TECH**BRIEF**

Evaluation of Lane Reduction and Late Merge Signing

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INTRODUCTION

When approaching a lane reduction, drivers typically attempt to merge into the appropriate lane as soon as possible, even in congested conditions. Aggressive driving can occur when drivers merge at the last minute because they are potentially perceived to be “cutting the line.” This perception could stem from traditional traffic control device messaging suggesting that the merging responsibilities differ by lane. For this reason, some transportation agencies have considered or used methods to encourage a late merge at a lane reduction, sometimes referred to as a “zipper merge,” in which drivers are encouraged to remain in their lane until the merge point and then alternate merging into one lane. While findings have shown the potential benefits of late merges, particularly during times of congestion, signing for these locations varies greatly across the country, with some agencies developing unique signs they think may be effective (Vaughan et al. 2018; Minnesota Department of Transportation 2008; McCoy and Pesti 2001; Lammers et al. 2017; Feldblum 2005; Idewu and Ishola 2009). Practices vary widely for both the number and placement of signs used on the approach where a late merge is encouraged at a lane reduction (hereafter referred to as a “late merge”). The degree of instruction provided through the sign messaging is different between agencies, with some agencies providing minimal instruction to drivers and others providing very detailed messages.

Because agencies provide many different options for implementing varying signing, little information or research on the effectiveness of these signs on driver behavior is available. Some documentation of piloted late merges is available at sites in North Carolina, Kentucky, Virginia, and Minnesota, among others; however, much of the research pertains to managed situations, such as work zones when sign messages can be changed based on traffic flow conditions (Vaughan et al. 2018; Lammers et al. 2017; Beacher, Fontaine, and Garber 2004; Minnesota Department of Transportation 2008). Additionally, most of these pilot locations have been on freeways and not on arterials. Therefore, a detailed study to investigate various sign designs, identify designs that are best understood and most likely to achieve the desired motorist behavior, and promote uniform deployment of signs is needed before they can be widely used in a consistent manner at static/unmanaged locations in the field and included in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) (FHWA 2009). The present research project was carried out under the Traffic Control Devices Pooled Fund Study (TCD PFS). The members of the TCD PFS determined that this research effort should focus on arterials due to the limited research and information on late merge signs used on arterials.

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OBJECTIVE

This research project explores and evaluates the effectiveness of different static late merge signing for use on arterials.

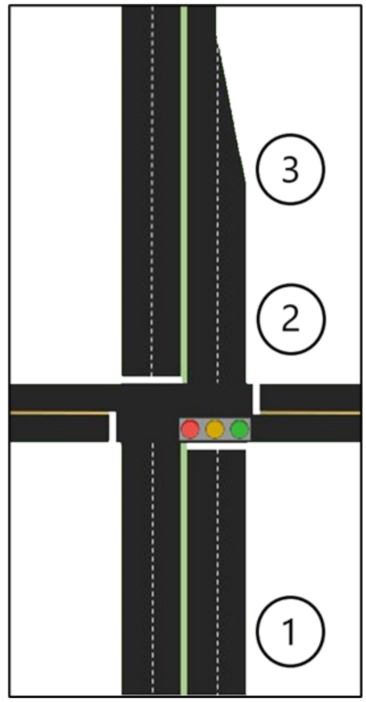
APPROACH

The research team collected data through a laboratory and a field study. The laboratory study assessed the comprehension of the different sign alternatives and determined which sign series to evaluate in the field. The field study evaluated a single sign series at 12 different sites across 3 States to evaluate driver behavior in response to the signs.

Before beginning the laboratory study, the research team conducted a literature and state-of-the-practice review to identify methods for signing late merge locations. As a part of the state-of-the-practice review, the research team consulted with the TCD PFS members who were part of the project panel to determine what signing approaches were being used in their States. The TCD PFS members provided feedback on which signs they thought were effective and should be included in the study.

The research team identified five late merge sign series alternatives for potential use on arterial roads with a lane reduction after a signalized intersection where a right lane ends, which was the roadway configuration used throughout the project. The sign series alternatives were selected based on signs proposed in the Notice of Proposed Amendments (NPA) for the 11th edition of the MUTCD and on signs that are implemented in current State practices and/or have shown success in other evaluations (FHWA 2020; Colorado Department of Transportation n.d.; Beacher, Fontaine, and Garber 2004; Minnesota Department of Transportation 2008; Vaughan et al. 2018; Zafian 2018; Feldblum 2005; Idewu and Ishola 2009). Each sign series consisted of three signs with the following placement: in advance of the intersection (first sign), downstream of the intersection (second sign), or at the merge point (third sign). Figure 1 shows the general placement or location of each sign in the series. Table 1 shows the signs included in each of the five sign series alternatives.

Figure 1. Graphic. General location of each sign within the sign series.



Source: FHWA.

Table 1. Sign series alternatives.

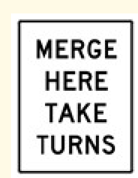
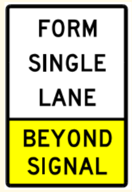
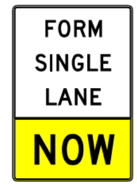
Zipper Merge Sign Series	1st Sign in Series	2nd Sign in Series	3rd Sign in Series
Alternative 1			
Alternative 2			

Table 1. Sign series alternatives. (Continued)

Zipper Merge Sign Series	1st Sign in Series	2nd Sign in Series	3rd Sign in Series
Alternative 3			
Alternative 4			
Alternative 5			

As shown in Table 1, the second and third signs in sign series alternatives 1 and 2, respectively, are the Lane Ends (W4-2) symbol sign included in the MUTCD; the second sign in sign series alternative 2 is the "LANE ENDS MERGE LEFT" (W9-2) sign included in the MUTCD (FHWA 2009). The other signs are new concepts evaluated in this study.

LABORATORY STUDY

Method

Due to the coronavirus pandemic, the laboratory study was conducted online to avoid in-person testing of participants. One hundred participants were recruited through online advertising and took part in the virtual laboratory study. Of the 100 participants, 53 were female and 47 were male. Participants ranged in age from 18 to 78 yr old (mean = 44 yr old). Participants were from 17 different States, with the majority located in Virginia (36.3 percent), Maryland (19.8 percent), North Carolina (12.1 percent), Connecticut (6.6 percent), and Pennsylvania (5.5 percent). Participants joined a virtual conference call with a researcher who shared the screen with the participants to conduct the study. The laboratory data collection consisted of three sections: comprehension testing, subjective rankings, and sign series creation. Each of these data collections is described in the following sections (comprehension, rankings, and create-a-sign series).

Comprehension

For the comprehension testing, participants viewed video-based simulations of the sign series alternatives as if they were driving toward them on a roadway. The videos paused at each sign, with the sign still in view, while participants were asked a series of multiple-choice questions. At each of the three signs, participants were asked, "Based on the sign(s) you've seen so far, will you/do you need to merge?" and "Do you need to merge right now?" At the second and third signs participants were also asked a third question: "Do you have the right-of-way?"

Two videos were developed for each of the five sign series alternatives: one from the perspective of a driver in the right lane, and another from the perspective of a driver in the left lane. Participants were exposed to two sign series alternatives randomized within six distractor sign scenarios that were also presented as video-based simulations.

Rankings

After completing the comprehension testing, participants viewed a brief video explaining the concept of a late merge and were given the opportunity to ask questions. Participants were then asked to rank the late merge signs on how well they thought the signs would work to convey the late merge concept. Participants were told that the signs were designed as a three-sign series and were shown the general intended placement of each sign. Participants were given the first sign in each of the five sign series alternatives and asked to rank them based on how well they would work in sign location one (figure 1). They continued this process for the second and third sign locations using the second signs and third signs, respectively, in each series to provide rankings.

Create-a-Sign-Series

Finally, participants were asked to create their ideal three-sign series for conveying a late merge. They were given a sign bank for each of the three sign locations and selected a series of three signs that would work best to convey the late merge concept.

Data Analysis and Results

The comprehension portion of the laboratory study provided more objective information on participants' understanding of the intended sign messages, whereas the rankings and create-a-sign-series portions provided participants' subjective preference for signs and a series of signs. As such, the research team prioritized the comprehension results when considering what sign alternatives warranted further consideration for field testing. Subjective rankings and create-a-sign-series results supplemented the comprehension results.

The following sections report response percentages for comprehension questions, and means and standard deviations for rankings.

Comprehension

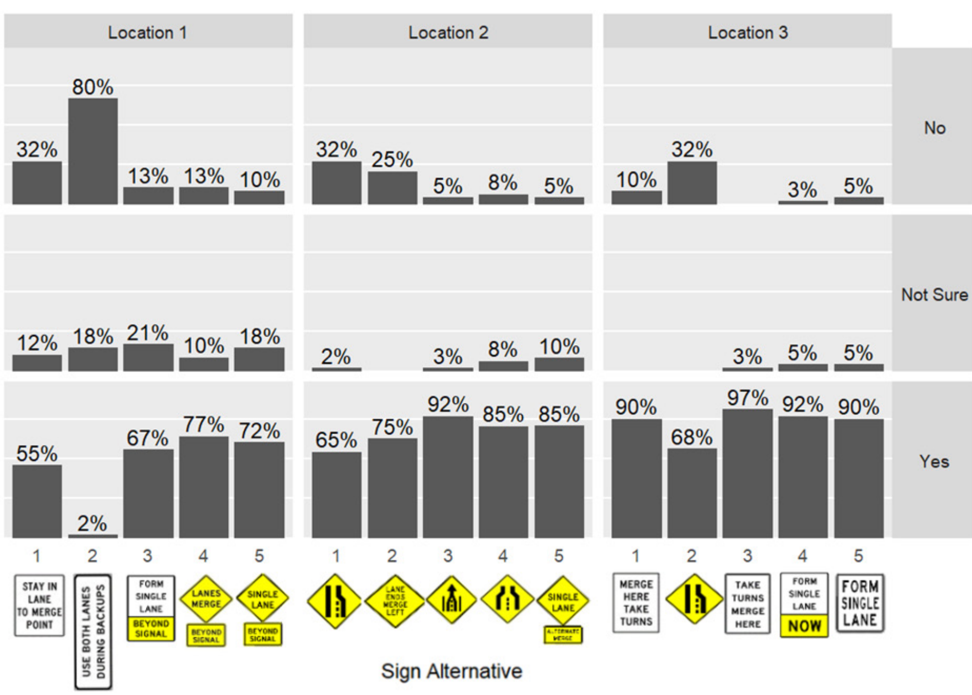
The following information describes the results for each comprehension question the participants were asked.

Question 1: Based on the sign(s) you have seen so far, will you/do you need to merge?

Figure 2 shows the participant responses to question 1 by sign location and sign alternative. For this question, the research team looked at responses to determine whether the signs indicated to participants that they would need to participate in a merge. Ideally, participants would respond "yes" to this question because participants would be actively participating in the merge action regardless of whether they were in the lane that was ending if the concept of the late merge, i.e., that vehicles should take turns and alternate merging into one lane, was clear.

Participants viewing the signs from the right-lane perspective (i.e., the lane that was ending) were more likely to respond "yes" or "not sure" to question 1, while participants viewing the signs from the left-lane

Figure 2. Graphic. Participant responses to comprehension question 1: "Based on the sign(s) you have seen so far, will you/do you need to merge?"



Source: FHWA.

perspective were more likely to respond "no" to question 1, but these differences were not statistically significant.

For the first sign location, participants were between 2.9- and 8.4-times more likely to respond "yes," (indicating that they would need to merge) when viewing sign alternatives 1, 3, 4, or 5 compared to when they were viewing sign alternative 2. For the second sign location, participants were more likely to respond "no" (indicating that they would not need to merge) when viewing sign alternatives 1 or 2. This response suggests that sign alternatives 1 and 2 are less likely to convey to participants that they would need to merge at some point, regardless of lane perspective (right lane or left lane).

Question 2: Do you need to merge right now?

Figure 3 shows the participant responses to question 2 by sign location and alternative. A goal of the late merge is for drivers to use all lanes until the merge point, so participant responses would ideally indicate that they understood that there was not a need to merge until they reached the merge point, sign location 3.

Participants viewing the signs from the right-lane perspective (i.e., the lane that was ending) were more likely to respond "yes" or "not sure" to question 2, while participants viewing the signs from the left-lane perspective were more likely to respond "no" to question 2, although these differences were not statistically significant.

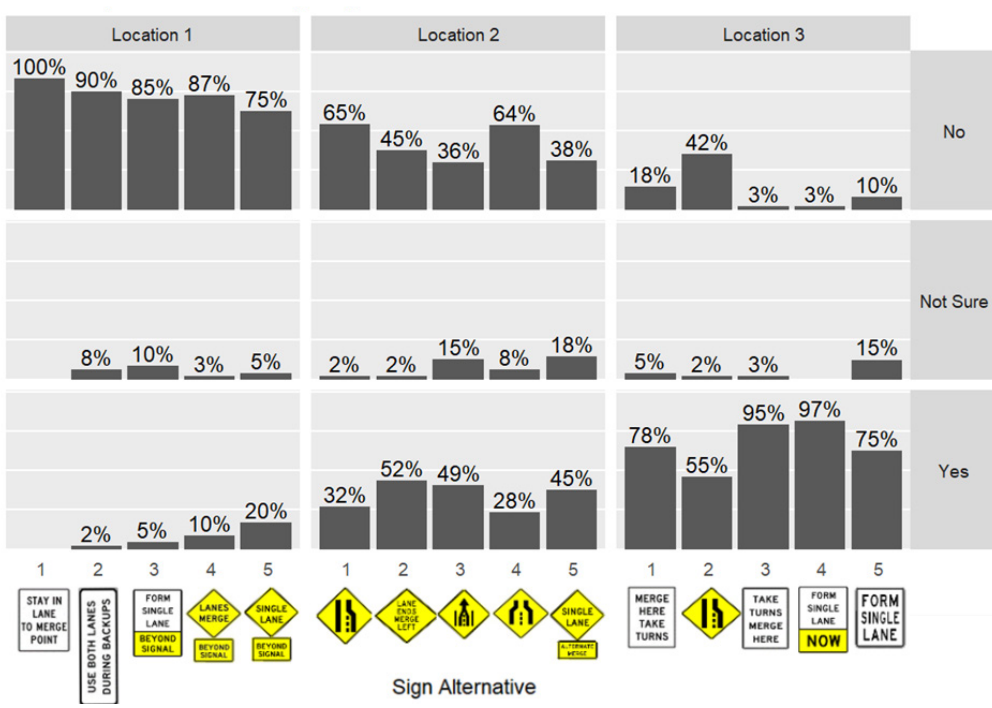
For all sign alternatives, the number of participants indicating that they needed to merge right increased as they progressed to each sign location. Participants viewing alternatives 3 and 5 were more likely, at all sign locations, to indicate that they were not sure whether they had to merge right now, although these differences were not statistically significant.

Question 3: Do you have the right-of-way?

Question 3 was only asked at sign locations 2 and 3. Figure 4 shows the participant responses to Question 3 by sign location and alternative. A goal of the late merge is for drivers to alternate the merge, or to take turns merging into one lane. Ideally, participants would respond to the question with "no, each lane should take turns merging into one lane."

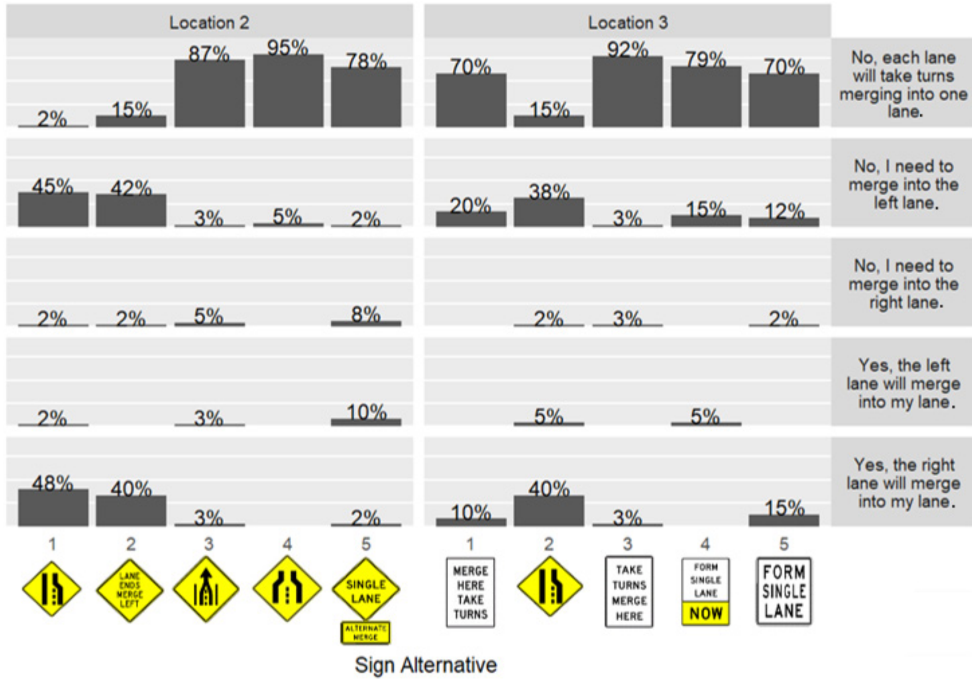
Participants viewing the signs from the left-lane perspective (the lane that was not ending) were more likely to respond "yes," indicating that they thought they had the right-of-way, and this difference was significant for sign alternatives 1 and 2. Regardless of lane perspective, participants were significantly more likely to respond "no—each lane will take turns merging into one lane" when they were viewing sign alternatives 3, 4, and 5, compared to when they were viewing sign alternatives 1 and 2. These findings suggest that alternatives 3, 4, and 5 are more likely to convey that vehicles in both lanes should alternate, or take turns, merging.

Figure 3. Graphic. Participant responses to comprehension question 2: "Do you need to merge right now?"



Source: FHWA.

Figure 4. Graphic. Participant responses to comprehension question 3: "Do you have the right-of-way?"



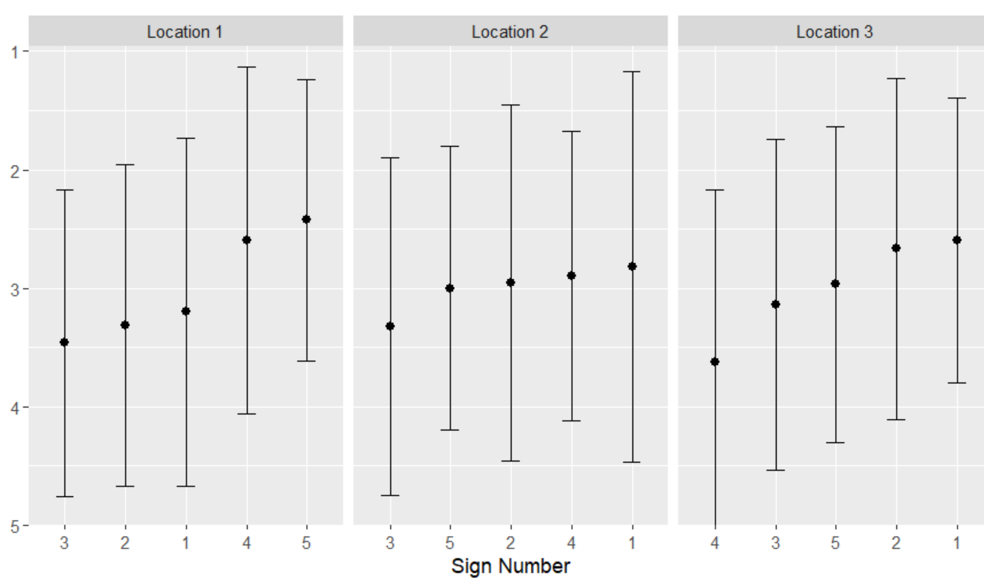
Source: FHWA.

Based on the comprehension results, alternatives 3, 4, and 5 were considered further for field testing based on the results of the rankings and create-a-sign-series results. These sign series alternatives better conveyed the eventual need to merge, the desired location of the merge, and the requirement for each lane to take turns merging into one lane. The following sections discuss the ranking and create-a-sign-series results, particularly for alternatives 3, 4, and 5.

Rankings

Participants ranked signs based on how well they would work in each sign location (figure 1) to convey a late merge scenario. For each sign location, signs ranked the highest (best) were given a ranking of 1, and signs ranked the lowest (worst) were given a ranking of 5. Figure 5 provides the results of the sign rankings for each location, ordering the sign alternatives from best to worst.

Figure 5. Graphic. Average rank (± 1 standard deviation) for all signs and positions (1 indicates the most preferred option, 5 the least preferred).



Source: FHWA.

At position 1, alternative 5 (the "SINGLE LANE" sign with "BEYOND SIGNAL" plaque) was ranked higher than all other sign alternatives, followed closely by alternative 4 (the "LANES MERGE" sign with "BEYOND SIGNAL" plaque). Therefore, alternatives 4 and 5 for sign location 1 were further considered for field testing.

There were no obvious differences between the five sign alternatives at position 2. Sign alternatives 1 and 2 were already excluded from consideration due to their low comprehension results. Additionally, sign alternatives 1 and 2 are standard signs used for a typical lane drop, as opposed to a late merge, which could explain why they did not perform as well in the comprehension testing. Sign alternative 3 was ranked in the lowest (worst) position, compared to alternatives 4 and 5; therefore, the research team focused on sign alternatives 4 and 5 for further consideration.

There were no obvious differences between the alternatives at position 3 either. Sign alternatives 1 and 2 were already excluded from consideration due to their low comprehension results. Alternative 4 was excluded from further consideration due to the high percentage (63 percent) of lower rankings (rankings of 4 or 5). Sign alternative 3 ("TAKE TURNS MERGE HERE"), and sign alternative 5 ("FORM SINGLE LANE") were further considered for field testing due to rankings and high comprehension.

Create-a-Sign-Series

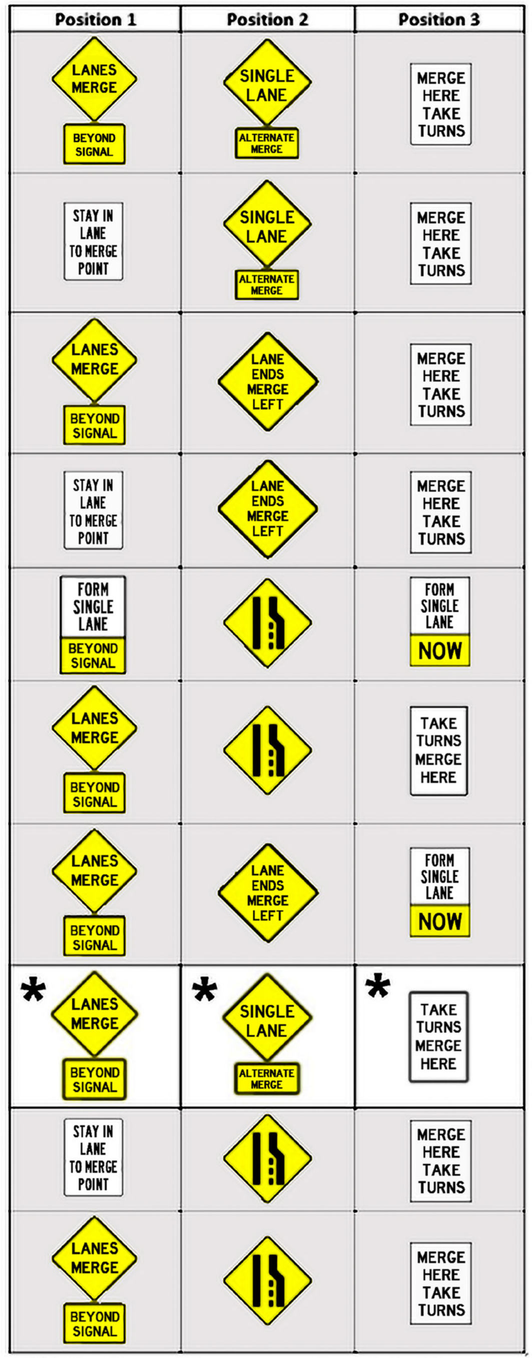
Participants were asked to create their ideal three-sign series to convey the late merge concept. Figure 6 shows the top 10 most selected sign series, which covered 48 percent of all participant-created sign series.

Of the participant-created top 10 sign series, all but 1 included signs that were already excluded based on comprehension results and/or rankings. The create-a-sign-series results suggested that participants tended to gravitate toward signs that they were familiar with, even if the comprehension results indicated that these signs may not have been good options for conveying the late merge concept.

Selection of Sign Series for Field Study

After excluding signs based first on comprehension results, followed by rankings and create-a-sign-series results, there was a single sign series that remained, as shown in figure 6. This sign series included the first sign from sign series alternative 4 and the second sign and third sign from sign series alternative 5. However, for sign location 2, the comprehension and rankings were the same for the sign for alternative 5 and the

Figure 6. Graphic. Top 10 3 signs series created by participants.



*White boxes (not grayed out) indicate the sign series that was not excluded due to comprehension and/or ranking results.

Source: FHWA.

symbolic late or “zipper” merge sign from alternative 4. Given that the symbolic late or “zipper” merge sign from alternative 4 was of particular interest because it is included in the NPA for the 11th edition of the MUTCD, the research team recommended a combination of the two signs using the alternative 4 symbol sign and adding the “ALTERNATE MERGE” plaque from alternative 5. The resulting sign series that was used for field testing is shown in figure 8. All three signs in this series were new concepts evaluated in this study and did not exist in the 2009 MUTCD.

Figure 7. Graphic. Recommended sign series for field testing.

Source: FHWA.

FIELD STUDY

Method

The field study evaluated driver behavior in response to the selected sign series (figure 7). The research team collected data at 12 different sites across 3 States: Maryland, North Carolina, and New Hampshire. The team installed cameras before the intersection and at the merge point to capture driver behavior before and after installing the late merge signs.

Right lane utilization (RLU) was the primary measure of sign effectiveness that was collected. The research team used this measure to identify the use of the lane being dropped at the merge point compared to the use of that same lane at the upstream intersection, i.e., the intersection before the lane drop. This measure was of the most interest because the goal of a late merge is to use both (or all) lanes up to the merge point and, in typical or early merge scenarios, drivers tend to merge out of the right lane (for a right lane drop configuration) as early as possible. The research team also collected traffic volumes and cycle failures. A cycle failure occurs when the light is not green long enough to allow all queued vehicles to pass through the intersection. Cycle failures provide an opportunity to look at differences in lane utilization upstream of the signal and merge behavior downstream of the signal before and after congestion takes place. Cycle failure is also a measure of how efficient the signal can run when the auxiliary lane is being used more often.

Site Selection and Descriptions

The research team focused on identifying sites that experienced significant queues, as larger traffic volumes and more queuing create more incentive for outside lane utilization and thus increase the likelihood of drivers alternating (zippering) the merge. Sites that experienced cycle failure were also ideal, as cycle failure leads to increased queuing. Sites with major upstream signal impacts (e.g., metering) were excluded. Additionally, sites ideally had no side streets or driveways between the intersection and the merge point. However, in some cases, sites were selected with a limited number of driveways.

The research team also considered several characteristics of the lane drop itself. The team prioritized sites that had a two-to-one lane drop, right-turn impacts from cross streets (e.g., channelized right-turn lanes), and lane drops that occurred 400–1,320 ft after the signalized intersection. Additionally, only sites with a right-lane drop were selected for consistency. Table 2 provides a description of each site included in the field study.

Table 3 provides a description of the relevant pavement markings in place at each site, and the signing related to the lane drop that was in place before the implementation of the late merge signs.

The North Carolina sites used merge arrow pavement markings that were in place before and during the field testing. These same sites also used lane lines that extended through the merge, as opposed to lane lines that stop before the lane begins to taper. As shown in table 2, there was variation in the signing practices that were in place before the field testing. Notably, both Maryland sites (MD-1 and MD-2) had existing signing in place that included a “SINGLE LANE” warning sign with an “ALTERNATE MERGE” plaque. Furthermore, MD-1 did not remove the existing signing before installing the late merge test signs, i.e., both the existing signs and the test signs were in place during the data collection periods. At the MD-2 site, the late merge test signs were duplicated (i.e., placed on both sides of the roadway). Test signs were also duplicated at sign location 2 of the NC-4 site.

Table 2. Description of each field study test site.

Site Name	State	Intersection	Number of Lanes	Lane Drop Distance (ft)*	Shoulder Width at Merge Point (ft)**	Driveways or Businesses Present on Right Side of Road
MD-1	Maryland	MD 193 at Lottsford Road	2-to-1 lane	750	6	No
MD-2	Maryland	MD 43 at Walther Boulevard	2-to-1 lane	1,150	12	No
NC-1	North Carolina	NC 115 at NC 73	2-to-1 lane	1,100	3	No
NC-2	North Carolina	NC 54 at Fayetteville Road	2-to-1 lane	650	1	Yes
NC-3	North Carolina	NC 42 at Bratton Drive/Son-Lan Parkway	2-to-1 lane	1,000	No Shoulder	No
NC-4	North Carolina	New Hope Road at US 64 Business	2-to-1 lane	1,000	1	Yes
NC-5	North Carolina	Falls of Neuse Road at Capital Boulevard	3-to-2 lanes	1,000	10	No
NC-6	North Carolina	US 70 Business at Shotwell Road	3-to-2 lanes	1,375	No Shoulder	Yes
NH-1	New Hampshire	NH-111 E at NH-28	2-to-1 lane	1,150	8	No
NH-2	New Hampshire	NH-28 N at NH-111	2-to-1 lane	550	3	No
NH-3	New Hampshire	NH-111 W at Enterprise Drive	2-to-1 lane	400	5	No
NH-4	New Hampshire	NH-102 W at Winding Pond Road	2-to-1 lane	700	11	No

*Lane drop distances are approximate distances from the road edge of the intersection closest to the lane drop to where the lane begins to taper.

**Shoulder widths are approximate widths at the beginning of the taper.

Table 3. Existing pavement markings and signing in place at each site before the field study.

Site Name	Merge Arrow Pavement Markings (Presence)	Lane Lines Pavement Markings	Existing Signing in Advance of Signal	Existing Signing Between Signal and Merge	Existing Signing at Merge Point
MD-1	No	Stops before the lanes begin to taper	N/A	"SINGLE LANE" warning sign with XX Feet (W16-2P) plaque "SINGLE LANE" warning sign with "ALTERNATE MERGE" panel	"FORM SINGLE LANE" regulatory sign
MD-2	No	Stops before the lanes begin to taper	"SINGLE LANE" warning sign with "BEYOND SIGNAL" plaque	"SINGLE LANE" warning sign with XX Feet (W16-9P) plaque "SINGLE LANE" warning sign with "ALTERNATE MERGE" panel	"FORM SINGLE LANE" regulatory sign
NC-1	Yes	Extends through the merge	N/A	RIGHT LANE ENDS (W9-1) sign Lane Ends (W4-2) sign	N/A
NC-2	Yes	Extends through the merge	N/A	N/A	N/A
NC-3	Yes	Extends through the merge	N/A	RIGHT LANE ENDS (W9-1) sign	N/A
NC-4	Yes	Extends through the merge	N/A	LANE ENDS (W4-2) sign	N/A
NC-5	Yes	Extends through the merge	N/A	W4-2 RIGHT LANE ENDS (W9-1) sign	N/A
NC-6	Yes	Extends through the merge	N/A	"LANE ENDS 2000 FT" regulatory sign LANE ENDS MERGE LEFT (W9 2) sign	N/A
NH-1	No	Stops before the lanes begin to taper	N/A	LANE ENDS MERGE LEFT (W9 2) sign modified*	N/A
NH-2	No	Stops before the lanes begin to taper	N/A	LANE ENDS MERGE LEFT (W9 2) sign modified*	N/A
NH-3	No	Stops before the lanes begin to taper	N/A	RIGHT LANE ENDS (W9-1) sign	W4-2 with "RIGHT LANE ENDS" plaque
NH-4	No	Stops before the lanes begin to taper	N/A	LANE ENDS (W4-2) sign	N/A

N/A = Not applicable.

*Message matches the W9-2 sign, but text sizes/layout are different.

Observation Periods

There were three observation periods for each site. The "before" period observed the existing conditions (i.e., the signing that was already in place) before the late merge sign series was installed. The "transition" period occurred immediately after the late merge sign series was installed. The "after" period occurred at least 6 w after the late merge sign series was installed to allow time for regular travelers to learn the intended behavior.

Each observation period lasted at least 2 d (48 h). Data collection occurred continuously during these periods to ensure the capture of the sites' peak periods when traffic volumes were typically the highest. Table 4 shows date ranges when data were reduced and analyzed for each observation period at each site.

Data Analysis and Results

The research team reduced 350 h of video footage to identify changes in driving behavior associated with the installation of the late merge signs. Reduction was focused on the peak periods at each site. The morning peaks typically occurred from 7 a.m. to 9 a.m., and the afternoon peaks typically occurred from 4 p.m. to 6 p.m. Video quality issues prevented the reliable reduction of signal cycles and failures, travel time (i.e., the time to travel between a point well upstream of the signalized approach (free flow) and the downstream late merge location), and conflicts. Each observation consisted of several identifiers (site, location, date, and collection period), the number of vehicles observed, observation length (minutes), and RLU. The RLU was defined as the proportion of all vehicles observed that occupied the

Table 4. Dates ranges for observational periods used in analyses.

Site Name	Before	Transition	After
MD-1	5/17/22–5/19/22	5/23/22–5/27/22	7/18/22–7/20/22
MD-2	5/17/22–5/20/22	5/23/22–5/27/22	7/18/22–7/19/22
NC-1	2/3/22–2/11/22	2/14/22–2/15/22	4/13/22–4/20/22
NC-2	2/8/22–2/10/22	3/1/22–3/3/22	4/25/22–4/29/22
NC-3	2/8/22–2/10/22	3/1/22–3/3/22	4/25/22–5/5/22
NC-4	2/8/22–2/10/22	3/1/22–3/4/22	4/25/22–4/29/22
NC-5	2/8/22–2/10/22	3/1/22–3/3/22	4/25/22–5/5/22
NC-6	2/8/22–2/10/22	3/1/22–3/2/22	4/25/22–4/29/22
NH-1	11/6/21–11/9/21	11/11/21–11/12/21	3/28/22–4/1/22
NH-2	11/9/21–11/10/21	11/10/21–11/12/21	3/28/22–4/1/22
NH-3	11/8/21–11/9/21	11/11/21–11/12/21	3/28/22–4/1/22
NH-4	11/8/21–11/9/21	11/11/21–11/12/21	3/28/22–4/1/22

right lane (which is dropped at the merge point). The research team excluded 18 observations (5.8 percent) with fewer than 100 vehicles from further analysis. This exclusion was done to eliminate potentially unreliable RLU measures made on small samples and to remove observations with extremely low volumes.

NC-6 was excluded from analysis because the right lane was being used primarily for right turns into a fast-food restaurant. Additionally, right-lane usage was discouraged because of shrubbery and debris partially blocking the lane.

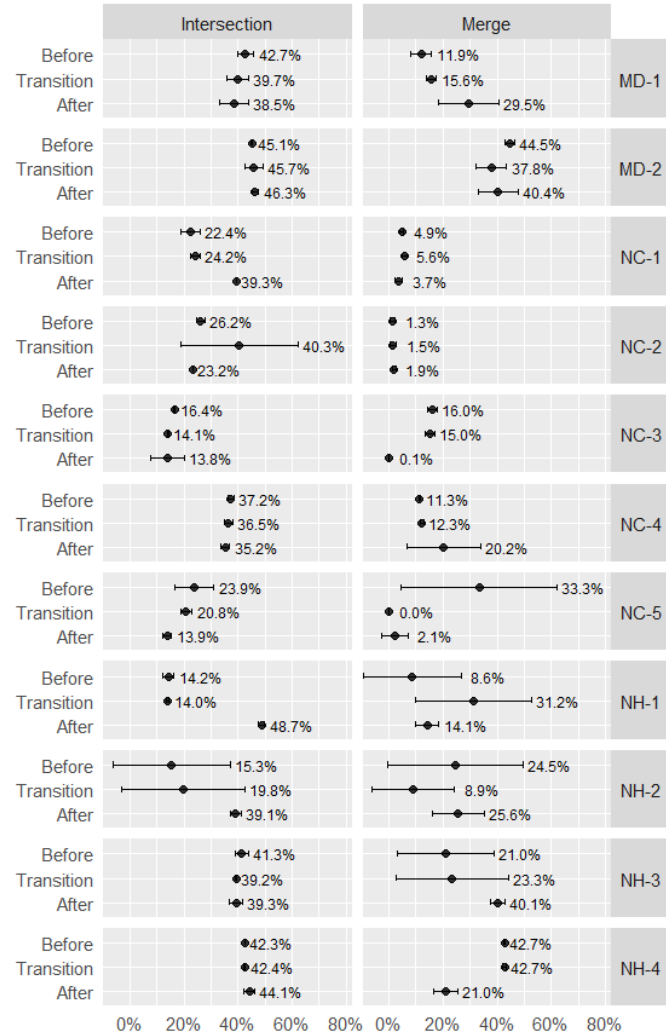
The following sections provide observed and estimated RLU. Observed means are reported with standard deviation (SDs), while estimated values are reported with standard error (SEs). Sample sizes (N), F-values (F), and p-values (p) are also provided where appropriate.

Figure 8 provides the observed RLU at each site, location, and period. There was considerable variation both across and within sites. At the intersection, six sites (MD-1, MD-2, NC-3, NC-4, NH-3, and NH-4) showed no significant change in RLU between the three data collection periods. Three sites (NC-1, NH-1, and NH-2) showed an increase in RLU from the before period to the after period. At the merge point, MD-1, NC-4, and NH-3 showed the anticipated trend of a small increase in RLU in the transition period and a larger increase in the after period. Other sites followed unexpected trends, such as a decrease in the after period (MD-2, NC-3, NC-5, NH-4), nonlinearities (NC-3, NH-1, and NH-2), and very low overall RLU (NC-1 and NC-2).

The research team developed statistical models to estimate RLU by location (intersection, followed by merge point), data collection period (before installation, during a transition period soon after installation, and several months thereafter), volume, and roadway characteristics (lane drop type, shoulder width at merge, presence of driveways or businesses on the right side of the road, and the presence of merge arrow pavement markings). Volume was considered a potential determinant of RLU and quantified as vehicles per minute. The research team explored various ways to incorporate volume into statistical models. Ultimately, the best-performing model (highest adjusted R^2 of 0.40) was also the simplest, with the raw vehicle-per-minutes metric and no interaction terms ($N = 291$, $F = 22.1$, $p < 0.01$).

The results indicated that RLU at the merge point (combined across all sites) is 12.6-percentage-points lower than at the intersection regardless of sign configuration (SE = 0.016, $p < 0.01$).

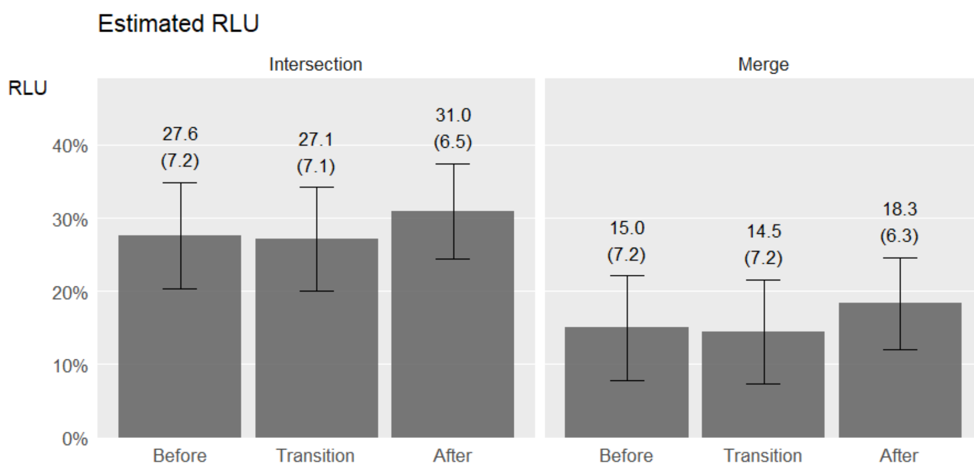
Figure 8. Graphic. Observed RLU (mean ± 1 standard deviation) at each site, location, and time.



Source: FHWA.

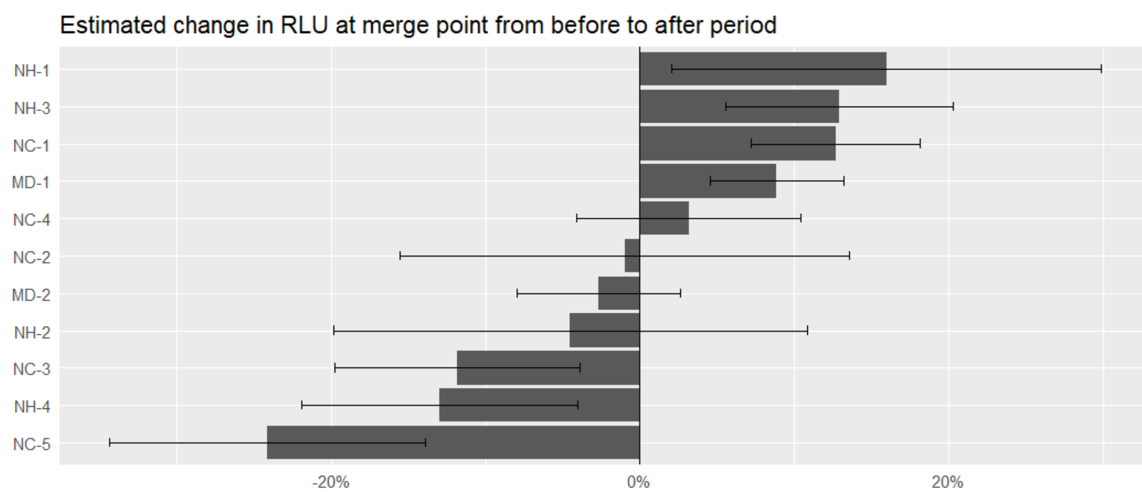
Overall, RLU did not change during the transition period (difference = - 0.005, SE = 0.022, $p > 0.10$), but increased by 3.3 percentage points in the after period (SE = 0.020, $p < 0.10$). Volume, lane drop distance, lane drop type, and shoulder width were not statistically significant. The presence of driveways and businesses was associated with an 8.7-percentage-point increase in RLU (SE = 0.034, $p < 0.05$). The most significant factor regarding RLU was the presence of merge arrow pavement markings: RLU was 21.4-percentage-points lower at sites with the markings compared to sites without (SE = 0.027, $p < 0.01$). Notably, all the sites that used merge arrow pavement markings also included lane lines that extended through the merge, as opposed to lane lines that stop before the lane begins to taper (which is what was present at all other sites that did not include merge arrow pavement markings).

Figure 9. Graphic. Estimated RLU (mean ± 1 standard error) by location and period, averaged across other site characteristics.



Source: FHWA.

Figure 10. Graphic. Estimated change in RLU ± 1 standard error from before to after period.



Source: FHWA.

In summary, installing the late merge signs increased RLU at both the intersection and the merge location in the long term, but not in the short term. In addition, no evidence that the signs increased RLU at the merge point more than at the intersection is available. Figure 9 shows the estimated RLU by location and period averaged across other site characteristics.

Changes in RLU varied by site. Figure 10 shows the estimated change in RLU from the before to the after period at each site. The best statistical model, however, indicated no difference in the change in RLU at different locations. In other words, RLU did not increase any more or less at the merge point than at the intersection. This analysis, therefore, does not differentiate between changes at the intersection and changes at the merge point. RLU increased by 9 to 16 percentage points ($p < 0.05$) at four sites (NH-1, NH-3, NC-1, and MD-1) and decreased by 12 to 24 percentage points ($p < 0.05$) at three sites (NC-3, NH-4, and NC-5). The remaining four sites did not exhibit a significant change in RLU in either direction.

Cycle Failure

Cycle failures during the data collection periods were minimal; therefore, the research team was unable to analyze this measure.

DISCUSSION

The research team focused on the measure of RLU as the goal of a late merge is to use all lanes up to the merge point. Overall, the results were encouraging considering that the late merge signs that were installed increased RLU at both the intersection and the merge point. Interestingly, the RLU increased similarly at the intersection as it did at the merge point, given that the first sign in the series (“LANES MERGE” with “BEYOND SIGNAL” plaque), which was the only sign in the series located before the intersection, does not indicate the specifics of the merge or that drivers should use both lanes. One possible explanation is that drivers familiar with the route on a daily or regular basis would have known to use the right lane after navigating the merge and seeing the entire sign series the first time, and thus be more likely to stay in their lane at the intersection the next time they drove the route. The presence of familiar drivers would also explain the findings that the late merge signs increased RLU in the long term (after period) but not in the short term (transition period); drivers who drive the route regularly may have needed to see the signs a couple of times before changing their behavior.

Considerable variation occurred across and within the individual sites, while RLU increased overall. This outcome is not necessarily unexpected, given that the results indicated that several of the factors that varied across the sites influenced RLU, including the use of merge arrow pavement markings and the presence of driveways or businesses on the right side of the road. Additionally, the signs and markings that were in place before the installation of the late merge test signs could also influence driver behavior in response to the late merge signs. For example, the Maryland sites (MD-1 and MD-2) had existing signing in place that included a “SINGLE LANE” warning sign with “ALTERNATE MERGE” plaque, and these signs were left in place at the MD-1 site. As depicted in figure 10, MD-1 showed a significant increase in RLU, while MD-2 did not exhibit a significant change in RLU. Although the existing signs were not included in the formal data analysis due to the variation in signing across sites, existing signing and markings could have influenced RLU at some sites.

RLU was significantly lower at the sites that included merge arrow pavement markings (and lane lines that extended through the merge), because the arrows could suggest to drivers in the right lane that they have different responsibilities in the merge than drivers in the left lane and/or that they should begin the merge earlier than intended by the late merge signs. The North Carolina sites were the only sites that included the merge arrow pavement markings, which could explain why five of the six North Carolina sites showed unexpected trends in RLU at the merge point, as depicted in figure 9, as follows: NC-3 and NC-5 showed a decrease in RLU after the late merge signs were installed, while NC-1 and NC-2 showed very low overall RLU. The potentially perceived contradictions between the merge arrows and the intent of the late merge signs may have led to some of these unexpected trends in RLU for the North Carolina sites. Additional research could help to identify the specific effects of merge arrows and other pavement markings on merging behavior in various scenarios (e.g., when late merges are ideal versus when early merges are ideal).

The effect of driveways and businesses on the right side of the road was an interesting finding. RLU was 8.7-percentage-points higher when there were driveways or businesses present on the right side of the road. This result could potentially be due to vehicles entering the right lane of the roadway from the driveways or businesses. Depending on the distance from the driveways or businesses to the merge point, the opportunity to move into the adjacent lane before the merge point might have been diminished, potentially leading to a higher RLU at these locations.

Similar to the findings of the literature and state-of-the-practice review, this study found that the effectiveness of late merges tend to vary across locations. Several researchers and agencies have cited other factors, in addition to signing, that could influence the success of the late merge, such as the presence of trucks and shoulder width (Lammers et al. 2017; Vaughan et al. 2018). Although shoulder width was not statistically significant in the present study, future research that controls for some of the other roadway characteristics (e.g., presence of businesses and driveways, pavement markings, etc.) could be used to better determine the specific effects of shoulder width in late merge scenarios. Although public outreach was not a component of the present research effort, previous efforts have found both signing and public outreach to be crucial factors in contributing to the success of a late merge (Vaughan et al. 2018). Vaughan et al. (2018) indicated that outreach through press releases and other means are vital to the success of the late merge and should be very specific, instructing drivers precisely where to merge and not to merge earlier than prompted. Lammers et al. (2017) indicated that public awareness is one of the most important aspects of implementing a late merge because drivers must understand how a late merge works and that merging in this manner benefits them.

Drivers commonly think it is impolite to continue driving in the lane that is ending while the drivers who have merged early (i.e., moved into the slower moving adjacent lane in anticipation of the lane drop) are viewed as doing the appropriate thing because they are patiently waiting their turn. Due to this mindset, and the relative unfamiliarity of the late merge concept, drivers are less likely to change their behavior unless the desired actions are clearly conveyed, and they see other drivers participating in the late merge as well.

In addition to a public outreach campaign, the research team believes that there might be a benefit to using a supplemental sign before the intersection that indicates to drivers to "USE BOTH LANES." Although a "USE BOTH LANES DURING BACKUPS" sign was evaluated in the laboratory study (alternative 2, sign location 1), it did not do well to convey to participants (either in the right-lane or left-lane perspectives) that they would need to merge at some point. Additionally, this sign was not ranked as highly as the other sign alternatives for sign location 1. Many participants indicated that they were confused by the "during backups" portion of the sign message and did not necessarily understand what this meant. The sign series that was examined in this study resulted in an overall increase in RLU. However, effectiveness might be further increased by supplementing this sign series with a "USE BOTH LANES" sign, in conjunction with a public outreach campaign, to better convey to drivers that using all lanes until the merge point is both acceptable and preferable.

CONCLUSION

The late merge signs that were installed in this study were effective in increasing RLU at both the intersection and the merge point. The presence of familiar drivers is a potential explanation for the RLU increasing similarly at the intersection and at the merge point, and for the RLU increasing in the long term (after period) but not in the short term (transition period), although the presence of familiar drivers was not evaluated by this research effort.

Several factors, in addition to the late merge signs, influenced RLU, including merge arrow pavement markings and the presence of driveways and businesses on the right side of the road. RLU was significantly lower at sites where merge arrow pavement markings were present, which could have been due to the potentially perceived contradictions between the merge arrows and the intent of the late merge signs. Additional research could be helpful in identifying the specific effects of merge arrows and other pavement markings on merging behavior, particularly when used in conjunction with late merge signs. RLU was significantly higher when there were driveways or businesses present on the right side of the roadway. This result could potentially be due to vehicles entering the right lane from the driveways or businesses; however, research would be needed to verify the specific behaviors of vehicles using businesses on the right side of the road. Finally, although the existing signs were not included in the formal data analysis due to the variation in signing across sites, it is possible that the existing signing and markings at the test sites could have influenced RLU.

It is possible that the effectiveness of the sign series evaluated in this study might be further increased by using a supplemental sign before the intersection that indicates to drivers to "USE BOTH LANES." Future research would be useful in verifying whether this supplemental information would be effective. Future research could also be useful in determining the extent to which public outreach, used in conjunction with the sign series, would help convey to drivers that they should use both lanes until the merge point.

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