DRIVER UNDERSTANDING OF RED RETROREFLECTIVE RAISED PAVEMENT MARKERS

Publication No. FHWA-CFL/TD-06-008 **PB2007-106995**

November 2006

U.S. Department of Transportation
Federal Highway Administration

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division

12300 West Dakota Avenue

Lakewood, CO 80228

FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

This study investigated drivers' understanding of red retroreflective raised pavement markings (RRPMs) as traditionally used (i.e., to mark wrong way direction on one-way highways) and as used to mark wrong way direction on two-way undivided highways. A survey was administered to almost 200 participants. This survey featured five different roadway configurations, each with four different marking patterns. Survey participants were asked several questions aimed at determining their understanding of the pavement markings and the supplemental markings (i.e., RRPMs, pavement marking arrows) while watching video clips of various pavement marking patterns on laptop computers. Three participant groups were targeted for the surveys: drivers from left-hand drive countries, drivers from Hawaii, and drivers from right-hand drive countries.

The findings of the survey show that drivers do not become confused when red RRPMs are used on undivided highways. Furthermore, the understanding rate of drivers from left-hand drive countries was always improved when supplemental red RRPMs were included on undivided highways. The findings also show that red RRPMs do little to help drivers understand that they are traveling the wrong direction on one-way divided highways. In areas where driver confusion may be a problem, the findings show that directional pavement marking arrows provide much better means of communication to all drivers. Based on these findings, it has been recommended that the Manual of Uniform Traffic Control Devices (MUTCD) language be reworded to allow for red RRPMs on undivided highways, and additional emphasis should be provided such that directional pavement marking arrows are used in locations where driver confusion regarding direction of travel may be a concern.

James W. Keeley, P.E., Director of Project Delivery
Federal Highway Administration
Central Federal Lands Highway Division

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-CFL/TD-06-008	PB2007-106995	
4. Title and Subtitle *Driver Understanding of Red Retroreflective Raised Pavement Markers*		5. Report Date November 2006 6. Performing Organization Code
7. Author(s) Paul J. Carlson and Jeffrey D. Miles		8. Performing Organization Report No.
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH68-05-X-00012
12. Sponsoring Agency Name and Address Federal Highway Administration Central Federal Lands Highway Division 12300 W. Dakota Avenue, Suite 210-B Lakewood, CO 80228		13. Type of Report and Period Covered Final Report January 2005 – August 2006 14. Sponsoring Agency Code HFTS-16.4

15. Supplementary Notes

COTR: Greg Schertz, FHWA-FLH; Advisory Panel Members: Ed Demming, FHWA-CFLHD; Richelle Takara, FHWA-HI; and Karl Kunishige and Steven Yoshida, HiDOT. This FLH Technology Deployment project was funded under the FLH HI SR 200(1) Saddle Road, Hawaii.

16. Abstract

In the United States, the use of red retroreflective raised pavement markers (RRPMs) has been traditionally reserved to mark wrong way direction on one-way roadways. 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 edge line). This application is used in areas with frequent tourists from left-hand drive countries. The red RRPMs are used to remind the tourists that they are driving in the United States, which is a right-hand drive country. When traveling in the correct direction on these undivided highways, the red RRPMs are visible during nighttime conditions. This has raised concerns regarding current practices and drivers' understanding of the red RRPMs.

This study investigated drivers' understanding of red RRPMs as traditionally used (i.e., to mark wrong way direction on one-way highways) and as used in unique applications (such as described above). A survey administered to almost 200 participants. This survey featured five different roadway configurations, each with four different marking patterns. 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: drivers from left-hand drive countries, drivers from Hawaii, and drivers from right-hand drive countries.

The findings of the survey show that drivers do not become confused when red RRPMs are used on undivided highways. Furthermore, the understanding rate of drivers from left-hand drive countries was always improved when supplemental red RRPMs were included on undivided highways. The findings also show that red RRPMs do little to help drivers understand that they are traveling the wrong direction on one-way divided highways. In areas where driver confusion may be a problem, the findings show that directional pavement marking arrows provide much better means of communication to all drivers. Based on these findings, it has been recommended that the *Manual of Uniform Traffic Control Devices* (MUTCD) language be reworded to allow for red RRPMs on undivided highways. However, additional emphasis should be provided such that directional pavement marking arrows are used in locations where driver confusion regarding direction of travel may be a concern.

17. Key Words	18. Distribution Statement
RAISED RETROREFLECTIVE PAVEMENT MARKER, DRIVER UNDERSTANDING, TRAFFIC CONTROL DEVICE, PAVEMENT MARKING, PAVEMENT MARKING ARROWS	No restriction. This document is available to the public from the sponsoring agency at the website http://www.cflhd.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	55	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

CFLHD	Central Federal Lands Highway Division
CFR	Code of Federal Regulations
COTR	Contracting Officer’s Technical Representative
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
FLTW	Four-lane two-way
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)
HI	Hawaii
HiDOT	Hawaii Department of Transportation
LEFT	survey participants from left-hand driving countries
MUTCD	Manual on Uniform Traffic Control Devices
RIGHT	Survey participants from right-hand driving countries
RRPM	Retroreflective raised pavement markings
TLOW	Two-lane one-way
TLOWW	Two-lane one-way wrong direction
TLTW	Two-lane two-way
TLTWNP	Two-lane two-way no-passing
TLTWP	Two-lane two-way passing
TTI	Texas Transportation Institute
U.S.	United States
VIP	Visitor Information Program

ACKNOWLEDGEMENTS

The authors would like to thank the Federal Highway Administration (FHWA) and the Hawaii Department of Transportation (HiDOT) who cooperated on the study, the Central Federal Lands Highway Division (CFLHD) who sponsored it, and the following individuals who provided guidance and expertise in various phases of the project:

- Greg Schertz, COTR, Functional Discipline Leader for Safety, FHWA-FLH;
- Ed Demming, Safety Engineer, FHWA-CFLHD;
- Richelle Takara, Transportation Engineer, FHWA-HI;
- Karl Kunishige, Highways Traffic Design Section Head, HiDOT;
- Steven Yoshida, Highways Traffic Design, Consultant Project Manager, HiDOT;
- Scott Wainwright, Highway Engineer MUTCD Team, FHWA-HQ; and
- Hari Kalla, MUTCD Team Leader, FHWA-HQ.

The following Hawaii Department of Transportation supervisors deserve special thanks for their cooperation and support of this study:

- Brennon T. Morioka, Deputy Director-Highways;
- Brian H. Sekiguchi, Deputy Director-Airports; and
- Alvin A. Takeshita, Highways Traffic Branch Head.

The authors also wish to acknowledge the following individuals at the Texas Transportation Institute (TTI) who as Research Assistants proved invaluable during this project:

- Nada Trout;
- Brooke Ullman;
- Sandra Schoeneman; and
- Ivan Lorenz.

The following additional specific Hawaii Department of Transportation personnel from the Visitor Information Program (VIP) at the Honolulu International Airport also deserve special thanks for their cooperation and willingness to work with the authors:

- Kenneth M. Muranaka, HiDOT Honolulu International Airport VIP Administrator; and
- Lorraine Kadota, HiDOT Honolulu International Airport VIP Staff Coordinator.

EXECUTIVE SUMMARY

This study was conducted to evaluate drivers' understanding of red retroreflective raised pavement markings (RRPMs) on two-lane and four-lane undivided roadways and divided roadways. Multiple pavement marking patterns were tested using a laptop video survey that was administered to volunteer survey participants recruited at the Honolulu International Airport. Using various pavement marking patterns, the following five roadway configurations were tested: (1) two-lane, two-way undivided roadway marked for no-passing, (2) two-lane, two-way undivided roadway marked for passing, (3) four-lane, two-way undivided roadway, (4) two-lane, one-way roadway with travel in the correct direction, and (5) two-lane, one-way roadway with travel in the wrong direction (going against the flow of traffic).

For each roadway configuration, typical pavement markings were shown as a baseline condition, and then, there were three alternate marking patterns. Two of the alternative marking patterns consisted of two different combinations of supplemental RRPMs, and the third alternate pattern consisted of supplemental pavement marking arrows without RRPMs. Almost 200 survey participants completed the study, equally divided between three participant groups: drivers from left-hand drive countries, drivers from Hawaii, and drivers from the continental United States (U.S.). The main recommendations from this project are listed below.

- 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 drivers from left-hand drive countries are more likely to realize they are traveling in the wrong direction when red RRPMs are adjacent to their driving lane.

- 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, because 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 edge line allows pavement marking arrows to be installed approximately every quarter mile (see calculations in Appendix C).

- On one-way roadways where the correct response rates were so low, pavement markings 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.

CHAPTER 1 – INTRODUCTION

BACKGROUND

The use of retroreflective raised pavement markers (RRPMs) has long been recognized as an effective means to delineate the nighttime roadway. RRPMs provide all weather nighttime delineation to assist drivers in recognizing the roadway alignment and maintaining lane positioning.

The Manual on Uniform Traffic Control Devices (MUTCD) defines the standards used by road authorities nationwide to install and maintain traffic control devices on all streets and highways.[(1)] The MUTCD is published by the Federal Highway Administration (FHWA) under the Code of Federal Regulations (CFR), Title 23, Part 655, Subpart F. The use of RRPMs is identified in the MUTCD.

Color coding is a key element of traffic control device design, use, and vehicle to convey information to the driver. Color coding is included in all aspects of traffic control devices such as traffic signals, signs, and pavement markings. RRPMs are also color coded. White and yellow RRPMs are used in conjunction with white and yellow pavement markings. Blue RRPMs are used to indicate fire hydrant locations. Red RRPMs are used to indicate wrong-way direction.

Part 3 of the MUTCD, which covers traffic control devices such as pavement markings and markers, provides specific language for the use of RRPMs such as:

- "When used, red raised pavement markers shall delineate roadways 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 serve as a positioning guide, or for which they supplement or substitute." (Section 3B.11).
- "The bidirectional marker is capable of displaying the applicable color for each direction of travel." (Section 3B.11).

- "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).

PROBLEM STATEMENT

Because of the wording of Section 3B.04, "When used, red raised pavement markers shall delineate roadways that shall not be entered or used," almost all applications of red RRPMs in the U.S. have been limited to bidirectional applications so that the wrong way of divided highways is marked with red RRPMs. However, both the state of Hawaii and territory of Guam have been using red RRPMs on undivided highways for many years. Specifically, the agencies use bidirectional (white/red) RRPMs on the edge lines and lane lines of divided and undivided highways along with yellow RRPMs along the centerlines. On the undivided two-lane highways the bidirectional RRPMs are used to supplement the near edge line with the white retroreflective face and they are used to show wrong way direction along the far edge line with the red retroreflective face. The bidirectional RRPMs are oriented in the same direction along lane lines on undivided multilane highways. This application is thought to be particularly effective for visitors from other countries that normally drive on the opposite side of the road, such as Australia, Japan, and the United Kingdom. However, when driving on the right side of the road, as we do in the U.S., the red RRPMs on the far edge line and lane lines are clearly visible during nighttime conditions.

Recently, the use of red RRPMs on undivided highways has been questioned by the FHWA. The specific issues are summarized below:

- The use of bidirectional (white/red) RRPMs on the edge lines of two-lane highways. While this application results in white RRPMs supplementing the right edge line and red

RRPMs on the far left edge line, which are visible to nighttime drivers, the main concern was the use of red RRPMs (not the white RRPMs supplementing the right edge line).

- The use of bidirectional (white/red) RRPMs on the lane lines of undivided multilane highways. The concern here is that nighttime drivers see the red RRPMs on the opposite direction lane lines.

OBJECTIVES

As a result of the concerns listed above, this study was initiated to identify, in a scientific and credible manner, if:

- Red RRPMs on the far edge line of a two-lane undivided highway confuse drivers who are not on the wrong side of the centerline.
- Red RRPMs on the opposite direction lane lines of multilane undivided highways confuse drivers who are not on the wrong side of the centerline.
- To the extent feasible, the use of red RRPMs as used in Hawaii diminishes their impact and effectiveness where they are used most—to discourage wrong-way movements at freeway off-ramps and "wrong" sides of divided highways.

REPORT ORGANIZATION

This report is organized into four chapters, reference section, and three appendices. Chapter 1 includes a description of the problem and the study objectives. Chapter 2 describes the study design, and includes the data collection activities. Chapter 3 consists of the data analysis results. Chapter 4 presents a summary of the study and includes the recommendations. Appendix A includes the survey instrument that was used to collect the data. Appendix B includes the detailed results from the data analyses. Appendix C contains a cost analysis of the use of red RRPMs and directional pavement marking arrows.

CHAPTER 2 – STUDY DESIGN

This chapter includes a description of the study approach used to complete the study. The development and use of the survey tool that was used to assess drivers' understanding of pavement markings and markers is also described. The last section of this chapter includes a description of the data analysis techniques used to assess the survey responses.

STUDY APPROACH

The study approach was selected to meet the project objectives through the conduct of a credible well-designed experimental plan. Because of the focus of this project, and that drivers use signs and other traffic as the primary cue to determine direction of travel, the study investigators focused on developing an experimental plan that would assess drivers' understanding of markings and markers without including any additional cues.

Initially, a number of studies focused drivers' understanding of pavement markings were reviewed for their approach and specific results.[2,3,4] Some of the studies used diagrams to survey drivers, some used pictures, and some asked a series of situational questions using diagrams and pictures. Beyond the review of pertinent literature, the study investigators also contemplated using in-vehicle testing techniques on closed-course facilities or even on the open road. Simulator testing was also considered. However, given the objectives of this study, all of these techniques have limitations that would lead to questionable validity of the results.

After reviewing the investigation techniques that had been used in the past, in addition to in-vehicle testing and simulator testing, it was clear that a new approach would be needed for this study. One aspect of this study that makes it unique from others performed in the past is that the study of RRPM color meaning and application must be set up in a nighttime environment when RRPMs are used by drivers. In addition, the appearance, size, and color of the RRPM must be realistic. Finally, there was a concern about presentation of the stimuli. Photographs can provide a rich environment of information. However, the study investigators were concerned that a photograph of RRPMs in a nighttime environment would not provide a realistic enough

scenario for drivers to provide representative responses to survey questions regarding the meaning of the RRPMs. Therefore, the study team decided to embark on a unique survey tool that included nighttime video of various roadway configurations marked in various ways.
The key concepts of the video survey technique that led to its selection were that the study team 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 patterns 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 study investigators 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.

SURVEY TOOL

Once video testing was chosen as the main data collection instrument, four key efforts were completed to develop the initial survey. In the first step, study investigators went to Hawaii and Guam to meet with transportation officials to discuss their marking and marker policies and review the goals of the study. During these visits, the study investigators also videotaped the roadways under nighttime conditions. The second step was selecting the roadway configurations and marking patterns that would be tested with the video survey and developing a series of questions to be asked in coordination with the video. The third step included the collection of video for each roadway configuration and pavement marking pattern to be tested. The last step was finalizing the questions and the testing protocol.

After the study team returned with actual footage of the highways in Hawaii and Guam, an initial set of questions were developed for a preliminary list of roadway configurations and marking patterns. The design of the questions and the selection of the roadway configurations and marking patterns were carefully synchronized so that the survey participants would view a balanced set of video segments and questions but not be overwhelmed with long videos or too many questions. A target time of 10 to 15 minutes was set for the completion of the final video survey.

The study investigators' preliminary list of roadway configurations and marking patterns totaled 38 different combinations. The different pavement marking layouts were subdivided into five roadway configurations:

- Two-lane, two-way undivided roadway marked for no-passing (TLTWNP).
- Two-lane, two-way undivided roadway marked for passing (TLTWP).
- Four-lane, two-way undivided roadway (FLTW).
- Two-lane, one-way divided roadway (traveling in the correct direction) (TLOW).
- Two-lane, one-way divided roadway (traveling in the wrong direction) (TLOWW).

After some early discussions and reconsiderations of the project objectives, the preliminary number of combinations was reduced to 33 pavement marking patterns grouped into the five roadway configurations listed above. For each of the five roadway configurations, there were at least four different marking patterns. The marking patterns consisted of typical pavement markings without RRPMs, typical pavement markings supplemented with various applications of RRPMs, and pavement marking arrows without RRPMs. The final 20 pavement marking patterns chosen to test are listed and described in Table 1.

Table 1. Tested Pavement Marking Treatments.

Roadway Configuration	Marking Pattern	Description
UNDIVIDED Two-lane, two-way, no-passing	Default	Typical markings
	Alternate 1 - Supplemental RRPMs	Typical markings supplemented with yellow centerline RRPMs and white near edge line RRPMs
	Alternate 2 - Supplemental RRPMs with red RRPMs	Same as Alternate 1 but with supplemental red far edge line RRPMs
	Alternate 3 - No RRPMs but arrows	Markings supplemented with arrows
UNDIVIDED Two-lane, two-way, passing	Default	Typical markings
	Alternate 1 - Supplemental RRPMs	Typical markings supplemented with yellow centerline RRPMs and white near edge line RRPMs
	Alternate 2 - Supplemental RRPMs with red RRPMs	Same as Alterntate 1 but with supplemental red far edgeline RRPMs
	Alternate 3 - No RRPMs but arrows	Markings supplemented with arrows
UNDIVIDED Four-lane, two-way	Default	Typical markings
	Alternate 1 - Supplemental RRPMs and arrows	Typical markings supplemented with yellow centerline RRPMs, white near lane line RRPMs, and arrows
	Alternate 2 - Supplemental RRPMs with red RRPMs	Typical markings supplemented with yellow centerline RRPMs, white near lane line RRPMs, and red far lane line and far edge line RRPMs
	Alternate 3 - No RRPMs but arrows	Markings supplemented with arrows
DIVIDED Two-lane, one-way, correct direction	Default	Typical markings
	Alternate 1 - Supplemental RRPMs	Typical markings supplemented with yellow edge line RRPMs and white lane line RRPMs
	Alternate 2 - Supplemental RRPMs including right edge line	Same as Alternate 1 but with supplemental white edge line RRPMs
	Alternate 3 - No RRPMs but arrows	Markings supplemented with arrows
DIVIDED Two-lane, one-way, wrong way direction	Default	Typical markings
	Alternate 1 - Supplemental RRPMs on lane line	Typical markings supplemented with red lane line RRPMs
	Alternate 2 - Supplemental RRPMs including edge line	Same as Alternative 1 but with supplemented RRPMs on edge lines (red on white and yellow on yellow)
	Alternate 3 - No RRPMs but arrows	Markings supplemented with arrows

Each of the treatments shown in Table 1 was setup along a runway at the TTI Riverside Campus (a former military airport). Figure 1 shows an aerial view of the TTI Riverside Campus. This closed-course facility was ideal because large sections of unmarked concrete pavement can be used to mark the roadway configurations and marking patterns. The longitudinal pavement marking lines were placed using a preformed tape. 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 study investigators to pick up and move the arrows at will but still be retroreflective and representative of an arrow on a roadway). RRPMs were added to the setup as needed, placed manually at predetermined locations. 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.

Figure 1. Photograph. TTI Riverside Campus.

The video clips were then edited and cut down to 10 second clips that looped continuously until stopped by the survey administrator. The video clips were programmed to play in a coordinated fashion with respect to the questions asked by the study investigator. 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. An example set of these questions is in Figure 10 through Figure 12 in Appendix A. The video clips are available at http://tcd.tamu.edu/documents/HawaiiVideo/Hawaii.pdf. Figure 2 contains two still shots of two different video clips used in the laptop based survey.

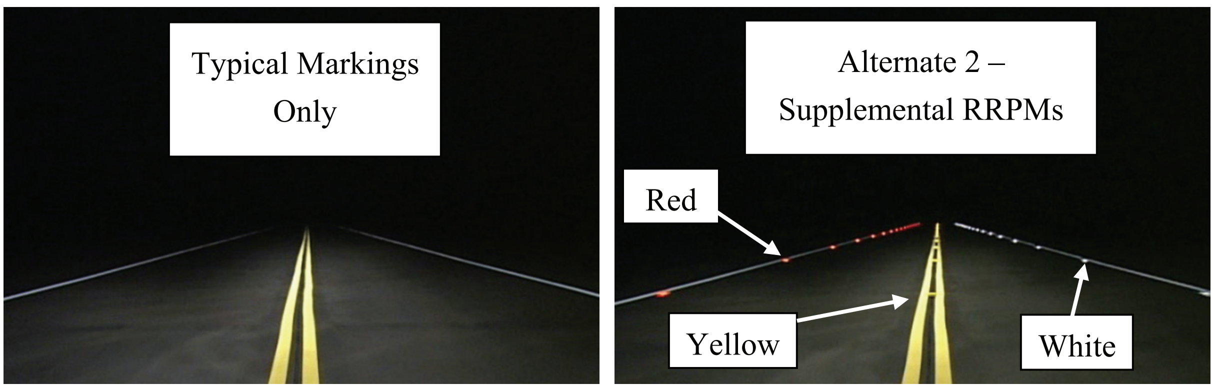

Figure 2. Photograph. Two-Lane, Two-Way Undivided Roadway Marked for No-Passing.

Pilot Study

The purpose of the pilot study was to assess the administration procedures, determine the length of the time needed for each participant to complete the survey session, assess the format of the survey, and identify any question deficiencies. The study investigators pilot-tested the initial survey instrument using TTI administrative employees (i.e., those that are not experts in the meaning of traffic control devices). The pilot survey participants were asked to review video footage for various lengths of time. Then, using pictures from the video clips, the pilot survey participants were asked questions concerning the video clips they just viewed.

The survey was expected to take about 10 to 15 minutes, but after multiple survey participants completed the initial survey, it was found that the survey was too long with too many treatments that were too similar. The pilot survey participants were not catching the small changes to some video clips and became suspicious that the survey was set up to trick them.

The study investigator also learned during the pilot efforts that the survey participants were confused by the pictures (even though they were screen captures from the video they had just viewed). However, the use of the video seemed to help the pilot survey participants understand the situation and more clearly convey their interpretation of the pavement markings. As a result, the survey was changed by showing participants full-screen looping video of each treatment while the test administrators asked questions.

The final survey was shortened and four smaller separate surveys were created. The treatments and order of the treatments for each of the four surveys are presented in Appendix A.

Survey Participants

A goal was established to obtain at least 180 completed surveys, split equally into three groups of participants defined by their native driving locale. The three groups of participants were defined as follows:

- 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.

Experimental Session Procedure

Four study team members 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 survey participants completed the survey while waiting for their flights departing

Honolulu International Airport (see Figure 3). Participation was voluntary. Each participant was administered the survey on a one-to-one basis with an administrator.

The session included some introductory remarks and a series of demographic questions. The participants then viewed a short video of one of the configurations on the computer screen. When the video started, the study investigator asked the survey participants a series of questions about the video looping on the laptop screen. When the questions were answered, the survey 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 a portion of 20 treatments.

Figure 3. Photograph. Field Data Collection.

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 study investigator gave all instructions and survey questions verbally, and recorded the participants' responses onto an answer sheet form. Figure 10, Figure 11, and Figure 12 in Appendix A are examples of the answer form. On several occasions, a Japanese language translator was used for those individuals from Japan that did not speak English.

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 percentage of correct responses for each roadway configuration, marking pattern, 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. 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 patterns. 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.[5] 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 0.0083; and the z-statistic was equal to ±2.394.

To test the difference among the marking patterns 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.

CHAPTER 3 – FINDINGS

The analyses were divided into two sections. In the first section, the demographics of the survey participants are summarized. The second section includes the analyses of the survey participants' understanding of the marking patterns presented in the video surveys.

DEMOGRAPHICS

Survey data were collected from 195 participants at the Honolulu International Airport. Attempts were made to ensure an equal distribution of participants between the three demographic groups: (1) drivers from countries that drive on the LEFT side of the road, (2) drivers native to HAWAII or from a United States territory with identical pavement marking layout designs (e.g., American Samoa, Guam), and (3) drivers from countries that drive on the RIGHT that do not fit into the second group. From this point forward the overall demographic groups will be referred to as "LEFT," "HAWAII," and "RIGHT." In addition to the equal distribution by the three demographic groups described above, the study investigators also strived to maintain an equal distribution across the four different versions of the video survey. Table 2 contains the breakdown of the number of participants by overall demographic grouping and the survey version administered.

Table 2. Demographic Breakdown of Survey Participants.

Survey Version	LEFT	HAWAII	RIGHT
A1	16	17	15
A2	16	17	16
B1	16	16	16
B2	17	16	17
Total	65	66	64

Data from 4 of the 195 participants who completed the survey were removed before the analyses started. The data collected from one survey participant from the HAWAII group and one survey participant from the RIGHT group had suspect data that could not be explained and were subsequently removed from the data for analysis. In addition, there were only two survey participants from countries outside the continental United States that fit into the RIGHT group.

They were removed which made the RIGHT group consisting of 61 drivers from the continental United States.

Other demographic data were collected such as age, years of driving experience, how often the participants drive in HAWAII, and education. Figure 4 shows a summary of these data.

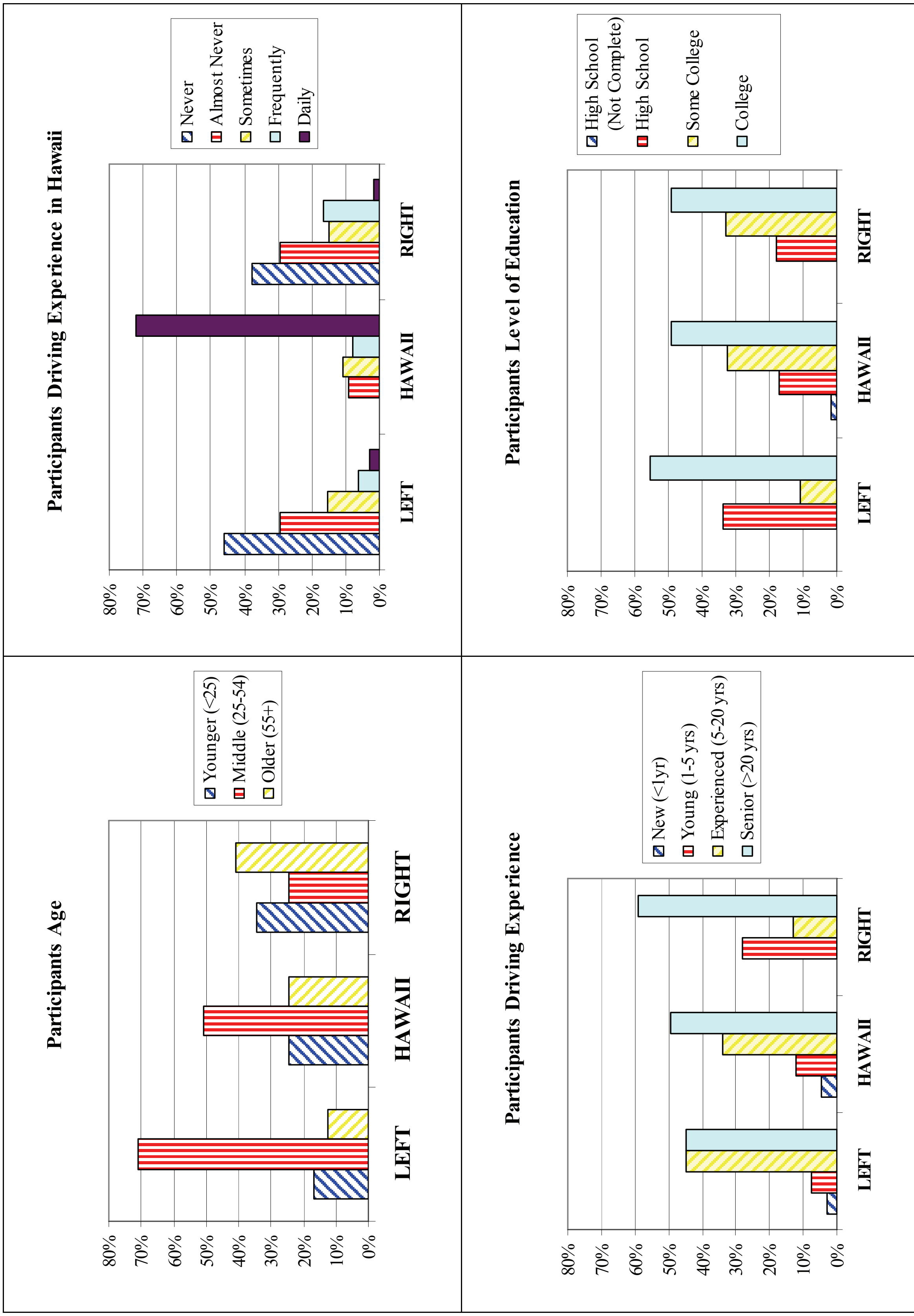

Figure 4. Chart. Additional Demographic Data.

DRIVER UNDERSTANDING

The results in this section are presented in graphs that show the percentage of correct responses. This part of the chapter is broken down 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 base line 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?

All of the tables listed 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 their results were almost always not statistically different.

Two-Lane Two-Way Undivided Roadway Marked For No-Passing

The two-lane two-way undivided roadway marked for no passing was expected to be one of the most straightforward configurations of the study. The results of this configuration are shown in Figure 5. Each participant group performed similar regardless of the pavement marking pattern. 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.

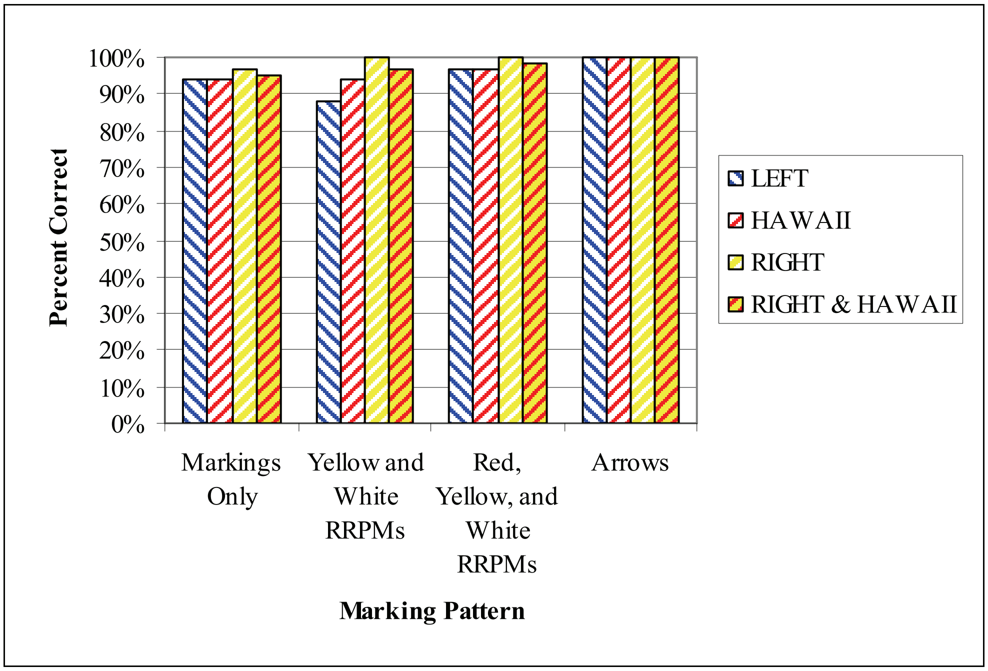

Figure 5. Chart. Two-Lane, Two-Way Undivided Roadway Marked for No-Passing Data.

The pattern showing only pavement markings provided a 94 percent correct response among LEFT drivers, and an average of 95 percent correct response rate among the RIGHT & HAWAII drivers. These levels establish the baseline performance of the pavement markings for this roadway configuration. Adding yellow and white RRPMs to the centerline and right edge line provided a slight decrease in the correct response rate among LEFT drivers (88 percent). When red RRPMs were added to the far left edge line, the response rate of LEFT drivers increased to 97 percent. Finally, when the RRPMs were removed and arrows were added, the correct response rate rose to 100 percent for all driver groups.

Overall, the addition of red RRPMs provided a 9 percent gain in driver understanding for LEFT drivers. The use of arrows provided a 12 percent gain in performance for the LEFT group. For the HAWAII group, the performance gain was the same for red RRPMs and arrows (a 3 percent improvement). For the RIGHT group, the performance for all alternative patterns was perfect (100 percent).

Discussion of Incorrect Responses

The responses from the participants who did not understand this roadway configuration are noteworthy. In the majority of incorrect responses (7 out of 13), 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 and the marking pattern with red, yellow, and white RRPMs meant wrong-way direction because the RRPMs looked like headlamps from oncoming traffic. Five of the other incorrect responses indicated the marking only pattern represented a two-lane two-way passing condition. The last incorrect response came from a participant in the LEFT group and indicated that the marking only configuration represented a two-lane two-way roadway except with the directions flipped, as in the participant's home country.

It should be pointed out that all of the survey participants that reported incorrect responses successfully provided correct responses when they viewed the arrow pattern. In addition, all of the participants from the LEFT group that incorrectly interpreted the traffic to be one-way or two-way but driving on the LEFT (similar to their homeland) chose not to drive while in HAWAII. The participants from the LEFT and RIGHT groups that did drive in HAWAII all correctly identified that the roadway was two-way traffic.

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. The sampling error for this roadway configuration was estimated to be ± 3 percent. This indicates that the only difference of statistical significance within this roadway configuration was for the LEFT group and between the yellow and white supplemental RRPM pattern and the same pattern but with red RRPMs added to the far edge line. In this case, the red RRPMs clearly assisted the left-hand drivers in understanding the intended message of the markings (when compared to supplemental yellow and white RRPMs).

Again, adding yellow and white supplemental RRPMs to the typical markings appeared to confuse drivers (reduction of 6 percent) from the LEFT group, while adding red RRPMs increased their understanding (9 percent increase above the marking only pattern). These findings suggest that adding only white and yellow supplemental RRPMs to the markings of two-lane, two-way, no-passing configurations may not be as useful for drivers from left-hand driving countries unless red RRPMs are also included. But providing markings only with no supplemental RRPMs results in statistically equivalent driver understand rates compared to markings supplemented with either red, yellow, and white RRPMs, or arrows.

Two-Lane Two-Way Undivided Roadway Marked For Passing

Figure 6 contains a graph of the percent of correct responses for the second roadway configuration, two-lane two-way undivided roadway marking for passing. Overall, the percent of correct responses for the two-lane, two-way *passing* configuration were not as high as they were for the two-lane, two-way *no-passing* configuration. On average, 80 percent of the responses were correct, versus 96 percent for the two-lane two-way *no-passing* configuration.

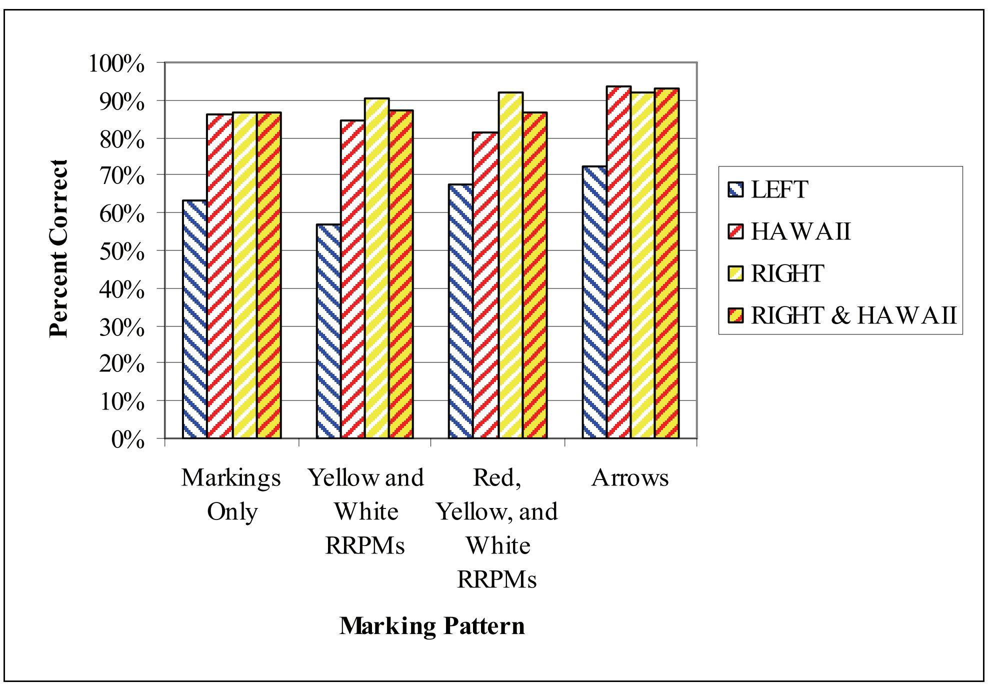

Figure 6. Chart. Two-Lane, Two-Way Undivided Roadway Marked for Passing Data.

In this case, the LEFT group had a 63 percent correct response rate with only pavement markings. Adding yellow and white RRPMs to the centerline and near edge line dropped the rate to 55 percent. Adding the red RRPMs on the far LEFT edge line increased the percent correct to 68 percent. Finally, replacing the RRPMs with arrows brought the correct response rate to a high of 72 percent for the LEFT group.

The HAWAII and RIGHT groups had much higher correct response rates. For the markings only pattern, the responses were 86 and 87 percent, respectively. Adding yellow and white RRPMs to the centerline and near edge line did not have much of an effect for either participant group. Adding red RRPMs decreased the HAWAII response to 82 percent but increased the RIGHT response to 92 percent. Again, the highest percent of correct responses was obtained when the RRPMs were removed and arrows were used instead. The HAWAII group reached 94 percent and the RIGHT group remained at 92 percent.

Overall, the use of red RRPMs provided a 13 percent gain in driver understanding for LEFT drivers (compared to pavement markings supplemented with yellow and white RRPMs). The use of arrows provided a 17 percent gain in performance for the LEFT group. For the HAWAII group, the performance fell 3 percent with red RRPMs compared to a 9 percent increase with arrows. The RIGHT group had the same 2 percent performance gain for both the red RRPMs and the arrows.

Discussion of Incorrect Responses

Out of the 764 responses recorded for this roadway 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. There were 49 responses that indicated at least one of the marking patterns 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.

There were 18, 4, and 5 participants from the LEFT, HAWAII, and RIGHT groups, respectively, that believed the arrows indicated the direction of travel and suggested that passing was not allowed. 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

For each marking pattern tested in this roadway configuration, both the RIGHT and HAWAII groups had a statistically significant better understanding of the marking patterns compared to the LEFT group. For every configuration, the z-statistic for the test of proportions was less than -3.

The sampling error for this roadway configuration was estimated to be ± 6 percent. Therefore, the same results permeate through the groups and patterns as before, just with overall lower scores. In other words, for right-hand drivers, there was no difference between any of the patterns. However, the patterns for left-hand drivers showed a statistical difference in one case: marking supplemented with yellow and white RRPMs compared to markings supplemented with arrows. Similar to the two-lane two-way *no-passing* configuration, these findings suggest that adding only white and yellow supplemental RRPMs to the markings of two-lane two-way *passing* configurations may not be as useful for drivers from left-hand countries unless red RRPMs are also included. But providing markings only with no supplemental RRPMs results in statistically equivalent driver understand rates compared to markings supplemented with either red, yellow, and white RRPMs, or arrows.

Four-Lane Two-Way Undivided Roadway

The four-lane two-way undivided highway configuration was the most understood roadway configuration presented to the survey participants (overall, 99 percent of the responses were correct). Figure 7 shows that all participant groups correctly understood the marking patterns between 97 and 100 percent of the time. Out of 96 participants, only two incorrectly identified the roadway configuration and marking patterns as something other than what was intended. There were no statistically significant differences among the results.

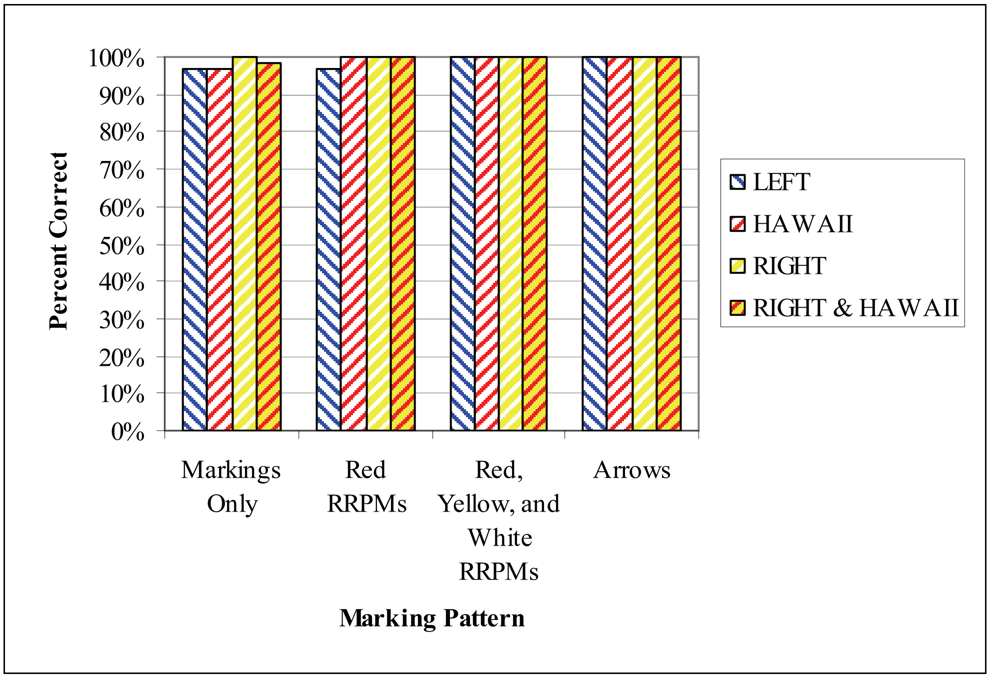

Figure 7. Chart. Four-Lane, Two-Way Undivided Roadway Data.

Two-Lane One-Way Divided Roadway (Traveling In the Correct Direction)

The data presented in Figure 8 indicate the participants had a poor understanding of the one-way divided highway configuration (the overall percent correct was 68 percent). It should be noted that for this configuration there were no red RRPMs shown. The test patterns were pavement markings only, white RRPMs supplementing the lane line and yellow RRPMs supplementing the LEFT edge line, color coordinated RRPMs supplementing all markings, and no RRPMs but arrows in both lanes.

The addition of the RRPMs had little effect on the LEFT group but provided some improved driver understanding for the HAWAII and RIGHT groups (about a 15 percent increase). However, the arrows provided the most benefit, increasing the performance of the LEFT group to 100 percent and almost reaching 100 percent for the HAWAII and RIGHT groups.

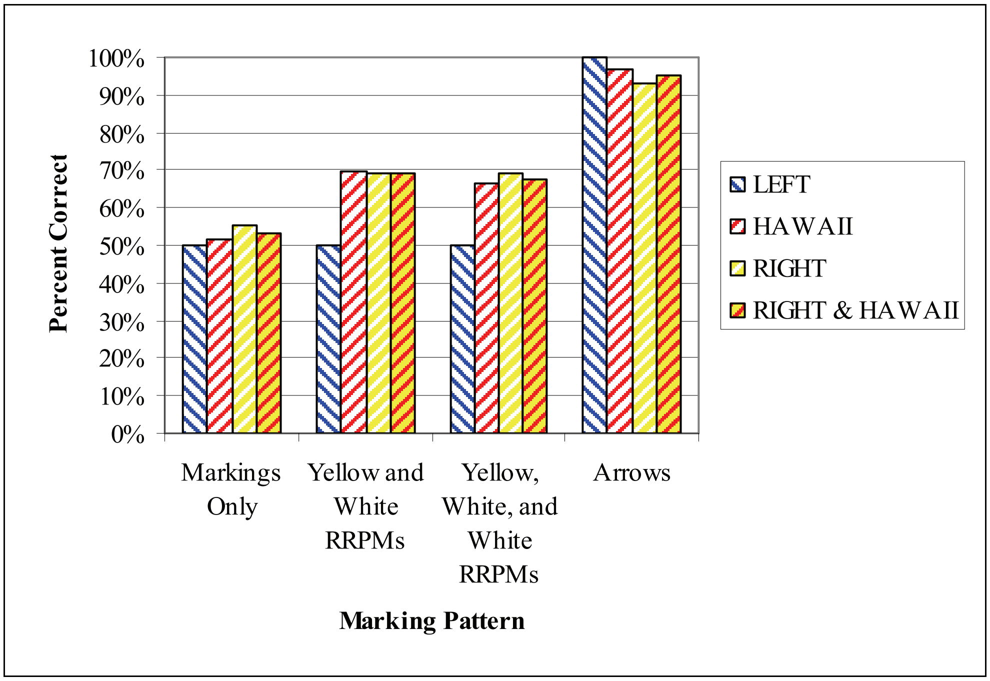

Figure 8. Chart. Two-Lane, One-Way Roadway Data (Driving in the Correct Direction).

Discussion of Incorrect Responses

The common response that each participant group reported was a two-way roadway instead of a one-way roadway (accounting for 92 percent of the incorrect responses). Of the other incorrect responses, 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.

Statistical Results

The test of proportions failed to produce statistically significant difference between the participant groups. The sampling error for this roadway configuration was estimated to be ± 7 percent. For the left-hand drivers, 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 driver understanding when supplemental RRPMs were added to the typical 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).

Two-Lane One-Way Divided Roadway (Traveling In the Wrong Direction)

Overall, the lowest driver understanding rates for all groups was for the two-lane, one-way divided roadway configurations where the participant viewed the markings from a perspective of wrong way travel (the overall percent correct was just 48 percent). Figure 9 contains the percent correct response for each of the study groups. For this case the baseline condition was with the white edge line on the left, the yellow edge line on the right, and a standard lane line down the middle of the roadway. The first alternate pattern had red RRPMs supplementing the lane lines. The second alternate pattern included red RRPMs supplementing the lane line and white edge line, and yellow RRPMs supplementing the yellow edge line. A third alternate pattern contained arrows in both lanes in lieu of any supplemental RRPMs.

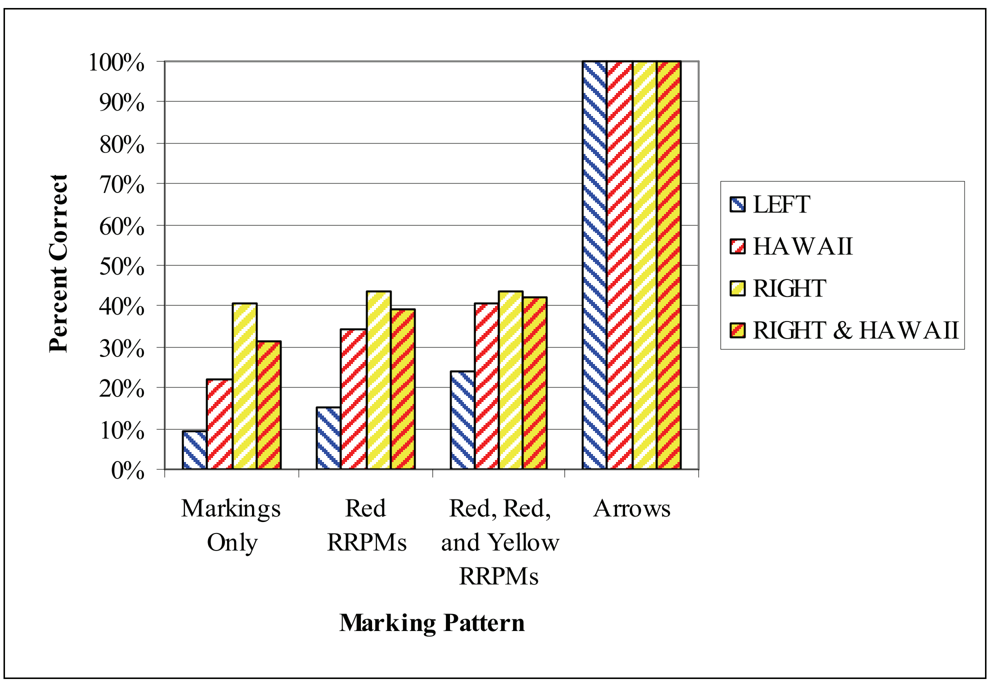

Figure 9. Chart. Two-Lane, One-Way Roadway Data (Driving in the Wrong Direction).

The participants in the LEFT group had a hard time identifying the direction of travel as the wrong way when only pavement markings were used (only 9 percent correct). The HAWAII and

RIGHT groups performed better (22 and 41 percent correct, respectively), but this was still considered low when compared to driver understanding rates of the previous roadway configurations and marking patterns, When the MUTCD-compliant red RRPMs were added to the lane lines, the scores improved, but only modestly. The LEFT group improved to 15 percent correct, the HAWAII group improved to 34 percent correct, and the RIGHT group improved to 44 percent. Adding additional RRPMs to the edge lines helped some, but the improvements were slight. The three marking/marker patterns tested with this roadway configuration failed to produce correct response rates above 50 percent. By far, the most significant improvement was achieved when the RRPMs were removed and the arrows were added. In this case the LEFT and HAWAII groups scored 100 percent correct and the RIGHT group scored 97 percent correct.

Discussion of Incorrect Responses

For the participants that experienced the one-way wrong way roadway configuration, 64 percent believed they were traveling along a two-way roadway. The remaining incorrect responses 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 driver understanding but for some participants the red RRPMs were misunderstood to represent a two-lane two-way roadway marked for no-passing.

Statistical Results

When participants viewed the one-way roadway in the wrong direction, the HAWAII and RIGHT groups had responses that indicated statistically significant better understanding of the markings than the LEFT group. The sampling error for this roadway configuration was estimated to be ± 7 percent. Therefore, the addition of the supplemental red RRPMs on the lane lines 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 edge lines were supplemented with additional RRPMs (yellow and red RRPMs for the pattern 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 pattern with the supplemental arrows showed statistically significant higher driver understanding rates with respect to the direction of flow.

CHAPTER 4 – SUMMARY, RECOMMENDATIONS, AND FURTHER STUDY

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. Multiple pavement marking patterns were laid out at the TTI Riverside Campus and then videotaped under nighttime conditions. The video was edited and used to develop a laptop video survey to test drivers' understanding of pavement markings and markers. Particular attention was devoted to the making of the video so that the only visual cues available for participants to evaluate the roadway scenario shown on video would be provided by the pavement marking and markers (i.e., no signing, or vehicular traffic). Study investigators recruited survey participants at the Honolulu International Airport. The survey participants were asked a series of questions while they viewed looping video clips of various treatments.

There were five roadway configurations tested using various pavement marking patterns. The five roadway configurations were: (1) two-lane two-way undivided roadway marked for no-passing, (2) two-lane two-way undivided roadway marked for passing, (3) four-lane two-way undivided roadway, (4) two-lane one-way roadway with travel in the correct direction, and (5) two-lane one-way roadway with travel in the wrong direction (going against the flow of traffic). For each roadway configuration, typical pavement markings were shown as a baseline condition. Three alternate marking patterns were also tested for each roadway configuration. In general, two of the alternative marking patterns consisted of two different combinations of supplemental RRPMs and the third alternate pattern consisted of supplemental pavement marking arrows without RRPMs.

SUMMARY

The key effort of this study was a driver survey conducted to evaluate how well drivers understand pavement markings and markers, with particular attention devoted to red RRPMs. Almost 200 survey participants completed the study, equally divided between three participant groups: drivers from left-hand drive countries, drivers from Hawaii, and drivers from right-hand drive countries. The survey findings revealed many interesting results. The results related to the primary objectives are summarized below:

- One of the most current and common uses of red RRPMs is on one-way divided roadways to indicate the wrong direction of travel. When drivers were presented wrong-way video without and then with supplemental red RRPMs on the lane lines, their understanding of the wrong-way direction improved in all cases but the improvement was not statistically significant.

- Currently, red RRPMs are not generally used on undivided roadways (except Hawaii and surrounding U.S. territories). The findings of this study show that the use of supplemental red RRPMs on undivided roadways can improve driver understanding but with mixed results. For drivers from left-hand drive countries, the use of red RRPMs on undivided roadways improved driver understanding, but this finding was not statistically significant for all configurations. On undivided roadways, drivers from Hawaii and the continental United States had a statistically similar understanding of the rules of the road with and without supplemental red RRPMs.

- Compared to typical pavement markings only, there was no tested treatment where adding supplemental red RRPMs had a statistically significant impact (either positive or negative) on driver understanding of the traffic flow direction (including all five roadway configurations across all three participant groups). However, when supplemental red RRPMs were added to the typical pavement markings, there was always a modest improvement in driver understanding of the traffic flow direction.

- In order to determine whether the use of supplemental red RRPMs as used in Hawaii might diminish their effectiveness where they are used most—to discourage wrong-way movements at freeway off-ramps and "wrong" sides of divided highways, a comparison of the Hawaiian and continental U.S. responses for the one-way wrong way treatments was made. Under the typical condition when red RRPMs are used on the lane lines to show wrong way direction, correct responses rate for the Hawaiians was 34 percent and for the continental United States drivers it was 44 percent. It is not unreasonable to assume that Hawaiians see red RRPMs more often than drivers from the continental United States (in Hawaii they are used on undivided highways but in the continental United States they are reserved for wrong way direction on one-way roadways). Therefore, it was expected that the Hawaii group could have lower overall scores. While this was the case, the difference was not statistically significant. Adding the red RRPMs actually helped improve the Hawaii group score much more than it helped the continental United States group score. In addition, the results also show that the reserved meaning of the red RRPMs in the continental United States is not well understood (there was only a 3 percent increase in driver understanding when the red RRPMs were added to the typical pavement markings).

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

    - For two-lane two-way roadways marked for passing, the arrows were sometimes (less than 4 percent) interpreted as meaning no passing. However, this would be a safe misunderstanding.

    - The improvement associated with pavement marking arrows was statistically significant for the one-way roadways. For the one-way roadways, the correct response rates only reached a reasonable level of driver understanding when the pavement marking arrows were included.

In addition to the primary findings described above, the study investigators also identified another set of related findings. These findings are associated with drivers' general understanding of pavement markings and markers:

- All driver groups had high correct response rates (> 90 percent) for marking patterns in the two-lane no-passing and four-lane undivided roadway configurations. In other words, drivers understand that a double solid line separates direction of travel and indicates do not cross. When asked, however, only 60 percent of the participants knew the color yellow signified a two-way roadway

(72 percent for continental U.S. drivers). No other color of double solid centerline was tested.

- All U.S. drivers clearly understand the meaning of the double solid centerline line for undivided highways (97 percent correct). However, U.S. drivers do not have such a strong understanding of the broken yellow centerline for two-lane undivided highways (87 percent correct). Most of the incorrect responses from U.S. drivers showed that they understand continuity (continuous versus broken) more than color.

- Unfortunately, without any cues other than markings (i.e., signs or nearby traffic), U.S. drivers have a hard time identifying the meaning of one-way divided highway markings. When the video showed travel in the correct direction, only 53 percent of the U.S. drivers reported correct answers. Worse yet, only 31 percent of the U.S. drivers understood they were traveling in the wrong direction of a one-way highway.

RECOMMENDATIONS

The recommendations have been generated in two specific areas. The primary recommendations relate to the objectives of this study—identifying driver understanding of red RRPMs used in various applications. The secondary recommendations relate to the general understanding of pavement markings and markers.

Primary 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 edge line allows pavement marking arrows to be installed approximately every quarter mile (see calculations in Appendix C).

- On one-way roadways where the correct response rates were so low, pavement markings 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.

Secondary Recommendations

- 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.

- There needs to be an increase in pavement marking meaning during driver training with respect to color and continuity (i.e., continuous versus broken). 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.

FURTHER STUDY

- This study used the latest technologies to develop an innovative survey instrument that provides a direct understanding of pavement marking color and patterns. A follow-up effort should be sponsored using the same or a similar approach to study driver understanding of pavement markings.

- 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 can 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 edge line. Additional investigation would be needed to test this possibility.

- The MUTCD does not currently allow for supplemental RRPMs on edge lines. While this was not included in the scope of this project, the survey responses indicate that supplemental RRPMs on edge lines 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.

REFERENCES

1. FHWA. Manual on Uniform Traffic Control Devices (MUTCD). Federal Highway Administration, Washington, D.C., 2002.
2. Hawkins, H.G. Jr. Traffic Control Devices in Texas Border Areas: Summary of Research and Recommendations. FHWA/TX-99/1274-S, Texas Transportation Institute, Texas A&M University, College Station, TX, March 1999.
3. Carlson, P.J., E.R. Rose, S.T. Chrysler, and A.L. Bischoff. Simplifying Delineator and Chevron Applications for Horizontal Curves. FHWA/TX-04/0-4052-1, Texas Transportation Institute, Texas A&M University, College Station, TX, March 2004.
4. Hawkins, H.G. Jr., A.H. Parham, and K.N. Womack. Feasibility Study for an All-White Pavement Marking System. NCHRP Report 484, National Cooperative Highway Research Program, Washington, D.C., 2002.
5. Hawaiian Airlines. www.hawaiianair.com. Accessed March 15, 2006.
6. Mendenhall, W. and T. Sincich. A Second Course in Statistics: Regression Analysis, Fifth Edition. Prentice Hall, Inc., New Jersey, 1996.
7. Texas Department of Transportation. Average Low Bid Unit Price. http://www.dot.state.tx.us/business/avgd.htm. Accessed April 29, 2006.
8. Traffic Operations Division. Pavement Marking Handbook. Texas Department of Transportation, August 2004.

APPENDIX A – SURVEY

Hawaii Survey

This is not a test. It has no impact on your license. The survey will be conducted using a computer; however the only thing that you are going to have to do is press the space bar. Before we get to the driving questions we need to get a little information about you first. This is just so we can study the results in a meaningful way. We don't ask you anything that would later tell us who you are.

How long have you been driving?

Less than 1 year　　1-5 years
6-20 years　　More than 20 years

What is your age group?

Under 25　　25-54　　55 or above

What is the last level of education that you have completed? ________________________

How often do you drive on highways in Hawaii?

Daily　　Frequently　　Sometimes　　Almost never　　Never

Where do you live? *(country, if USA - state)*______________________________________

1) Hawaiian Islands

2) Right Lane Drivers- USA(mainland), Canada, China, France, Mexico, Spain
Other: ____

3) Left Lane Drivers - Australia, Japan, England, New Zealand, India, Fiji
Other: ____

Now, we are going to show you 12 short video clips of a roadway on the computer screen. Some of the situations you will see may be made up to see how people will react to them and to find out how people would interpret something new. Try to think like you would if you driving on a road in Hawaii and encountered these situations.

As you watch these videos, assume that this is the view through your windshield as you are driving along the road. You will be asked several questions about which lane(s) you can drive or pass in. Press the space bar when you are ready to view the first video clip.

Figure 10. Questionnaire. Demographic Survey Questions.

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
   - **can you drive in the right-two lanes?** Yes No
   - **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.

Figure 11. Questionnaire. Example of Pavement Marking Video Survey Questions.

We are going to ask you a few final questions about different things that you saw on the road in the videos. The first questions will be about the reflective raised pavement markers *(have example picture).*

1) Where do you think you would see <u>white</u> markers?________________________________
____
____

2) Where do you think you would see <u>yellow</u> markers? ________________________________
____
____

3) Where do you think you would see <u>red</u> markers? ________________________________
____
____

4) Were do you think you would see <u>orange</u> markers? ________________________________
____
____

Arrows –

You saw several different videos that had arrows on the road; did you think the arrows were confusing or helpful? Confusing Helpful

Why? ____
____
____
____

Figure 12. Questionnaire. Closing Pavement Marking Summary Survey Questions.

Table 3. Survey Marking Pattern Order.

Roadway Configuration	Marking Pattern	Survey			
		A1	A2	B1	B2
UNDIVIDED Two-lane, two-way, no-passing	Default	2	-	-	1
	Alternate 1- Supplemental RRPMs	10	-	-	6
	Alternate 2 - Supplemental RRPMs with red RRPMs	4	-	-	12
	Alternate 3 - No RRPMs but arrows	7	-	-	8
UNDIVIDED Two-lane, two-way, passing	Default	3	3	2	2
	Alternate 1- Supplemental RRPMs	6	10	7	9
	Alternate 2 - Supplemental RRPMs with red RRPMs	11	5	6	10
	Alternate 3 - No RRPMs but arrows	9	7	11	5
UNDIVIDED Four-lane, two-way	Default	-	2	1	-
	Alternate 1- Supplemental RRPMs and arrows	-	12	4	-
	Alternate 2 - Supplemental RRPMs with red RRPMs	-	6	10	-
	Alternate 3 - No RRPMs but arrows	-	9	8	-
DIVIDED Two-lane, one-way, correct direction	Default	-	1	-	-
	Alternate 1 - Supplemental RRPMs	-	8	-	-
	Alternate 2 - Supplemental RRPMs including right edge line	-	11	-	-
	Alternate 3 - No RRPMs but arrows	-	4	-	-
DIVIDED Two-lane, one-way, wrong way direction	Default	-	-	-	3
	Alternate 1 - Supplemental RRPMs on lane line	-	-	-	4
	Alternate 2 - Supplemental RRPMs including edge line	-	-	-	7
	Alternate 3 - No RRPMs but arrows	-	-	-	11

APPENDIX B – RESPONSE DATA

Table 4. Percent Correct Response by Marking Pattern and Group.

Roadway Configuration	Marking Pattern	Group			
		Left	Hawaii	Right	Right & Hawaii
UNDIVIDED Two-lane, two-way, no-passing	Sample Size	33	32	30	62
	Default	94%	94%	97%	95%
	Alternate 1- Supplemental RRPMs	88%	94%	100%	97%
	Alternate 2 - Supplemental RRPMs with red RRPMs	97%	97%	100%	98%
	Alternate 3 - No RRPMs but arrows	100%	100%	100%	100%
UNDIVIDED Two-lane, two-way, passing	Sample Size	65	65	61	126
	Default	63%	86%	87%	87%
	Alternate 1- Supplemental RRPMs	57%	85%	90%	87%
	Alternate 2 - Supplemental RRPMs with red RRPMs	68%	82%	92%	87%
	Alternate 3 - No RRPMs but arrows	72%	94%	92%	93%
UNDIVIDED Four-lane, two-way	Sample Size	32	33	31	64
	Default	97%	97%	100%	98%
	Alternate 1- Supplemental RRPMs and arrows	97%	100%	100%	100%
	Alternate 2 - Supplemental RRPMs with red RRPMs	100%	100%	100%	100%
	Alternate 3 - No RRPMs but arrows	100%	100%	100%	100%
DIVIDED Two-lane, one-way, correct direction	Sample Size	32	33	29	62
	Default	50%	52%	55%	53%
	Alternate 1 - Supplemental RRPMs	50%	70%	69%	69%
	Alternate 2 - Supplemental RRPMs including right edge line	50%	67%	69%	68%
	Alternate 3 - No RRPMs but arrows	100%	97%	93%	95%
DIVIDED Two-lane, one-way, wrong way direction	Sample Size	33	32	32	64
	Default	9%	22%	41%	31%
	Alternate 1 - Supplemental RRPMs on lane line	15%	34%	44%	39%
	Alternate 2 - Supplemental RRPMs including edge line	24%	41%	44%	42%
	Alternate 3 - No RRPMs but arrows	100%	100%	100%	100%

APPENDIX C – COST COMPARISON

COST ANALYSIS

A cost analysis was completed to estimate the costs of using red RRPMs in accordance with current Hawaii DOT policy versus the use of direction pavement markings arrows. Cost information for clear/red RRPMs and preformed arrows were obtained from the Texas Department of Transportation on-line pricing database [(7)]. The average maintenance replacement cost for clear/red RRPMs was \$2.77 per RRPM, and \$91.85 per pavement marking straight arrow. Assuming that the preformed thermoplastic arrows (125 mils in thickness) have a similar cycle life to standard thermoplastic pavement markings of similar thickness, the arrows should last up to 4 years in traffic below 10,000 ADT and up to 3 years in traffic above 10,000 ADT [(8)]. Assuming RRPMs have a similar expected life cycle and they are spaced every 40-ft, direction arrows could be spaced approximately every quarter mile for a similar cost. These calculations are detailed below:

$$\begin{aligned}
&\mathrm{D}_A = \text{distance between arrows}\\
&\mathrm{A} = \text{cost per arrow}\\
&\mathrm{R} = \text{cost per clear/red RRPM}\\
&\mathrm{S} = \text{spacing between RRPMs}\\
&D_A = \frac{A}{R} s_R\\
&D_A = \frac{\$91.85 / arrow}{\$2.77 / RRPM}\left(40\, ft / RRPM\right)\\
&D_A = 1326\, ft \bullet arrow / RRPM
\end{aligned}$$

Figure 13. Equation. Pavement Marking Arrow versus RRPM Cost Comparison.