeds did not fall over time.

SPACE LEFT BLANK TO FACILITATE TABLE FORMATTING

Table 7. 85th-percentile speeds for Virginia.

Sign	Statistic	Before	Initial-After	Second-After
Used oversized Curve Warning sign (1)	Q85	61.00	60.00	61.00
Used oversized Curve Warning sign (1)	SD	7.27	7.80	7.13
Added yellow NOTICE header to Speed Limit sign	Q85	56.00	56.00	55.00
Added yellow NOTICE header to Speed Limit sign	SD	5.60	5.70	5.44
Increased Speed Limit sign size	Q85	54.00	54.00	54.00
Increased Speed Limit sign size	SD	4.66	4.66	4.69
Added white retroreflective strip to Speed Limit sign	Q85	63.00	63.00	64.00
Added white retroreflective strip to Speed Limit sign	SD	5.36	5.57	5.14
Used oversized Curve Warning sign (2)	Q85	53.00	—	51.00
Used oversized Curve Warning sign (2)	SD	8.79	—	6.91

—No data.

Mean speeds were analyzed based on vehicle classification (small, medium, large). However, no significant differences in average speeds before and after treatment installation were found based on vehicle size, and the research team noted a limited number of small vehicles during the study periods. The conspicuity treatments implemented in Virginia resulted in only minimal reductions in vehicle speeds.

Virginia Eye Tracking

The research team analyzed data from 48 participants, manually recording glances at each sign and the speedometer whenever the signs were visible. They also noted critical variables, such as the presence of leading vehicles and weather conditions. A full Poisson regression model was fitted to both the glances at each sign and the glances at the speedometer, using stepwise selection to eliminate variables that did not significantly impact the models.

The results showed that participants looked at Sign 1 (duplicate signs) and Sign 2 (fluorescent yellow NOTICE headers) more frequently than the control signs. Additionally, they glanced at the speedometer more often when Signs 1 and 2 were visible compared to the control sign. Sign

3 (white retroreflective strip on the signpost) did not yield statistically significant results for the number of glances at the sign or the speedometer.

The research team identified age and gender as influential variables. Older participants made fewer glances at the signs compared to younger participants, with age considered as a continuous variable indicating that higher ages led to fewer glances tto the sign. Male participants looked at the speedometer less often than female participants. Furthermore, the presence of a leading vehicle was associated with fewer glances to the signs and even fewer glances to the speedometer.

CONCLUSION

Overall, the study found that conspicuity treatments applied to Speed Limit signs generally resulted in only minimal reductions in driver speeds. Eye-tracking data showed that participants looked more frequently at signs with duplicate displays and fluorescent yellow NOTICE headers compared to control signs. Additionally, drivers paid more attention to their speedometers when these conspicuity treatments were present. However, the addition of white retroreflective strips to signposts did not produce statistically significant results in terms of glance frequency or speedometer attention. These findings suggest that while conspicuity enhancements might improve visibility, they do not necessarily lead to changes in driving speed.

For Curve Warning signs, using oversized signs resulted in only minimal reductions in mean speeds, with one oversized sign even associated with a slight speed increase. Treatments like white retroreflective strips, sign duplication, and increased sign sizes appeared ineffective in altering mean speeds, while fluorescent NOTICE headers showed more promise. It’s important to note that these findings were derived from different states with varying environmental and traffic conditions, which could influence driver behavior.

Regarding stopping and turning behaviors, results were also varied. Yellow retroreflective strips on railroad signs in New Hampshire increased compliance, while their use on pedestrian warning signs had little effect overall, except for a slight decrease in stopping at ramps in one location. The fluorescent yellow NOTICE header on a NO RIGHT TURN ON RED sign did not change turning behavior, and a red retroreflective strip on a STOP sign in Virginia showed no immediate effect on complete stops but resulted in a significant increase during a later observation period. Given that most sites were familiar to drivers, the enhancements might have drawn attention without prompting behavioral changes. This suggests that conspicuity improvements could be more effective for unfamiliar signs or those introducing new regulations. A broader examination of various treatments and installations could provide deeper insights into their impacts on driver behavior.


YIELD

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PAPER 006

Case Study on the Application of Temporary Orange Pavement Markings in Work Zones

The contents of this document has been modified from a Synthesis Document ATSSA compiled for its members. The contents are intended for informational purposes only as the industry investigates the use of orange pavement markings as an experiment.

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To further advance traffic safety and reduce work zone injuries and fatalities, ATSSA promotes innovation in work zone traffic control practices, materials, and equipment. Recently, the ATSSA Pavement Marking Committee brought together individuals from various public and private organizations with different backgrounds to identify needs and challenges, share new technology and information, and discover and advocate for proven safety countermeasures. One recent focus for the committee included the application of temporary orange pavement markings in work zones, an experimental technique per the Manual on Uniform Traffic Control Devices (MUTCD). To assess orange pavement marking practices, ATSSA created a task force focused on this innovation. Seven DOTs have applied orange pavement markings in various configurations to improve work zone safety for the traveling public.

Since 1969, the American Traffic Safety Services Association (ATSSA) has represented companies and individuals in the traffic control and roadway safety industry. ATSSA members provide many features, services, and devices used to make America's roadways safer. Being our nation's leader means that ATSSA remains current and relevant, and ATSSA continuously strives to address modern day problems through collaboration and consensus, to move Toward Zero Deaths on the nation's roads. ATSSA represents the roadway safety infrastructure industry with effective legislative advocacy, roadway safety training, and a far-reaching member partnership. ATSSA helps shift the focus of transportation towards saving lives and reducing injuries.

As evidenced below, ATSSA's core purpose is to advance roadway safety.

- ATSSA members accomplish the advancement of roadway safety through the design, manufacture, and installation of road safety and traffic control devices.
- ATSSA brings together members, road safety experts, and public agencies to identify and solve road safety issues.
- ATSSA's primary focus is to move Toward Zero Deaths on our nation's roads.
- ATSSA staff, members, and local chapters have a finger on the pulse of the needs and challenges facing practitioners today.

ATSSA is a member partnership comprised of approximately 1,500 companies representing over 11,000 industry professionals in sign manufacturing, pavement marking, guardrail and barrier, traffic services, and traffic signals technical divisions. ATSSA carries out its work as a national-level highway safety advocate through a robust and comprehensive structure of committees, subcommittees, councils, and task forces, with each group having a specific purpose. The Association depends on the dedication and commitment of its members to ensure the vitality of the Association's progress. Each year, hundreds of members serve on committees. ATSSA's work with transportation officials within ATSSA membership, its chapter network, and during ATSSA's Annual Convention and Traffic Expo have also resulted in meaningful and long-term relationships with state departments of transportation (DOT) that give ATSSA an inside look at specific organizations to gain a deep understanding of an individual state's needs, trends, or requirements.

In 2023, ATSSA created a synthesis document[1] on the application of different types of temporary orange pavement markings in the United States. To date, the following agencies have implemented this work zone application:

- California Department of Transportation (paint)
- Indiana Department of Transportation (paint and tape)
- Kentucky Transportation Cabinet (paint, thermoplastic)
- Michigan Department of Transportation (paint)
- North Texas Tollway Authority (thermoplastic)
- Washington Department of Transportation (paint)
- Wisconsin Department of Transportation (paint, epoxy and tape)

Orange pavement markings have also been used internationally in Australia, Canada, New Zealand, and Switzerland. The international applications typically focused on efforts to match the pavement marking colors to the color of the channelizing devices and other features in use. In general, the primary focus is on alleviating the issue of "ghost" markings at permanent lane line and edge line locations that are removed for the new construction traffic pattern. One consistent theme from U.S. experiments is greater visibility of the temporary markings at locations with complex driving maneuvers, such as lane shifts approaching the workspace.

The following section highlights this traffic control innovation as an example of the how ATSSA promotes innovation in work zone traffic control. The following section highlights Wisconsin's application of orange pavement markings.

Interstate 94 locations near Milwaukee and Oconomowoc, Wisconsin

The Wisconsin Department of Transportation (WisDOT) installed orange temporary pavement markings on I-94 as part of the $1.7 billion, six-year Zoo Interchange Reconstruction Project on the west side of Milwaukee. This interchange is a major freeway connector for downtown Milwaukee, Chicago, Madison and Fond Du Lac and carries over 350,000 vehicles per day at the intersection of I-94 and Interstate 41.

WisDOT considered the potential benefits of applying the orange pavement markings, including greater visibility for drivers, especially for lane shifts in winter conditions. However, the DOT also considered several challenges prior to implementation, including industry experience, availability of orange marking materials, specification needs, and cost effectiveness.

Project Summary	
Location:	Interstate 94 (Zoo Interchange) and a section near Oconomowoc
Cross Section:	4-lane freeway with limited shoulders during construction
Material Used:	Non-fluorescent paint, fluorescent epoxy, and tape
Configuration:	Lane line and edge line markings
Timeline:	2014 – 2016
Metrics:	Percentage of vehicles straddling lanes (video), visibility, driver comprehension, overall driver perception

In developing the specifications for the project, potential marking solutions included paint with standard glass beads, paint with enhanced prismatic beads, Methyl Methacrylate (MMA), and epoxy. WisDOT developed a change order for the contractor that included epoxy supplied by the DOT (in cooperation with a local vendor) with provisions for the contractor to perform the application. The experimental project request included an 18-month evaluation period, with one direction maintained with traditional pavement marking colors to serve as a control for comparison.

The initial application worked well (See Figure 1), and WisDOT requested that FHWA allow orange markings in both directions, which FHWA granted. After the first year of application, WisDOT requested a 2-year extension to further experiment on a bridge re-decking project on I-94. This project included a crossover with orange temporary tape installed throughout the crossover. Evaluation results showed similar metrics between control sites and the bridge deck project. From driver surveys, 27% of drivers noted the orange markings were much easier to see than white markings and 20% noted the orange markings were somewhat easier to see. Engineers also noted better visibility with the orange tape. After several adjustments to the orange markings, WisDOT determined that using fluorescent orange epoxy from November to April worked well for winter conditions and a non-fluorescent orange latex paint supplemented by orange raised pavement markers (RPM) worked well from May to October for warm weather conditions. A less vibrant orange paint was shown to have better ultraviolet light resistance.

Additionally, WisDOT procured orange preformed tape for use in locations where small sections of the orange markings required fixes, such as where potholes may form along the painted line. WisDOT also determined that a 5-inch-wide pavement marking would provide enhanced visibility as compared with a traditional 4-inch-wide marking.

Assessment of cost effectiveness included metrics such as improved traffic safety during the winter, in addition to contractor economies of scale for volume of application. With application trucks already using traditional white and yellow paint, each application of orange required the contractor to clean the equipment prior to placement – leading to some cost increases in application. While the cost of orange markings was higher in each case, WisDOT concluded that there was enough increase in overall traffic safety benefit with use. In addition, WisDOT anticipates lower costs with more widespread use.

Figure 1. Orange Temporary Marking on Asphalt Surface

User surveys from local businesses showed that initial orange markings were not as visible as users expected, especially at night. The addition of the enhanced prismatic beads and higher overall material fluorescence produced an 80% favorable rating by surveyed users for the orange temporary pavement markings. Video evidence showed drivers maintained their lane better and the DOT received 95% fewer complaint calls regarding pavement markings. The percentage of vehicles straddling lanes was marginally lower under dusk and rain conditions with the orange pavement markings. Law enforcement and project staff also observed better driver navigation at the lane shifts.

Several observations from the orange marking experiments are included in the list below.

- Temporary orange contrast markings may be an approach that some agencies take since permanent markings often include black contrast lines in addition to the traditional yellow and white edge and lane lines.
- Agencies are commonly using orange markings at the approaches to project lane shifts to alleviate lane straddling and improve safety, especially for larger commercial vehicles.
- Temporary orange marking application should be evaluated against other types of strategies, such as longer shifting taper lengths that accommodate larger vehicles (i.e., exceeding the 1/2L minimum shifting taper as outlined in the MUTCD).
- Some agencies also use wider lane lines on transitions within work zones to alleviate the potential risks of drivers missing the intended movements (even with appropriate signing).
- Future application of connected vehicle technologies will need to include further investigations to determine if the variation in color of orange markings will identify work zones or approaches to lane shifts or other more complex temporary traffic patterns.
- Guidance on line widths, material thickness and type of material best suited to long-term work zone applications could benefit decision-makers and those implementing policies for use of orange markings as a work zone safety strategy.

REFERENCES

1. American Traffic Safety Services Association, *Synthesis Report on the Application of Temporary Orange Pavement Markings in Work Zones,* June 2023


JUNCTION
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Observational Assessment of the Effectiveness of Traffic Control Devices on Lane Use Compliance on Motorways

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CONTENTS

TABLE OF FIGURES

ABSTRACT

Modern roadway design philosophy assumes that slower and non-continuing vehicles remain in the outside lanes of motorways, which are median-divided, multi-lane, high-speed free-flow roads characterized by controlled and limited access, e.g., freeways. Correspondingly, proper selection of a travel lane by the vehicle operator is generally understood to enhance safety and operational performance.

Lane selection according to the *basic rule* assumes that the innermost (median-adjacent) lane of the roadway in each direction functions as an auxiliary lane, being reserved for vehicles expediting passing maneuvers and subsequently vacating the lane. Cultural perspectives indicate a conflict between those who value the flexibility of passing lane availability and others who demand strict compliance with the speed limit, constraining the availability of this auxiliary lane. Such inflexible adherence to speed limits by vehicle automation systems and Intelligent Speed Assistance will further exacerbate the prevalence of antisocial inappropriate lane use.

This paper presents a model developed to identify the position (*leftward*, *rightward*) and status (*expediting*, *blocking*, *cruising*) of vehicles using the inside lane, based on time-space relationships. Application of this discrete model to a heuristic field investigation of basic rule conformance and responsiveness indicated limited local and systemic effectiveness of regulatory signing in the United States. Cruising and blocking behaviors were observed to be commonplace, suggesting imbalanced enforcement with respect to speed and a need for additional auxiliary lanes along uphill grades and within interchanges. Alongside adjustments to policy, enforcement, and education, tactical deployments of active-feedback signing hold potential for improving conformance with the basic rule.

TREATISE

In the early 20th century, concomitant with an increase in vehicle capabilities at higher speeds, transportation engineers began to design high-speed roadways that featured separation of traffic movements. Roadways such as the Autobahn in Europe and the Pennsylvania Turnpike in North America were designed for free-flowing motorized traffic, allowing for unlimited speeds on account of what can be described as the basic rule. The basic rule is imbued in modern design philosophy, a means of promoting courtesy and order. It governs the use of the innermost lane – the left lane in left-hand-drive countries – requiring users to keep right unless actively passing another vehicle, such that any vehicle in the left lane must yield the left lane to all faster traffic.

The basic rule thereby also requires that heavy vehicles and slower vehicles will also typically keep right and are often restricted to the right lane or lanes for the purposes of improving operations. Traffic operations engineers thus often seek to limit passing activity that would inhibit the on-demand use of the left lane by faster vehicles while planning and implementing projects that improve motorway capacity and safety to support the broadest possible applicability of the basic rule, which is not consistently applied where inadequate capacity exists or where safety risks are identified.

Of interest to many in the transportation field is the notion that the basic rule itself is ubiquitous and often signed in pedestrian, bicycle, and mixed-use applications. At airports with moving walkways, patrons are asked to stand to the right and walk on the left with a combination of signing and word messages incorporated into the treads of the moving walkway itself. On shared-use paths, people walking are expected to keep to the right to allow faster users, such as people bicycling, to pass on the left. From an early age, in the classroom and the lunch line, children learn that standing to the right and yielding the left side of the body to moving and faster people is commonplace. This lesson inferred from the simple observation of movement and occasionally enforced with the voice of a kindergarten teacher, is a reminder of the basic courtesy that is offered to all.

Because the intent of the left lane under free-flow conditions is that it serves a transient purpose, the left lane is considered an auxiliary lane, even as it is typically continuous. Motorway design standards in Europe, the Middle East, and Southeast Asia allow for a left shoulder width that is narrower than what is called for in the publication *A Policy on the Geometric Design of Highways and Streets*, a design resource used in the United States of America referred to as the *"Green Book",* published by the American Association of State Highway and Transportation Officials. The *Green Book* itself describes auxiliary lanes, including deceleration, acceleration, and part-time use lanes. The latter application is the purpose of the left-most lane on the vast majority of rural motorways and rural multi-lane divided highways with motorway characteristics. The exception to the transient availability of the left lane occurs when flow regimes exceed the capacity of the right lane, a function of demand, the composition of the traffic stream, and environmental conditions.

Such free-flowing roads ("freeways") are designed for motor vehicles ("motorways"), providing an express route compared to conventional roads ("expressways"), incurring dramatic benefits in terms of time, comparative safety performance, fuel economy, and emissions reductions, particularly when compared to economic productivity. The distinct advantage of a motorway lies in its provisions for the separation of traffic. Grade separations are used to remove conflicts between the motorway and intersecting roadways, separating crossing traffic. Roadway geometry is used at junctions to provide for decelerating and accelerating traffic, separating maneuvering traffic from continuing traffic. Continuing traffic itself is also likewise separated by the basic rule through stratification, without the need for barriers or bridges.

Even without accommodations for separating traffic, the horizontal and vertical alignment of a four-lane rural free-flow road often incurs higher speeds in tangent segments and through sag vertical curves. Correspondingly, differing energy demand profiles in various segments illustrate the need for speed-based stratification of vehicles of contrasting power delivery capabilities. The effects of inferred design speed[a] must therefore be considered irrespective of the provision of access, given that roadway alignment influences driver selection of speed, along with roadside design.

Stratification of vehicles among the lanes of the motorway as a result of slower-moving vehicles occurs in concert with the harmonization of vehicle and vehicle operator capabilities. Reserving the left lane of the motorway for transient operations by the most flexible and capable vehicles preserves order in operations on the motorway, one of the primary goals of a motorway operations engineer. Promoting order in high-risk environments is a means of achieving optimal safety performance. Stratification according to contrasting vehicle speeds and vehicle capabilities is a function of user action. Users perform the task of choosing a lane in order to maintain occupancy of the appropriate lane. This practice is colloquially referred to as lane discipline and is distinct from lane use control, which is implemented most often with regulatory signs, but sometimes supplemented with markings or signals, indicating the use of lanes for intended turning movements or restrictions on vehicle types and activities.

Taken together, the action of lane discipline based on lane use control can be considered lane use compliance, the topic of this paper. Lane use compliance, being a function of the user and the vehicle, is also influenced by the actions of other users, particularly with regard to vehicle posture and vehicle indications, including the headlights, a common practice in Europe.

This paper presents the results of field observations, a sign inventory, a practice-based model for passing activity, and recommendations related to further analysis and safety-driven countermeasures. A recommendation for follow-on research activities includes suggestions for revisions to existing signing and marking applications, changes to policies, and proposed practices that can enhance the performance of at-risk motorway segments and corridors.

[a] The concept of inferred design speed was popularized in pioneering research led by practitioners including RJ Porter. Motorways and rural highways typically feature generous horizontal and vertical curves, an indication to vehicle operators that the road will safely support speeds much higher than the actual design speed, which typically controls the minimum values for various geometric design features.

INTRODUCTION

Motorway operators worldwide use a variety of traffic signing and lane markings to convey messages to road users regarding the anticipated, appropriate, proper, and, as required, lawful, use of various lanes on roadways. On arterial roads approaching intersections, signing and markings indicate lane use control, or restrictions on the use of lanes. Similarly, on motorways, arrows, letters, and symbols are used to convey guidance and regulatory information in advance of interchanges and along segments. Restricted-use lanes, such as those dedicated to use by high-occupancy vehicles, are often continuously marked and signed at intervals as little as 500 meters (approximately 1500 feet), often accompanied by pavement marking symbols such as a passenger bus outline or a diamond.

Lanes not intended for use by continuing traffic are considered auxiliary lanes, with a variety of applications being described in the AASHTO *"Green Book"*. The anticipated use of auxiliary lanes is not merely to be inferred but is often an intended outcome of roadway geometric design for both intersection auxiliary lanes and continuous auxiliary lanes. In addition to geometric design cues such as taper rates and curb type, signing and markings apply to auxiliary lanes.

Intersection auxiliary lanes are typically dedicated to turning movements or, in some cases, passing of transient left-turning vehicles occupying the through lane. Located on intersection approaches and departures, the lengths of these auxiliary lanes for turning movements are typically determined by the expected queue length or required distance for vehicle velocity changes. Continuous auxiliary lanes are located along roadway segments and include lanes dedicated to various uses such as continuous right turns, mass transit vehicles, trucks when climbing vertical grades, part-time shoulder use, and, by custom and code in many places, continuing and unrestricted lanes dedicated to vehicles passing using the innermost lane.

Research Theory and Hypothesis

The impetus for this research activity is a growing concern regarding the safety performance of at-risk motorway segments. Such at-risk segments exhibit some degree of degradation in operations and marginal scores for surrogate safety measures, such as following distance. Often, this degradation in safety is evident in the failure to apply and enforce the *basic rule*. (The basic rule is described in the treatise that begins this paper, on pages 1 and 2.)

While certain operational effects can be readily corrected through spot capacity improvements, such as auxiliary lanes, these improvements may have limited effect if the basic rule is not inured and compliance enforced such that adherence to the basic rule is ubiquitous.

Identifying, characterizing, and assessing compliance with the basic rule will aid motorway traffic operations engineers with designing and implementing traffic control devices that induce compliance and aid enforcement of the basic rule, thereby protecting the liberty of travelers on the motorway with respect to vehicle and operator capabilities and limitations. In essence, such an approach to roadway operations respects human factors science, particularly with respect to behavioral analysis.

The working theory of this research activity is described in three parts, each of which describes characteristics of the basic rule, that is, that slower and heavier vehicles will remain to the right on motorway segments and that all vehicles will minimize time spent in the left lane by expediting passing maneuvers. Three theories regarding the basic rule are listed below.

1. **Basic rule compliance improves operations**, both in terms of safety performance and a reduction in behaviors with higher risk factors. Such behavior includes, but is not limited to, following too closely, sudden and erratic lane changes, and driving practices that may be associated with social-behavioral disorders, such as consistently denying other vehicle operators the use of a lane or repeatedly wantonly violating a signal indication.
2. **Basic rule compliance can be measured according to a space-time relationship** analysis of vehicles in the flow of traffic, such that violations of the basic rule are mathematically represented through conventional safety-based driving behavior and human factors analysis and, correspondingly, a means of improving the Level of Service.
3. **Basic rule compliance is an act of courtesy, influenced by statute, training, traffic control devices, enforcement campaigns, and the behavior of other drivers** with respect to vehicle posture; attention to basic rule compliance is a philosophical approach to motorway operations that values order and flexibility for the most capable users.

Based on this theory, a two-part hypothesis was used to provide a framework for evaluating the effectiveness of traffic signing related to use of the left lane on motorways.

Hypothesis 1 states "The approximate time-to-complete for a passing activity is a primary and **independent indicator of the disruption incurred by other vehicles intending to use the left lane** and can be related to the instantaneous observed Level of Service (an indication of the ability of vehicle operators to change lanes) by vehicles whose operators are not achieving the desired speed."

Hypothesis 2 states "Accounting for variances associated with geography, fraction of heavy vehicles, and the observed Level of Service in a segment, **it is common that vehicles will be inhibiting the flow of traffic in the left lane**."

Examination of these hypotheses is undertaken with an examination of vehicle state with respect to time. This examination considers the position of interacting vehicles and the change in position, which occurs as a result of speed changes, also resulting in changes in headways.

Description of Vehicle States

Contemporary literature does not appear to address a description of various vehicle states with regard to passing maneuvers. The vehicle states proposed in this research relate vehicle position to a space-time diagram, with the goal of measuring left lane occupancy in terms of *total time to pass*. Vehicle position can be characterized by lane selection, by relative position to other vehicles, and by the vehicle's impact on other vehicles.

Vehicles in the mixed flow of traffic include continuing and non-continuing vehicles. Vehicles remaining out of the left lane are *rightward* vehicles. Vehicles using the left lane are *leftward* vehicles.

Vehicles in either lane may be a *transient vehicle* or *cruising vehicle,* but cruising is explicitly disallowed by the basic rule yet effectively unavoidable once a certain volume threshold (level of saturation) is obtained. Any leftward vehicle can be a blocking vehicle. The status of *blocking* is conferred according to the *time tolerance* of the following vehicle, considering that the *time to pass* is based on the *relative speeds* and vehicle lengths.

Leftward vehicles expediting a passing activity of one or more vehicles are considered *passing vehicles*. Vehicles that are passing but fail to do so expeditiously are considered *micropassing* vehicles. Vehicles remaining in the left lane indefinitely after completing a passing activity, whether approaching a subsequent slower rightward vehicle or not, are *cruising* vehicles, irrespective of relative speed. Often, *cruising* vehicles become *blocking* vehicles when a faster *following vehicle* approaches, whether that faster vehicle is approaching *rightward* or *leftward*. Any *leading* vehicle that fails to vacate the left lane for a *following vehicle* with an incipient higher speed is considered a *blocking* vehicle, whether *cruising* or *micropassing*.

Even though a failure to vacate the left lane when cruising and maintaining a following distance of a rightward vehicle may not inhibit traffic, such cruising does force all faster following vehicles to make two lane change maneuvers in order to maintain speed. Mitigation of cruising and micropassing therefore reduces crash risk for numerous vehicles, particularly those traveling at higher speeds. Even when not inhibiting traffic, slower vehicles remaining in the right lane reduces conflicts for all faster vehicles, maintaining order on the motorway. Signing indicating this is used beyond most interchange ramps in several states, including Wisconsin, as displayed in the photograph below.

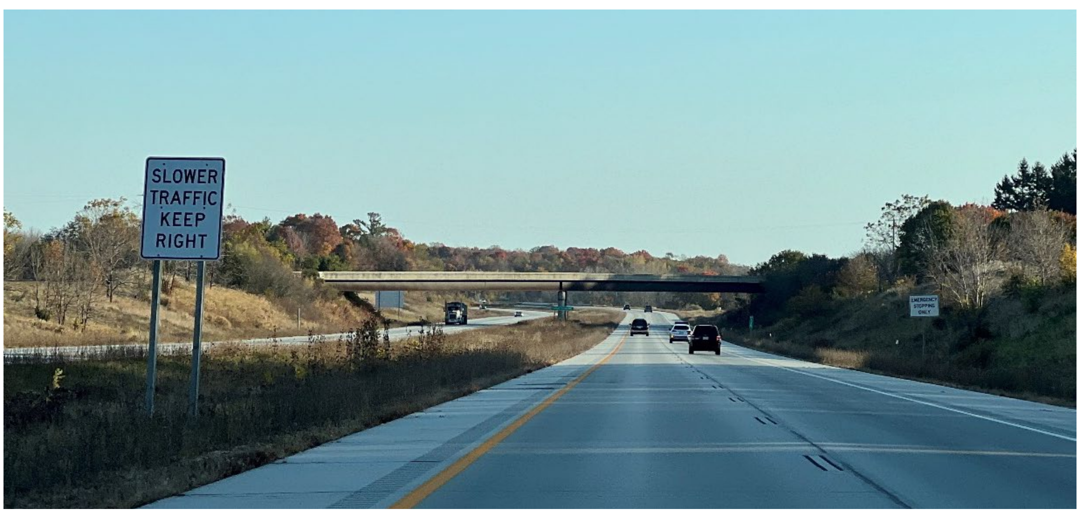


Figure 1 SLOWER TRAFFIC KEEP RIGHT signing along the Interstate 43 motorway in Wisconsin, USA

Various regulatory signing has been developed to discourage the presence of blocking and cruising vehicles. Among the states in the United States, signs largely reflect statutes laying out two distinct approaches. One approach is to preserve the left-most lane for passing only, irrespective of relative speeds. The other approach is to direct slower traffic to remain right or move right. Neither approach explicitly directs traffic to expedite passing, although statutes requiring traffic to KEEP RIGHT EXCEPT TO PASS can be cited in administrative and civil infractions involving *cruising* and *micropassing* alike.

Defining the Blocking Vehicle

The definition of a *blocking* vehicle is considered exclusively in terms of disruption to the existing speed, desired speed, or desired minimum headway of any following vehicle. Differences among vehicle operator perceptions prevent a fixed definition of a *blocking* vehicle. Vehicles with lower rates of power delivery and higher power-to-weight ratios may be less tolerant of *blocking* vehicles, particularly when approaching uphill grades. The balance between speed, deceleration, and power settings is expressed in the selection of headway by *following* vehicles.

In Figure 2, below, a rightward following vehicle “f” is approaching two vehicles. A *blocking* vehicle “b” is failing to expeditiously pass the rightward cruising vehicle “r”, or *micropassing*. Once the following vehicle reaches its minimum tolerance for following distance, expressed in terms of time, the vehicle operator will move into the left lane, where it becomes both a *following* and a *passing* vehicle. Where basic rule compliance exists, the speed of the vehicle will remain unchanged, or the operator may select a higher speed to expedite the passing maneuver. In this case, however, should the blocking vehicle fail to increase speed, the result is a reduction of the speed of the faster vehicle to control headway.

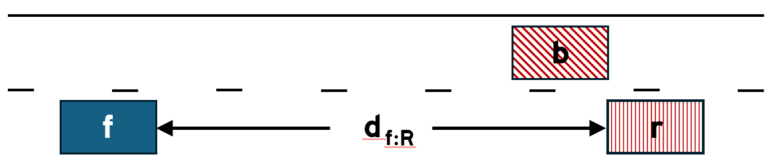


Figure 2. Graphical description of an incipient passing maneuver wherein the fastest *passing* vehicle “f” is subjected to potential delay by a *micropassing* vehicle “b”, thereby a *blocking vehicle*

In many localities in the United States, passing on the right is legal (under specific circumstances), in contrast to the German Autobahn. Aggressive law enforcement might assume that behavior to be a violation of certain statutes in some regions. Even if passing on the right is possible without approaching any minimum tolerable headways, the *blocking vehicle* in the left lane is defined by its relative position and relative relationship to the rightward vehicle; rightward passing is assumed to be nonviable.

Crucial Relationship to Following Distance

Because *blocking* vehicles often incur following distances that are shorter than desirable at higher speeds, particularly in conditions where demand exceeds that supported by Level of Service A or B[b], such vehicles directly impact operations and increase crash risk. This observation is uniform on all motorways worldwide, irrespective of the presence of speed restrictions and often despite the presence of traffic law enforcement activity. The relationship between headway and speed is an expression of efficiency, being determinants of the volume of a lane at any given screen line.

Headways are a function of speed and following distance. Reducing the occurrence of sub-optimal headways reduces the likelihood of speed and/or lane changes that disrupt the flow of vehicles in a lane or group of lanes. In this sense, the presence of an auxiliary lane allows for headway management by *following* vehicles and those intending to pass, so long as passing is expedited to ensure the availability of the auxiliary lane for other vehicles. Expeditious passing reduces the workload of the vehicle operators using the passing lane and reduces the likelihood of speed variability leading to sub-optimal headways.

Maintaining Left Lane Availability

The relationship between workload and Level of Service in the context of auxiliary lane availability is likely the most important finding of this paper. The availability of the passing lane on motorways is directly correlated theoretical behavioral safety performance, is likely associated with improvements in actual safety performance, and likely incurs dramatic public health and societal benefits across a wide variety of measurement metrics associated with human interaction and social cohesion.

[b] The computational and observational methods for determining or evaluating the Level of Service (LOS) are described in the *Highway Capacity Manual,* published by the Transportation Research Board of the National Academies. In recent years, some activists have attempted to diminish the use of LOS as a performance metric in urban environments at signalized intersections. The applicability of LOS to motorway segments is invaluable, however, because it provides a distinct correlation between volume, capacity, and, most importantly, the inhibition of lane changes by vehicles. Inhibition of lane changes reduces the overall value obtained by operators of vehicles with more flexible performance profiles. Inhibition of lane changes also incurs disbenefits in terms of safety because following distances are reduced in nearly all flow and maneuvering regimes.

MODEL DEVELOPMENT

For this research, the development of a model to address passing behavior considers both the functional activity and the measured relationships based on vehicle states.

Functionally, passing maneuvers on same-direction roadways involve observation, perception, reaction, and management of the vehicle controls on the part of the vehicle operator. Vehicle operators must assess following distance, gap length, relative speed, and the rate of change in the gap length. Lane change maneuvers are well-represented in the literature, typically understood in the United States to involve vehicles traveling within the pace, where large differences in vehicle speeds are not expected. Operation in an adjacent lane involves the assessment of leading traffic and precedes a second gap selection exercise and a lane change maneuver to the right.

Vehicle operator perception of delay is inferred from various changes in traffic flow experienced by the operator. A speed adjustment, headway adjustment, and time following a blocking vehicle are all factors in the behavioral response to a blocking vehicle. The time required by a vehicle for passing is therefore the dominant metric for assessing the road user experience. Variables used in passing equation are provided in Table 1 below.

Distance and Time Relationships

The framework presented here assumes that conditions associated with motorways prevail. In localities where unlimited speed conditions are in effect, the difference in speed between rightward vehicles ahead and vehicles intending to pass can exceed 150 km/hr (93 mi/hr). The tolerance for following distances at which lane changes are initiated are subsequently greater, although these tolerances vary based on terrain and the capabilities of the passing vehicle in conjunction with operator proficiency, confidence, perception of risk, and assessment of traffic conditions. In the United States, vehicle operators are more likely to be inexperienced with vehicle speed differences exceeding 40 km/hr (25 mi/hr), given that the pace on motorways in the United States occupies a smaller band.

Harmonizing observations irrespective of differences in vehicle speeds is accomplished with respect to time rather than distance. Time is likewise another component of vehicle operator tolerance, particularly with respect to blocking vehicles. With respect to time, blocking vehicles are therefore those that occupy the left lane for more time than is expected by a following vehicle with an intended higher speed. Time is also the means of measuring headways and following distances, which are functionally equivalent for most scenarios.

Operational Regimes

The model developed for this research assesses the relative position and space-time relationship of vehicles in the flow of traffic and characterizes vehicle activity according to time. Vehicle descriptions from the introduction[c] characterize the degree to which vehicles inhibit the flow of traffic.

[c] Refer to pages 3 and 6 of this document for a review of the characterization of various vehicles with respect to position, activity, and duration of occupancy in the passing lane.

Typical State

During typical operation that is compliant with recommended following distances, vehicles will exhibit a headway of two (2) or even three (3) seconds, which is nearly equivalent to a following gap time of the same duration. Competent or otherwise lawful drivers will allow additional time behind large vehicles, during inclement weather, and in lighter traffic. In vehicles equipped with Automated Driving Assistance System (ADAS) features, following distances can be set using Adaptive Cruise Control (ACC); some ACC systems will reduce vehicle speed to maintain following distance, a means of managing headway and reducing the risk of a rear-end collision.

Functional Description of Passing Activity

A rightward vehicle becomes a passing vehicle as soon as the lane change maneuver leftward is initiated. Prior to this, following rightward vehicles approaching another rightward vehicle are considered *incipient passing vehicles*. The determination of this designation varies according to the difference in speed and acceptable headways.

The passing maneuver itself is defined as a deviation from the rightward position. In some cases, this deviation involves travel closer to the pavement markings or joint separating the rightward lane from the leftward lane. In this analysis, that behavior is not included in the passing equation. However, the time taken to close from the earliest acceptable lane change headway to the critical headway is included, as the expectation of following vehicles is that a lane change could occur at any time after the acceptable lane change headway is achieved.

Closure to Critical Following Distance

Vehicle operators approaching another vehicle from behind must monitor the vehicle ahead and adjust speed as needed to complete the task of closure to a critical headway. In practice, this is a following distance that correlates to time. Following distances of 2 to 3 seconds are desirable and provide for adequate perception-reaction time in most circumstances.

Observations conducted for this research effort indicate variations between selected following distances according to the circumstances, outlined in the following three scenarios:

1. A rightward following vehicle approaches a slower rightward vehicle and executes a leftward lane change. Observed following distances range from 10 seconds to 1 seconds.
2. A rightward following vehicle approaches a slower rightward vehicle and cannot execute a leftward lane change, thus following the leading vehicle until the left lane is clear. Observed following distances range from 5 seconds to 1 second.
3. A leftward vehicle (either cruising or having just completed a lane change maneuver) approaches a leading but slower leftward vehicle. During this research effort, observed headways ranged from 3 seconds (uncommon) to less than one vehicle length, often less than 0.5 seconds, or 15 meters (approximately 50 feet, or two car lengths) at typical free-flow speeds. Occasionally, following distances of less than one car length were observed.

Observed headways in the latter scenario are often inadequate to accommodate the perception-reaction time (PRT) necessary in the event of an immediate braking activity of the leading vehicle, increasing the risk of a high-speed rear-end collision. In recognition of this risk, following too closely is a term used in police crash reports regarding the selection of an inappropriate following distance.

Incipient Passing and Leftward Lane Change

As the following distance decreases and vehicle operators assess the position and relative speeds of other vehicles, including vehicles ahead, vehicle operators typically prepare for a lane change maneuver. During this stage, a passing maneuver is evaluated and executed as the following distance reaches the acceptable tolerance. The presence of other vehicles can incur a lane change sooner than what is typical (larger headway) or later than what is typical (shorter headway), particularly when accommodating a leftward vehicle that will pass prior to the subject vehicle executing the lane change maneuver.

Observations conducted during the course of this research activity indicated that most vehicle operators will adjust vehicle speed to avoid headways of less than one (1) second, while inattentive vehicle operators with poor perception capabilities may execute a lane change with headways of up to 15 seconds, even if the rate of change in the headway does not present a hazard.

Envelope Approach, Maintenance, and Departure

During this stage of the passing activity, which follows the closure to critical headway, incipient pass, and leftward lane change stages, the following distance of the leftward vehicle with respect to the rear face of the rightward vehicle is reduced to zero. The subject vehicle then moves alongside the rightward vehicle and continues in the left lane until a headway of sufficient tolerance is obtained. Some vehicle operators will accelerate slightly during the stage, particularly alongside larger and heavier vehicles. When vehicles discharging airborne debris are in the right lane, a passing vehicle may maintain a longer following distance

Rightward Lane Change

The basic rule informs vehicle operators that continued operation in the left lane is not allowable unless a passing activity is occurring. Operators therefore seek the earliest opportunity to conduct a rightward lane change, which is typically predicated on reaching a minimum leading distance, which courteously allows for the rightward vehicle to maintain speed in conjunction with a desirable following distance.

Driver education programs suggest various ways to ensure that an adequate leading distance is offered by the passing vehicle. One such method involves visually determining that both headlights of the following vehicle are visible in the rear-view mirror of the passing vehicle. Operators of vehicles with blind-spot monitoring technology may depend on the indications afforded by the system rather than by an observational rule. In some cases, the duration over which these systems indicate a blind spot may not provide sufficient following distance for the rightward vehicle following a rightward lane change by the passing vehicle. Maintenance of leading distances by passing vehicles (equivalent to following distance for the following rightward vehicles) impacts headway and the selected speeds of other vehicles.

Driver education and road safety program materials typically suggest that additional distance be afforded when passing trucks. The leading distance afforded prior to a lane change to the right thereby varies according to the speed of the passing vehicle, any acceleration of the passing vehicle, the relative change in speeds of the relevant vehicles, and the speed of the rightward vehicle.

Downstream Interactions

While not considered part of the passing maneuver phase that blocks the path of other vehicles, a downstream vehicle can incur speed changes by the passed vehicle if the rightward lane chance occurs too soon and the selected leading distance incurs a speed change or lane change by a rightward vehicle.

Motorway Passing Equation

Developed in support of research activities, the motorway passing equation expresses the various stages of the passing maneuver as a sum of the time required to conduct each phase, as described above. Time is related to selected speeds, distances between vehicles, and vehicle lengths, with speed and distances between vehicles being variable.

t	time (seconds)	time required for completion of various stages, variable with speed
s	speed (km/hr)	speed of vehicles, independent
d	distance (meters)	distance between vehicle faces, e.g., headway, variable with speed
l	length (meters)	length of vehicles, independent

Table 1 List of variables used in the motorway passing equation

For the purposes of the equation, all passing maneuvers are considered fulfilled and the passing vehicle is uniformly referred to with a subscript p, irrespective of position. Positions include rightward following, leftward following, leftward adjacent (within the lateral projection of the slower vehicle's longitudinal envelope), leftward leading, or rightward leading vehicle. The relative time achieved determines the passing vehicle's status, whether expediting or micropassing. A cruising vehicle is not initially positioned rightward and likewise will not be positioned rightward at the conclusion of the pass.

In addition to considering the time required to conduct each phase of the passing maneuver, the Motorway Passing Equations also consider the speeds (s) of the passing and rightward vehicles, the distances between the following vehicle and the slower vehicle (upstream), and the distances between the slower vehicle and the leading vehicle (downstream). Vehicle lengths are also referenced as l_p and l_r, for the passing and rightward vehicles, respectively.

u	upstream (*d*, *l*)	denotes a vehicle upstream (following) of another vehicle
e	envelope (position)	denotes a vehicle that is occupying any portion of the lateral envelope of an adjacent vehicle
p	passing (position, *t*)	denotes a vehicle position in a lane to the left of rightward vehicles; denotes the time for the entirety of the passing activity, from the minimum following headway to the minimum leading headway, which may not include lane change activities
d	downstream (*d*, *t*)	vehicles ahead of rightward and followed passing vehicles are considered downstream, or further along the roadway
r	rightward (position)	denotes a vehicle position in a lane to the right of the passing vehicle
l	leftward (position)	denotes a vehicle position in the lane to the left of the vehicle being passed.

Table 2 List of subscripts designating position and other references for time (*t*), distance (*d*), and vehicle length (*l*) variables

Various subscripts pertaining to position and stages of the passing activity are applied to distinct time intervals, *t*. These terms of the passing equation, derived from speed, distance, and length variables and assigned by position and stage, are listed in Table 3 on the following page.

Term	Definition	Function Notes	Typical Values
t	total time occupying left lane, typically greater than t_p	$t = t_{fu} + t_l + t_u + t_e + t_d + t_r$	Less than 30 seconds is desirable for interactions between passenger cars
t_{fu}	time from earliest lane change opportunity to minimum following distance	Variable, depends on presence and relative speeds of leftward vehicles (both following and leading) attention, and tolerance of vehicle operators	Typically 5 to 30 seconds
t_l	time moving leftward	Primarily a function of vehicle speed and lateral acceleration tolerance, but influenced by presence of other vehicles	Typically 3 to 5 seconds
t_u	time occupying left lane, upstream and clear of rightward vehicle	Function of relative speeds, s_p and s_r, and initial d_u	Typically two or three times t_e
t_e	time adjacent to the rightward vehicle's envelope	Function of relative speeds s_p and s_r and length of rightward vehicle, l_r; a subset of t	Typically 2 to 10 seconds for cars and 8 to 30 seconds when passing trucks
t_p	total time passing rightward vehicle	Function of relative speeds (s_p and s_r), length of rightward vehicle (l_r), and following distance tolerances	Sum of t_u, t_e, and t_p, desirable if less than 45 seconds
t_d	time occupying left lane, downstream and clear of rightward vehicle	Function of relative speeds (s_p and s_r) and final d_d, related to following distance tolerances, often reduced when followed too closely	Typically 8 seconds, more when truck capabilities are respected
t_r	time moving rightward	Primarily function of vehicle speed and lateral acceleration tolerance	Typically 3 to 5 seconds
t_{fd}	time spent achieving the desired following distance ahead of the (leading) passed vehicle	Function of relative speeds and leading distance tolerance	Ranges from 0 seconds to long durations, particularly if initial speed difference is small

Table 3 Time variables used in the motorway passing equation

Passing Activity Characterization

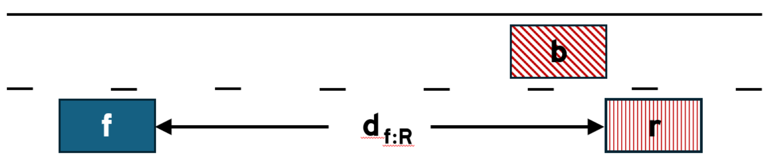
A non-compliant passing activity occurs whenever a leftward vehicle fails to vacate the left lane for faster traffic or upon achieving an acceptable headway in front of the leading rightward vehicle. The Motorway Passing Equation can be used to determine the various positions based on the vehicle speeds and lengths.

In general, the characteristics of non-compliant and blocking vehicles can be expressed in terms of a variance from the ideal or typical numbers in the motorway passing equation.

Micropassing Vehicle

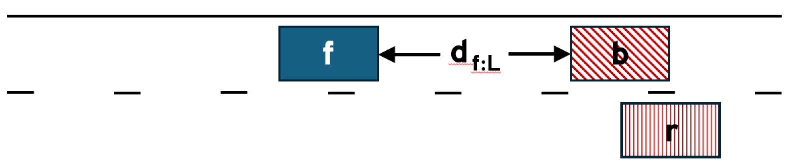
A *micropassing vehicle* was defined earlier as a vehicle that fails to expedite a passing maneuver. In practice, this means that the time for the overall passing maneuver is protracted beyond what would be expected and beyond the tolerance of the operator of a following vehicle. This is typically the case when the value for t_p exceeds 30 seconds for car interactions and 45 seconds when a car is passing a truck. The duration of the time spent passing (time spent fully in the left lane) is directly related to the difference in the vehicle speeds.

The depictions in the figure below indicate the position of a *blocking* vehicle, b, just prior to entering the envelope of the rightward vehicle. The disrupted passing activity is caused by the *micropassing* vehicle, which is a *blocking* vehicle due to the failure of the operator to vacate the left lane and the subsequent change in speed of following leftward vehicles.



DEPICTION 1

VEHICLE POSITIONS AT TIME t = 0 sec, d = 1450 ft



DEPICTION 2

VEHICLE POSITIONS AT TIME t=10, d = 200 ft

Figure 3 Vehicle Position Diagrams, Micropassing Activity

In practice, the operators of micropassing vehicles can mitigate traffic hazards by increasing speed by even as little as 3 km/hr (~2 mi/hr). Referencing Figure 4, if vehicle *b* had increased its speed by 2 mi/hr prior to entering the envelope, its passing time would have been reduced dramatically and its speed relative to the rightward vehicle would have tripled, from 1 ft/sec to 3 ft/sec.

Cruising Vehicle

A *cruising vehicle* is characterized in this research as a vehicle that enters the left lane well ahead of the critical following distance and/or fails to vacate the left lane upon reaching the critical leading distance. For some cruising vehicles, t_u and t_d appear to be infinite from the perspective of vehicle *r*. Any cruising vehicle can be considered a *micropassing vehicle* when t_e exceeds the tolerable value, irrespective of the values for t_u and t_d.

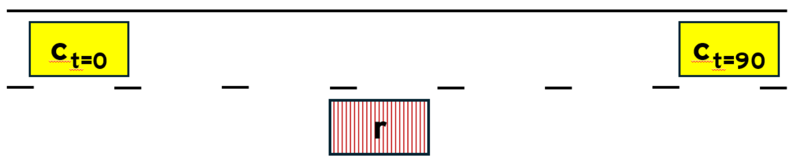


Figure 4 Vehicle Position Diagram, Cruising Activity

In the scenario presented in Figure 4, above, the cruising vehicle has far exceeded 30 seconds in the left lane. If no downstream rightward vehicles are present, the corollary of the basic rule, KEEP RIGHT EXCEPT TO PASS, demands that the cruising vehicle vacate the left lane.

Research activities generally indicated that the decision to vacate the left lane is largely a function of the anticipated time spent in the right lane prior to reaching the critical following distance upon approach to a subsequent downstream rightward vehicle. A minimum time in the right lane of 10 seconds is considered tolerable, while 15 to 30 seconds is considered comfortable.

Cruising Vehicles in Unlimited Zones

In Germany, cruising vehicles appear to be more commonplace because the higher speeds of passing vehicles (160 to 250 km/hr) reduce the time required to cover longer headways between subsequent rightward vehicles. Despite this, however, cruising vehicles are rarely blocking vehicles. Federal statutes in Germany govern the behavior of passing vehicles, and nearly all encountered cruising vehicles observed in the field by the authors vacated the left lane without prompting upon recognition of an approaching leftward vehicle.

In many cases, the speed differential between the leftward following (but non-blocked) vehicle and the cruising vehicle exceeded 50 km/hr (30 mi/hr), although willingness to vacate the left lane was similar even at lesser speed differentials. Of particular note is that the assumed relative capabilities and intentions of interacting vehicles appeared to influence the decision to vacate the left lane or increase speed to complete a subsequent passing maneuver. In Germany, operators of cruising vehicles exhibited increased willingness to move right when premium-segment vehicles were observed approaching from behind. This was less pronounced in Poland; the opposite appears to be true[d] in the United States.

Review of State Statutes

In the United States of America, signing for the use of the left lane on motorways and multi-lane high-speed roads takes various forms, generally being consistent within a given state. A 2018 review[1] of state statutes found that 29 states require that vehicles “traveling slower than the surrounding traffic must be in the right lane.” The same review found that 11 states reserve the left lane only for passing and for preparing to exit the roadway from the left side, such as at a left exit or through the use of a median opening. A summary of the generalized statutes complied in in 2022 is included below in Table 4.

Generalized Statute	Jurisdictions
SLOWER TRAFFIC KEEP RIGHT	AL, AZ, AR, CA, CO, CT, GA, HI, ID, IN, IA, KS, KY, LA, ME (posted less than 65 m/hr), MN, MS, NE, NH, NM, NY, ND, OK, OR, PA, RI, SC, SD, TN, TX, UT, VT, VA, WV, WI, WY
KEEP RIGHT EXCEPT TO PASS	AK, FL, IL, ME (posted 65 mi/hr and above), MD, MA, MI, MO, MT, NV, NJ, NC, OH, WA
DO NOT PASS ON RIGHT	NJ, [German Republic]

Table 4 Summary of Generalized Statutes for Left Lane Use by Jurisdiction[2]

Of note is the issue of relative speeds related to the SLOWER TRAFFIC KEEP RIGHT laws. For example, a vehicle in the left lane that is not passing must move right for a vehicle approaching, but it can return to the left lane upon being passed, as long as it does not impede the flow of traffic, given that there is no slower traffic with which it can be compared. This action defies the basic rule.

Summary of Operational Impacts

While operational impacts are imposed by the discrete obstruction to the flow of traffic, the impacts are conveyed and exacerbated by human factors, including those stemming from cognitive limitations and behavioral outcomes. Behavioral outcomes stem from user expectations and a desire for compliance with the requirements of both statutes and social order.

[d] A search for the term “BMW” on nearly any social media channel will produce results that might convince a person that BMW drivers in the United States are the worst in the world. Prejudiced attitudes toward other road users indicates a need to further assess various social-behavioral disorders that shape lane use courtesy attitudes.

A post on the popular social conversation forum Reddit asked the following question: "[I]s everyone that drives here a dumbass? How do you not see the line of traffic you're creating by hogging the lane while going 60 mph while texting[?]"[3] The evident impact is the long moving queue of vehicles behind a vehicle whose operator is failing to complete a passing maneuver, hence, operating a *blocking vehicle*. Observations during the course of this research indicate that where volumes approach 1500 vehicles per hour in two lanes, these queues can approach six to eight cars in length in less than 90 seconds, causing transient reductions in Level of Service and impacts to crash risk, particularly if heavy vehicles and/or longer vehicles are involved.

Decreased following distances, reduced on-task attention, and physiological effects such as increased heart rate and adrenaline response can create an increased risk of collisions, particularly rear-end collisions during inclement weather and low visibility. For vehicles that persist in the left lane upon completion of a pass, known as *cruising*, additional risks are conferred to the occupants of other vehicles, due to the need to change lanes to the right in order to maintain the desired speed.

Impacts of Vehicle Automation

Vehicles with speed governors and users who rely on cruise control when passing present a particular challenge with respect motorway operations. An overtaking vehicle that fails to exceed the speed of the vehicle(s) in the adjacent lanes is not vacating the left lane. This phenomenon, an unintentional micropassing activity, will become more prevalent with the fleet penetration of automated vehicles relying on software programmed to never exceed the posted speed limit. Mitigating the hazard of failed passing maneuvers will require an acceptance of speeds in excess of the posted speed limit.

Vehicles with ADAS equipment allow for the adjustment of tolerances for the ACC, which influences the time that vehicles occupy the left lane during a passing maneuver. While some vehicles govern speeds so as to prohibit exceeding the speed limit, other vehicles with Level 2 capabilities (reference the Society of Automative Engineers Levels of Driving Automation) allow for setting an "offset" from the speed limit, either as a percentage or a discrete value. This offset is applied to the cruise speed, however, and a small difference between the speed of rightward vehicle and the incipient passing vehicle can cause ADAS-equipped vehicles to become blocking vehicles during passing maneuvers when self-driving capabilities are engaged. Intervention by the supervising operator would be necessary to avoid blocking vehicle status in those cases.

METHODOLOGY AND LIMITIATIONS

Four activities supported the development of results for this research. Activities included ongoing field observations, an inventory of typical traffic signing, passing model development and testing, and an assessment of interventional techniques and the localized effects of traffic signing on behavior.

Field observations of left lane operations were made along roadway segments and in spot locations spanning a timeframe of ten years from 2014 to 2024. Based on these observations, a time-space model for motorway passing maneuvers was developed in 2022. Model validation was then conducted along roadway segments between 2022 and 2024. Field observations in both periods included an inventory of signing and observations related to the effectiveness of the signing, both systemically and tactically.

Because this research was conducted with limited resources and support, observations were largely heuristic and identified general trends. Recorded datasets are not available. This research is based on the repeatability of results when similar traffic conditions and research vehicle operations techniques are employed, demonstrating the consistency of human behavior across regions. These activities supported the development of practice recommendations and recommendations for ongoing research activities.

Excluded Conditions

Compliance with the basic rule requires that the left lane be available for use by vehicles irrespective of vehicle occupancy and in conditions where use of the left lane is not necessary for non-passing maneuvers. For this research, a list of excluded conditions was developed and is presented in the list below.

1. Motorway segments with high-occupancy vehicle lanes, express toll lanes, or other lanes where access to the left-most lane is restricted by vehicle occupancy and/or the requirement for payment
2. Rural divided high-speed highways and urban multi-lane arterials where left turns are accommodated, either from the mainline or from the intersecting roadways; longer distances between intersections can exacerbate the assumption of motorway speeds
3. Motorway segments featuring deceleration lanes or tapers of insufficient distance to permit deceleration to the minimum statutory or posted speed
4. Motorway segments with an inconsistent number of basic lanes[e] along distances of less than three (3) miles

[e] In this use, “basic lanes” does not correlate to the “basic rule”, but rather refers to a motorway design concept that involves ensuring that the same number of continuing lanes is carried through interchanges along segments with similar traffic volumes. In practice, where right lanes are terminated as mandatory exiting lanes, the concept of basic lanes falls short of the intended outcomes, which is to avoid disruption in traffic flow. In fact, if the number of basic lanes is counted from the left, then the effects of lane terminations and lane changes by heavier and slower vehicles are exacerbated. The most basic lane ought to be the right-most lane, where travel is expected.

Not excluded were motorways where vehicles classified as trucks (by wheel count, length, weight, or other characteristics) are not prohibited from using the left-most of three or more lanes. In Wisconsin, one of the regions where observations were conducted, trucks are not prohibited from using the left lane of roadways with more than two (2) lanes in the direction of travel. Examination of the impacts of heavy vehicle operations in these unique circumstances provides a contrast against states with specific and consistent restrictions, including South Carolina.

While field observations were conducted along segments with conditions matching those in the list below, the generalized results of observations in the excluded segments are not used to determine basic rule compliance in a region or along motorway segments with particular characteristics.

Research Techniques

Researchers conducted passive observations and observations in concert with active intervention techniques. Passive observation of a blocking vehicle involved maintaining speed behind a vehicle in the right lane so as to avoid compelling a change in speed; a three-second following distance was typically selected. Both researchers employed passive observation techniques in mixed traffic and from fixed vantage points.

In some localities, research activities were conducted using various vehicle types and both passive and active techniques. Observations in all localities were conducted on both motorways and multi-lane divided high-speed rural roads with limited intersections. In Wisconsin, Washington State, and South Dakota, most of the latter facilities did not include traffic signals. In Ohio and Maryland, isolated rural traffic signals were commonplace on these non-motorway facilities.

Across an estimated 3,000 hours of observation *in situ*, researchers interacted with and/or observed approximately 100,000 discrete blocking vehicles, with durations of observation exceeding 90 seconds in a fraction of the observations. Due to the limitations of the observational environment and in order to promote attention to the driving task, particularly in solo occupancy situations, researchers complied notes by memory and characterized the interactions in broad categories for later recall and classification.

Passive Observation Techniques

The majority of the research involved passive observations, where the posture of the vehicle and illumination status were neutral, so as to not induce a reaction from other vehicles. Additionally, researchers maintained following distances, even in mixed traffic and within moving queues of following vehicles. This occasionally allowed for a vehicle to take a forward gap, whereupon the researchers would increase the following distance again.

Active Intervention Techniques

Active intervention techniques involved adjustments to the research vehicle's posture and illumination status, conducted according to a controlled rubric. The corresponding author was the researcher solely responsible for engaging in active intervention techniques for observation in mixed traffic. Active intervention techniques were conducted along segments where regulatory signing was installed and along segments where at least five minutes of driving had passed since the posting of a regulatory sign.

Active intervention trials with observations were conducted on various rural free-flow multi-lane roads, with two longer contrast periods selected. One trial included long segments of Interstate 90, Interstate 94, and U.S. Highway 12 in Washington State, Idaho, Montana, Wyoming, South Dakota, and Minnesota, with observations conducted in 2021, 2023, and 2024, following on five years of passive observations and pre-trial posture evaluations within the same regions. The other trial included Interstate 80 between Hammond, Indiana, and the Cleveland area, along with other selected roads in Pennsylvania, Ontario, and Michigan, with observations conducted in July 2024.

In addition to the North American observations, an extensive (1500 kms) transit of motorways in Germany and Poland involved active intervention techniques. On European motorways, intermittent activation of the high beams is commonplace for an approaching vehicle to request that a leading vehicle to vacate the left lane, often occurring well ahead of the critical following distance. This was observed even irrespective of the potential for blocking behavior, and courtesy indication if overtaking intent.

Vehicle Posture

Vehicle posture comprises the vehicle's position, following distance, and indications. Various vehicle posture regimes were observed in pre-trial field observations. While sub-vehicle-length following distances are common among *following vehicles*, even at speeds exceeding 120 km/hr (75 mi/hr), a two-second following distance (2 sec) was achieved by researchers to avoid the risk associated with reduced following distances and to demonstrate courtesy.

Occasional variances in the lateral position of the research vehicle served two purposes. The first purpose was to provide for forward visibility, particularly around larger vehicles. The second purpose was to increase the visibility of the research vehicle's headlights in the outside mirrors of the blocking vehicle.

The most common indication of posture was sequenced use of the high beams. High beams can be activated well ahead of approaching a blocking vehicle, at distances exceeding 500 meters (approximately 1500 feet). Sequenced activation of the high beams is most commonly a three-burst notice with a duration of approximately two seconds. In Germany, Poland, and some parts of the United States, this was sufficient to obtain a response from the blocking or cruising vehicle. In other parts of the United States, operators of blocking vehicles gave heed only when continuous sequenced bursts were employed, and some did not give heed at all under any circumstances. A frequency of 40 activations per minute was chosen to allow for differentiation between the sequenced bursts (which were more similar to the three-burst method) and other types of sequenced headlight activations associated with emergency response vehicles.

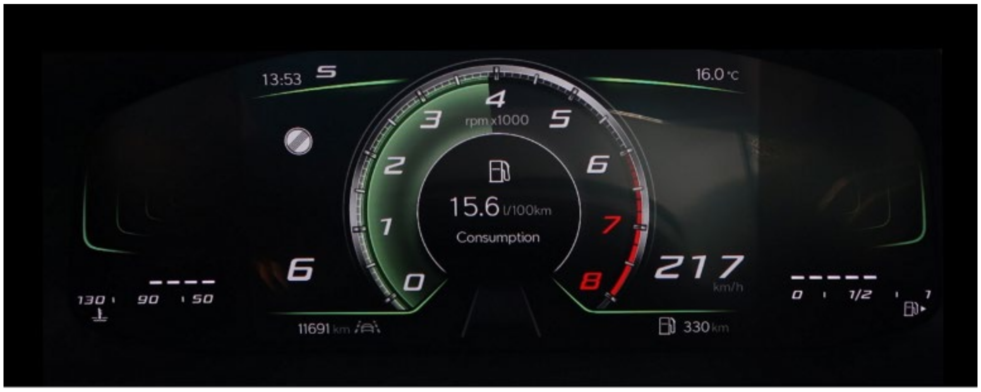


Figure 5 In unlimited zones (notice Intelligent Speed Assistance sign recognition display in upper-left corner), speeds in excess of 200 km/hr are readily and continuously obtained on the German Autobahn, even when passing cars and trucks.[f]

Assessment of the posture of *blocking*, *following*, *tailing following*, and *rightward* vehicles revealed opportunities for improved education and enforcement, particularly with regard to blocking vehicles. Blocking vehicles often maintained a position relative to rightward vehicles such that the blocking vehicle was in the blind spot of the rightward vehicle, particularly common when trucks were in the right lane. Following vehicles, in addition to following closely, also drifted rightward on occasion, even when rightward vehicles were present within the reaction envelope.

[f] It is unlikely that autonomous vehicle manufacturers will accept this level of risk, a potential pathway for justifying electronically-enforced lane restrictions for autonomous vehicles that do not achieve parity with humans.[SK]

SUMMARY OF OBSERVATIONS AND SIGNING INVENTORY

While it is possible to capture anecdotal evidence in conversation with individuals who frequently operate vehicles on motorways, a rigorous approach involving numerical measurements provided information on the operations most likely to inhibit the availability of the left lane. Researchers observed the presence of cruising vehicles, the following distances at which lane changes occurred, the durations of passing maneuvers, the lead distances at which vehicles vacated the left lane, the prevalence of turn indicator operation[g], the durations of lane changes, and speed variability during maneuvers for leftward passing vehicles (whether expediting or micropassing), leftward cruising vehicles, rightward vehicles, leading vehicles, and tailing vehicles.

Signing Inventory

A global signing inventory was conducted during field observations. In general, most signs conveyed information regarding traffic regulations and prohibitions. In the United States, regulatory signs with text were commonplace.

Sign Message	Placement	Localities
KEEP RIGHT EXCEPT TO PASS	Typically right side, occasionally left side	Michigan, Illinois (USA)
LEFT LANE FOR PASSING ONLY	Typically left side	Infrequently observed
SLOWER TRAFFIC KEEP RIGHT	Typically left side Occasionally right side	Wisconsin (USA) Indiana, Pennsylvania (USA)
SLOWER TRAFFIC MOVE RIGHT	Typically left side	Minnesota, USA

Table 5 Summary of traffic signing addressing left lane restrictions

[g] Across the various states, vehicle code statutes are harmonized such that a motorist shall use a turn signal when changing lanes. However, motorist behavior is not consistent, even within regions of the same state. Compliance with this law in Maryland and Michigan is observed to be poor. Such an opinion might be subjective but when a neighboring state's DOT calls it out on social media, the opinion carries some weight: https://x.com/VaDOTNOVA/status/1818435680957042883[AG]

Table 5 addresses static signing only, typically classified as "regulatory" signing in the United States. Some motorway segments, particularly those on the Autobahn and in Northern Virginia (Washington, DC, metropolitan area), Seattle, and Las Vegas operate with dynamic controls through an active traffic management system. Most commonly, these signs display specific restrictions or exemptions related to lane use control. For example, on the Autobahn in Germany, messages exclude trucks from the left lanes during "stau" (German language, semi-colloquial, meaning periods of congestion). In Seattle, Washington State, high-occupancy vehicle restrictions are temporarily lifted during road work and the left lane becomes available for passing.

Figure 6 Changeable message sign on the Autobahn in Germany, entering a restricted speed zone; the standard symbol sign conveys the meaning that trucks are prohibited from occupying the left lane.

In European countries, symbolic signs indicating restrictions on passing are commonplace along motorway segments, particularly in sections with more than two lanes in each direction, within interchange areas, along uphill grades, and in areas where inclement weather and reduced visibility are expected. While the majority of those restrictions are imposed with static signs, regularly-spaced changeable message signs (mounted to the side) and overhead changeable message signs are also used to prohibit trucks from the left lane in congested areas and during periods where traffic volumes are high. In this way, the free-flow characteristics of the motorway are maintained by reducing the disruption of the flow of traffic, just as is done with ramp meters.

Field Observations of Passing Behavior

Field observations were conducted in five countries, listed below in Table 6. The prevalence of cruising and blocking behaviors is characterized for each locality. In general, these observations were conducted in free-flow conditions (Level of Service A or B[4]), in rural segments with two or three lanes in each direction, and during daylight conditions where the road surface was clear and dry. Atmospheric conditions varied, although observations were suspended in heavy rain and snow where visibility was reduced. The responsiveness of blocking vehicles to intervention techniques, described in the next section, is also broadly characterized in Table 5.

Locality	Period(s)	Blocking Behaviors	Responsiveness
Germany	2017, 2019, 2024	Rare to Occasional	Immediate
Poland	2024	Occasional	More likely
United Arab Emirates	2017, 2019	Common, particularly cruising	Inconsistent
South Dakota, USA	2014, 2020, 2023	Cruising occasional; trucks pass on long grades	Occasional
Texas, USA	2019, 2022	Widespread	Unlikely
Croatia	2018, 2019	Occasional	Immediate
California, USA	2017, 2021	Cruising ubiquitous	Unlikely
Wisconsin, USA	All Years	Cruising commonplace	Limited
Washington State, USA	All Years	Cruising commonplace; HOV network effects	Less likely
Maryland, USA	All Years	Cruising commonplace	Limited
Montana, USA	All Years	More likely for vehicles with trailing units	Limited
Ohio, USA (Turnpike)	2024	Micropassing commonplace	More likely
Ontario, Canada	2017, 2024	Cruising observed	Inconsistent
British Columbia, Canada	2016-2024	Micropassing commonplace, cruising widespread	Limited

Table 6 Summary of Field Observation Activities and Inferences

Findings from the field observation and model development activities were largely heuristic in nature. While large datasets are not available for analysis, the efforts of researchers to conduct observations over a long period of time allowed for pattern recognition, posture characterization, and the characterization of regimes that allowed for model development.

Information in Table 6 above is a summary of the generalized observations from all observational periods and presents specific observations related to interventional activities associated with vehicle posture.

Non-Compliant Passing Factors and Mitigation

Specific operational effects associated with vehicles, traffic control devices, roadway design, and behavior were also identified in the research activities. Very often, one or more of these effects contributed to a non-compliant passing behavior.

Impacts of Heavy Vehicles

Heavy vehicles include trucks, buses, and other large vehicles with power-to-weight ratios fractionally less than that of cars. These vehicles cannot sustain speeds on uphill grades and many commercially-regulated heavy vehicles are subjected to speed limiters. In the United States and the European Union, commercial and government regulation of heavy vehicle speeds limits speeds to 100 km/hr for buses and even as low as 80 km/hr for many trucks, even on motorways. Because of these limitations, operation of trucks in the left-most lane is often prohibited by statute and signing.

Despite these prohibitions and the clear limitations of trucks, trucks were frequently observed inhibiting traffic. Micropassing and cruising by trucks was commonplace in many states. Even on the Autobahn, where enforcement of basic rule compliance is more common, trucks frequently violated restrictions imposed by signing ahead of and along uphill grades.

Impacts of Inattentiveness

While popular culture indicates a willingness to ascribe blocking activities to the motive of malice, it is more likely that inattentiveness accounts for some blocking and cruising activities observed. Operating a vehicle on the motorway involves a demanding set of tasks. Proper training and reminders of the special obligations associated with operating a vehicle on the motorway hold the potential to reduce inattentiveness. Enforcement activity focused solely on blocking and cruising can also raise awareness of the need for attentive driving and compliance with lane use courtesy statutes and signing.

Effects of Vehicle Posture

A neutral vehicle posture was unlikely to generate a response from a blocking vehicle. The majority of cruising vehicles failed to vacate the left lane upon reaching a leading distance of three seconds.

Sequenced activations of high beam headlights (flashing, as described earlier) incurred varying effects. The type of vehicle and intensity of the sequenced activations did appear to correlate with responsiveness. In general, the use of sequenced high-beam activations engendered increased responsiveness. The list below contrasts various circumstances where flashing occurs.

- flashing from taller vehicles was more effective than shorter vehicles
- cruising vehicles were more likely to respond than micropassing vehicles
- flashing activations whilst in the left lane were more effective on all types of blocking vehicles than those from the right lane
- flashing in a continuous sequence at a rate of 40 alterations per minute for more than 15 seconds was more effective than what is typically observed, which is three to five alternations, with potential multiple discontinuous sequences
- earlier onset of continuous-sequence flashing was more effective than later onset; earlier onset of flashing typically necessitated an earlier vacation of the left lane

In general, responsiveness to flashing appeared to correlate more strongly with a culture of courtesy, which indicates regional variations.

Effects of Traffic Signing

Traffic signing with the messages outlined in Table 5 was present in approximately two-thirds of the motorway segments whereupon observations and interventions were conducted. In the United States, there was little observed correlation between the location of the traffic signing and the compliance of road users. Interventional techniques did not appear to increase the effectiveness of traffic signing.

Effects of Regional Variations

Cultural courtesy, topography, and road network topology all appear to have an impact on compliance with lane use statutes. Further study of these regional variations would consider these factors along with understanding the contribution of driver education, enforcement emphases, and the use of social media to discuss enforcement activities. The observations summarized in Table 6 indicate regional variations and variations between behavior in the United States, Poland, Canada, and Germany.

Within the United States, lane use compliance associated with the termination of micropassing activity was most apparent in central Pennsylvania and South Dakota. Avoidance of cruising was most apparent in central Pennsylvania. Blocking activities were most prevalent in Maryland and Indiana. These regional variations do not appear to correlate with the generalized statutes outlined in Table 4 or the associated messages on regulatory signing described in Table 5.

This lack of correlation suggests that statutes and signing, while formative and according to the rule of law, are less effective than enforcement and cultural norms. Further to this theory, researchers observed variations in the presence of blocking activities in areas where observed lane use courtesy was more prevalent. On primary highways with a greater percentage of through traffic and out-of-area number plates ("license plates"), blocking activities did not correlate strongly with what was observed on lower-volume roads serving regional and interregional traffic.

Figure 7 View of the eastbound Indiana Toll Road at the near South Bend, Indiana, USA. The trucks visible in the left lane had inhibited passing vehicles for nearly two miles, a period of nearly two minutes.[h]

The presence of trucks causes considerable inhibition of the availability of the left lane for passing, particularly along segments where only two lanes are available in the direction of travel. Inhibition of the left lane was observed to be more pronounced in hilly terrain, in areas with long uphill grades, along corridors where development favored commercial and logistics operations, and in states where statute fails to prohibit heavy vehicles from the left lanes.

[h] Note the lack of dotted lane line markings and dotted extension markings and the incorrect selection of a warning sign ahead of a lane reduction taper.

RECOMMENDATIONS

Research activities indicated that selection of speed when passing influences the time to pass and perception of improper passing by observers operating other vehicles. Approaches that reduce the time spent occupying the left lane will reduce the likelihood of conflicts arising between blocking vehicles and other passing vehicles. These approaches include recommendations addressing the following topics:

1. Speed management and statutory revisions
2. Geometric design and pavement marking revisions
3. Availability of left-side high-occupancy vehicle lanes
4. Lane use compliance enforcement and education
5. Dynamic traffic signing with the LUCID System, introduced by this paper

Statutory Speed Limits, Speed, and Facilitating Passing Activities

The basic rule reflects the reality that vehicle operators will be constrained in various ways by human limitations and the limitations of various types of vehicles by allowing for flexibility and order. Despite this, statutes, policies, and enforcement activities in the United States and Canada fail to adequately reflect human capabilities and limitations related to operation of vehicles on motorways. Speed limits are uniformly set below appropriate or comfortable operating speeds.

Heuristic observations in the United States, Europe, and the Middle East indicate a free-flow speed for prevailing traffic of approximately 125 to 130 km/hr (80 to 85 mi/hr). In rural areas where roadway geometry and cross section are generous, the majority of vehicle operators in the general-purpose lanes (those not restricted by occupancy or vehicle type) will select speeds approaching 140 km/hr (90 mi/hr), particularly in areas where enforcement is less prevalent. In Germany, in unlimited sections, even vehicles with modest power-to-weight ratios often exceeded 160 km/hr (100 mi/hr) when passing trucks, a recognition that expedited passing reduces exposure when adjacent to the vehicle envelope!

Revisions to statutes can reflect the reality of motorway operations with two general changes that constitute scenario-based enforcement enabled by technology advancements in real-time monitoring and measurement of traffic flow characteristics. These revisions include

a) codifying penalties only for speeds above the 95^{th}-percentile rather than speeds above the posted speed limit and prioritizing enforcement of order rather than speed compliance; and

b) allowing for various scenarios where higher speeds do not constitute an infraction. The most obvious scenario is the need to increase speed when passing.

Allowing vehicle operators to expedite a passing maneuver by marginally exceeding the speed limit or the prevailing speed of traffic reduces the time a vehicle will spend in the left lane and alongside slower vehicles. In South Dakota, Codified Law 32-25-28 allows a vehicle to exceed the posted speed limit when passing on a two-lane highway. This statute is cited at the top of the next page.

32-25-28. Exceeding posted speed limit permitted under certain conditions.
The speed limit is increased by ten miles per hour over the posted speed limit, if a person is driving a vehicle that is:
(1) On a two-lane highway that has one lane for each direction of travel;
(2) On a highway with a posted speed limit that is equal to or exceeds sixty-five miles per hour;
(3) Overtaking and passing another vehicle proceeding in the same direction of travel; and
(4) Passing a vehicle that is moving slower than the posted speed limit.

If statutes were to reflect that higher speeds are permissible when passing using the left lane, regulatory signing can reinforce education and enforcement campaigns. Recommended regulatory signing in Figure 8, below, includes a sign clearly stating that an increase in speed is required to expedite a pass. Initially, field evaluations of sign effectiveness could be conducted ahead of long grades, at the beginning of tangent sections, and in areas where probe data indicates that congestion is recurring.

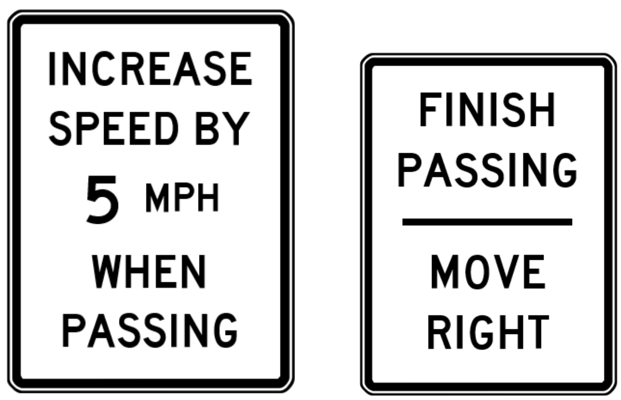


Figure 8 Proposed sign sequence indicating that increased speeds when passing are permitted and expedited passing is required

The second sign in the figure above is an adaptation of the SLOWER TRAFFIC MOVE RIGHT signs used by the Minnesota Department of Transportation. This sign could be placed at the beginning of long grades, along tangent sections in advance of horizontal curves, and at other locations where the availability of the left lane would be improved by the absence of inhibiting vehicles.

Geometric Design and Pavement Markings

Geometric design, lane arrangement, and pavement markings are all used to guide vehicles within the traveled way by inhibiting or promoting movements based on the degree of desirability and hazard. On motorways, lane arrangements should reduce the need for lane changes for continuing traffic, particularly lane changes by heavy vehicles and vehicles that are generally moving more slowly than the prevailing speed of traffic.

Roadway segments with higher volumes present the opportunity to add capacity[i] in pursuit of the goals of reducing queue spillback, improving operations on sections where slower speeds are observed, and increasing the availability of the left lane. Left lane availability can be increased by mitigating conditions that incur lane changes to the left (generally to avoid slower vehicles) and/or by providing use of an additional lane on the left, even if that lane is provided for short distances.

Acceleration Lanes

Acceleration lanes (also known as Speed Change Lanes) allow vehicle operators entering the motorway to harmonize speed with adjacent traffic, select a gap, and execute a lane change maneuver. Acceleration lanes on motorways are preferable to the AASHTO "tapered entry" in that these lanes allow operators to execute several tasks simultaneously and discretely, rather than complicating the lane change task with a speed change, curvature, and sub-optimal viewing angles from the operator's seat. On motorways, acceleration lanes that are longer than the minimum distance specified in various design resources can introduce resilience, particularly in areas where growth in heavy vehicle traffic is expected.

Signing for longer acceleration lanes occasionally consists of a RIGHT LANE ENDS (W9-2) warning sign. For acceleration lanes of any length, a proposed MERGE with Type A ARROW sign can be used near the beginning of the lane reduction taper, clearly identifying the location where the acceleration lane ends. Additionally, enhanced delineation can be installed along the taper for nighttime conspicuity.

Figure 9 MERGE with *MUTCD* Type A ARROW warning sign, used by the Minnesota Department of Transportation

[i] Despite the insistence to the contrary of anti-roadway and anti-car activists, adding capacity to the motorway system attracts traffic to the highest-order roadway links and reduces demand on lower-order links. Facilitating access to the highest-order links by reducing intersection and network delay serves the demand induced by development and corresponding economic activity and reduces the congestion caused by density.

Pavement markings in acceleration lanes aid vehicle operators in understanding the purpose of the lane and recognizing where the acceleration lane terminates. A pattern consisting of a solid white line adjacent to a dotted lane line can be used along the length of the full width of the lane to discourage lane changes into the lane. When followed by a dotted extension line, the shorter lines and a narrower marking width provide a clear differentiation between the available lane and the length of the taper.[j]

Deceleration Lanes

Deceleration lanes allow vehicle operators exiting the motorway to reduce speed in a separate lane, mitigating conflicts with vehicles in the right-most lane. Because deceleration lanes aid continuing heavy vehicles in maintaining speed and avoiding drastic or substantial speed reductions, they incur operational, fuel economy, and emissions benefits. An activity analysis of entering a deceleration lane indicates that the risk of task saturation is lower, although the reduction in task saturation risk is not as pronounced as with parallel-style acceleration lane installations.

Signing for deceleration lanes typically consists of a guide sign and, if specified, various warning signs and advisory speed signs included in Part 2 of the *MUTCD*. In Germany, deceleration lanes are signed with "countdown" signs indicating 300, 200, and 100 meter distances to the departure taper or beginning of the first horizontal curve. In Colorado, the R3-5 RIGHT TURN ONLY and other R3-series signs have been adapted for use alongside the full width of a deceleration or exit only lane.

Pavement markings for deceleration lanes likewise aid vehicle operators in recognizing that such lanes are non-continuing lanes. A pattern consisting of a dotted extension line along the opening taper, a dotted lane line along the full width, and a solid lane line ahead of the departure taper provides increasingly-restrictive markings that are differentiated by position along the lane and differentiated from a continuing lane. Continuing traffic is discouraged from entering the lane by the dotted extension markings, which would not be present if a continuing lane were added on the right. In California and Washington State, lane use arrows are used, featuring the very long aspect ratio typical of freeway-type markings, which are intended to be recognized at speed.

Transient Motorway Passing Lanes

In Germany and in Missouri (USA), motorway operators have installed passing lanes on the left side of the roadway along uphill grades. The provision of an additional lane on the left side of the roadway creates immediate availability. Trucks and slower vehicles are not required to conduct a lane change to the right, as would be the case where a climbing lane is provided. In general, the flow of traffic remains stabilized while the left lane remains available for faster and more flexible vehicles.

Selection of pavement markings indicating the special use of the left lane should have the intention of reducing the likelihood of errant lane changes. Specifically, marking of the left lane as reserved solely for passing can be accomplished with a new marking pattern (perhaps 1:1 cycles continuous) and the use of letters and symbols with accompanying signing.

[j] In Massachusetts, updated State standard plans reflect this differentiation and adaptation to the needs of autonomous vehicle camera systems and improved information for human vehicle operators

Restriction on Off-Peak Use of Left-Side HOV Lanes

In Washington State, Virginia, Maryland, California, Minnesota, and other states, left-side HOV lanes are commonplace in metropolitan areas. On some motorway segments, the restrictions are in place solely during commuting hours (e.g., 6 a.m. to 9 a.m.), throughout the day (e.g., 5 a.m. to 7 p.m.), or, occasionally and more commonplace with HOT facilities, restrictions are dynamically assigned.

When HOV lanes are not restricted to HOV traffic only, some vehicles still cruise in the HOV lane, either by habit or for individual convenience. Other vehicles appear to avoid the HOV lane even when it is not restricted to multi-occupant vehicles. These HOV lanes represent an opportunity to provide lanes for transient passing only. In locations where continuous solid lane lines are used to demarcate these special-purpose lanes, inhibition of lane changes is in place. Existing regulatory signing, changeable message signing, and VMS displays can all be used as a platform for a trial passing section in location where demand causes congestion but the fraction of HOV-eligible vehicles is too low to maximize the capacity of the lane.

Pavement Markings

While pavement markings separating continuing lanes are typically a broken lane line in a ratio of 1:3 or 1:4 (e.g., Minnesota), some agencies use dotted lane line patterns and solid lane lines to indicate the intended use of auxiliary lanes. The use of a solid lane line adjacent to the continuing lane alongside a dotted lane line adjacent to an acceleration lane, for example, indicates that crossing into the acceleration lane is discouraged even as vacating the acceleration lane is the intended and necessary maneuver. Research conducted by the Pooled Fund Study[5] validated the performance of this marking pattern.

Use of a solid lane line along the latter distance of truck climbing lanes can likewise discourage movement into the general lanes prior to the crest of a hill. In some selected interchanges, a single solid lane line or even a double solid lane line can be used as a boundary between the left-most lane of a motorway and the remaining lanes.

Enforcement and Education Campaigns

On motorways today, enforcement activities largely consist of speed interdiction and monitoring of commercial vehicle activities. Traffic data from various agencies indicates a uniform prevalence of speeds above the posted speed limit by non-commercial vehicle operators, a reflection of the human factors challenge associated with blanket speed limits on high-speed roadways. Because these speeds exist and cannot be enforced uniformly and entirely, the promotion of order is best undertaken by law enforcement.

A survey of law enforcement agencies was not conducted during the course of this research. However, limited enforcement of lane use courtesy was observed even as speed enforcement activity was reported by media outlets to have declined during a period following early 2020. Correspondingly, researchers observed little investment in traffic safety messages regarding the preservation of order and the availability of the left lane.

Enforcement of Left Lane Restrictions

In Germany, enforcement of passing restrictions is understood to be aggressive. Use of photo enforcement for speed zones is common on the Autobahn and sections of the Polish Autostrada. Enforcement of passing restrictions for trucks, which are dynamic in Germany by use of the Active Traffic Management System (ATMS) displays and other signing, appears to promote uniform compliance.

Figure 10 Signing on the Polish Autostrada[k] indicates that restrictions on passing by trucks will be enforced using camera systems

The targeted enforcement section gateway signing displayed in Figure 10 is posted in advance of a section of the motorway passing through a river valley, where dense fog and low visibility are expected. Wet pavement conditions are more likely to occur even when pavement on the approaches to this area are clear and dry. Reserving the left lane for passing by cars only reduces the airborne spray caused by truck tires and reduces the likelihood of a high-speed rear-end collision associated with slower trucks.

Variable Message Signs

While many jurisdictions limit the use of variable message signs to cogent and pertinent messages, the use of Variable Message Sign (VMS) displays on motorways for traffic safety and statutory reminders continues to grow. Messages such as “CAMP IN THE WOODS / NOT IN THE LEFT LANE” are intended to remind vehicle operators of the requirement to avoid cruising by moving right when finished passing. As with static signing, these messages appeared to be uniformly ignored by vehicle operators. Ignorance of VMS displays and a general unwillingness to display courtesy remain a vexing challenge on motorways under both normal operations and during incidents.

[k] European motorway operators use a superior deposition system for pavement markings, visible in this photo, taken approximately 20 minutes after sunset. Of note in the Balkans and in Poland is the use of red reflectors to denote the edges of the roadway, a contrast to the white reflectors used in Germany and utterly inconsistent with the intention of red markers in the United States. These markers do give a U.S.-trained driver pause on the first night![SK]

Dynamic Traffic Signing

This research demonstrated the success of active intervention techniques, particularly the use of sequential intermittent activation of the vehicle high beams. This indicates that some vehicle operators will respond to a reminder or request regarding the need to vacate the passing lane and return to the driving lane(s).

Policies regarding the use of static regulatory signing in areas where observed lane use compliance is implicated in operational and safety performance degradation could likewise be applied to dynamic traffic signing. Dynamic traffic signing, that is, signing that displays one or more fixed messages in response to traffic conditions, is commonly used in curve speed warning applications, speed feedback displays, intersection control advance warning signing beacons and displays, and other applications where a change in roadway conditions may not be adequately conveyed using a single fixed-message or static signing.

These systems, intended to alert vehicle operators to the need to maintain lane discipline, referenced here as Lane Use Compliance Information Display (LUCID) systems, would be intended to increase the lucidity of vehicle operators, inducing heightened attention, improved command of the traffic situation, and ongoing compliance in similar settings.

Proposed Sign Messages

The LUCID system is intended to target vehicles approaching VMS installations according to conditional assessment of the traffic composition. LUCID signing could be either display a dynamic message identical to the static signing or display a variety of specialized messages. Three examples of potential messages displayed dynamically are included below.

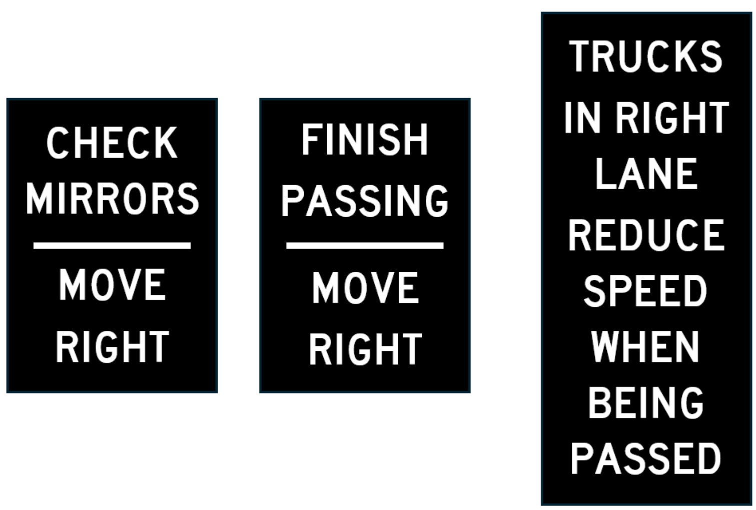


Figure 11 Depictions of displayed word messages in the LUCID System

LUCID systems could range from simple displays triggered by a narrow-beam radar-based speed reading to a comprehensive system using automatic number plate readers (ANPR) and logic-driven control systems addressing traffic over long distances. The technology integration, concept of operations, and costs are addressed here in a conceptual systems engineering description.

Technology Integration

Dynamic traffic signing for lane use compliance can be deployed using common hardware operating over modern interfaces. Such signs would readily mirror the application of signing for speed feedback displays, which are typically powered by an integrated and often internal battery system that is charged using solar photovoltaic panels. Communications equipment ranges from simple point-to-point systems to remotely-accessible IP-addressable equipment interfacing with a central system via cellular telecommunications systems.

Concept of Operations

The comprehensive LUCID system would operate using ANPR cameras, a central processing system, speed measuring devices, and a sequence of displays. Each target location would feature the full suite of equipment, and information would be shared between locations.

As Level of Service degrades, vehicle operators experience increasing difficulty with maintaining lane use compliance. LUCID system operations would be curtailed when certain conditions prevail, operating according to logic regarding vehicle speeds, density, volumes, and the composition of various vehicle classes in the flow of traffic.

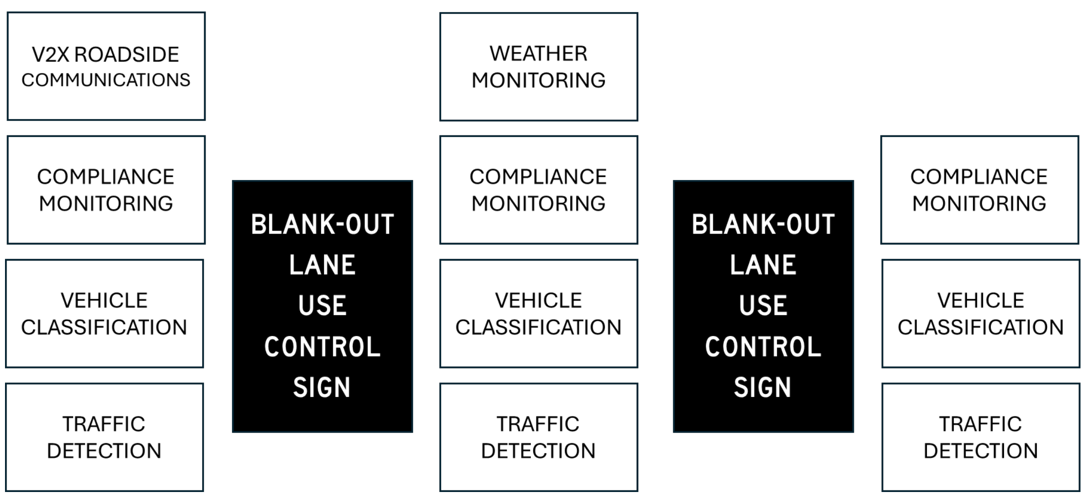


Figure 12 Dynamic Lane Use Compliance Demonstrative System Architecture

Privacy Concerns

Protecting the liberty of the traveling public must remain the chief goal[1] of all government agencies. While numerous cities use ANPR technology for traffic management activities, strict data protection, retention, and use restrictions exist, an outcome of the European Union's General Data Protection Regulation.

Use of ANPR technology and acquired data for LUCID operations is likely to be considered strictly a driving aid (as is the case with speed feedback displays) and not made accessible for general law enforcement for use in direct punitive actions related to traffic statute violations. It is possible, however, that data from LUCID systems could be used to identify locations where targeted lane use compliance enforcement activities would be most effective.

Where data protection and use regulations allow, it is also possible to affect the behavior of repeat offenders, those who repeatedly cruise in the left lane in numerous locations over a period of time, despite receiving LUCID feedback. Such interactions might include courtesy letters or other contact from traffic enforcement personnel. For egregious offenders, site observation and operator contact could lead to driving license actions, arrest, and vehicle impoundment.

In sharp contrast to punitive camera systems that use photographs, video, and measurement devices such as lasers to generate citations, the LUCID system would merely inform traffic enforcement personnel of the presence of repeat offenders, allowing for direct contact with a higher probability of corrective action. As with any statutory civil or criminal violation, the strictest standards of due process are applied in order to preserve the integrity of the observation and intervention process, allow for constructive appeals, and demonstrate a corrective impact on traffic operations, safety, and vehicle operator behavior, beginning with the least punitive measures.

Capital and Operations Costs

The LUCID system could be readily installed without the need for electrical service, wired communications, or other utility expenses. Relying on solar photovoltaic power generation and battery energy storage, some LUCID systems could even be made portable on trailers and moved to sites where surveillance and data analysis indicate that left lane availability is limited by micropassing and blocking. The initial cost for most motorway operators would be software, although ANPR integrations using application process interfaces are likely to become more prevalent.

[1] While most agencies would cite "safety" as the chief goal, safety is largely the responsibility of the road user in the context of the designed and built environment. Liberty, defined as the freedom to act responsibly without undue constraints, is always at risk in cultures driven by statistical analysis, which fails to account for individual needs.[SK]

CONTINUING RESEARCH

This heuristic research activity used engineering analysis and the application of traffic operations theory to validate common cultural perceptions regarding use of the left lane on motorways and high-speed multi-lane divided rural highways. Researchers also identified operational effects of disorder on the motorway, recognizing that motorways where order is prioritized can accommodate unlimited speeds. Additional research can illuminate the opportunities for implementing an order-based approach to statutes, enforcement, education, and in practice on motorways in the United States.

Signing Compliance Assessment

Compliance with existing and proposed regulatory and VMS messages is not well understood, despite the readily-apparent disregard exhibited throughout the period of this assessment. Correlation of compliance with sign presence and sign type, frequency of enforcement, and operational effects of geometric design are present opportunities for further statistical research.

Scenario-Based Speed Compliance Penalties

Recognized already in the reality of the variations in leeway afforded by public safety officers and camera-based revenue generation systems, research into the variability of enforcement effectiveness can help agencies prioritize scarce resources. Scenario-based enforcement would recognize that the speed and flow regimes vary according to Level of Service, ambient conditions, traffic composition, and other factors that influence speed selection such that speeds greater than the posted speed limit do not necessarily indicate that a violation of the intent of the statutes has occurred.

Understanding Regional Behavioral Variations

While obvious differences between Germany and the United States exist with regard to passing behavior on motorways, regional variances throughout the United States and even within states are worthy of additional study. In particular, the impacts of education, enforcement, cultural mores, and road user behavior are not documented in contemporary literature addressing passing behavior on motorways.

Maximizing Use of Special-Purpose Lanes

During off-peak periods, many HOV and High-Occupancy Toll Lane (HOT Lane) facilities could provide for separated lanes dedicated for passing only, for higher speeds, or autonomous vehicles operating according to the basic rule, where minimization of time in the left lane is a primary goal. Field trials using dynamic message signing associated with ATMS deployments can reveal the additional capacity and safety benefits available by using the HOV or HOT network as a part-time passing lane.

Assessing Impacts on Operations

Understanding the effects of blocking and cruising can aid in justifying the implementation of various measures to mitigate inappropriate use of the passing lane. Operations assessments and analysis of motorway operations using probe data, camera-based flow data, and other real-time collection of traffic operations information is likely to reveal regional differences and corroborate with various policy implementations.

Special Enforcement and Education Campaigns

While the effectiveness of emphasis patrols for speed and other behaviors is represented in the literature, a thorough literature review can illuminate opportunities for special-purpose enforcement focused solely on lane use compliance. New technologies supporting less punitive approaches can also aid law enforcement personnel in providing direct contact, education, and written warnings so that repeat offenders are subjected to escalating punishment. Assessing the impacts of enforcement and education campaigns on cultural perception may also provide insights into the general effectiveness of an education-first approach to lane use courtesy.

LUCID Systems Implementation

An intense traffic monitoring system deployment is already being undertaken by Institut für Verkehrssystemtechnik at the Deutsches Centre für Luft um Raumfahrt in Braunschweig, Neidersachsen, Germany. Development and deployment of LUCID systems can allow for further field data collection regarding the effectiveness of systems that also provide detailed information regarding traffic flow. Research on ANPR integration with such systems will be needed to validate system compliance with privacy and security protocols and statutes.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of various public safety officials, professional transportation industry colleagues, and vehicle manufacturers, suppliers, and systems integrators. The authors gratefully acknowledge more than 50 people who participated in *ad hoc* conversations regarding perspectives and practices related to passing on motorways, in the United States, Canada, Germany, and Poland.

The authors gratefully acknowledge their spouses for the opportunity to discuss following distance, speed, courtesy, and traffic operations theory while operating a motor vehicle or observing the operation of other motor vehicles. These conversations, focused on human factors and observations, mutually benefitted the authors and their spouses, engendering continued growth in a commitment to attentive and courteous driving, demonstrating a personal commitment to traffic safety. As a result of the unusual circumstances incurred during this research, the corresponding author also now recognizes that a raised forward-facing palm means "You are starting to follow too closely for my comfort" without excluding "Yes, you do know what you're doing because you are a professional, and you are focused on this right now."

The authors gratefully acknowledge every single road user who moved to the right when sufficient headway for rightward vehicles was obtained, thereby increasing the availability of the left lane. Vehicle operators who remained rightward for other vehicles already occupying the left lane are especially commended for their courtesy and kindness.

This paper's editorial process was intensely thorough. Gratitude to the editorial team of the *Journal of Traffic Control Device Research* is therefore heartily expressed!

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COMPLIANCE STATEMENT

During the production of the second volume of the *Journal of Traffic Control Device Research*, Scott O. Kuznicki serves as the Managing Editor and was responsible for the production of the *Journal*. As the corresponding author of this paper, Mr. Kuznicki recused himself from all paper review and selection activities associated with the first issue of second volume of the *Journal of Traffic Control Device Research,* the document for which this paper was submitted for publication. Similarly, the authors did not request, obtain, or represent special consideration on account of their membership in, participation within, and/or contributions to professional organizations, including Sponsoring Organizations of the National Committee on Uniform Traffic Control Devices.

REFERENCES

[1] Matthiesen, Wickert, Lehrer. SLOWER TRAFFIC KEEP RIGHT: A Summary of State "Keep Right" Laws. https://www.mwl-law.com/slower-traffic-keep-right-a-summary-of-state-keep-right-traffic-laws, Hartford, CT. Accessed August 2024.

[2] Matthiesen, Wickert, Lehrer. SLOWER TRAFFIC KEEP RIGHT: A Summary of State "Keep Right" Laws. https://www.mwl-law.com/slower-traffic-keep-right-a-summary-of-state-keep-right-traffic-laws, Hartford, CT. Accessed August 2024.

[3] https://www.reddit.com/r/wisconsin/comments/112x6rz/is_wisconsin_the_only_state_where_the_cruising/. Accessed August 2024

[4] *Highway Capacity Manual*. Transportation Research Board of the National Academies.

[5] Balk, Stacy A, Jackson, Steven. Lane Line Markings in Advance of Lane-Reduction Transitions: Final Report. Pooled Fund Study. February 2016.


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ABOUT THE IMAGERY

Photos exhibited apart from the research papers in this publication are intended to highlight useful, innovative, unusual, unique, archaic, or even nostalgic traffic control devices. A description of the photos in order is provided below.

> *Reversible lanes along Interstate 90 on Mercer Island, Washington State, once served a crucial transportation purpose but will someday carry light-capacity transit service to and from downtown Seattle.*
>
> *Closely-spaced interchanges along a trenched section of Interstate 17 near downtown Phoenix, Arizona, complicate motorway operations on the approach to the system interchange with Interstate 10.*
>
> *A rare red indication is displayed in a traffic signal along Naito Parkway in Portland, Oregon, where some bicycle service operates on recall.*
>
> *Minnesota's "cylinder delineator" serves as an inexpensive yet elegant solution for marking roadway boundaries in median crossovers.*
>
> *Button copy still adorns thousands of guide signs in California, Arizona, Ohio, and Indiana, proving quite legible after decades of service.*
>
> *Some numerals in this mile-posting are correctly rendered in the FHWA Standard Alphabet, but the stylized U.S. Highway route marker won't do.*
>
> *Rural highways in Montana generally feature comprehensive delineation, evident along this section of State Highway 200 west of Helena.*

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.

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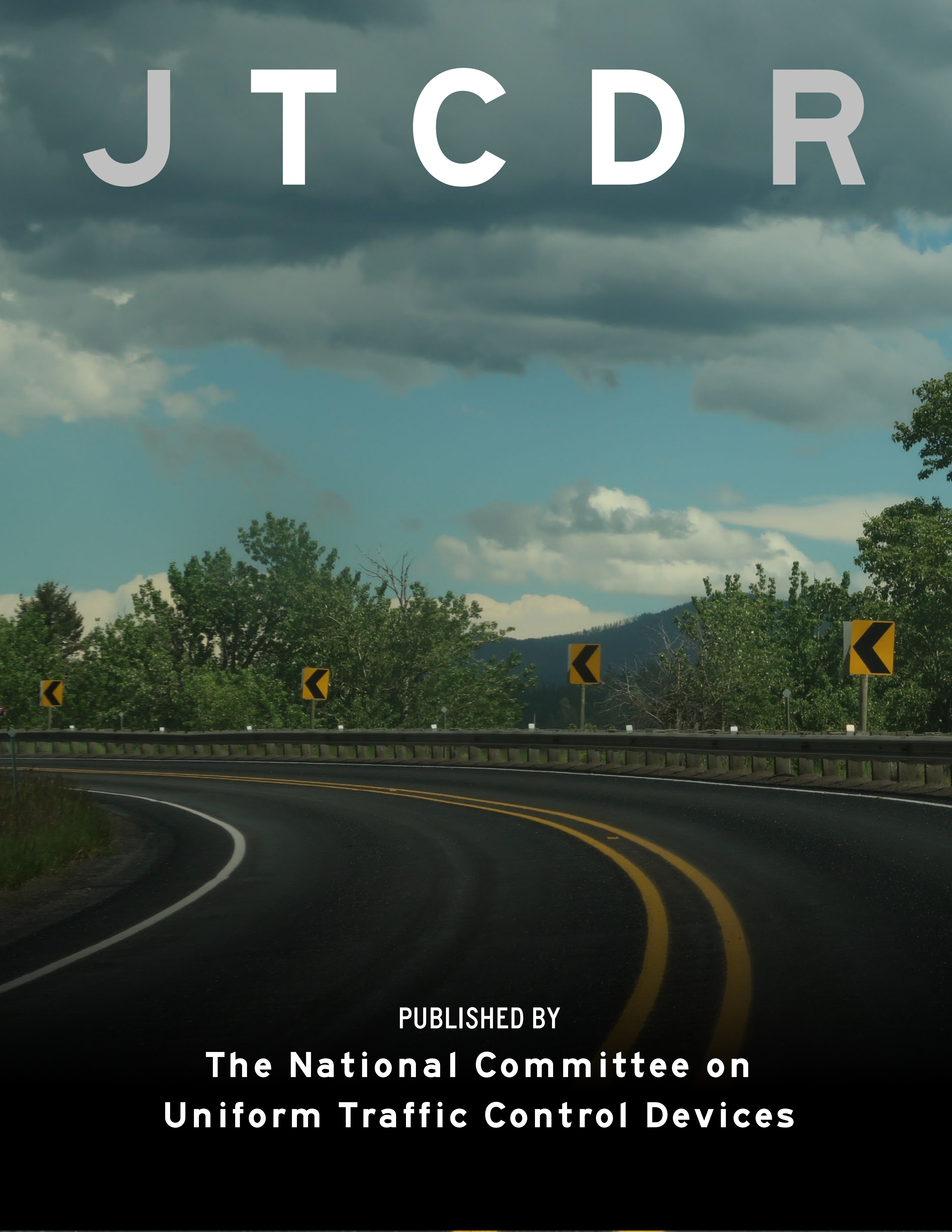

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