Driver Understanding of the Purpose of Red Retroreflective Raised Pavement Markings

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ABSTRACT

Research was conducted to evaluate drivers’ understanding of red retroreflective raised pavement markings (RRPMs) on two-lane and four-lane undivided and divided roadways. The study included 191 survey participants, equally divided between three participant groups: drivers from left-hand drive countries (e.g., Australia, United Kingdom, and Japan), drivers from Hawaii, and drivers from the continental United States (U.S.). Five typical roadway configurations were tested using a laptop survey.

For each roadway configuration, standard pavement markings were shown as a baseline condition. Three alternate marking treatments were also shown for each typical roadway configuration. Two of the alternative marking treatments consisted of different combinations of supplemental RRPMs, and the third alternate treatment consisted of supplemental pavement marking arrows without RRPMs. The general findings were:

- Red RRPMs on one-way divided roadways used to indicate the wrong direction of travel helped drivers realize when they were going the wrong direction.
- Red RRPMs on undivided roadways can improve driver understanding for drivers from left-hand drive countries without negatively impacting the driver understanding of drivers from Hawaii and the continental U.S.
- Replacing supplemental RRPMs with supplemental arrows always improved the correct response rates for all roadway configurations and for all participant groups.
INTRODUCTION

Reflectorized raised pavement markers (RRPMs) are an effective means to delineate roadways under nighttime conditions, and especially, under adverse nighttime weather conditions. RRPMs are color coded in a similar manner to pavement marking to convey information to drivers. The standard colors for RRPMs are white, yellow, red, and blue. White and yellow RRPMs are matched with white and yellow pavement markings. Blue RRPMs are used to indicate fire hydrant locations. Red RRPMs are used to mark wrong way direction on one-way roadways, and it is the use of red RRPMs which is of key interest in this research.

There are some agencies such as the State of Hawaii and surrounding U.S. territories that use red RRPMs on undivided highways to mark wrong way direction on two-way roadways (the red RRPMs are installed on the far edgeline). This application is used because of frequent tourists from left-hand drive countries (e.g., Australia, Japan, United Kingdom). The red RRPMs are used to remind these tourists that they are driving in a right-hand drive country (e.g., United States, Germany, China). When traveling in the correct direction on these undivided highways, the red RRPMs are visible during nighttime conditions. This has raised concerns regarding drivers’ understanding of the red RRPMs.

The current MUTCD does not allow for red RRPMs to be used along undivided highways as described above (1).

- “When used, red raised pavement markers shall delineate roadways that shall not be entered or used.” (Section 3A.04).
- “Directional configurations should be used to maximize correct information and to minimize confusing information provided to the road user. Directional configurations also should be used to avoid confusion resulting from visibility of markers that do not apply to the road user.” (Section 3B.11).
- “Raised pavement markers should not supplement right edge line markings.” (Section 3B.13).
- “The side of a raised pavement marker that is visible to traffic proceeding in the wrong direction may be red.” (Section 3B.14).

On undivided roadways drivers can see red RRPMs on the opposite side of the roadway, and one theory is that this can confuse drivers because it would contradict driver expectancy (see Section 3B.11 below), and that the increased exposure to red RRPMs might reduce their effectiveness on divided roadways. In addition, Section 3B.13 states that RRPMs should not be used to supplement edgelines. Only Section 3B.14 can be used to support the use of red RRPMs on undivided roadways.

OBJECTIVES

As a result of the concerns stated above, Federal Highway Administration (FHWA) sponsored research to investigate these issues (2). The objectives of this study were to address whether the use of:
• Red RRPMs on the far edgeline of a two-lane undivided highway confuse drivers who are not on the wrong side of the centerline.
• Red RRPMs on the opposite direction lanelines of multilane undivided highways confuse drivers who are not on the wrong side of the centerline.
• Red RRPMs, as used in Hawaii, diminishes their impact and effectiveness at discouraging wrong-way movements along divided highways.

METHODOLOGY

Initially, a number of studies focused on drivers’ understanding of pavement markings were reviewed for their approach and specific results (3,4,5,6,7). Beyond the review of pertinent literature, the researchers also contemplated using in-vehicle testing techniques on closed-course facilities or even on the open road. Simulator testing was also considered. However, it was necessary to gather data from a population of drivers exposed to the Hawaii roadway system that uses red RRPMs in an unconventional manner, and so, it was not feasible to use the instrumented vehicle, closed-course facilities, or simulator available to the researchers in Texas.

Hence, an innovative laptop survey was developed and administered to 191 survey participants. The laptop survey featured five different roadway configurations, each with four different marking treatments. Survey participants were asked several questions aimed at determining their understanding of the markings and markers while watching the video on the laptop computers. Three participant groups were targeted for the surveys:
• LEFT—survey participants from left-hand driving countries.
• HAWAII—survey participants from Hawaii or a United States territory that has similar pavement marking layouts that include the use of red RRPMs along undivided highways (e.g., Guam and American Samoa).
• RIGHT—survey participants from right-hand driving countries.

Survey Development

Drivers use signs and other traffic as the primary cue to determine direction of travel, subsequently the researchers focused on developing an experimental plan that would assess drivers’ understanding of markings and markers without including any additional cues. Therefore, the researchers decided to develop a unique survey tool that included nighttime video of various roadway configurations marked in various ways.

Pavement Marking Treatments

The researchers considered 38 different pavement marking layouts for various roadway configurations before selecting the final 20 pavement marking layouts that were used in the study. The final 20 treatments were selected based on the most likely roadway configurations that might include and/or benefit from the use of red RRPMs. In addition, treatments were also chosen that included pavement marking arrows as they serve a similar purpose to the intended use of the red RRPMs in Hawaii, to aid drivers in interpreting the intended direction of travel.
Research has shown pavement marking arrows improve driver understanding of the intended direction of travel (7). The different pavement marking layouts were subdivided into five roadway configurations, and the 20 layouts are listed and described in detail in Table 1. The base pavement marking treatments consisted of standard pavement markings lines as required by the MUTCD (1). The far right columns in Table 1 indicate the order of the treatments as they were presented in each survey.

Four different versions of the survey were developed to avoid order bias in the data. It was also found that the initial surveys exceeded the time limit set to ease recruitment of participants and to avoid issues with participant load due to repetition discovered during pilot testing. Each survey contained three different standard pavement marking treatments and their respective alternate treatments for a maximum of 12 treatments within each survey. Subsequently, not all treatments could be viewed by each participant but the surveys were distributed equally between the three demographic groups to also balance the study design.

Table 1. Presentation Order of Survey Marking Treatments.

<table>
<thead>
<tr>
<th>Roadway Configuration</th>
<th>Marking Treatment</th>
<th>Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>Two-Lane, Two-Way, No-Passing</td>
<td>Standard markings</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Alternate 1- Supplemental RRPMs</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Alternate 2 - Supplemental RRPMs with red RRPMs</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Alternate 3 - No RRPMs but arrows</td>
<td>7</td>
</tr>
<tr>
<td>Two-Lane, Two-Way, Passing</td>
<td>Standard markings</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Alternate 1- Supplemental RRPMs</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Alternate 2 - Supplemental RRPMs with red RRPMs</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Alternate 3 - No RRPMs but arrows</td>
<td>9</td>
</tr>
<tr>
<td>Four-Lane, Two-Way</td>
<td>Standard markings</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Alternate 1- Supplemental RRPMs and arrows</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Alternate 2 - Supplemental RRPMs with red RRPMs</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Alternate 3 - No RRPMs but arrows</td>
<td>-</td>
</tr>
<tr>
<td>Two-Lane, One-Way, Correct Direction</td>
<td>Standard markings</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Alternate 1 - Supplemental RRPMs</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Alternate 2 - Supplemental RRPMs including right edgeline</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Alternate 3 - No RRPMs but arrows</td>
<td>12</td>
</tr>
<tr>
<td>Two-Lane, One-Way, Wrong Way Direction</td>
<td>Standard markings</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Alternate 1 - Supplemental RRPMs on lane line</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Alternate 2 - Supplemental RRPMs including edgeline</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Alternate 3 - No RRPMs but arrows</td>
<td>-</td>
</tr>
</tbody>
</table>
Video Development

The key concepts of the video survey technique that led to its selection were that the researchers could mark various roadway configurations on a closed-course facility and video drive-throughs at various speeds and at various angles without having to worry about safety concerns of traffic. In addition, the roadway configurations and marking treatments could be designed to be unique and not necessarily something that would be used on any roadway and devoid of any other visual cues (i.e., signage or other vehicles) that might supplement the information provided by the test treatments. Finally, the playback of nighttime video is always tricky in terms of producing a video that represents the actual nighttime condition. By using a closed-course facility to record the video, the researchers were able to determine the optimal lighting configurations, video settings, and video position so that the playback of the video best represented nighttime viewing conditions. Researchers also traveled to Hawaii and Guam to view and videotape the various roadway configurations under nighttime conditions to ensure that the final video footage used in the laptop survey would be a representative of real world conditions.

Each of the treatments shown in Table 1 was setup along a runway at the TTI Riverside Campus (a former military airport). This closed-course facility was ideal because large sections of unmarked concrete pavement can be used to mark the roadway configurations and marking treatments. The longitudinal pavement marking lines were placed using a preformed tape. Standard pavement marking arrows were made by applying hot-tape to aluminum substrate that had been cut out the same shape as the arrows (allowing the researchers to pick up and move the arrows at will but still be retroreflective and representative of an arrow on a roadway). They were placed to approximate 200 foot spacing between arrows. RRPMs were added to the setup as needed, placed manually at predetermined locations at 40-foot spacing. The video data were collected with a Sony DCR-VX2000 digital video camera mounted on the windshield of a passenger car. To avoid biasing the perspective of the video footage in terms of providing cues as to the RRPMs meaning, the video was recorded so that the centerline of the roadway corresponded to the center of the video. In addition, multiple runs were completed using various sources to illuminate the pavement and retroreflective markings and markers. The goal was for the video to be as representative as possible of actual driving conditions. The final footage was shot with the vehicle headlamps on the high position and no other sources of illumination.

The video clips were then edited and cut down to 10 second clips that looped continuously until stopped by the participant. The video clips were programmed to play in a coordinated fashion with respect to the questions asked by the researcher. Some of the questions required “Yes/No” responses, some required short answer responses, and one question required the survey participants to rate their level of confidence in their answer. The video clips are available at http://tcd.tamu.edu/documents/HawaiiVideo/Hawaii.pdf. Figure 1 contains two still shots of two different video clips used in the laptop based survey, note the white boxes were not present on the video but have been added here to illustrate the marking configuration.
Survey Administration Procedure

Four researchers spent approximately two weeks at the Honolulu International Airport in January 2006 recruiting participants and administering the video survey. The Honolulu International Airport was chosen as the ideal place to conduct the survey because it would be easy to find survey participants from each of the three groups, LEFT, HAWAII, and RIGHT. Most of the participants completed the survey while waiting for their flights departing Honolulu International Airport. Participation was voluntary. Each participant was administered the survey on a one-to-one basis with a researcher.

The session included some introductory remarks and a series of demographic questions followed by the individual treatments shown in sequence. When the video for each treatment started, the researcher asked the participant a series of questions about the treatment in the video. The questions asked in the survey are in Figure 2. When the questions were completed, the participant hit the space bar on the laptop and the next video would begin to play. This procedure was repeated for each of the 12 treatments viewed by each participant. Again, each participant only viewed 12 of 20 treatments due to time constraints.

Although the experimental sessions were conducted using laptop computers, it was not necessary for the survey participant to have prior computer experience. The only capability required of the survey participant was to press the space bar. The researcher gave all instructions and survey questions verbally, and recorded the participants’ responses onto an answer sheet form. On several occasions, a Japanese language translator was used for those individuals from Japan that did not speak English.
SLIDE #1
1. Can you drive in the direction the video is going? Yes No
   a. Can you pass on this road? Yes No
   b. When not passing:
      - can you drive in the right-hand lane? Yes No
      - can you drive in the left-hand lane? Yes No
2. How can you tell that you can or can not drive in each of these lanes?
   RIGHT:
   LEFT:
3. Using a scale of 1 – 5, tell me how sure you are of your answer(s)?
   1 – Very Sure
   2 – Sure
   3 – Somewhat Sure
   4 – Not Sure
   5 – Guessing
Please press the space bar to see the next video.

SLIDE #2
1. Can you drive in the direction the video is going? Yes No
   a. Can you drive in the right-two lanes? Yes No
   b. Can you drive in the left-two lanes? Yes No
2. How can you tell that you can or can not drive in (Right/Left) two lanes?
   RIGHT 2:
   LEFT 2:
3. Using a scale of 1 – 5, tell me how sure you are of your answer(s)?
   1 – Very Sure
   2 – Sure
   3 – Somewhat Sure
   4 – Not Sure
   5 – Guessing
Please press the space bar to see the next video.

Data Analysis

The collected survey data consisted of subjective and objective responses that were categorized for subsequent analyses. The demographic information was summarized using percentages to describe the distribution of the survey participant sample. The specific responses associated with each treatment were used to categorize the response for data analyses. The data were reduced to the percentage of correct responses for each roadway configuration, marking treatment, and participant group. Correct responses were defined as such when both of the following criteria were satisfied:

- The responses indicated that the participants understood what direction they were allowed to drive in each lane of the roadway configuration presented in the video.
- The responses indicated that the participants understood that they were allowed to cross certain markings to pass other slower traveling vehicles.

A test of proportions was used to assess whether there were any statistically significant differences between the participant groups for each roadway configuration (see Equation 1 and 2). A two-tailed 95 percent confidence interval was used to test whether there was a difference in the participant groups’ understanding of the different marking treatments. The Bonferroni multiple comparison procedure for general contrasts was used to adjust the α-value for tests between the participant groups to ensure that the overall α-value was still appropriate for a 95 percent confidence interval (8). This procedure requires dividing the α-value by the number of comparisons that will be tested. Because there were three comparisons for each roadway configuration, the adjusted α-value was equal to 0.0167; and the z-statistic for a two-tailed test – based on ½ the α-value – was equal to ±2.394.
\( N_i \) – represents the sample size of population \( i \).
\( P_i \) – represents the proportion of correct responses of population \( i \).

\[
P_{AB} = \frac{P_A n_A + P_B n_B}{n_A + n_B} \hspace{2cm} \text{Equation 1}
\]

\[
Z_{AB} = \frac{P_A - P_B}{\sqrt{P_{AB}(1 - P_{AB})\left(\frac{1}{n_A} + \frac{1}{n_B}\right)}} \hspace{2cm} \text{Equation 2}
\]

To test the difference among the marking treatments within each roadway configuration, the error rate of the sampling was estimated for each roadway configuration (assuming an unbiased random sample). In this case, the target confidence interval was 95 percent as in the test of proportions. The sample size was 195, and from such a large population that the exact number or estimate is not needed.

**FINDINGS**

Survey data were collected from 195 participants at the Honolulu International Airport. Data from 4 of the 195 participants who completed the survey were removed before the analyses started because data were missing or questionable. Attempts were made to ensure an equal distribution of participants between the three demographic groups: LEFT (65), HAWAII (65), and RIGHT (61). Within the LEFT group, there were 50, 11, and 4 participants from the countries of Australia, Japan, and the United Kingdom, respectively. While it was the intent to have the RIGHT group include drivers from various countries that require driving on the right-side of the roadway, all 61 participants in the RIGHT ended up coming from the continental United States. In addition to the equal distribution by the three demographic groups described above, the researchers also strived to maintain an equal distribution across the four different versions of the video survey, and across demographic groups (i.e., age, driving experience, education). Table 2 shows a summary of these data.

It should be noted that study participants from the LEFT and RIGHT groups had a slightly different criteria when establishing driving experience in Hawaii as stated in Table 2. were only considered to be “daily drivers” in Hawaii if they drive daily and annual visit for business or vacation. Otherwise, for those groups the terms can be defined as follows:

- Daily – one who annual visits for business or vacation, and drives daily while visiting;
- Frequent - one who has visited more than once, and drives daily while visiting Hawaii;
- Sometimes – one who has visited more than once, and drives several of the days while visiting, but not daily; and
- Almost never – one who has only driven once while visiting.
Table 2. Survey Distribution between Demographic Groups.

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategory</th>
<th>LEFT</th>
<th>HAWAII</th>
<th>RIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey</td>
<td>A1</td>
<td>16</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>16</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>17</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Age</td>
<td>Younger (&lt;25)</td>
<td>11</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Middle (25-54)</td>
<td>46</td>
<td>33</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Older (55+)</td>
<td>8</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>Driver Experience</td>
<td>New (&lt;1yr)</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Young (1-5 yrs)</td>
<td>5</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Experienced (5-20 yrs)</td>
<td>29</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Senior (&gt;20 yrs)</td>
<td>29</td>
<td>32</td>
<td>36</td>
</tr>
<tr>
<td>Drives in Hawaii</td>
<td>Never</td>
<td>30</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Almost Never (less than 1 day a week)</td>
<td>19</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Sometimes (1-2 days a week)</td>
<td>10</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Frequently (3-6 days a week)</td>
<td>4</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Daily</td>
<td>2</td>
<td>47</td>
<td>1</td>
</tr>
<tr>
<td>Education</td>
<td>High School (Not Complete)</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>High School</td>
<td>22</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Some College</td>
<td>7</td>
<td>21</td>
<td>20</td>
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<tr>
<td></td>
<td>College</td>
<td>36</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>65</td>
<td>65</td>
<td>61</td>
</tr>
</tbody>
</table>

The results are presented in Figure 3 and Figure 4 as the percentage of correct responses, and the information is presented using the following logical sequence for each of the five different roadway configurations tested:

1. How well did the participants understand the typical pavement marking configurations (this includes only the markings and is used as a baseline level of understanding to compare all alternative treatments to, within each of the five roadway configurations)?
2. What happens to the results when yellow and white RRPMs are added to supplement the markings?
3. What happens to the results when red RRPMs are also included (representing the Hawaii Department of Transportation (HiDOT) practices)?
4. What happens to the results when pavement marking arrows are used in lieu of RRPMs?
Graphs in Figure 3 and Figure 4 in this section contain four columns—one column for each participant group and a fourth column for a group consisting of both the RIGHT and HAWAII groups. These groups were combined because the test of proportions did not show a statistically significant difference. The study findings are focused into separate discussions of undivided and divided roadway configurations, and then, the overall implications of how the results may impact the future use of red RRPMs are addressed in the Summary and Recommendation sections. It was not possible to present all of the detailed data analysis tables, which may be found. It should be noted that a z-statistic of ±1.960, and not ±2.394, was used for establishing significance for LEFT versus RIGHT and HAWAII.

Undivided Roadways

Each participant group performed similarly regardless of the pavement marking treatment for TLTWNP configuration (see Figure 3a). On average, 96 percent of the survey participants correctly answered the survey questions—meaning that they understood the direction of flow and meaning of the double yellow centerline. The treatment showing only pavement markings provided a 94 percent correct response among LEFT study participants, and an average of 95 percent correct response rate among the RIGHT & HAWAII participants. These levels establish the baseline performance of the pavement markings for this roadway configuration. When red RRPMs were added to the far left edgeline, the response rate of LEFT study participants increased to 97 percent. Finally, when the RRPMs were removed and arrows were added, the correct response rate rose to 100 percent for all groups.

Figure 3a contains the percent of correct responses for the TLTWP configuration. Overall, the percent of correct responses for the passing configuration were not as high as they were for the no-passing configuration. On average, 80 percent of the responses were correct, versus 96 percent for the no-passing configuration. The HAWAII and RIGHT groups had much higher correct response rates (86 and 87 percent, respectively) than the LEFT group (63 percent) for the pavement markings only treatment. Adding the red RRPMs on the far left edgeline increased the percent correct for the LEFT and RIGHT groups to 68 and 92 percent, respectively, but the HAWAII group showed a drop to 82 percent. However, this drop was not statistically significant, and the difference between the HAWAII and the RIGHT groups was not statistically significant. Again, the highest percent of correct responses was obtained when the RRPMs were removed and arrows were used instead. The correct response rate increased to 72, 94, and 92 percent for the LEFT, HAWAII, and RIGHT groups respectively.

The FLTW configuration was the most understood roadway configuration presented to the survey participants (overall, 99 percent of the responses were correct). Figure 3c shows that all participant groups correctly understood the marking treatments between 97 and 100 percent of the time. Out of 96 participants, only two incorrectly identified the roadway configuration and marking treatments as something other than what was intended. There were no statistically significant differences among the results.
Overall, the addition of red RRPMs provides the greatest benefit to study participants from the LEFT group. There was a 9 percent gain for the TLTWNP and a 13 percent gain for the TLTWP configurations. Also, some improvement was seen in the correct response rate under the FLT W condition when red RRPMs were added to supplement the standard pavement marking treatment. However, in all cases, the use of arrows to supplement the standard pavement marking treatment provided the highest overall response rate for all undivided roadway configurations.

**Discussion of Incorrect Responses**

The responses from the participants who did not understand the undivided roadway configurations are noteworthy. For the *no-passing* configuration, the majority of incorrect responses (7 out of 13) indicated the participants believed they were driving on a one-way...
roadway, and these beliefs were roughly split between the LEFT and HAWAII groups. One survey participant from the LEFT group thought the roadway configuration represented a one-way roadway traveling against traffic with the RRPMs reflecting light to represent headlights from on-coming. The six other incorrect responses suggested the roadway was two-way traffic, but that passing was allowed. It should be pointed out that all of the survey participants that reported incorrect responses successfully provided correct responses when they viewed the arrow treatment. In addition, all of the participants from the LEFT group that incorrectly identified the intended traffic flow chose not to drive while in Hawaii.

Out of the 764 responses recorded for the passing configuration, there were 150 incorrect responses provided from 74 participants (40, 17, and 17 from the LEFT, HAWAII, and RIGHT groups, respectively). Over one third of the incorrect responses indicated that the participants believed they were viewing a two-lane, two-way roadway marked for no-passing, which while incorrect, this response would still result in a safe driving condition. There were 49 responses that indicated at least one of the marking treatments without arrows represented a one-way roadway. However, when the alternate configuration of markings and arrows was viewed, all of these participants understood the two-way condition. The reason why their responses were coded as incorrect was because they interpreted the arrows to also indicate no-passing. It is also good to note that 18 of the participants that believed they were viewing a one-way roadway chose not to drive in Hawaii.

Statistical Results

The test of proportions was used to determine that there were no statistical differences between the percent of correct responses between each participant group for the TLTWNP and FLTW configurations, but this was not the case for the TLTWP. For each marking treatment tested for the TLTWP roadway configuration, both the RIGHT and HAWAII groups had a statistically significant better understanding of the marking treatments compared to the LEFT group. For every configuration, the z-statistic for the test of proportions was less than -3.

Sampling error was used to investigate differences between treatments within participant groups, and it was found that the LEFT group benefited from red RRPMs or arrows for both the no-passing and passing two-way two-lane configurations. For the no-passing and passing roadway configurations the sampling error was estimated to be ±3 percent and ±6 percent, respectively. This indicates that the only difference of statistical significance for the no-passing configuration was for the LEFT group and between the yellow and white supplemental RRPM treatment and the same treatment but with red RRPMs added to the far edgeline. In this case, the red RRPMs clearly assisted the LEFT group in understanding the intended message of the markings (when compared to supplemental yellow and white RRPMs).

For the passing configurations, the treatments for LEFT group showed a statistical difference in one case: marking supplemented with yellow and white RRPMs compared to markings supplemented with arrows. Adding yellow and white supplemental RRPMs to the standard markings appeared to confuse study participants from the LEFT group. However, providing markings only with no supplemental RRPMs results in statistically equivalent study participant understanding rates compared to markings supplemented with either red, yellow, and white RRPMs, or arrows for both the no-passing and passing configurations. These findings suggest
that adding only white and yellow supplemental RRPMs may not be as useful for drivers from left-hand driving countries unless red RRPMs or arrows are also included.

**Divided Roadways**

The data presented in Figure 4 indicate the participants had a poor understanding of the one-way divided highway configuration. The overall percent correct was 68 and 48 percent for the TLOW (correct direction) and the TLOWW (wrong direction) configurations, respectively. It should be noted that none of the treatments for the correct direction contained red RRPMs, and that the yellow edgeline was on the right for the wrong direction. The addition of the RRPMs had little effect on the LEFT group for the correct direction configurations, but provided some improved participant understanding for the HAWAII and RIGHT groups (about a 15 percent increase). The addition of red RRPMs helped all three groups for the wrong direction configurations. However, the treatments with the arrows provided the most benefit. For both the correct and wrong direction configurations, the correct responses increased to 100 percent for the LEFT group. The correct responses increased to 100 percent for the HAWAII and RIGHT groups when arrows were introduced for the wrong direction configuration, but they only increased to above 90 percent for the correct direction configuration.

**Discussion of Incorrect Responses**

The common response that each participant group reported was a two-way roadway instead of a one-way roadway, 92 and 64 percent of the incorrect responses for the correct and wrong directions, respectively. Of the other incorrect responses when traveling in the correct direction, one participant from the RIGHT group misinterpreted the arrows to mean that the broken line in
the center of the roadway should not be crossed. The remaining incorrect responses for the wrong direction indicated an understanding that the roadway configuration was a one-way roadway but they failed to realize the direction of travel was the wrong way. The addition of red RRPMs provided some improvement in participant understanding but for some participants the red RRPMs were misunderstood to represent a two-lane two-way roadway marked for no-passing.

Statistical Results

The test of proportions failed to produce statistically significant difference between the participant groups for the correct direction, but for the wrong direction, the LEFT group had a poorer understanding than the other groups. The sampling errors for the correct and wrong direction roadway configurations were estimated to be ± 7 percent. For the LEFT group, the improved understanding of the traffic flow direction was only statistically significant when arrows were used. For the HAWAII group, there was a statistically significant improvement in study participant understanding when supplemental RRPMs were added to the standard markings. The HAWAII group also showed another statistically significant improvement in their understanding of the markings when the supplemental RRPMs were replaced with supplemental arrows. The only condition in which the RIGHT group had statistically significant improvements in their understanding of the markings was when the arrows were used (all other patterns for this group were statistically equivalent).

Therefore, the addition of the supplemental red RRPMs on the lanelines as traditionally used in the U.S. on one-way divided highways to mark wrong way direction was found to be ineffective for all participant groups. When the edgelines were supplemented with additional RRPMs (yellow and red RRPMs for the treatment tested herein), the LEFT and HAWAII groups both showed a statistically higher understanding rate of the traffic flow direction (compared to markings only). This finding was not statistically significant for the RIGHT group. For all groups, the marking treatment with the supplemental arrows showed statistically significant higher participant understanding rates with respect to the direction of flow.

SUMMARY

This study was conducted to evaluate drivers’ understanding of red retroreflective raised pavement markings on two-lane and four-lane undivided roadways and divided roadways. There were five roadway configurations tested using various pavement marking treatments. The five roadway configurations were: TLTWNP, TLTWP, FLTWP, TLOW, and TLOWW. For each roadway configuration, standard pavement markings were shown as a baseline condition. Three alternate marking treatments were also tested for each roadway configuration. In general, two of the alternative marking treatments consisted different combinations of supplemental RRPMs and the third alternate treatment consisted of supplemental pavement marking arrows without RRPMs.

There were 191 participants in the study, equally divided between three groups: LEFT, HAWAII, and RIGHT. The results related to the primary objectives are summarized below.
The use of supplemental red RRPMs on undivided roadways improved participant understanding but with mixed results.

- For participants from left-hand drive countries, the use of red RRPMs on undivided roadways improved participant understanding, but this finding was not statistically significant for all configurations.
- On undivided roadways, participants from Hawaii and the continental United States had a statistically similar understanding of the rules of the road with and without supplemental red RRPMs.

When participants were presented wrong-way video without and then with supplemental red RRPMs on the lanelines, their understanding of the wrong-way direction improved in all cases but the improvement was not statistically significant.

Compared to standard pavement markings only, there was no treatment where adding supplemental red RRPMs had a statistically significant impact (either positive or negative) on participant understanding of the traffic flow direction.

Replacing supplemental RRPMs with supplemental arrows always improved the correct response rates and resulted in the highest correct response rates for all roadway configurations and for all participant groups.

RECOMMENDATIONS

The recommendations have been generated in three specific areas. The general recommendations relate to the objectives of this study—identifying driver understanding of red RRPMs used in various applications. These recommendations are followed by recommended changes to the language of the MUTCD with respect to red RRPM usage as deemed appropriate based on the research findings. The final list of recommendations contain recommended future research needs based on the research findings and any related issues discovered during the process of the research, but not addressed by the research.

General Recommendations

- Using red RRPMs on undivided highways, as used in Hawaii and surrounding U.S. Territories such as Guam, should be a viable option permitted by the MUTCD. The red RRPMs produce no negative impact in terms of driver confusion and provide an improved meaning of the intended direction of travel for drivers from left-hand drive countries.
- The use of pavement marking arrows should be considered above and beyond red RRPMs when there is a concern about drivers misinterpreting the intended direction of travel. For all conditions tested, the highest percent correct response rate for all driving groups and for all roadway configurations was achieved when pavement marking arrows were used to supplement the longitudinal pavement markings in lieu of RRPMs. The breakeven costs between arrows and red RRPMs along the far edgeline allows pavement marking arrows to be installed approximately every quarter mile (2).
- On one-way roadways where the correct response rates were relatively low, pavement marking arrows should be used along the ramps and at other locations where wrong way entry is possible. These areas should be supplemented with the appropriate signing.
• There needs to be an increase in training with respect to the meanings of pavement marking color and continuity (i.e., continuous versus broken) during driver education. The survey found poor response rates from all participant groups for the one-way roadway configurations. In addition, there was a surprising drop in U.S. participant correct response rates when the double yellow centerline was replaced with a single yellow broken centerline.

**Recommendations for Potential MUTCD Revisions**

The MUTCD language needs to be clearer about the intended use of colored RRPMs. The language associated with the use of red RRPMs is not as clear as it could be. Based on the recommendations above, the following revisions are suggested to the MUTCD. All of the revisions are in italics.

• “When used, red raised pavement markers shall delineate lanes that shall not be entered or used.” (Section 3A.04)
• “The color of raised pavement markers under both daylight and nighttime conditions shall conform to the color of the marking for which they supplement or substitute as a positioning guide in the direction of travel associated with the marking.” (Section 3B.11)
• If used, the pattern and color of the raised pavement markers should simulate the pattern and color of the markings for which they substitute in the intended direction of travel. (Section 3B.14)
• The side of a raised pavement marker that would delineate the lane for traffic proceeding in the wrong direction may be red.

**FURTHER INVESTIGATION**

• The MUTCD does not currently allow for supplemental RRPMs on edgelines. While this was not included in the scope of this project, the survey responses indicate that supplemental RRPMs on edgelines would not cause drivers to misinterpret the number of lanes. However, a more directed study should be performed in order to fully address this issue.
• A study is needed to find a better way to mark one-way roadways so that the intended direction of travel is better understood. Under wrong way scenarios with only pavement markings, the average percent correct response rate was 24 percent. In other words, the use of a yellow edge line is not by itself adequate. While signing helps, perhaps innovative pavement marking treatments would be better understood by drivers traveling in the wrong direction.
• A study is needed to determine the most appropriate spacing and locations for directional pavement marking arrows.
• Because of the nighttime focus of this study, one potential caveat of using pavement marking arrows is their ability to maintain their retroreflective performance under rainy nighttime conditions. In areas where this is a concern, it could be potentially useful to use the bi-directional white/red or mono-direction white RRPMs in the shape of an arrow.
instead of along the far edgeline. Additional investigation would be needed to test this possibility.
REFERENCES