Effectiveness of Using Diagonal Yellow Arrows on Lane-Use Control Signals

Nancy Dutta, Ramkumar Venkatanarayana, and Michael D. Fontaine

Lane-use control signals (LUCSs) are important elements of a traffic management strategy for mitigating congestion and enhancing safety, especially during peak travel times. The *Manual on Uniform Traffic Control Devices* (MUTCD) allows the use of a downward green arrow indication as well as a yellow X-indication and a red X-indication. In 2014, the Virginia Department of Transportation requested and obtained FHWA approval for an experiment to evaluate the diagonal downward yellow arrow indication. Previous studies had shown that this indication had several benefits relative to the yellow X-indication. A stated preference survey was conducted to evaluate driver understanding of LUCSs on I-66 and on I-95 express lanes. Survey results indicated that more than six times as many participants preferred the diagonal downward yellow arrow indication to the yellow X-indication, regardless of driver age or travel frequency on the test corridors. Traffic operations center staff anecdotally observed several positive changes in driver behavior while the diagonal downward yellow arrow indication was in use. Preliminary operational and safety results were reviewed after deployment of the diagonal downward yellow arrow indication. Results indicated that driver understanding of the diagonal downward yellow arrow indication was superior to that of the MUTCD-approved yellow X-indication, and no negative effects on safety or operations were observed. The diagonal downward yellow arrow indication appears to be a useful new LUCS indication and could improve traffic management.

Used to dynamically open or close lanes to travel, freeway lane-use control signals (LUCSs) provide advanced warning of lane closures or permit dynamic operation of shoulder lanes. They can be an important element of a traffic management strategy for mitigating congestion and enhancing safety, especially during peak travel times. The *Manual on Uniform Traffic Control Devices* (MUTCD) defines LUCSs as "special overhead signals that permit or prohibit the use of specific lanes of a street or highway or that indicate the impending prohibition of their use" (*1*). Chapter 4M of the current MUTCD allows the use of the downward green arrow indication as well as yellow and red X-indications. The Virginia Department of Transportation (DOT) has long used the green arrow indication and the red X-indication for part-time running on the hard shoulder of I-66 and I-264. The Virginia DOT recently expanded LUCS use to freeway main-line lanes at other locations as part of the deployment of active traffic management (ATM) systems and managed lanes.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2624, 2017, pp. 38–47.
http://dx.doi.org/10.3141/2624-05

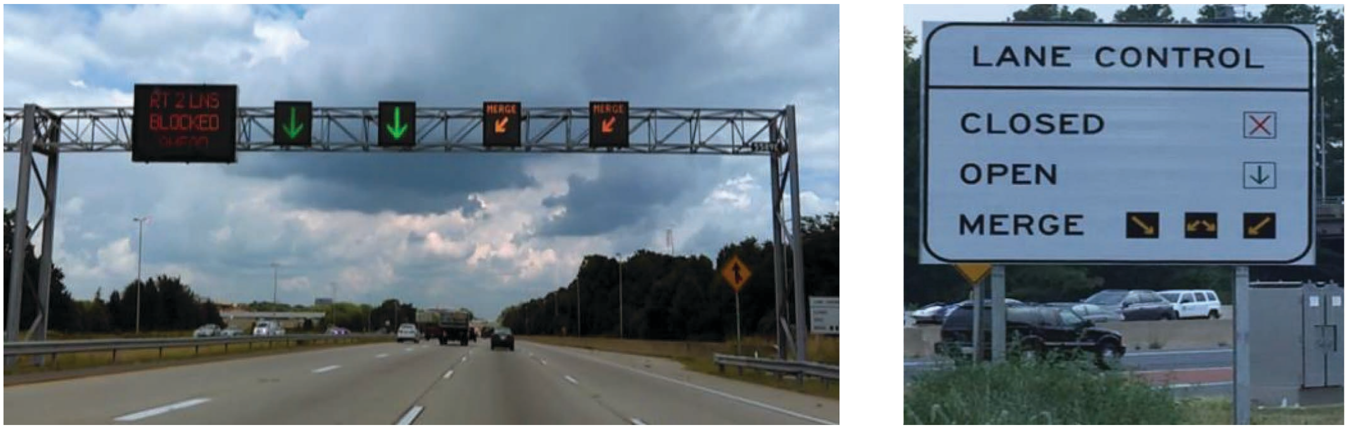
With the expansion of LUCSs to nonshoulder lanes, the Virginia DOT wanted to include an indication (other than the green arrow indication and the red X-indication) to indicate that a driver should be prepared to vacate the lane ahead. Even though the MUTCD-approved yellow X-indication has this meaning, Virginia DOT staff were concerned that the yellow X-indication did not convey a clear message to act in response to the signal. All Virginia DOT freeways with LUCS deployments have high traffic volume and congestion; therefore, high legibility and quick comprehension of the LUCS indications are critical to reduce perception–reaction time and, in turn, reduce traffic turbulence and crashes. Furthermore, the Virginia sites serve large military installations and high volumes of recreational traffic that bring in many drivers unfamiliar with the area. Therefore, clearly comprehensible traffic control indications are essential.

Past studies have documented the benefits of the diagonal downward yellow arrow indication as an alternative to the yellow X-indication (*2, 3*). The angled yellow arrow indication indicates the recommended direction in which the traffic should merge (left, right, or either direction). It can be used in advance of a lane closure with a red X-indication or in advance of the closure of a part-time shoulder lane. In 2014, the Virginia DOT requested and obtained FHWA approval for an experiment to evaluate the diagonal downward yellow arrow indication on several facilities in Virginia (Figure 1).

The Virginia DOT experiment is active at three sites: I-66, I-95 express lanes, and I-264 (*4*). As part of the experimentation, the Virginia DOT developed an evaluation plan encompassing several goal areas (driver behavior, mobility, and safety), perspectives (drivers and system operators), and qualitative and quantitative measures. This paper describes the research efforts of the Virginia DOT and provides preliminary results on the effectiveness of diagonal downward yellow arrow indications. Previous studies have focused mainly on simulations and closed course studies, but this effort includes real-world field data and perceptions of actual drivers and system operators along each roadway after deployment of the diagonal yellow arrow indication.

OBJECTIVES AND SCOPE

The objective of this study was to assess the effectiveness of the diagonal downward yellow arrow indication, with a focus on driver understanding and system operator observations. To achieve this objective, a stated preference survey was conducted to determine the level of understanding and preference of drivers between the yellow arrow indication and the yellow X-indication. Staff members from all three traffic operations centers (TOCs) that use the diagonal downward yellow arrow indications were interviewed to gather observations about the general effectiveness of the yellow arrow indications and the X-indications and, specifically, on driver behavior.



(a) (b)

FIGURE 1 Examples of (*a*) LUCS indicators in use on I-66 and (*b*) educational sign offering guidance to LUCS indicators in use.

Mobility and safety analyses were conducted, and preliminary results are presented.

LITERATURE REVIEW

Interest in using diagonal downward yellow arrow indication surfaced in the mid-1990s. In 1996, the Texas Transportation Institute (TTI) conducted a study that examined the legibility, driver understanding, and impact on operations of the diagonal downward yellow arrow indicator (*3*). At that time in Texas, the downward yellow arrow indication was being used on freeways in San Antonio, and the yellow X-indication was being used in the Dallas–Fort Worth area. A closed-course study examined the legibility distances of a diagonal downward yellow arrow indication a yellow X-indication. The researchers found that older drivers had more legibility problems with both indicators than younger drivers did. For drivers older than 65 years, the legibility distances were 93% of those of 18- to 24-year-old drivers for the yellow arrow indication and only 60% of those of the younger drivers for the yellow X-indication.

TTI also conducted a driver survey to examine driver understanding of the two indications (*3*). On average, the diagonal downward yellow arrow indication was rated as helpful by 3% to 4% more respondents than the yellow X-indication. An interesting finding was that 12% of drivers who never had seen the diagonal downward yellow arrow indication before found it confusing and 31% of drivers who never had seen the yellow X-indication before found it confusing. The researchers noted this lack of inherent understanding of the yellow X-indication as a concern.

A 2012 driving simulator study examined the diagonal downward yellow arrow indication and the yellow X-indication (*5*). Harder and Bloomfield reported that with no other traffic on the road, drivers vacated the closed lane at the yellow X-indication in only 189 of 480 trials (39.4%); when a diagonal downward yellow arrow indication was displayed, drivers vacated the lane in 267 of 480 trials (55.6%). The diagonal downward yellow arrow indication was found to be the most effective LUCS in direct comparisons with various combinations of merge text and chevrons. Drivers merged to neighboring lanes at an average distance of 54 feet before the text-only merge indication, 123 feet before the dynamic chevrons indication, and 266 feet before the diagonal downward yellow arrow indication.

In 2011, the Washington State DOT conducted an experiment with a slanted arrow indication and a double arrow indication, similar to those used on the MUTCD W12-1 double arrow sign (*6*). The Washington State DOT proposed to use these signs on I-5, I- 90, and SR-520 in the Washington State Puget Sound Metropolitan Area. The focus of the experiment was to develop lane control signage that would provide effective, accurate, reliable, up-to-date information with quicker driver comprehension than that provided by standard MUTCD signage. However, this project was canceled after deployment, and no evaluation report is available.

A 2013 human factors study tested multiple symbols used for dynamic lane assignment in Minnesota and Washington (*7*). The findings showed that the steady diagonal yellow arrow indication and the sequential yellow chevron indication provided clear messages about the proper action across all study scenarios. However, the correct interpretation of the steady yellow X-indication depended on other LUCSs displayed at the same time.

In 2016, Rindels et al. documented the effectiveness of several ATM LUCS indications, including a downward yellow arrow indication (to indicate caution), chevrons with merge text (to indicate merging to an adjacent lane—right, left, or both directions), yellow X-indication (to indicate a closed lane ahead), and a "Lane Closed Ahead" text message (*8*). Even though a diagonal yellow arrow indication was not included in the experiment, the study findings support the usefulness of similar indications, and the chevrons with merge text were most effective.

METHODOLOGY

The evaluation conducted in this study consists of both quantitative and qualitative measures. Driver understanding and behavior were evaluated with qualitative driver surveys and TOC staff interviews. Quantitative measures of effectiveness encompassed both safety and mobility goal areas. For safety, the numbers of crashes were examined, total and by type. For operational mobility measures, traffic volumes and speeds were examined. The use of yellow arrow indications or X-indications at each site also was monitored to quantify the frequency of use at each site. These measures are described in detail later in the paper, after the site descriptions.

Site Descriptions

The three active experimentation sites are located in the Northern (I-66 and I-95 express lanes) and Eastern (I-264) Operations Regions of Virginia DOT, and each site has several unique characteristics. Table 1 summarizes these characteristics as well as the specific elements of the LUCS deployment at each location. Individual site descriptions follow.

Interstate 66

An ATM system was deployed on I-66 in September 2015, and LUCSs were installed on overhead gantries that span all lanes between Exit 52 (Lee Highway, Route 29) and Exit 64 (I-495). Segments of the right-hand hard shoulder at this site are opened dynamically for travel during congested periods, and a concurrent high-occupancy vehicle lane is present on the left throughout the section. The ATM system is managed by the Virginia DOT Northern Region TOC. The LUCSs can be activated at any time of day or night.

Interstate 95 Express Lanes

The I-95 express lanes (referred to in this paper as I-95) opened to travelers in December 2014 as a high-occupancy toll facility; it previously had operated as a two-lane barrier-separated reversible high-occupancy vehicle facility without LUCSs. Now, LUCSs are installed on overhead gantries that span all lanes wherever the cross section has three travel lanes, which is between Exit 158 on I-95 (Prince William Parkway) and near Exit 2 on I-395 (Edsall Road), a distance of 19.0 miles.

The I-95 express lanes currently use only the yellow X-indication, not the yellow arrow indication. Software issues have delayed implementation of the diagonal downward yellow arrow indication; however, this delay has allowed the researchers to better evaluate the MUTCD-compliant yellow X-indication. This system is operated by the private concessionaire Transurban. The LUCSs on the express lanes are active for whichever travel direction is currently in operation, during any time of day or night.

Interstate 264

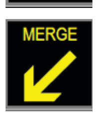
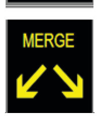
I-264 allows peak-period use of the shoulder as a travel lane to alleviate congestion. LUCSs are deployed from Exit 16 (Rosemont Road) to Exit 18 (Witchduck Road), where the shoulder lane is open to travel. The LUCSs are installed over only the shoulder lane and not any other lanes. This system is operated by the Virginia DOT Eastern Region TOC. The LUCSs are used only when the shoulder is open to travel: on weekdays from 4 to 6 p.m. in the eastbound direction and from 6 to 8 a.m. in the westbound direction.

Use of Yellow Indication

The frequency, purpose, and duration of LUCS yellow indications were summarized for each site (Table 2). The date and time, duration, and location (roadway, direction, mile marker, lane) of each LUCS activation were logged by the operating TOC. Activation logs were cross-referenced with incident and work zone data from the Virginia DOT database, VA Traffic, by using date–time and location fields to determine the purpose of activation. This analysis quantified the extent to which the LUCSs were applied to manage traffic at each site. Although not a measure of effectiveness, quantification of yellow arrow indication or X-indication use provides normalization for observed mobility and safety effects.

At the I-264 and I-95 sites, data from March to August 2015 were examined. Because the I-66 system was activated later, the analysis period was from October 2015 to February 2016. Because the analysis

TABLE 1 Summary of Test Sites and LUCSs at Each Location

Site (start date)	Directional Length (mi)	LUCS Yellow Indication	LUCS Dimensions	No. of Gantries (mean spacing)	No. of LUCSs	Conditions Before Experiment	2015 AADT (both directions)
I-66 eastbound and westbound (Sept. 2015)	12.5	  	54 in. H × 54 in. W	44 (1,000 ft to 3,500 ft)	176	Green arrow indication or red X-indication, only on shoulder lane	71,400 to 92,500
I-95 northbound and southbound (Dec. 2014)	19.0		22 in. H × 30 in. W	63 (approx. 2,640 ft)	189	No LUCS	25,000 to 40,000
I-264 eastbound and westbound (March 2015)	4.0		49 in. H × 53 in. W	20 (600 ft to 2,200 ft)	20	Green arrow indication or red X-indication, only on shoulder lane	37,500 to 76,860

NOTE: AADT = annual average daily traffic.

TABLE 2 Use of LUCSs (Yellow Arrow Indication or Yellow X-Indication)

	I-95 EL[a]		I-66		I-264	
LUCS Usage	NB	SB	EB	WB	EB	WB
Total number of gantries on roadway	31	32	22	22	10	10
Average number of activations/gantry/month	0.88	1.25	2.46	1.46	0.85	0.75
Average hours per activations/gantry/month	0.92	0.61	2.28	1.29	0.25	0.37
Average number of incident-related activations/gantry/month	0.07	0.24	1.65	1.18	0.43	0.15
Average hours of incident-related activations/gantry/month	0.03	0.13	1.10	0.54	0.15	0.03
Average number of work zone–related activations/gantry/month	0.11	0.23	0.06	0.01	—	—
Average hours of work zone–related activations/gantry/month	0.09	0.18	0.35	0.03	—	—

NOTE: NB = northbound, SB = southbound, EB = eastbound, and WB = westbound.
[a]I-95 express lanes (EL) use MUTCD approved yellow X-indication only.

periods, numbers of gantries, and numbers of lanes varied across sites, the measures of LUCS use were normalized per month, per gantry.

Driver Comprehension Survey

To explore driver understanding of and preference for the yellow indication, a stated preference survey was conducted. First, the authors predefined the regions of interest as several Virginia counties (Fairfax, Fauquier, Loudoun, Prince William, Spotsylvania, and Stafford) where the primary users of I-66 and I-95 were likely to live, then determined the applicable zip codes for those regions. These zip codes were cross-checked against the Commuter Connections database of the Metropolitan Washington Council of Governments to identify potential survey participants in the regions of interest who also could be contacted by email. The authors created a survey with Survey Monkey, then emailed invitations to participate in the survey to commuters who lived in the targeted jurisdictions.

The survey requested sociodemographic data (gender and age) from each respondent as well as the frequency that the respondent traveled on I-95 or I-66. Respondents were given the option to add name and contact information or submit the survey anonymously. The online survey was administered during May and June 2016. The survey allowed only one submission per IP address, so one participant could not submit responses more than once.

The survey included six hypothetical scenarios that showed the LUCS yellow arrow or X-indications on simulated overhead gantries on a five-lane cross section, which is typical for the I-66 site. From left to right, the lanes were designated as Lane 1 (leftmost lane) through Lane 4, and the rightmost lane was labeled as the paved shoulder (Figure 2). The three basic configurations presented in the six scenarios were

- LUCS (yellow arrow indication or yellow X-indication) over the shoulder lane,
- LUCS (yellow arrow indication or yellow X-indication) over a middle lane, and
- LUCS over the shoulder lane (red X-indication) and rightmost travel lane (yellow arrow indication or yellow X-indication).

Each scenario displayed the yellow arrow indication or the yellow X-indication, so the same scenario was presented once with each indication. For each scenario, participants were asked to choose, from seven choices, the answer that they believed best represented what was shown in the image. For example, the answer choices for Scenario 1 (Figure 2) were the following:

1. All travel lanes are open.
2. Shoulder is closed to traffic at this location.
3. Shoulder is closed ahead; traffic on the shoulder should merge to Lane 4 when possible.
4. Drive cautiously on the shoulder.
5. Merging traffic ahead on the shoulder.
6. Stop immediately on the shoulder.
7. Don't know what it means.

The correct answer varied according to the scenario presented. For Scenario 1, the third answer was the correct choice. The presentation order of scenarios and answer choices were randomized to minimize proximal bias. Respondents could not go back and alter the answer to any previous scenario after seeing another question. After all of the scenarios had been evaluated, a final question offered definitions of the yellow X-indication and the yellow arrow indication and asked the respondent whether one was preferred over the other. Reaction time was not explicitly evaluated.

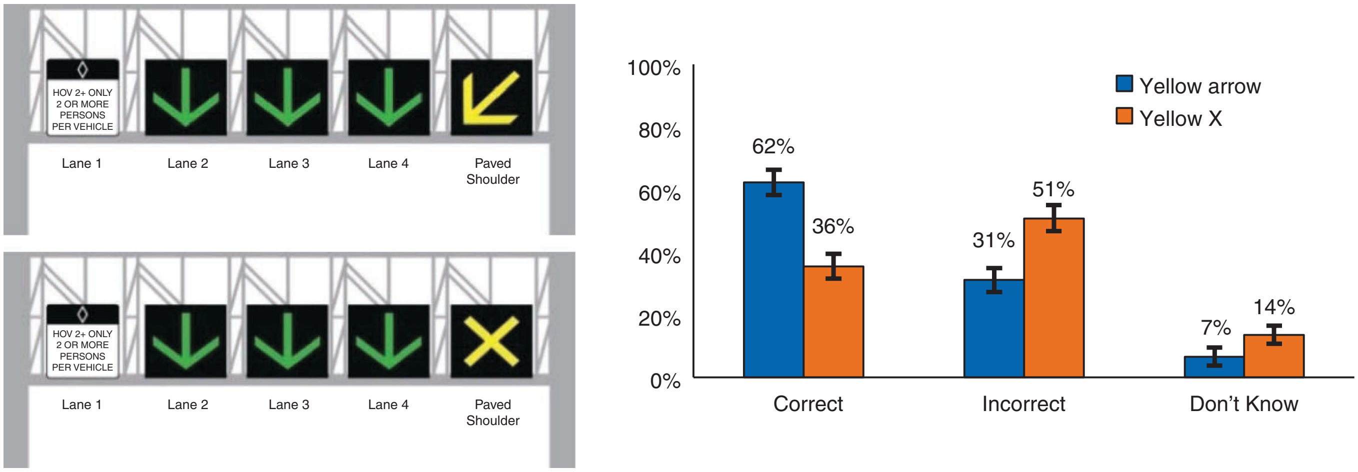
Because use of the diagonal downward yellow arrow indication on I-264 involved only a 4-mile part-time shoulder running section, users in that corridor were not surveyed because many regional users are not exposed to the treatment. Even so, many survey respondents indicated that they did not frequently drive the corridors where the yellow arrow indication or the X-indication was deployed.

A detailed analysis was performed on the survey results. To determine whether the proportion of answers differed significantly, confidence intervals were calculated with

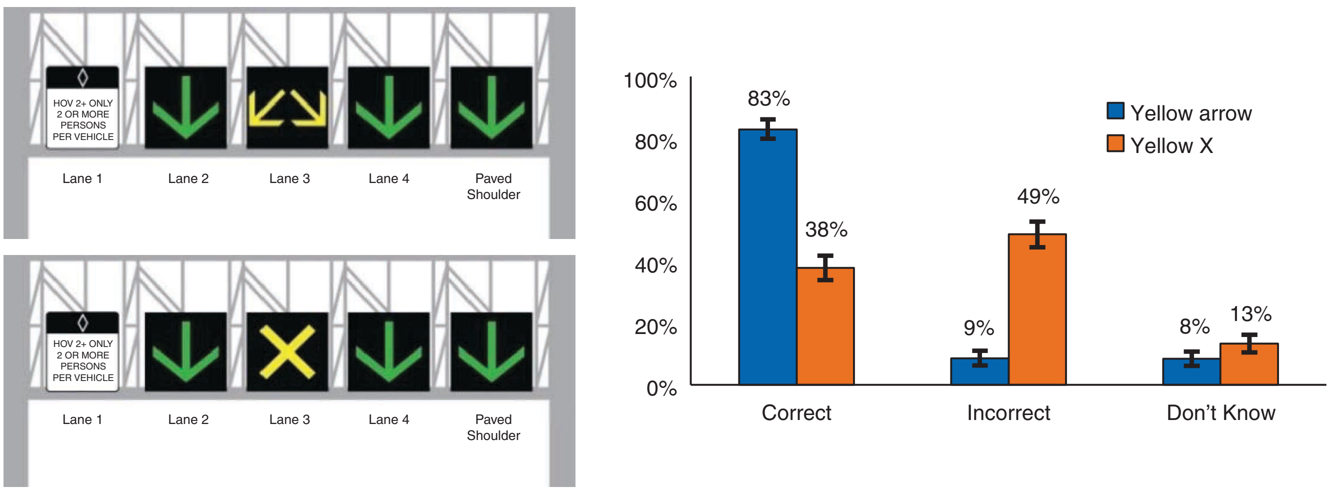
$$\hat{p} \pm Z\sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \quad (1)$$

where

$\hat{p}$ = sample proportion (p/n),
p = population proportion,
n = sample size, and
Z = 1.96 (for 95% significance level).



(a)



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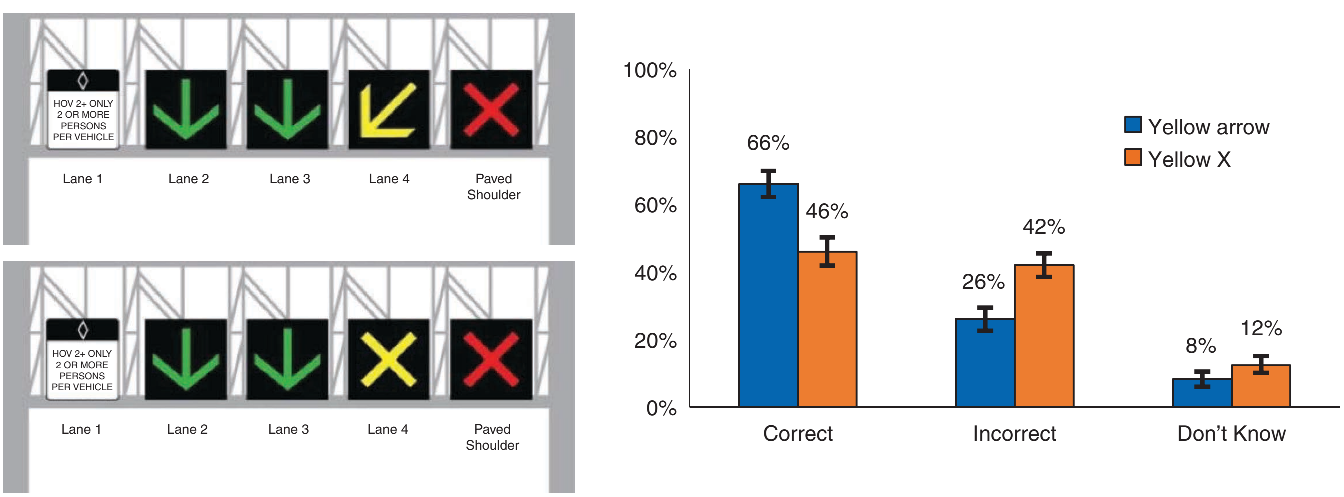


(c)

FIGURE 2 Driver understanding of diagonal downward yellow arrow indication versus yellow X-indication: (*a*) Scenario 1 (yellow arrow) versus Scenario 2 (yellow X), (*b*) Scenario 3 (yellow arrow) versus Scenario 4 (yellow X), and (*c*) Scenario 5 (yellow arrow) versus Scenario 6 (yellow X).

TOC Staff Observations

At TOCs, system operators continually monitor closed-circuit television images across the roadway network and observe a great deal of driver behavior. TOC staff were interviewed to capture observations of driver behavior before, during, and after activation of the diagonal downward yellow arrow indication or the X-indication. For the I-66 and I-264 sites, TOC staff at Virginia DOT were interviewed. For the I-95 express lanes, the TOC staff interviewed were from the Transurban Group, which was responsible for actively monitoring those lanes and indications. Because only the yellow X-indication was used on I-95, system operator opinions were compared with those of Virginia DOT system operators at locations where the yellow arrow indication was deployed.

The topics discussed during the operator interviews were

- Standard operating procedures for LUCS activation, including evolution of practices;
- Observations related to driver behavior during LUCS activation, including differences between work zone, incident, and shoulder running applications;
- Differences in behavior between congested and uncongested conditions;
- Differences in behavior between trucks and passenger cars; and
- Level of satisfaction with LUCS applications.

Mobility Measures

Side-fire radars were installed along all three project sites, covering all or most of the travel lanes and the shoulder. Sensors typically were spaced 0.3 to 0.5 miles apart. Detector data during activations (of the yellow arrow indication or X-indication) were examined to assess the location and magnitude of changes in traffic speed, volume, and lane-level volume distribution. Several conditions must have been met simultaneously to observe mobility impacts with detector data:

1. An incident, crash, or work zone had to block a travel lane near a LUCS that was displaying a yellow arrow indication or a yellow X-indication;
2. The duration of the lane closure had to be long enough to observe impacts on traffic;
3. Detector data had to use suitable aggregation intervals and be available, of high quality, and near the LUCS display;
4. No interchanges were located between adjacent detectors; and
5. Traffic volumes had to be high enough that changes in performance could be observed but not so high that drivers tried to use whatever capacity was available across all lanes (including closed ones) until they were forced to merge into an open lane.

Given the relatively rare use of yellow arrow indications or yellow X-indications, meeting all five conditions simultaneously was understandably challenging. Therefore, preliminary changes in mobility are examined in this paper with the use of a case study, and the investigation of operational effects is ongoing.

Safety Measures

Because the diagonal yellow arrow indication had been operational only since March 2015 on I-264 and since September 2015 on I-66, available crash data were limited. Crash data for 5 to 6 months after deployment of the diagonal downward yellow arrow indication were examined and contrasted with data from the corresponding months during the 2 years before the yellow arrow indication or X-indication was deployed (Table 3). This limited data set did not allow any statistically significant conclusions to be drawn but provided a preliminary indication of the extent of changes in safety.

TABLE 3 Average Number of Crashes per Month Before (2013, 2014) and After (2015) LUCS Implementation

Average Number of Crash Type	Direction	2013	2014	2015[a]
I-66 (available October to February)				
Total	Eastbound	45.4	49.2	44.6
	Westbound	44.0	50.0	45.8
Fatal or injury	Eastbound	14.0	16.6	13.8
	Westbound	13.8	13.0	13.2
I-95 (available March to August)				
Total	Northbound	5.8	4.0	3.5
	Southbound	5.5	3.5	2.7
Fatal or injury	Northbound	1.5	0.3	0.3
	Southbound	1.7	0.8	0.5
I-264 (available April to August)				
Total	Eastbound	4.2	4.4	3.0
	Westbound	0.6	1.6	1.0
Fatal or injury	Eastbound	2.0	1.4	1.0
	Westbound	0.0	0.8	0.6

[a]LUCS in operation.

RESULTS

LUCS Use

Table 2 summarizes the use of the yellow arrow indication and the yellow X-indication at the three sites. For I-264, only LUCS activations during the regularly scheduled time of day hard shoulder running periods are quantified. The data show that yellow arrow indication and yellow X-indication use was relatively infrequent on all facilities, from 0.75 to 2.46 activations per gantry per month. The average time per activation was 0.25 to 2.28 hours.

Incident-related activations were much more common than work zone–related activations; however, in several instances, no cause of activation could be determined from historic event databases. Reasons for the undocumented activations included system testing; gaps in the incident databases; operator error (e.g., TOC staff activated the wrong indication, which usually was for a short duration); errors in the time stamp, direction, or mile marker of the incidents or work zones in the database; mobile work zones; and activation of LUCSs during snow events to direct traffic into clear lanes.

Driver Comprehension Survey

The driver survey produced 587 separate valid responses. Approximately 49.8% of the respondents were female, 46.9% were male, and the remainder declined to answer. Each respondent was categorized by age as younger than 55 or older than 55 years. Most (69%) of the participants were younger than 55 years. Across Virginia, 66% of licensed drivers are younger than 55 years, so this sample is in close agreement with the overall Virginia driving population (*9*).

Six yellow arrow indication or yellow X-indication scenarios were presented to test driver understanding of the different indications, and answers were summarized in three categories: correct answer, incorrect answer, and don't know. The incorrect category comprises responses for all answer choices besides the correct answer and don't know. For each category, confidence intervals were calculated using a 95% significance level. Furthermore, the responses were divided by age (i.e., whether the participant was older than or younger than 55 years). A preliminary analysis was completed between the groups, and the results were not statistically significant. To provide greater statistical power, the groups were combined and evaluated.

Figure 2 summarizes the driver responses for each scenario, with confidence intervals for each response. Survey results consistently showed driver understanding of the yellow arrow indication was superior to that of the yellow X-indication, regardless of driver age or scenario. Differences were most pronounced when the indication was activated over the middle lane, in which case around 83% of the participants interpreted the yellow arrow indication correctly (Scenario 3) versus 38% for the yellow X-indication (Scenario 4).

For each scenario, some participants interpreted the LUCSs incorrectly and a small percentage indicated that they did not understand the sign. The most common misinterpretation of the yellow X-indication was that it meant to drive with caution. For Scenario 2 (yellow X-indication over the paved shoulder), 36% of participants chose the correct answer ("Shoulder is closed ahead, traffic on the shoulder should merge left to Lane 4 when possible") and 30% of participants chose "Drive cautiously on the shoulder." When the participants saw the same situation with a yellow arrow indication (Scenario 1), 63% of the participants made the right choice. The most common (23% of participants) misinterpretation was "Merging traffic ahead on the shoulder." Similar trends were observed for other scenarios. Even though each signal indication was interpreted incorrectly by some participants, driver understanding of the yellow arrow indication was consistently and significantly higher than that of the yellow X-indication.

Asked directly about their preference between the two indicators, a significant number of participants preferred the yellow arrow indication over the yellow X-indication (Figure 3). These results reveal that driver attitude toward the yellow arrow indication is more positive than toward the yellow X-indication, and confidence intervals do not overlap. Participant preferences were cross-referenced with participant travel frequencies on I-66 and I-95. The difference in preference as a function of travel frequency on either or both facilities was not significant, and the yellow arrow indication was preferred consistently across all cases.

TOC Staff Observations

Next, TOC staff were interviewed about how drivers actually respond to both the yellow X-indication and the yellow arrow indication. Comments were anecdotal, but staff had observed driver reactions to the yellow X-indication and the yellow arrow indication under various circumstances. TOC staff for the I-95 express lanes stated that under severely congested conditions, many drivers did not respond to the yellow X-indication and continued to travel in the closed lane until physically forced to merge into the adjacent open lane. In contrast, during daytime incidents under less congested conditions and during overnight work zones, drivers responded better and the yellow X-indication facilitated earlier merging. The operators noted that in general, the yellow X-indication seemed to be inherently confusing because it did not direct the driver to merge in any specific direction.

Staff from Virginia DOT TOCs were interviewed to gain information about the yellow arrow indication. Eastern Region TOC staff mentioned that the LUCSs have allowed them to better manage traffic on I-264 when the shoulder was opened to travel outside of peak periods; they have opened the shoulder lanes during nonpeak periods to alleviate congestion caused by work zones or incidents that closed down one or more travel lanes. They also noted that drivers appeared to respond to the yellow arrow indication better during off-peak periods than during peak-hour incidents. In the absence of work zone lane closures, drivers did not always respond to the display message or signal. Overall, interviewed staff were satisfied with the yellow arrow indication and thought that its use at lane closures made driver behavior smoother than the red X-indication alone. They reported that drivers changed lanes earlier than before the yellow arrow indication was activated.

Northern Region staff also reported that drivers on I-66 merged into open travel lanes earlier after the yellow arrow indication was implemented than previously, when only a red X-indication was used. With the corresponding dynamic message signs, LUCSs increased driver awareness in the event of an incident (especially multiple lane closures). This staff also noted that when the road was extremely congested, drivers still occupied all lanes until reaching the lane-closure taper. Therefore, the effectiveness was observed primarily during uncongested conditions. The overall effectiveness was perceived

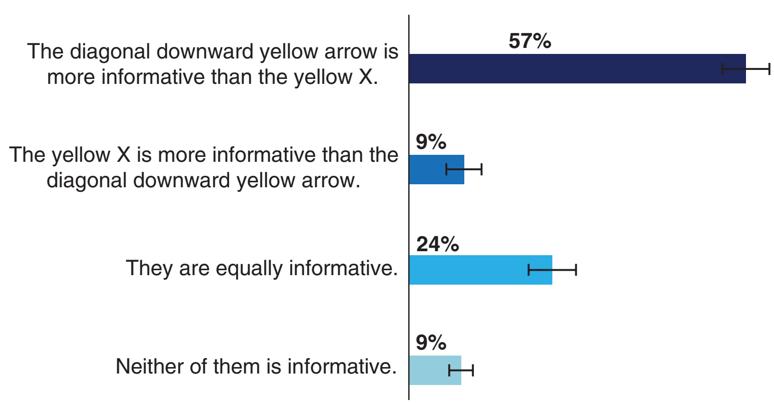


FIGURE 3 Driver preference for LUCS indications.

to be the same for both work zones and incidents. The staff did not report any significant differences in driver behavior by vehicle type or time of day. They also reported an innovative use of yellow arrow indications during snow events: directing drivers toward lanes that already had been plowed to improve the safety and efficiency of snow clearance on the remaining lanes.

In essence, drivers behave similarly across sites and between yellow arrow indications and yellow X-indications, with less early merging when congestion is severe and more early merging when congestion is low. Like in the driver survey, comprehension of the yellow arrow indication appeared to present no inherent confusion, but the specific action that drivers should take was less clear with the yellow X-indication.

Preliminary Mobility Analysis

Because the driver survey and TOC staff comments were positive overall, operational data also were examined to determine whether improved driver understanding produced corresponding flow improvements. The relatively infrequent activation of the yellow arrow indications and X-indications (Table 2), as well as the stringent concurrent requirements (e.g., the incident had to occur near functional detectors), presented challenges to statistically sound operational analysis. Furthermore, project-specific data could not be collected manually because the vast majority of activations were due to crashes or disabled vehicles, which are inherently rare and random events.

Some initial analyses were performed on the speed and volume data collected from the detectors at all three sites. Because current sample sizes are small, this part of the research study is still under way. A case study of the analysis is presented here to illustrate preliminary findings and challenges.

On Sunday, November 8, 2015, two separate crashes occurred on I-66 eastbound: Crash 1 at mile marker (MM) 53.0 and Crash 2 at MM 52.0. Crash 1 resulted in multiple main-line lane closures for more than 40 minutes during the congested afternoon peak, and Crash 2 blocked a lane on the off-ramp. The locations of detectors and LUCSs are shown in Figure 4*a* and the LUCS activations corresponding to these two incidents in Figure 4*b*. Lanes 1 through 4 are numbered from left to right, and the LUCS indicators were green arrow (g), left-facing diagonal downward yellow arrow (y), or red X-indicator (r); blank sign (b) denotes no indicator.

Detectors located at MM 52.6 and MM 3.0 covered the section of I-66 most affected by these incidents. Changes in 5-minute traffic volumes and volume-weighted speeds across all lanes before, during, and after the lane closures at these sites are presented in Figure 5 for both crashes. The time spans between crash occurrence and lane openings also are shown for both crashes.

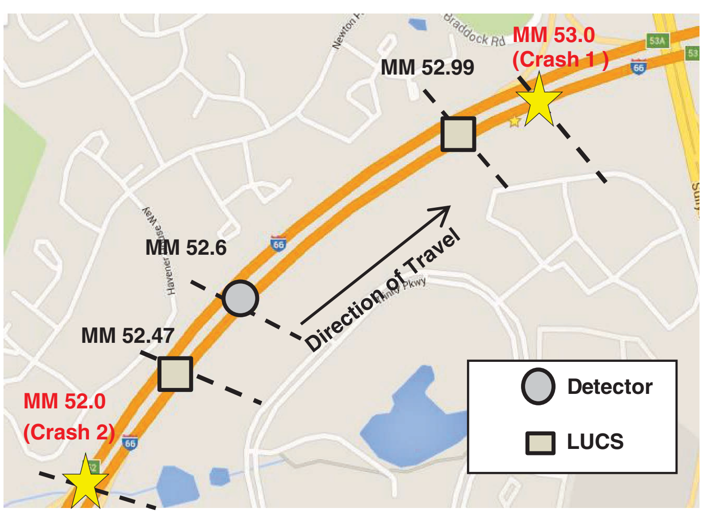
Low speeds on all open lanes at both detector locations between 14:40 and 16:00 highlight the congested conditions after the crashes. The times of opening and closing lanes as indicated on LUCSs matched closely with the volume and speed data at detector at MM 53.0. Between 14:51 and 15:21, Lane 1 was the only open travel lane at MM 53.0, according to the LUCSs. Drivers were forced to leave the other lanes as indicated by the zero volumes and speeds. Lane 2 opened at 15:21, and Lane 3 opened 12 minutes later; Lane 4 opened last. As lanes became available, traffic volumes on these lanes increased to become comparable to volume in Lane 1.

At MM 52.6, volumes and speeds across all lanes dropped and rose in line with lane closure and opening times but did not differ drastically across the lanes. Because Crash 2 blocked the off-ramp, traffic volume on the main line remained steady or increased after this crash at both detector locations. Drivers saw the yellow arrow indications but did not merge into the open travel lane immediately; this pattern confirms the TOC staff observation that, under congested conditions, drivers use all available capacity and do not leave their travel lanes until forced.

The graphs in Figure 5 also reflect the differences in time stamps between lane closure and LUCS activation. The precision of recorded crash start and end times and the aggregation interval of traffic data can present limitations for detailed analyses.

Preliminary Safety Analysis

The safety evaluation of LUCSs was limited in several ways. First, on I-66, the safety effects of the yellow arrow indication were difficult to isolate because LUCSs were deployed in conjunction with

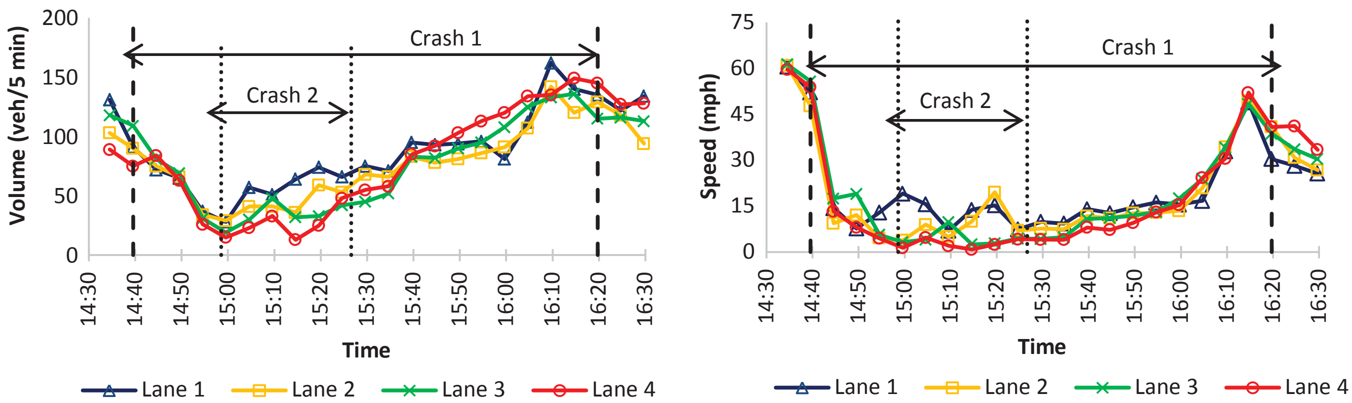


(a)

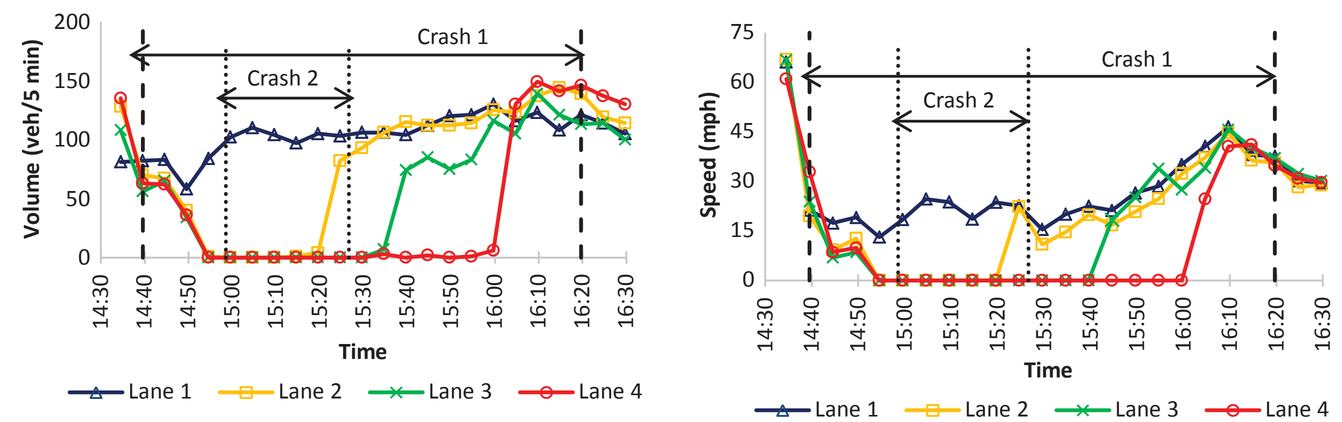
		MM 52.47	MM 52.99
Time	14:51	Lane 1 (g)	Lane 1 (g)
		Lane 2 (y)	Lane 2 (r)
		Lane 3 (y)	Lane 3 (r)
		Lane 4 (y)	Lane 4 (r)
	15:21	Lane 1 (g)	Lane 1 (g)
		Lane 2 (g)	Lane 2 (g)
		Lane 3 (y)	Lane 3 (r)
		Lane 4 (y)	Lane 4 (r)
	15:33	Lane 1 (g)	Lane 1 (g)
		Lane 2 (g)	Lane 2 (g)
		Lane 3 (g)	Lane 3 (g)
		Lane 4 (y)	Lane 4 (r)
	15:58	Lane 1 (b)	Lane 1 (b)
		Lane 2 (b)	Lane 2 (b)
		Lane 3 (b)	Lane 3 (b)
		Lane 4 (b)	Lane 4 (b)

(b)

FIGURE 4 For two crash incidents on Nov. 8, 2015: (*a*) locations of LUCSs and detectors and (*b*) LUCS activations.



(a)



(b)

FIGURE 5 Traffic volumes and speeds during November 8, 2015, incidents at (*a*) MM 52.6 and (*b*) MM 53.0.

several ATM techniques (e.g., advisory variable speed limits). Furthermore, at all sites, the amount of data available after activation of a yellow arrow indication or a yellow X-indication was limited. The average number of crashes (total crashes and fatal or injury crashes) per month are listed for each site in Table 3. The observed diversity in crash values stem from the diverse site characteristics, including length of project site and annual average daily traffic (Table 1). The Virginia DOT will continue to monitor and evaluate changes in safety at these sites as more crash data are collected. Preliminary data exhibit no evidence of degradation in total safety at any site; however, this conclusion is based on limited data.

CONCLUSIONS

Data collected and analyzed to date indicate that the diagonal yellow arrow indication conveys several significant benefits. Responses to the driver survey showed a clear preference for the yellow arrow indication over the yellow X-indication, and the yellow arrow indication was much more likely to be interpreted correctly than the yellow X-indication for the scenarios evaluated. TOC staff generally were supportive of the yellow arrow indication but indicated that drivers did not respond as intended under severely congested traffic conditions; most benefits of the indication occurred during less congested periods. The I-95 TOC staff also noted a perceived lack of understanding of the yellow X-indication, which does not specify a merge direction.

Translating the results of this driver understanding study into quantitative operational and safety results has been difficult. A detailed statistical analysis of crashes is not possible because limited crash data are available since deployment of the yellow arrow indication. Preliminary data indicate that safety does not appear to have worsened, but crash data monitoring will continue.

Evaluating the operational data also has been challenging because a lane-blocking incident must occur near a LUCS and functional detectors and because traffic volume should not be too high or too low. Because use of the yellow arrow indication and the yellow X-indication is infrequent and the activation locations are random, observable traffic operations are limited. With time, additional case studies will become available and the operational impacts of the yellow arrow indication on speed, throughput, and lane use will be available for direct comparison with the yellow X-indication. TOC staff comments about driver behavior and data available so far indicate that operational differences may be minor under congested conditions.

Even though operational and safety data are limited, preliminary analysis indicates that driver comprehension of the diagonal yellow arrow indication may be superior to that of the yellow X-indication. Future monitoring and evaluation of the safety and operational impacts of the indication will provide additional data to determine whether changes to the MUTCD are warranted.

ACKNOWLEDGMENTS

The authors thank Ritchie Robbins, John Kornhiser, Kamal Suliman, Ed Correa, Hamlin Williams, Ollie Rose, and Nicole Schwartz of the Virginia DOT; Nicholas Ramfos of the Metropolitan Washington Council of Governments; and Larry Tansinda, Mike Stanley, and Trevor Agnolin of Transurban for support throughout the project.

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The Standing Committee on Traffic Control Devices peer-reviewed this paper.