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16. Abstract

Traffic control devices applied to the pavement can provide a significant amount of information for the driver. The objective of this research was to assess the effectiveness of various pavement marking materials, devices, and treatments that have potential to increase driver awareness and safety. The following pavement marking materials, devices, and treatments were investigated as part of this research project:

- yellow-green crosswalk material,
- in-roadway warning lights,
- fluorescent orange retroreflective raised pavement markers,
- “removable” pavement marking paint, and
- rumble strips.

This report includes recommendations for the application of in-roadway warning lights and rumble strips. Further research is needed on the yellow-green crosswalk material, fluorescent orange retroreflective raised pavement markers, and the “removable” pavement marking paint before application guidelines can be developed.

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AN ASSESSMENT OF VARIOUS RUMBLE STRIP DESIGNS AND PAVEMENT MARKING APPLICATIONS FOR CROSSWALKS AND WORK ZONES

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report. The engineer in charge of the project was Melisa D. Finley, P.E. (TX-90937).

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CHAPTER 1
INTRODUCTION

Although sometimes overlooked, traffic control devices applied to the pavement can provide a significant amount of information for the driver. Over the years, various pavement marking materials, devices, and treatments have been developed that have potential to increase driver awareness and safety. As part of this research project, the following were investigated: yellow-green (YG) crosswalk material, in-roadway warning lights (IRWLs), fluorescent orange retroreflective raised pavement markers (RRPMs), "removable" pavement marking paint, and rumble strips. The objective of this research was to assess the effectiveness of these new devices.

REPORT ORGANIZATION

The Texas Transportation Institute (TTI) conducted the research project described herein from September 1, 2003, to August 31, 2005. The activities that were completed, as well as the report organization, are described below.

- *Crosswalk Design Survey* – Researchers conducted a survey of the 25 Texas Department of Transportation (TxDOT) districts to gather information about the crosswalk designs used in each district and solicit input with respect to the types of pavement marking materials and applications that should be evaluated as part of the research project. Chapter 2 summarizes the results of this survey.
- *Yellow-Green Crosswalk Marking Survey* – Researchers conducted a survey of the agencies that have received approval from the Federal Highway Administration (FHWA) to experiment with YG crosswalk markings to assimilate the results of recently completed or ongoing evaluations, determine whether additional driver behavior studies are needed, and if possible make recommendations concerning the use of YG markings at crosswalks in school zones. The results of this survey are documented in Chapter 3.
- *Synthesis of In-Roadway Warning Lights Research* – Chapter 4 documents the results of previous research conducted to evaluate the effectiveness of IRWLs and summarizes existing applications guidelines.

- *Fluorescent Orange RRPMs Color Recognition Study* – Researchers conducted a color recognition study to evaluate the daytime and nighttime color of newly developed fluorescent orange RRPMs in a simulated work zone environment. Through this study, researchers also determined whether the fluorescent orange RRPMs were mistaken for red RRPMs. In total, 12 subjects viewed six treatments during the day and at night. Chapter 5 presents the experimental design and results from this study.
- *Evaluation of "Removable" Pavement Marking Paint* – Chapter 6 contains the results of durability evaluations conducted on a new "removable" pavement marking paint product, as well as an assessment of the installation and removal processes.
- *Rumble Strip Sound and Vibration Analysis* – Researchers measured the sound (inside and outside a vehicle) and vibration (inside a vehicle) caused by various types and designs of rumble strips for three different vehicles at two speeds in order to quantify the stimulation experienced by the driver and the impact on the surrounding environment. Chapter 7 documents the results of this effort.

CHAPTER 2
CROSSWALK DESIGN SURVEY

Over the past several years, new pavement marking applications for crosswalks have been introduced in an effort to improve the safety of pedestrians. Currently, TxDOT does not have a standard design for crosswalks. Thus, prior to conducting research with respect to innovative crosswalk pavement marking applications, researchers wanted to determine the crosswalk designs used by each TxDOT district, if the crosswalk design used in school zones differed from those located outside of school zones, and approximately how many crosswalks are located in school zones on state roadways. In addition, researchers wanted input with respect to the types of new devices that should be evaluated as part of the research project.

SURVEY

The survey contained eight questions that researchers used to determine the following for each district:

- the number of school zones located on state roadways,
- the number of school zones located on state roadways that include crosswalks,
- the number of crosswalks located in school zones on state roadways,
- the crosswalk designs used in school zones,
- the preferred crosswalk design in school zones,
- if the design of crosswalks located in school zones differs from those located outside of school zones,
- the types of devices used to enhance crosswalks located in school zones, and
- the types of new devices or innovative designs that should be considered in this research project.

Researchers mailed the survey to contacts in all 25 TxDOT districts and received responses from 23 of the districts (92 percent). Appendix A contains a copy of the survey and a list of contacts.

RESULTS

Table 1 shows the approximate number of school zones located on state roadways, the approximate percent of these school zones that include crosswalks, and the approximate number of crosswalks located in school zones on state roadways for each district. Ten districts (44 percent) have less than 50 school zones, nine districts (39 percent) have between 50 and 100 school zones, and four districts (17 percent) have more than 100 school zones. The average number of school zones in a district is 65. The greatest number of school zones (154) occurs in the Corpus Christi District, while the smallest number (13) occurs in the Childress District.

Table 1. Approximate Number of School Zones and Crosswalks on State Roadways.

District	Number of School Zones	Percent of School Zones that have Crosswalks	Number of Marked Crosswalks
Abilene	20	75%	15
Amarillo			
Atlanta	65	14%	
Austin	20	75%	15
Beaumont	70	33%	27
Brownwood	28	100%	28
Bryan	20	25%	6
Childress	13	100%	19
Corpus Christi	154	100%	154
Dallas	120	25%	30
El Paso	90	89%	75
Fort Worth	90	3%	3
Houston	125	64%	320
Laredo	34	71%	24
Lubbock	35	86%	30
Lufkin	71	7%	5
Odessa	70	93%	100
Paris	104	79%	85
Pharr	97	82%	80
San Angelo	35	100%	40
San Antonio			
Tyler	17	100%	19
Waco	85	71%	60
Wichita Falls	40	75%	30
Yoakum	65	85%	55

Shaded areas show the districts that did not respond.

On average, 67 percent of these school zones include marked crosswalks. Fourteen districts (64 percent) have less than 50 marked crosswalks located in school zones, six districts (27 percent) have between 50 and 100 marked crosswalks located in school zones, and two districts (9 percent) have more than 100 marked crosswalks located in school zones. The average number of marked crosswalks in school zones in a district is 55. The greatest number of marked crosswalks (320) occurs in the Houston District, while the smallest number (3) occurs in the Fort Worth District.

Both the 2003 *Manual on Uniform Traffic Control Devices* (MUTCD) (*1*) and the 2003 Texas MUTCD (*2*) document three typical crosswalk designs: basic transverse, diagonal continental, and longitudinal continental. Figure 1 shows examples of these three designs. Basic transverse markings are the standard crosswalk design. For added visibility, diagonal lines at a 45 degree angle or longitudinal lines parallel to traffic may be used. When diagonal or longitudinal lines are used, the transverse lines may be omitted. Longitudinal lines without transverse lines are commonly referred to as continental crosswalks. When transverse lines are used with longitudinal lines, the crosswalk is referred to as a ladder design. The zebra design is the common name for crosswalks that have diagonal lines with transverse lines.

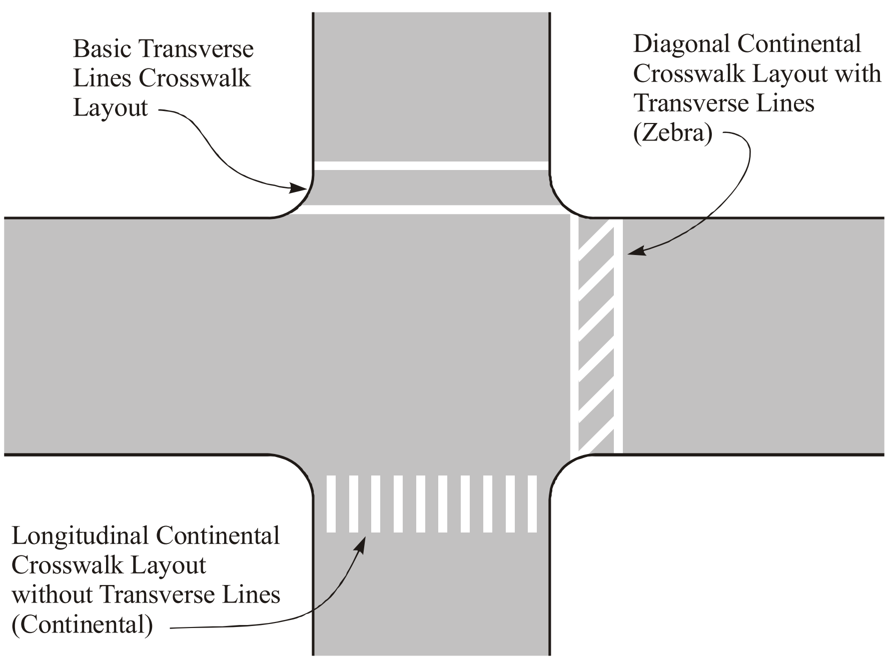


Figure 1. Typical Crosswalk Designs (*1, 2*).

Table 2 shows the crosswalk designs used in school zones. Most districts use the basic transverse, the longitudinal continental, or both. Fifty-seven percent of the districts prefer the longitudinal continental design because district personnel feel that they provide improved visibility, require less maintenance, and cause less confusion with stop bars.

Table 2. Crosswalk Designs Used in School Zones.

District	Type of Crosswalk Design				
	Basic Transverse	**Longitudinal Continental**	**Ladder**	**Diagonal Continental**	**Zebra**
Abilene		✓			
Amarillo					
Atlanta	✓	✓			
Austin					✓
Beaumont	✓	✓	✓		
Brownwood	✓	✓			
Bryan	✓				
Childress		✓			
Corpus Christi					
Dallas	✓				
El Paso		✓			
Fort Worth	✓				
Houston	✓				
Laredo	✓	✓			
Lubbock	✓				
Lufkin		✓			
Odessa	✓	✓			✓
Paris		✓			
Pharr	✓				
San Angelo	✓	✓	✓		
San Antonio					
Tyler		✓			
Waco		✓			
Wichita Falls		✓			
Yoakum	✓				
Total	13	14	2	0	2

Shaded areas show the districts that did not respond.

For consistency, the majority of the districts (20 out of 22) use the same crosswalk design independent of its location (i.e., whether or not the crosswalk is located in a school zone). The El Paso District specifically stated that it wants crosswalks located in school zones to look different from those at other locations. Thus, the El Paso District uses the longitudinal continental design in school zones and the basic transverse markings at all other crosswalk locations. Some of the other districts stated that in special cases the design of a crosswalk located in a school zone will differ from the typical crosswalk layout used in the district.

Currently the following devices are used to enhance crosswalks located in school zones: signs, beacons, pavement markings to denote the beginning and end of the school zone, and dynamic speed display signs (DSDSs). Below is a list of innovative traffic control devices the districts would like to see evaluated; of which only the first three are pavement marking applications (focus of this research project):

- IRWLs (6 districts),
- YG crosswalk markings (4 districts),
- pavement markings to denote school zone limits (1 district),
- DSDSs (3 districts),
- countdown pedestrian signals (2 districts), and
- light-emitting diode signs (1 district).

SUMMARY AND CONCLUSIONS

On average, 67 percent of the school zones located on state roadways have marked crosswalks. Most districts use the basic transverse markings, the longitudinal continental markings, or both of these crosswalk designs in school zones. The preferred crosswalk design is the longitudinal continental because district personnel feel that this layout improves visibility, requires less maintenance, and causes less confusion with stop bars. For consistency, the majority of the districts do not use a different crosswalk design specifically for crosswalks located in school zones. Based on the input received from the districts, the TxDOT project panel asked researchers to develop two syntheses documenting previous and ongoing research concerning IRWLs and YG crosswalk markings. Researchers were also to determine if additional driver behavior studies were needed and if possible make recommendations concerning the use of the two devices.

CHAPTER 3
YELLOW-GREEN CROSSWALK MARKINGS SURVEY

Various traffic control devices are currently used to improve the safety of school zones. Some examples of these devices include: flashing beacons, fluorescent YG signs, and DSDSs. YG pavement markings are a new product that is supposed to increase the visibility of crosswalks within school zones. The YG markings are intended to compliment the fluorescent yellow-green signs and act as an additional indication that the driver is still in a school zone.

YG crosswalk markings are currently not an approved traffic control device in the MUTCD (*1*). Thus, agencies who wish to use YG markings are required to request permission to experiment from the FHWA and report back the findings of their evaluations. Researchers conducted a survey of the agencies that have received approval from the FHWA to experiment with YG crosswalk markings to assimilate the results of recently completed or ongoing evaluations. The survey findings were then used to determine whether additional driver behavior studies were needed and if possible make recommendations concerning the use of YG markings at crosswalks in school zones.

MANUFACTURERS OF YG CROSSWALK MARKINGS

In 2003, the six manufacturers in Table 3 were identified as producers of YG markings. Four of the manufacturers produce pre-formed heated-in-place thermoplastic YG markings, one manufacturer produces a YG poly urea liquid marking, and one manufacturer produces a YG paint product.

Table 3. Manufacturers that Produce YG Markings.

Manufacturer	Product Name	Product
3M	Stamark™	Poly Urea Liquid Pavement Marking
Zumar Industries, Inc.	HotTape™	Pre-formed Heated-in-Place Thermoplastic
Dobco	Color Smart™	Pre-formed Heated-in-Place Thermoplastic
Ennis Paint, Inc.	Flame Tape™	Pre-formed Heated-in-Place Thermoplastic
Flint Trading, Inc.	PREMARK®	Pre-formed Heated-in-Place Thermoplastic
Franklin Paint Company		Paint

SURVEY

In September 2003, researchers identified 17 entities who received approval to experiment with YG crosswalk markings (3) and one University who had applied YG crosswalk markings (Table 4). An initial phone survey was completed with 16 out of the 18 agencies originally identified. The phone survey contained seven questions that inquired about:

- the type of YG crosswalk material used,
- the number of sites where the YG crosswalk markings were used,
- the location of the applications,
- the design of the crosswalks,
- what prompted the agency to apply the markings,
- the evaluations being completed, and
- problems experienced with the evaluations and material performance.

Table 4. Agencies Interviewed for Surveys.

Agency	Initial Survey	Follow-Up Survey
City of Chicago, IL	✓	✓
City of Fountain Valley, CA	✓	NA
Kentucky DOT	✓	✓
City of Logan, UT	✓	✓
City of Battle Creek, MI	✓	✓
Idaho DOT District 4	✓	✓
City of Vandalia, OH	✓	✓
City of Gilbert, AZ	✓	✓
City of Goodyear, AZ	✓	✓
City of Colorado Springs, CO	✓	✓
City of Scottsdale, AZ	✓	✓
City of Central Point, OR	✓	✓
City of Cranston, RI	✓	✓
City of Paramount, CA	✓	NA
City of Downers Grove, IL	✓	NA
City of Avondale, AZ	Unable to contact	✓
City of Paterson, NJ	Unable to contact	Unable to contact
Texas A&M University, TX	✓	NA
City of Spartanburg, SC	Unknown at the time	✓

NA – Not applicable since the agency had completed its evaluation or decided not to evaluate the YG markings.
DOT – Department of Transportation

Through the initial interviews researchers discovered that many of the agencies had not completed their evaluation or for that matter even developed an evaluation plan. Hence, a follow-up survey was developed and the agencies were contacted again between June and October of 2004. The main objectives of the follow-up survey were to determine the status of each agency's evaluations and assimilate any results. It should be noted that for the follow-up survey, researchers also contacted two additional agencies: one identified from the internet (City of Spartanburg,) and one of the two entities that was not interviewed previously (City of Avondale). Thus, in total researchers contacted 18 agencies. Appendix B contains the initial survey and the follow-up survey.

SURVEY RESULTS

Out of the 18 agencies contacted, 16 had installed or were in the process of installing YG crosswalk markings. Two agencies opted not to install the YG crosswalk markings either due to lack of funds or another agency's negative experience with product performance. Table 5 lists the agencies interviewed and either the number of crosswalks where YG markings have been installed or the number of schools where YG crosswalk markings have been installed. Since some agencies reported the number of schools (which may have several crosswalks) instead of the number of crosswalks, the total number of YG marking applications could not be determined. Agencies that provided the "number of crosswalks" had installed YG markings at 33 crosswalks and planned to install the markings at 13 to 23 additional crosswalks. Agencies who reported "number of schools" had installed YG markings at 74 schools and planned to install them at 60 additional schools.

Agencies were also asked what prompted them to try the YG crosswalk markings. Several agencies were approached by manufacturers and decided to try their product. The City of Chicago is using the YG crosswalk markings as part of a school zone system. This system includes YG centerlines; the word "school" painted in YG on the roadway, fluorescent YG pedestrian signs, dynamic speed display signs, and speed bumps on local roads adjacent to the school. The purpose of this school zone system is to establish a standard set of traffic control devices for school zones. The City of Spartanburg, City of Cranston, and the City of Paterson cited the Safe Walks to School Program as the catalyst for installing YG crosswalk markings. Both the City of Scottsdale and the City of Gilbert already used yellow crosswalk markings and decided to try the YG crosswalk markings to coordinate with their use of fluorescent YG signs. Other reasons included: complaints from pedestrians about difficulty crossing a specific intersection, suggestions from crossing guards who wanted to draw more attention to the crosswalks, and a desire to experiment with poly urea products.

Table 5. Summary of YG Crosswalk Marking Applications.

Agency	Product	Number of Crosswalks [a,b]	Number of Schools [c]
City of Chicago, IL	3M		40/100
City of Fountain Valley, CA	3M	1/1	
Texas A&M University, TX	3M	1/1	
City of Gilbert, AZ	3M	1/1	
City of Paramount, CA	3M	0/0 [d]	
City of Downers Grove, IL	3M	0/0 [e]	
Kentucky DOT	Zumar Industries, Inc.	3/10 to 20	
City of Battle Creek, MI	Zumar Industries, Inc.	3/3	
City of Vandalia, OH	Zumar Industries, Inc.	2/4	
City of Scottsdale, AZ	Ennis Paint, Inc.	1/1	
City of Avondale, AZ	Ennis Paint, Inc.	2/2	
City of Logan, UT	Flint Trading, Inc.		8/8
Idaho DOT District 4	Flint Trading, Inc.	1/4	
City of Goodyear, AZ	Flint Trading, Inc.	3/3	
City of Colorado Springs, CO	Flint Trading, Inc.	13/13	
City of Central Point, OR	Flint Trading, Inc.	1/1 [f]	
City of Spartanburg, SC	Flint Trading, Inc.	1/1	
City of Cranston, RI	Franklin Paint Company		26/26

[a] Number of crosswalks where YG markings installed/number of crosswalks anticipated for evaluation.
[b] The Kentucky DOT, the City of Fountain Valley, and the City of Goodyear have all removed one crosswalk due to durability issues.
[c] Number of schools where YG crosswalk markings installed/number of schools anticipated for evaluation.
[d] The City of Paramount chose not to use based on the City of Fountain Valley's experience.
[e] The City of Downers Grove chose not to use due to a lack of funds and time.
[f] Not a school zone application.

Crosswalk Design

As discussed in the previous chapter, the national MUTCD (*1*) and the Texas MUTCD (*2*) contain information regarding the design of crosswalks. Both manuals require that a crosswalk consist of white lines that are between 6 inches and 24 inches wide. If diagonal or longitudinal lines are used they should be 12 to 24 inches wide; however the manuals differ with respect to the spacing of these lines. The MUTCD recommends that the lines be spaced 12 to 60 inches apart, while the Texas MUTCD recommends a spacing of 12 to 24 inches. Figure 1 shows three typical crosswalk designs.

YG and White Crosswalks

Thirteen of the agencies use a combination of YG and white markings in their crosswalk design (as suggested by the FHWA). Of these agencies, 11 use some variation of the continental design shown in Figure 2. Differences in the continental design include variations in the width and spacing of the blocks, whether the blocks are diagonal or perpendicular to the direction of travel, and whether the continental crosswalk has transverse lines. The main difference with respect to color was whether there was space between the white and YG blocks. For example, Figure 2 shows a ladder crosswalk with a 2-ft wide space between alternating 2-ft wide YG and white blocks. In comparison, the continental crosswalk in Figure 3 does not include space between the two colors (i.e., consists of a 1-ft wide white block immediately followed by a 1-ft wide YG block). Figure 4 is a variation of a ladder crosswalk design that does not have space between the two colors. Table 6 provides a description of the YG and white continental crosswalks used by each entity.

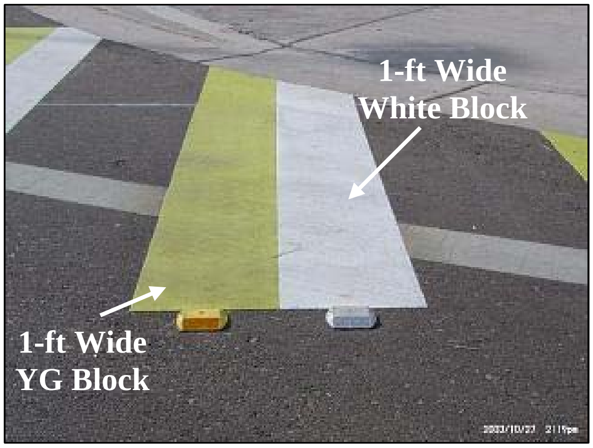
Three of the agencies installed YG and white basic transverse crosswalks. One of these agencies also utilized the ladder design, but chose to use the basic transverse design on lower traffic volume local roads. Table 7 provides a description of the basic transverse crosswalk designs used by each entity and Figure 5 contains an example of one of the YG and white basic transverse designs.

YG Only Crosswalks

Three agencies installed crosswalks constructed with only YG markings. Two of the agencies are using the continental crosswalk design, and one agency is using the basic transverse crosswalk design only on lower volume roads. Table 8 describes the YG only crosswalk designs that have been installed.

Figure 2. Example of a YG and White Ladder Crosswalk.

A. Full View.



B. Close-up.

Figure 3. Variation of YG and White Continental Crosswalk Used by the City of Goodyear.

Figure 4. Variation of YG and White Ladder Crosswalk Used by the City of Central Point.

Evaluations

Table 9 summarizes the types of evaluations being performed. Only six of the agencies are evaluating driver behavior through the use of speed studies. These speed studies consist of either a before and after study, a comparison to a similar crossing, or a comparison of upstream speeds to speeds at the crosswalk. One agency also plans to compare before (4 to 5 years prior to installation) and after (1.5 years after installation) crash data. Five of the agencies have surveyed or will survey parents, crossing guards, school faculty, and police officers. Other agencies assessed public response and material performance.

Speed Evaluations

Table 10 provides a brief description and the status of the speed evaluations. Only the City of Battle Creek, Idaho DOT, and the City of Cranston have collected data and reported results. The City of Battle Creek conducted speed studies at two crosswalks (both crosswalks were the YG and white basic transverse design). At the first site the 85th percentile speed was reduced from 41 mph to 35 mph; however, a DSDS was also installed at this site around the same time the YG crosswalk markings were installed. At the second site there was no DSDS, and only a small reduction (1 mph) in the 85th percentile speed was observed. The school zone speed limit at both sites was 30 mph.

Table 6. Description of YG and White Continental Crosswalk Designs.

Location	Continental Pattern
City of Chicago, IL	Longitudinal continental pattern with 12-inch wide white blocks alternating with 12 inch-wide YG blocks, spaced on 24-inch centers.
Kentucky DOT	Ladder pattern with alternating white and YG blocks.
City of Battle Creek, MI	Ladder pattern with 24-inch wide white blocks alternating with 24-inch wide YG blocks, spaced on 24-inch centers. .
Idaho DOT District 4	Ladder pattern with 24-inch wide white blocks alternating with 24-inch wide YG blocks, spaced on 24-inch centers. 12-inch wide transverse lines spaced 10 ft apart.
City of Vandalia, OH	Longitudinal continental pattern with 24-inch wide white blocks alternating with 24-inch wide YG blocks, spaced on 24-inch centers.
City of Goodyear, AZ	Longitudinal continental pattern with a 12-inch wide white block immediately followed by a 12-inch wide YG block, spaced on 24-inch centers. See Figure 3.
City of Cranston, RI	Ladder pattern with alternating white and YG diagonal blocks.
City of Spartanburg, SC	Ladder pattern with alternating white and YG blocks.
City of Central Point, OR	Ladder pattern with white block immediately followed by YG block. See Figure 4 for width and spacing.
City of Logan, UT	Ladder pattern with 12-inch wide white blocks alternating with 12-inch wide YG blocks, spaced on 12-inch centers.
City of Colorado Springs, CO	Two longitudinal continental patterns used: 1. 12-inch wide white block immediately followed by a 12-inch wide YG block, spaced on 5-ft to 6-ft centers (similar to Figure 3 but wider spacing) 2. 12-inch wide white block alternating with 12-inch wide YG block, spaced 5-ft to 6-ft on centers (more like Figure 2 but wider spacing and no transverse lines).

Table 7. Description of YG and White Basic Crosswalk Designs.

Location	Basic Pattern
City of Battle Creek, MI	Transverse 6-inch wide white lines, approximately 4 to 5 ft apart, with a 6-inch wide YG line on the leading edge of both white lines (see Figure 5).
City of Scottsdale, AZ	Transverse white lines with YG lines on the inside edge of both white lines (opposite of design in Figure 5).
City of Avondale, AZ	Transverse 12-inch wide white lines with a 4-inch wide YG line on the leading edge of both white lines (similar to Figure 5).

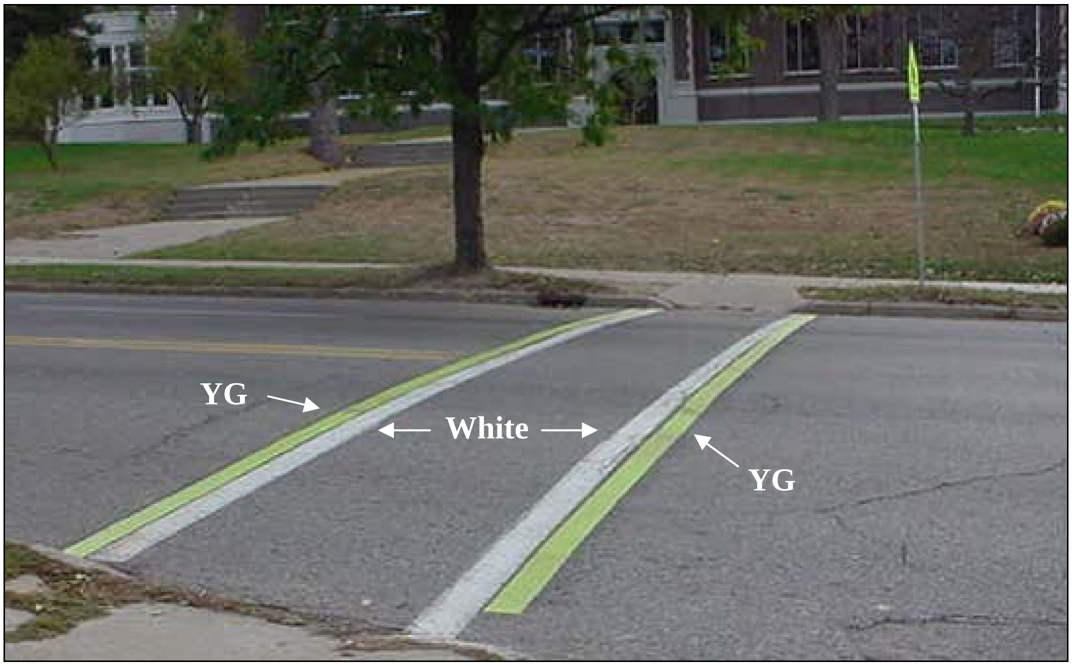


Figure 5. Example of Basic Crosswalk Design with YG Markings on the Leading Edges.

Table 8. YG Only Crosswalk Designs.

Location	Continental Pattern	Basic Pattern
City of Fountain Valley, CA	Ladder pattern with 12-inch wide YG blocks, spaced on 2-ft centers.	NA
Texas A&M University, TX	Longitudinal continental pattern with 24-inch YG blocks, spaced on 24-inch centers. .	NA
City of Chicago, IL	NA	Transverse 6-inch wide YG lines, spaced 5 to 6 ft apart.

NA – Not Applicable

Idaho DOT installed one YG and white ladder crosswalk design at a two-way stop-controlled intersection. Speed data were collected before, "shortly after," and eight months after the installation of the YG markings. The 85th percentile speed was reduced from 30 mph to 28 mph from the before condition to the "shortly after" condition. However, eight months after the installation of the YG and white continental crosswalk the 85th percentile speed rose to 31 mph. The posted speed limit at this site was 25 mph.

Table 9. Types of Evaluations Being Performed.

Location	Speed Study	Crash Analysis	Surveys	Public Response	Material Performance	No Evaluation
City of Chicago, IL	✓	✓	✓			
City of Fountain Valley, CA					✓	
Kentucky DOT	✓					
City of Logan, UT				✓		
City of Battle Creek, MI	✓		✓			
Idaho DOT District 4	✓				✓	
City of Vandalia, OH				✓		
City of Gilbert, AZ					✓	
City of Goodyear, AZ					✓	
City of Colorado Springs, CO			✓			
City of Scottsdale, AZ	✓		✓			
City of Central Point, OR				✓		
City of Cranston, RI	✓					
Texas A&M University, TX						✓
City of Avondale, AZ			✓			
City of Spartanburg, SC				✓		
City of Paramount, CA						✓
City of Downers Grove, IL						✓

The University of Rhode Island evaluated a YG and white ladder crosswalk design at one school for the City of Cranston. The YG markings had already been installed when the evaluation took place so upstream average speeds were compared to speeds closer to the crosswalk. A 5 percent reduction in average speed was observed between the upstream speeds and the crosswalk. A DSDS was also installed at this site.

The City of Chicago, as explained previously, is installing multiple traffic control devices including YG crosswalk markings to improve safety in school zones. In the spring of 2004, before speeds were collected at 15 different schools. The data collection for the after speed studies began in October of 2004. Four or five of these schools have DSDS, so the data from approximately 10 schools will not be influenced by a DSDS. Both Kentucky DOT and the City of Scottsdale experienced project delays but anticipated resuming their evaluations in the spring of 2005.

Table 10. Descripition and Status of Speed Studies.

Location	Speed Study Description and Status
City of Chicago, IL	Before and after speed studies at 15 schools. Before data collected. After data collection began in October 2004.
Kentucky DOT	Before and after speed studies. Durability problems at three initial sites, so they plan to switch products and conduct studies in the spring of 2005.
City of Battle Creek, MI	Before and after speed studies completed. One site had a 6 mph decrease in 85th percentile speeds (DSDS used), and one site had a 1 mph decrease in 85th percentile speeds (DSDS not used).
Idaho DOT District 4	Before, "shortly after," and 8 months after study completed. Initially found a 2 mph decrease in 85th percentile speeds, but 8 months later 85th percentile speed 1 mph faster than in before study.
City of Scottsdale, AZ	After speed study. Experienced delays. Plan to conduct study in spring of 2005.
City of Cranston, RI	After speed study comparing upstream speeds to speeds at the crosswalk completed. Found 5 percent reduction in average speed. DSDS used.

Surveys

Five entities have performed or will perform surveys as part of their evaluation of YG crosswalk markings. Of these five entities, two entities have collected the survey data, but have not completed analyzing the results. The other three entities are still developing their surveys. Table 11 contains a summary of the survey evaluations being conducted.

The City of Battle Creek conducted surveys of pedestrians crossing at YG and white basic transverse crosswalks. Subjects were asked if they noticed the new pavement markings. These data have not been completely reduced; however, preliminary results show that 29 percent of the subjects felt that the YG color was more noticeable than white, and 39 percent of the subjects felt that the area around the school zone would be more noticeable if the YG pavement markings were used. In contrast, approximately 22 percent of subjects did not notice the new YG crosswalks. The City of Avondale surveyed the parents of children who attended the school where two YG and white basic transverse crosswalks were installed. They also surveyed the crossing guards. However, the survey results have not been analyzed.

Table 11. Description of Surveys.

Location	Survey Description
City of Chicago, IL	Plans to survey crossing guards, assistant principals, and safety staff. Survey will be developed in late fall 2005 or spring 2006.
City of Battle Creek, MI	Have surveyed parents and faculty. Results not complete.
City of Colorado Springs, CO	Plans to survey parents. Survey to be developed.
City of Scottsdale, AZ	Plans to survey parents and crossing guards. Survey to be developed.
City of Avondale, AZ	Have surveyed parents and crossing guards. Results not complete.

Public Response

Four agencies evaluated their YG and white crosswalk designs by tracking public response. In general, all four of these agencies received positive feedback from the public. The City of Central Point did receive two negative comments; however, they were not directed at the YG pavement markings.

Material Performance

The Idaho DOT conducted the only formal evaluation of material performance. Retroreflectivity measurements were collected at a YG and white ladder crosswalk design shortly after installation and eight months after installation. Initial retroreflectivity measurements for the YG blocks were considered good and ranged between 631 and 309 mcd/m^2/lux, with an average retroreflectivity value of 447 mcd/m^2/lux. However, eight months later retroreflectivity values ranged between 17 and 91 mcd/m^2/lux, with an average value of 45 mcd/m^2/lux. White blocks at this crosswalk showed similar results.

During the survey, eight additional agencies provided comments concerning the performance of the product they had installed. Table 12 contains a summary of the responses. Many of the agencies reported durability problems. Four agencies cited problems with cracking and chipping, two agencies reported that the material became dull quickly or looked washed out, and two agencies reported that the material got dirty faster than white or standard yellow. The

City of Paramount decided not to try the YG crosswalk markings because of the performance issues experienced by the City of Fountain Valley. In contrast, four agencies reported either no performance problems or that the material was performing well.

Table 12. Summary of Material Performance.

Evaluation Type	Product	Material Performance
City of Fountain Valley, CA	3M	Dulled quickly, cracked, not thick enough.
City of Gilbert, AZ	3M	Cracking, chipped away quickly.
Battle Creek, MI	Zumar Industries, Inc.	Durability excellent, color stability very good.
City of Scottsdale, AZ	Ennis Paint, Inc.	Fading a little. Material gets dirty faster than standard yellow or white.
City of Avondale, AZ	Ennis Paint, Inc.	Material has been down 1 year and is performing well.
City of Logan, UT	Flint Trading, Inc.	Material more brittle than white and not as durable.
Idaho DOT District 4	Flint Trading, Inc.	Average initial retroreflectivity was 447 mcd/m^2/lux. Eight months later average retroreflectivity was 45 mcd/m^2/lux.
City of Goodyear, AZ	Flint Trading, Inc.	Chipping, flaking, and cracking. One site had to be replaced three times in one year.
Colorado Springs, CO	Flint Trading, Inc.	Minimal chipping experienced. Material gets dirty very quickly, but comes clean when rains. Not as bright as standard yellow or white.
City of Central Point, OR	Flint Trading, Inc.	Material has been down for 1 year. Have experienced no problems.
City of Spartanburg, SC	Flint Trading, Inc.	Material has been down for 1 year. Have experienced no problems.

OTHER RESEARCH

During a previous study conducted by TTI (4), researchers evaluated driver comprehension of the standard all-white ladder crosswalk and a YG and white ladder crosswalk. Both treatments were shown with a fluorescent YG school crossing sign. For both crosswalk treatments, the majority (7 out of 10) of the participants stated that the traffic control devices indicated a pedestrian crossing. The other three subjects interpreted the traffic control devices in both cases to indicate a school or children crossing. Six out of ten subjects noticed the color difference (all-white versus combination) between the two crosswalk treatments. The same six subjects believed there was not a difference in the meaning between the two crosswalk designs.

SUMMARY AND CONCLUSIONS

In September 2003, researchers identified 17 agencies who had received approval from the FHWA to experiment with YG pavement markings for school crosswalks. In addition, researchers discovered two other entities that had applied YG crosswalk markings. Phone surveys were completed with 18 out of the 19 agencies.

Even though numerous agencies are experimenting with YG crosswalk markings, with the exception of the City of Chicago, the number of crosswalks treated with the YG pavement markings is limited. The City of Chicago's experimentation plan includes speed studies, a crash analysis, and surveys of crossing guards and school personnel. However, as of October 2004, the City of Chicago was still collecting data; thus, no results were available.

Only three of the agencies surveyed had completed driver behavior studies. These speed studies resulted in a reduction in the 85th percentile speed (1 to 6 mph depending on the site) when the YG crosswalk markings were used. However, at several of the sites a DSDS was also used; thus, the isolated effect of the YG crosswalk markings could not be determined. It is also important to note that speed data at an upstream control point were not collected during any of the speed studies. Upstream speeds are used to reveal differences in the general traffic speeds between the before and after studies since changes in the normal speeds between studies can impact the overall results. In addition, none of the speed studies document whether pedestrians were or were not present.

Overall, the survey yielded limited results with respect to the application of YG markings at school crosswalks. Thus, at this time researchers do not feel that recommendations concerning the use of YG markings at school crosswalks can be developed. Instead, researchers recommend that guidelines be developed after the ongoing evaluations are completed. In addition, researchers recommend conducting a driver behavior study utilizing motorist compliance (percent of motorists yielding/stopping for pedestrians) as a measure of effectiveness. Researchers also recommend conducting a motorist survey downstream of the location where the motorist compliance data are collected. This survey could include questions concerning the following:

- whether the motorist noticed the crosswalk;
- the design of the crosswalk (e.g., What color was the crosswalk?);
- whether the motorist noticed the pedestrian; and
- why the motorist did or did not yield/stop for the pedestrian.

CHAPTER 4
SYNTHESIS OF IN-ROADWAY WARNING LIGHTS RESEARCH

In 2003, approximately 10 percent of all motor vehicle-related fatalities in Texas were pedestrians (*5*). Various roadway design elements and traffic control devices are used to improve pedestrian safety. One crosswalk enhancement that has seen an increase in use over the last 10 years is IRWLs. IRWLs are yellow lights installed in the roadway surface on both sides of a marked crosswalk, facing oncoming traffic. Upon activation (manually or through detection), the lights begin to flash at a constant rate to warn drivers of the presence of pedestrians in a marked crosswalk they are approaching. During this research project, researchers assimilated the results of previous research in order to determine the effectiveness of IRWL applications, ascertain whether additional research was needed, and if possible make recommendations concerning the use of IRWLs at marked crosswalks.

CROSSWALK APPLICATIONS

The use of IRWLs originated in the 1990s in California and Washington State. Since that time, IRWLs have been installed by numerous other cities in the United States, and various research projects on the effectiveness of IRWLs at crosswalks have been conducted. These studies have focused on driver reaction measures (driver yielding, braking distance, approach speed, etc.) and pedestrian reaction measures (wait time, hurried crossings, etc.).

Driver Reaction

The majority of the previous research studies have used driver yielding behavior as the main driver reaction measure. Table 13 contains a summary of the driver yielding behavior findings. For most installations, IRWLs have increased driver yielding into the 50 to 98 percent range (*6*, *7*, *8*, *9*, *10*, *11*). Results tend to be more dramatic at night with driver yielding increasing into the 64 to 97 percent range (*6*, *7*, *11*). For three installations (*7*, *12*, *13*), driver yielding did not increase above 45 percent, and for one installation driver yielding actually decreased (*13*). Only two of the studies (*7*, *10*) evaluated the long-term effects of IRWLs. After six months, three of the sites experienced an additional 5 to 25 percent increase in driver yielding, two sites saw an approximate 5 percent decrease in driver yielding, and one site had no change.

Table 13. Summary of Driver Yielding Behavior Findings.

Location	Day		Night	
	Before	After	Before	After
California (*6*)	28%	53%	13%	65%
California (*14,12*)	7 to 8% increase		-	-
California (*7*)	10% 12%	44% 54%	5% 5%	64% 68%
Colorado (*8*)	30%	74%	-	-
Florida (*12*)	13%	34%	-	-
Florida (*13*)	18% 81%	30% 75%	-	-
Hawaii (*9*)	30%	62%	-	-
Iowa (*10*)	63% 91%	85% 98%	-	-
Maryland (*15*)	30% increase		-	-
Washington (*11*)	51%	91%	39%	97%

"-" Not studied.

In conjunction with driver yielding, several studies (*6*, *7*, *11*) have assessed the distance upstream of the crosswalk where drivers begin to brake. As shown in Table 14, all but one location experienced an increase in the braking distance with the installation of IRWLs. During the day the increase in braking distance ranged from 26 to 102 ft. At night, larger increases occurred (74 to 219 ft).

Table 14. Summary of Braking Distance Findings.

Location	Day		Night	
	Before	After	Before	After
California (*6*)	133 ft	159 ft	133 ft	210 ft
California (*7*)	143 ft 214 ft	245 ft 186 ft	148 ft 105 ft	329 ft 324 ft
Washington (*11*)	218 ft	262 ft	190 ft	264 ft

Speed studies (*9*, *10*, *12*, *16*, *17*) have also been conducted in order to determine the effectiveness of IRWLs (Table 15). At most of the IRWL installations, the change in the average and 85th percentile speeds was less than 5 mph. Only one site (*9*) experienced a 10 mph reduction in the average speed and a 6 mph reduction in the 85th percentile speed.

Table 15. Summary of Speed Study Findings.

Location	Posted Speed Limit (mph)	Average Speed (mph)		85th Percentile Speed (mph)	
		Before	After	Before	After
California (16)	25	31	27	36	33
Florida (12)	Unknown	28	27	-	-
Hawaii (9)	35	40	30	45	39
Iowa (10)	25	17	18	21	22
New Jersey (17)	30	14 percent decrease		-	-

"-" Not provided.

One of the studies previously discussed (7) compared the effectiveness of IRWLs and standard overhead flashing beacons. The percentage of drivers yielding to a pedestrian during the day and at night increased considerably more after the installation of the IRWLs than after the installation of the flashing beacons. Also, at night the braking distance increased more with the IRWLs than with the flashing beacons. However, during the day with the IRWLs the findings were inconsistent; with one direction experiencing an increase and one direction experiencing a decrease in braking distance.

Another study (8) compared five different crosswalk enhancements: rumble strips, IRWLs, sign-mounted flashing lights, state law signing, and raised pedestrian crossings. The pedestrian activated, sign-mounted flashing lights resulted in the greatest increase in driver compliance (71 percent). Since the IRWLs were not as effective (60 percent increase in compliance) and were more costly, the use of the IRWLs was not continued.

Pedestrian Reaction

Many of the previous studies (6, 7, 10, 12, 13, 14) have conducted pedestrian surveys to determine the perceived safety benefit and level of compliance. However, only two studies (9, 15) used quantitative measures to evaluate the effectiveness of IRWLs with respect to pedestrian crossing behavior. A study in Hawaii (9) found that the wait time prior to crossing was reduced from 26.7 seconds to 13.2 seconds (approximately 50 percent) when IRWLs were used. Prior to the installation of the IRWLs 22 percent of the pedestrians made hurried crossings (i.e., ran) in order to avoid approaching traffic. This percentage decreased to 12 percent after the implementation of the IRWLs. A study in Maryland (15) found that the installation of IRWLs reduced the average pedestrian wait time from 5 seconds to 3.3 seconds on the near side of the crossing only. No effect on wait time was found for the far side of the crossing. For both sides, the percent of hurried crossings was reduced from 6 percent to 4 percent.

OTHER APPLICATIONS

In Europe, IRWLs are used to delineate the centerlines and edge lines of roadways, especially on curves and in tunnels to help alert drivers to unexpected alignment changes or direct drivers during inclement weather conditions (e.g., rain, fog, etc.). In the United States, IRWLs have also been used to delineate travel lanes (*18*), dual left-turn lanes (*19*), and crossovers and lane drops in work zones (*20*, *21*). Currently these applications are not approved by the MUTCD (*1*) or Texas MUTCD (*2*).

APPLICATION GUIDELINES

The application of IRWLs at marked crosswalks is addressed in the national MUTCD (*1*) and Texas MUTCD (*2*). Example applications include marked school crosswalks, marked mid-block crosswalks, marked crosswalks on uncontrolled approaches, and marked crosswalks in advance of roundabout intersections. Both manuals state that IRWLs shall not be used at crosswalks controlled by yield signs, stop signs, or traffic signals. However, these two manuals do not provide practitioners with specific criteria for determining when and where IRWLs are needed or justified. Both manuals do provide additional standards and guidance concerning the design of IRWLs.

Boyce and Van Derlofske (*17*) also provided very general guidance with respect to the installation of IRWLs. They recommended that IRWLs are most appropriately installed on crosswalks where:

- accident history reveals need for additional advanced warning;
- crosswalk is at an unusual location (e.g., mid-block);
- many other features in the surrounding environment are competing for drivers' attention; and
- distance at which crosswalk can first be seen requires drivers to immediately respond to pedestrians under prevailing traffic conditions.

Based on the experiences with IRWLs in California and Washington, Whitlock and Weinberger Transportation, Inc. *(6)* recommended that the following guidelines be met for the installation of IRWLs:

- IRWLs should be used at uncontrolled crosswalks.
- Main street average approach speeds should be 45 mph or less.
- Main street traffic volumes should be between 5000 and 30,000 vehicles per day (vpd).
- At speeds less than 35 mph, approaching drivers should have visibility of IRWLs at least 400 ft upstream of crosswalk. At speeds greater than 35 mph, appropriate additional sight distance to the IRWLs should be provided.
- There should be no other crosswalks or traffic control devices at least 250 ft upstream or downstream of the crosswalk location where the IRWLs will be installed.
- Minimum pedestrian volume should be 100 pedestrians per day (ppd).

Huang and Huang, et al. *(12, 13)* agreed with these recommendations but increased the range of the main street traffic volumes to 35,000 vpd. The Florida Department of Transportation *(22)* added that IRWLs should not be installed on roadways with more than four lanes. The California Supplement to the 2003 MUTCD *(23)* uses different pedestrian and traffic volume criteria: at least 40 pedestrians regularly use the crossing during each of any two hours during a 24-hour period and vehicular volume exceeds 200 vehicles per hour (vph) in urban areas or 140 vph in rural areas during peak-hour pedestrian usage. Both the Florida DOT and California DOT criteria require an engineering study.

The City of Kirkland *(11)* uses a ranking system, similar to the process used to rank capital improvement projects, to select and prioritize the locations where IRWLs would be installed. The City of Kirkland decided that the installation of IRWLs at crosswalks already benefiting from improvements should be delayed and priority be given to locations that were less developed. Ultimately, criteria for installing IRWLs were developed (Appendix C). These criteria include threshold conditions (marked crosswalk and stopping sight distance adequate), engineering considerations (approach speed, average daily traffic, and cost), connection information (distance to nearest crosswalk, type of facility, school crosswalk, type of facilities in vicinity of crosswalk), and safety considerations (serves vulnerable population, accident history, existing improvements). Under each category, the criteria are assigned points. The total points are then used to prioritize the locations with respect to installing IRWLs.

Instead of a point system, a binary decision-making installation warrant was recommended by Katz, Okitsu & Associates for the City of Fountain Valley *(24)* (Appendix D). Practitioners simply answer "yes" or "no" to eight criteria that address the type of pedestrian crossing, speed on the main street, average daily traffic, safe stopping distance, pedestrian volume, adjacent crosswalks or traffic control, roadway cross section, and other treatments. These criteria are very similar to those recommended by Whitlock and Weinberger Transportation, Inc. *(6)* with the following exceptions.

- If the vehicular approach speed on the main street is between 35 mph and 40 mph, the stopping sight distance must be at least 500 ft prior to the crosswalk. If the vehicular approach speed on the main street is between 40 mph and 45 mph, the stopping sight distance must be at least 600 ft prior to the crosswalk.
- There must be no marked crosswalks or controlled intersections within 300 ft upstream or downstream of the crosswalk.
- The cross section of the main street to be crossed must be a minimum of three lanes.

The installation warrant is satisfied if all eight of the criteria are met (i.e., all answers are "yes"). If the warrant is met, the site is then prioritized using a pedestrian crossing intensity parameter, which is a measure of the magnitude of the conflict between vehicles and pedestrians and the vulnerability of the population group using the crosswalk.

More recently, Arnold *(25)* completed an effort to develop guidelines for IRWLs for the Virginia DOT. The guidelines include both planning and design elements. The planning guidelines focus on when and where to use IRWLs, while the design guidelines focus on the design features or IRWLs. Appendix E contains the planning guidelines.

First and foremost, the location being considered for IRWLs must have an identified pedestrian safety problem. Since the location must have a marked crosswalk with applicable warning signs *(1)*, Arnold recommends that Virginia DOT's most recent version of *Guidelines for the Installation of Marked Crosswalks* *(26)* be consulted to determine if IRWLs are identified as a potential special treatment. Table 16 shows the recommendations for considering marked crosswalks and identifies possible alternative enhancement measures to consider. These measures are categorized into the following five levels:

- Level 1 Devices – standard crosswalk, raised mid-block crosswalk, rumble strips;
- Level 2 Devices – high visibility crosswalks;
- Level 3 Devices – refuge islands, split pedestrian crossover, bulbouts;
- Level 4 Devices – overhead signs and flashing beacons, IRWLs; and
- Level 5 Devices – pedestrian-actuated signals, grade-separated crossings.

Once IRWLs are identified as a potential special treatment, a set of additional guidelines is used to determine if IRWLs are justified (see Appendix E). However, these additional guidelines are just a combination of the Whitlock and Weinberger Transportation, Inc. (6) and California guidelines (23), with specific stopping sight distance criteria used by the Virginia DOT.

Currently, joint Transit Cooperative Research Program (TCRP) and National Cooperative Highway Research Program (NCHRP) project D-08/3-71 is identifying and evaluating enhanced crosswalk treatments to determine which treatments are effective under various conditions. The objectives of this research are to recommend selected engineering treatments to improve safety for pedestrians crossing high-volume and high-speed roadways at unsignalized locations and recommend modifications to the MUTCD traffic signal pedestrian warrant. As part of this project, researchers are planning to develop one set of quantitative guidelines that provides advice on the use of a number of pedestrian crossing treatments including IRWLs.

SUMMARY AND CONCLUSIONS

IRWLs originated in California and Washington State in the 1990s. Since that time, IRWLs have been installed by numerous other cities in the United States, and various research projects on their effectiveness have been conducted. For most installations, IRWLs have increased driver yielding into the 50 to 98 percent range. In addition, IRWLs typically increase the distance drivers' first brake for a pedestrian, reduce pedestrian wait time prior to crossing, and reduce the percent of hurried crossings. The driver reaction results tend to be more dramatic at night than during the day.

Table 16. Virginia DOT Recommendations for Considering Marked Crosswalks and Other Needed Pedestrian Improvements at Uncontrolled Locations [a] (*26*).

	≤ 9,000 ADT			> 9,000 ADT to ≤ 12,000 ADT			> 12,000 ADT to ≤ 15,000 ADT			> 15,000 ADT		
	≤30 mph	35 mph	≥40 mph	≤30 mph	35 mph	≥40 mph	≤30 mph	35 mph	≥40 mph	≤30 mph	35 mph	≥40 mph[b]
2 lanes			hatched			hatched			solid		hatched	solid
3 lanes			hatched		hatched	hatched	hatched	hatched	solid	hatched	solid	solid
++4 lanes, raised median[c]			hatched		hatched	solid	hatched	hatched	solid	solid	solid	solid
++4 lanes, no median		hatched	solid	hatched	hatched	solid	solid	solid	solid	solid	solid	solid

☐ **Candidate sites for marked crosswalks.** Marked crosswalks must be installed carefully and selectively. First, an engineering study is needed to determine whether the location is suitable for a marked crosswalk. For an engineering study, a site review may be sufficient at some locations, but a more in-depth study of pedestrian volume, vehicle speed, sight distance, vehicle mix, etc., may be needed at other sites. If the speed limit is less than or equal to 30 mph, use **Level 1** or **Level 2** devices. If the speed limit exceeds 30 mph, use **Level 2** devices. *Refer to Level 1 and Level 2 devices in the Special Treatments section*.

(hatched) **Probable candidate sites for marked crosswalks.** Pedestrian crash risk may increase if marked crosswalks are added without other pedestrian facility enhancements. Add **Level 3** or **Level 4** devices if feasible. *Refer to Level 3 and Level 4 devices in the Special Treatments section*.

(solid) **Marked crosswalks alone are insufficient, since pedestrian crash risk may increase if only marked crosswalks are provided.** Consider using **Level 5** devices if feasible. If not feasible, use multiple treatments from **Level 2, Level 3,** or **Level 4** devices. *Refer to Level 5 devices in the Special Treatments section*.

[a]These guidelines include intersection and mid-block locations with no traffic signal or stop sign on the approach to the crossing. They do not apply to school crossings. A two -way center turn lane is not considered a median. Crosswalks should not be installed at locations that could present an increased safety risk to pedestrians, such as where there is poor site distance, complex or confusing designs, substantial volumes of heavy trucks, or other dangers, without first providing adequate design features and/or traffic control devices. Adding crosswalks alone will not make a crossing safer or necessarily result in more drivers stopping for pedestrians. Whenever marked crosswalks are installed, it is important to consider other pedestrian facility enhancements, as needed, to improve the safety of the crossing (for example, raised median, traffic signal, roadway narrowing, enhanced overhead lighting, traffic calming measures, curb extensions). **These are general recommendations; an engineering study should be performed to determine where to install marked crosswalks.**

[b]Where the posted speed limit or 85th percentile speed exceeds 40 mph, marked crosswalks alone should not be used at uncontrolled intersections with an ADT greater than 15,000.

[c]The raised median or refuge island must be at least 4 feet (1.2 meters) wide and 6 feet (1.8 meters) long to adequately serve as a refuge area for pedestrians.

The installation of IRWLs is addressed in the MUTCD (*1*) and Texas MUTCD (*2*); however, these manuals do not provide practitioners with specific criteria for determining when and where IRWLs are needed or justified. As part of an ongoing TCRP/NCHRP project D-08/3-71, researchers are planning to develop one set of quantitative guidelines that provides advice on the use of a number of pedestrian crossing treatments including IRWLs. However, in the interim TxDOT needs guidance with respect to installation of IRWLs to ensure statewide uniformity. Based on the review of previous research, researchers recommended that TxDOT utilize the following criteria to determine if IRWLs are an applicable potential treatment:

- An engineering study should be conducted to determine if there is a pedestrian safety problem (*22*, *23*, *25*).
- The location must have a marked crosswalk with applicable warning signs (*1*, *2*).
- Alternative measures to mitigate the pedestrian safety problem should have been tried and proven unsuccessful or engineering judgment should have determined that other alternative measures are not feasible (*25*).
- The 85th percentile speed of vehicles approaching the crosswalk from either direction should not be more than 45 mph (*23*-*25*).
- The average daily traffic on the street being crossed should be between 5000 and 30,000 vpd (*6*, *24*, *25*) or vehicular volume through the crossing should exceed 200 vph in urban areas or 140 vph in rural areas during peak-hour pedestrian usage (*23*, *25*).
- The daily pedestrian crossing volume should be at least 100 ppd (*6*, *12*, *13*, *24*, *25*) or at least 40 pedestrians should regularly use the crossing during each of any two hours (not necessarily consecutive) during a 24-hour period (*23*, *25*).
- The existing stopping sight distance from both directions should not be less than the stopping sight distance criteria in the current version of the TxDOT *Roadway Design Manual* (*27*).

These guidelines do not address all situations. Thus, the final decision as to whether to install IRWLs at a location should be left to engineering judgment.

CHAPTER 5
FLUORESCENT ORANGE RRPMS COLOR RECOGNITION STUDY

RRPMs provide a significant amount of information for nighttime drivers, especially during inclement weather. Unfortunately, RRPMs are essentially designed for nighttime conditions only, as they are nearly impossible to see during daytime conditions. However, recent innovations in the traffic control device industry have resulted in the introduction of fluorescent properties into the design of RRPMs. The introduction of fluorescent coloring of RRPMs is potentially a revolution in terms of adding daytime delineation to the roadway. Another advantage of adding fluorescent coloring to RRPMs is the ability to create new colors of RRPMs that have not been previously developed or tested. For instance, fluorescent orange (FO) RRPMs can be made to match the color of fluorescent orange signing used in work zones.

Before fluorescent orange RRPMs can be used on a widespread basis, two aspects need to be resolved. The first is to determine whether drivers can correctly distinguish the color of the fluorescent orange RRPMs from traditional RRPM colors. The second aspect is to identify the most effective application(s) of fluorescent orange RRPMs. During this project, researchers conducted a color recognition study to address the first of these two issues.

BACKGROUND

There have been two previous research projects (*4*, *28*) related to the color recognition of fluorescent orange RRPMs. Both of these studies were performed by TTI and both were funded by industry. The goal of both projects was to determine the daytime and nighttime color recognition of RRPMs. The treatments included isolated RRPMs, RRPMs in a work zone environment, and grouped RRPMs.

The first project found that during the day, the subjects were able to identify the colors of the fluorescent orange RRPMs as well and usually better than the standard longitudinal RRPM colors (white, yellow, and red). However, at night the subjects had a more difficult time correctly identifying the fluorescent orange RRPMs when compared to the responses for the standard longitudinal RRPM colors. In the simulated work zone environment, at night approximately half of the subjects could not distinguish between red and fluorescent orange RRPMs. In contrast, at least 80 percent of the subjects were able to identify the difference between the red and fluorescent orange RRPMs at night when they were in isolated conditions (i.e., without other traffic control devices).

Because these findings were not entirely favorable in terms of color recognition and maintaining a similar color appearance during day and night conditions (a requirement of the MUTCD [*1*]), a follow-up research project was completed with two additional shades of the fluorescent orange RRPMs. During the day, the participants were able to identify the color of both shades of the fluorescent orange RRPMs as well and usually better than the standard red RRPMs. At night in the simulated work zone environment, 90 percent of the participants correctly identified the color of the fluorescent orange shade 1 RRPMs. In contrast, only 50 percent of the participants correctly identified the color of the fluorescent orange shade 2 RRPMs in a work zone. As a result of these findings, researchers recommended that additional research was needed in order to investigate motorist understanding of the fluorescent orange shade 1 RRPMs, as well as to identify the most effective application(s) of the fluorescent orange shade 1 RRPMs.

Project 0-4728 (documented herein) was initiated with the assumption that the color issues regarding fluorescent orange RRPMs were resolved (i.e., drivers viewed fluorescent orange RRPMs as orange under both daytime and nighttime conditions, and drivers do not confuse fluorescent orange RRPMs with red RRPMs). However, during a demonstration of the fluorescent orange RRPMs, some members of the TxDOT project panel thought that the nighttime color of the fluorescent orange RRPMs looked red. Due to TxDOT's continued concern that the fluorescent orange RRPMs would be mistaken for red RRPMs (used to denote roadways that shall not be entered or used), researchers conducted a closed-course study to evaluate the daytime and nighttime color recognition of the fluorescent orange RRPMs in a simulated work zone.

FLUORESCENT ORANGE RRPM MANUFACTURERS

Three manufacturers currently make fluorescent orange RRPMs: Avery Dennison, Filtrona Extrusion (Davidson Traffic Control Products), and Rayolite®. Researchers contacted all three manufacturers and received samples of their fluorescent orange RRPMs (Figure 6). After reviewing the samples and discussions with the manufacturers and TxDOT, researchers decided to only include the Avery Dennison and Filtrona Extrusion fluorescent orange RRPMs in the color recognition study. Henceforth, the Avery Dennison and Filtrona Extrusion fluorescent orange RRPMs are referred to as Type 1 and Type 2 fluorescent orange RRPMs, respectively.

1a. Avery Dennison Product.

1b. Filtrona Extrusion Product.

1c. Rayolite Product.

Figure 6. Fluorescent Orange RRPMs.

The Rayolite fluorescent orange RRPMs were not included in the color recognition study because only the base of the marker was fluorescent orange. At the time of this project, Rayolite did not produce a fluorescent orange retroreflective lens. Thus, the marker was comprised of two colors: a fluorescent orange base and white lens.

The Avery Dennison fluorescent orange RRPMs are approximately 4 inches long and 3 inches wide. They have a fluorescent orange body and a fluorescent orange retroreflective lens on each side. The Filtrona Extrusion fluorescent orange RRPMs are approximately 4 inches long and 4 inches wide. They have a fluorescent orange body and a strip of fluorescent orange prismatic retroreflective sheeting on each side.

Currently, the American Society for Testing and Materials (ASTM) Standard Specification D4280-02 *(29)* specifies the color regions shown in Figure 7 for white, yellow, red, green, and blue extended life type, nonplowable, RRPMs. In order to determine the nighttime color of the Avery Dennison and Filtrona Extrusion fluorescent orange RRPMs, researchers sent two samples of each fluorescent orange marker to the National Institute of Standards and Technology (NIST). NIST measured the nighttime color of the lens of these markers at an entrance angle of 88.76 degrees and an observation angle of 1.05 degrees using the Illuminant A standard source and the International Commission on Illumination (CIE) 2 degree standard observer. Based on these measurements, the average xy chromaticity coordinates were computed for each fluorescent orange marker and plotted on Figure 7. The nighttime color of the Type 1 fluorescent orange RRPMs tends more toward the yellow color region, while the color of the Type 2 fluorescent orange RRPMs tends more toward the red color region.

COLOR RECOGNITION STUDY

A color recognition study was conducted to evaluate the daytime and nighttime color recognition of standard color RRPMs (yellow, white, and red) and experimental fluorescent orange RRPMs in a simulated work zone environment. Researchers also determined whether the fluorescent orange RRPMs were mistaken for red RRPMs (used to denote roadways that shall not be entered or used).

Experimental Design

Study Location

The closed-course studies were conducted at the Texas A&M University Riverside Campus in Bryan, Texas. This campus is a 2000-acre complex of research and training facilities located 12 miles northwest of the Texas A&M University main campus. The Riverside Campus is a former military aircraft base comprised of four major runways and associated taxiways. These concrete runways and taxiways are ideally suited for experimental research and testing of retroreflective road markings.

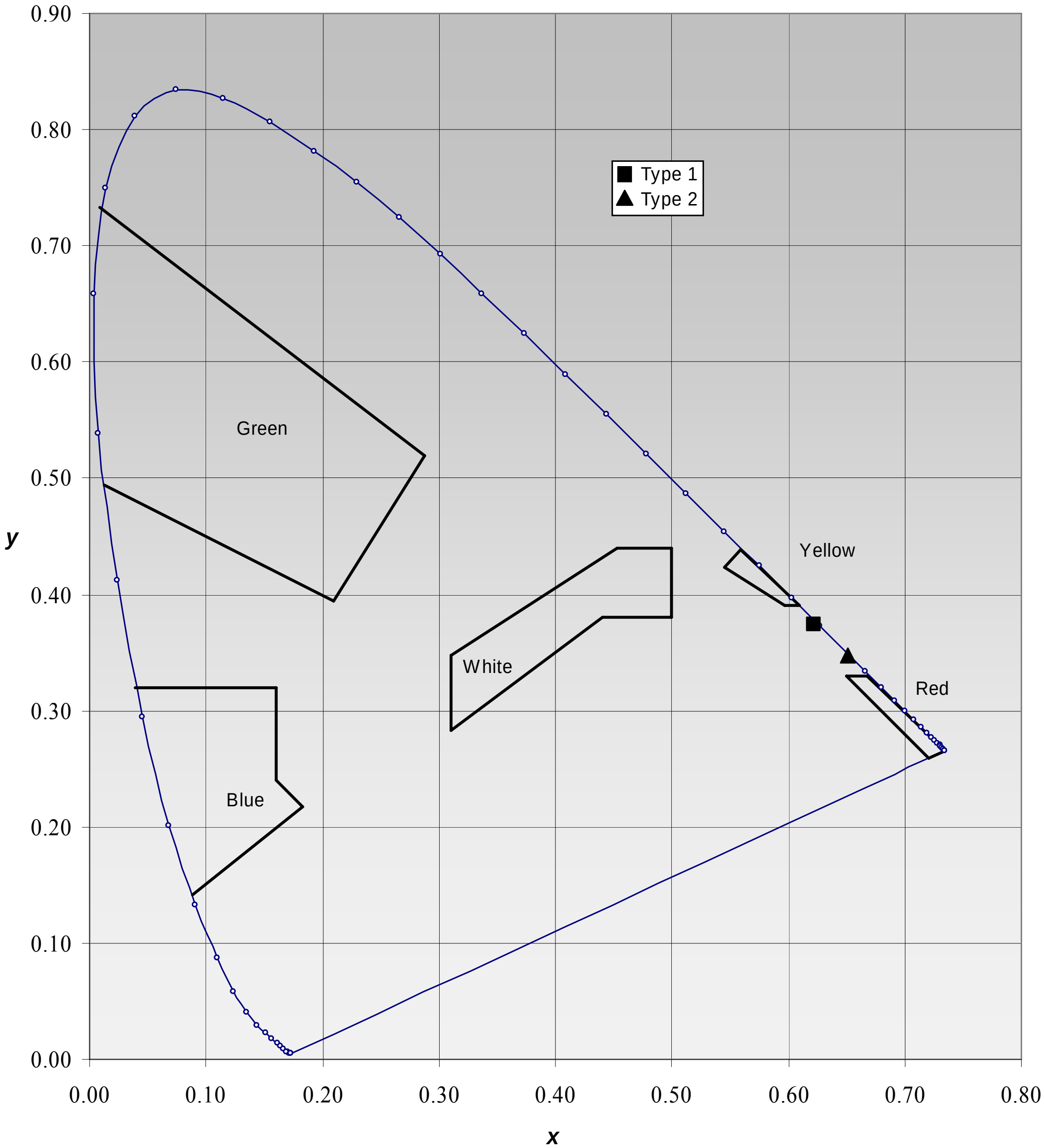


Figure 7. CIE 1931 Chromaticity Diagram with ASTM D4280 Color Regions (*29*) and Fluorescent Orange RRPMs Color Coordinates.

Subject Recruitment and Screening

A total of 12 subjects were recruited from the Bryan-College Station area to participate under daytime and nighttime conditions. The subjects were required to have a current valid driver's license without nighttime or special equipment restrictions and not be colorblind.

Table 17 shows the distribution of subjects by age, gender, and education level. The average age and visual acuity of the 18 to 35 year old age group were 21 and 20/20, respectively. The average age and visual acuity of the 55 plus age group were 65 and 20/27, respectively.

Table 17. Distribution of Subjects by Age, Gender, and Education Level.

Age Category	Education Level				
	High School Diploma or Less		Some College/College Degree		Total
	Males	Females	Males	Females	
18-35	2	1	1	2	6
55+	1	2	2	1	6
Total	3	3	3	3	12

Treatments

Table 18 lists a description of the treatments, while Figure 8 shows the treatment layouts. Figure 9 through Figure 14 contain examples of the treatments. All of the fluorescent orange RRPMs were new and unweathered. The simulated work zone included yellow and white pavement markings, standard yellow and standard white RRPMs, a lane closure taper and tangent using barrels with Type III sheeting, and a Type VI roll-up fluorescent orange work zone sign placed on the approach. The work zone layout was designed for 30 mph and had the following characteristics:

- 180-ft taper length,
- seven barrels in the taper,
- 30-ft barrel spacing in the taper,
- 300-ft tangent length,
- five barrels in the tangent,
- 60-ft barrel spacing in the tangent,
- 12-ft lane width,
- flat grades, and
- straight alignment.

Table 18. Description of Treatments.

Treatment	RRPM Color					Description
	Yellow	White	Fluorescent Orange Type 1	Fluorescent Orange Type 2	Red	
1	✓	✓				Simulated work zone with yellow RRPMs adjacent to the left edge line and white RRPMs adjacent to the right edge line. Both colors of RRPMs spaced at 20-ft intervals.
2	✓	✓	✓			Treatment 1 replacing every other white RRPM with a Type 1 fluorescent orange RRPM. RRPMs are still spaced at 20-ft intervals, with each color of RRPM spaced at 40-ft intervals.
3	✓	✓			✓	Treatment 1 replacing every other white RRPM with a red RRPM. RRPMs are still spaced at 20-ft intervals, with each color of RRPM spaced at 40-ft intervals.
4	✓	✓	✓		✓	Treatment 1 replacing every other white RRPM with either a Type 1 fluorescent orange or red RRPM. RRPMs are still spaced at 20-ft intervals, with the white RRPMs spaced at 20-ft intervals and the fluorescent orange and red RRPMs spaced at 80-ft intervals.
5	✓	✓		✓		Treatment 1 replacing every other white RRPM with a Type 2 fluorescent orange RRPM. RRPMs are still spaced at 20-ft intervals, with each color of RRPM spaced at 40-ft intervals.
6	✓	✓		✓	✓	Treatment 1 replacing every other white RRPM with either a Type 2 fluorescent orange or red RRPM. RRPMs are still spaced at 20-ft intervals, with the white RRPMs spaced at 20-ft intervals and the fluorescent orange and red RRPMs spaced at 80-ft intervals.

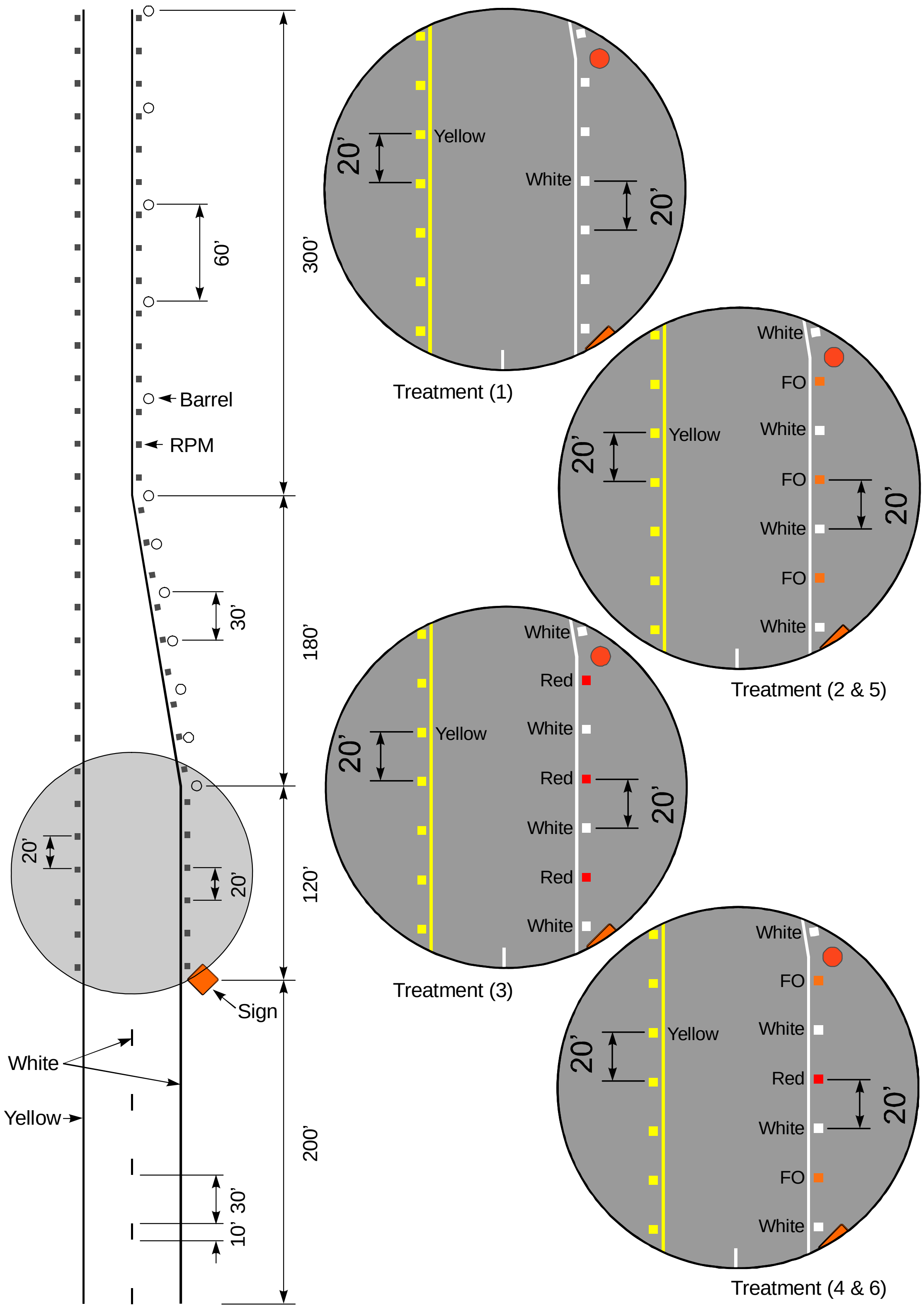


Figure 8. Layout of Treatments.

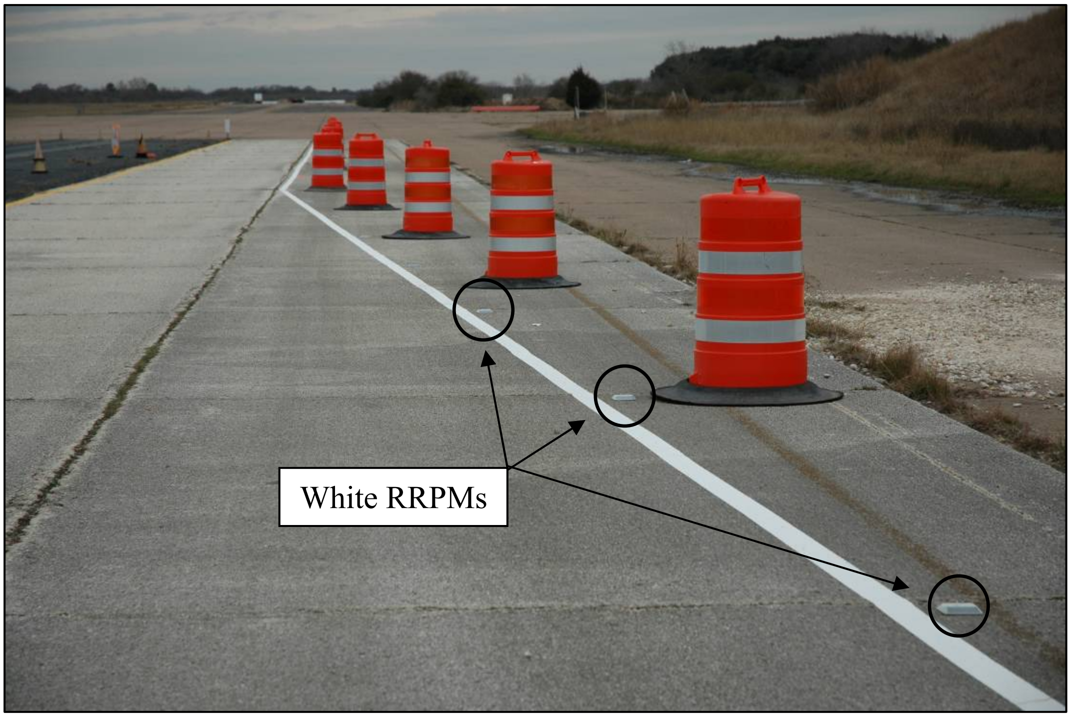


Figure 9. Treatment 1 – White RRPMs Only Adjacent to Right Edge Line.

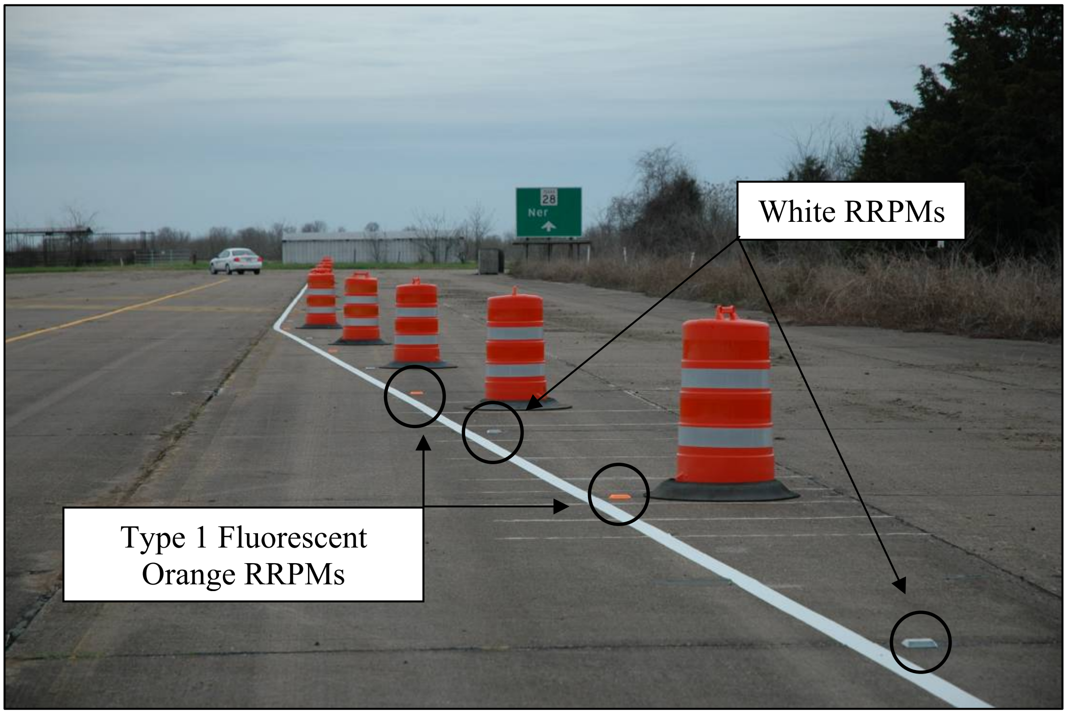


Figure 10. Treatment 2 – White RRPMs and Type 1 Fluorescent Orange RRPMs Adjacent to Right Edge Line.

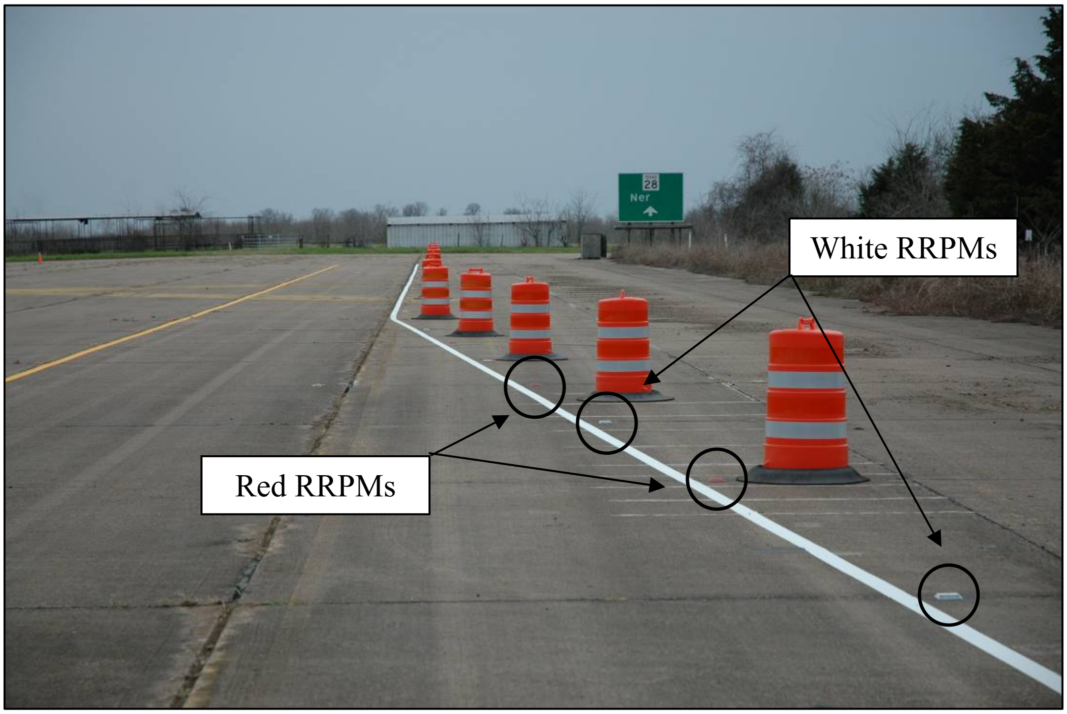


Figure 11. Treatment 3 – White RRPMs and Red RRPMs Adjacent to Right Edge Line.

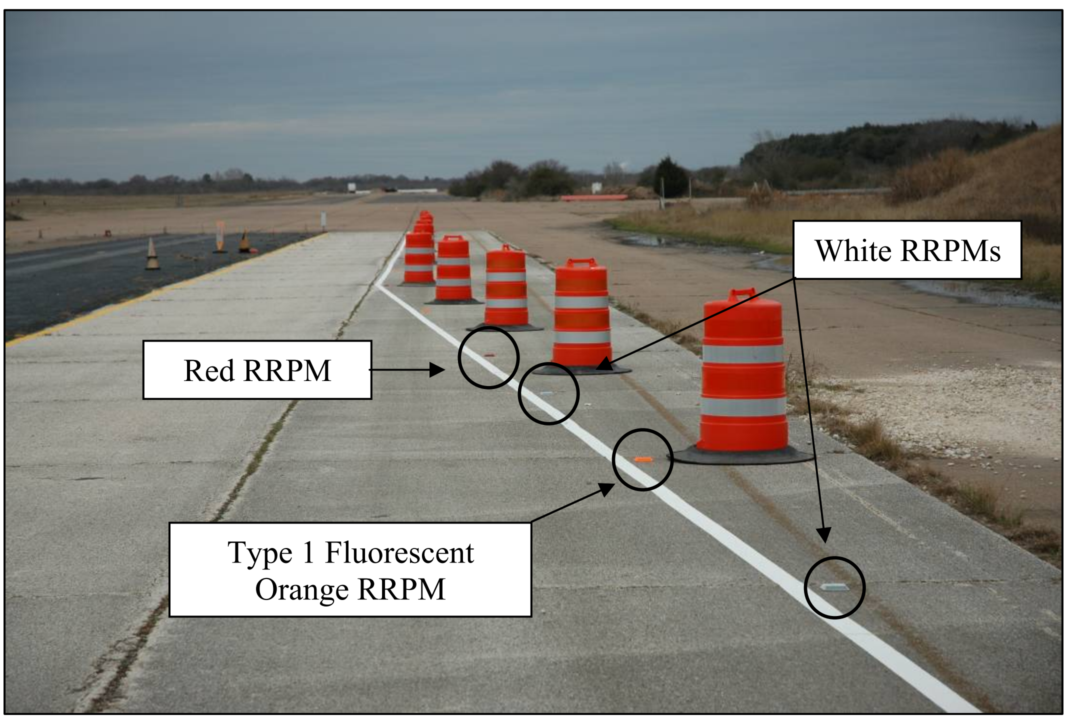


Figure 12. Treatment 4 – White RRPMs, Type 1 Fluorescent Orange, and Red RRPMs Adjacent to Right Edge Line.

Figure 13. Treatment 5 – White RRPMs and Type 2 Fluorescent Orange RRPMs Adjacent to Right Edge Line.

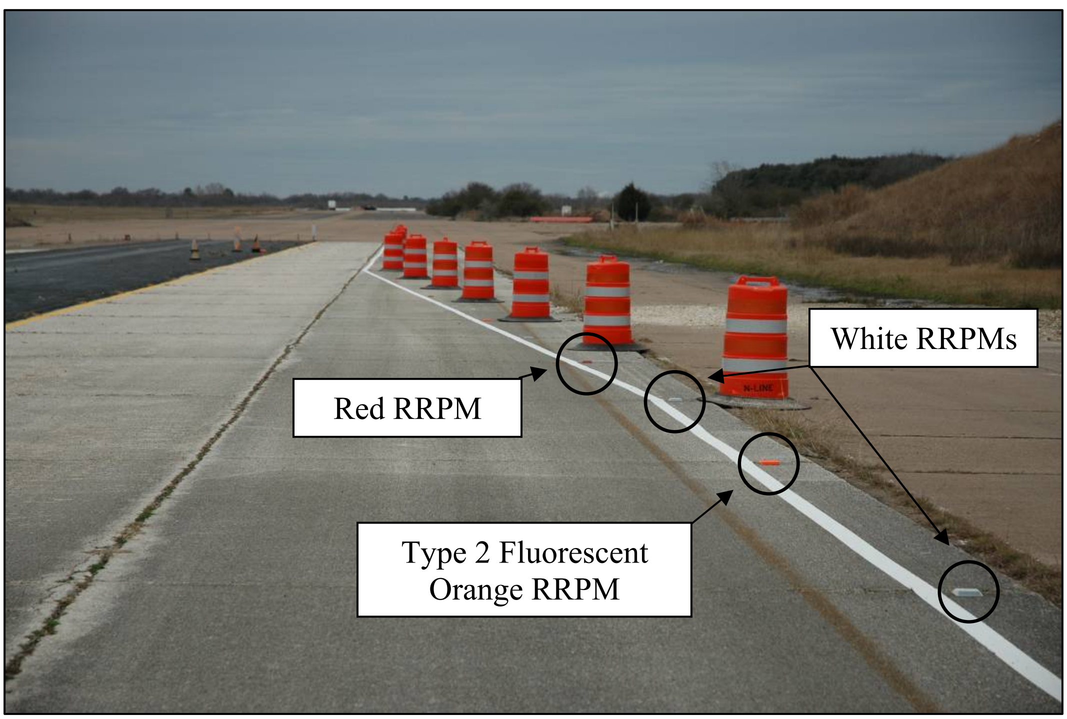


Figure 14. Treatment 6 – White RRPMs, Type 2 Fluorescent Orange RRPMs, and Red RRPMs Adjacent to Right Edge Line.

Study Protocol

Subject check-in and briefing took place at the TTI facility at the Texas A&M Riverside Campus in building 7091. Each subject participated in the daytime and nighttime sessions. Upon arrival to the study location, subjects were provided an explanation of the study and their driving task, and were asked to read and sign the informed consent document. They were given standard static visual acuity (Snellen), contrast sensitivity (Vistech), and colorblind screening tests prior to initiating the driving portion of the study. Each subject was compensated $60.00 ($30.00 for the daytime session and $30.00 for the nighttime session).

The study was conducted in a state-owned passenger vehicle with tungsten-halogen headlamps properly aimed and meeting FMVSS108 specifications. The subject drove the study vehicle on the closed-course at speeds not exceeding 30 mph. The study administrator accompanied the subject at all times, provided verbal directions to the subject, and recorded the subject's responses.

Originally, researchers planned to have the subjects evaluate the color of the RRPMs in each treatment at six stations beginning 2500 ft upstream of the beginning of the work zone (i.e., at the sign). However, based on the results of the pilot study, researchers determined that the subjects could not see any of the RRPMs at the 2500-ft, 2000-ft, and 1500-ft stations during the day and at night. Thus, the subjects began the course 1000 ft upstream of the beginning of the work zone and evaluated the color of the RRPMs at three stations (1000 ft, 500 ft, and at the sign). While parked at each station, the subjects stated the color and location of all of the RRPMs they could see. The subjects then drove to the next station, stopped the vehicle, and again stated the color and location of all of the RRPMs they could see. The subject repeated this process until they had evaluated the color of the RRPMs at all three stations. The subjects were then asked a series of questions regarding the treatment they just viewed. The subjects repeated the same process for each of the remaining treatments.

Each subject was shown all six treatments during the day and at night. The first treatment for each subject was always treatment 1. The remaining treatments were randomized in an effort to counter any learning effects. In addition, half of the subjects participated in the daytime study first and the nighttime study second. The remaining half completed the nighttime study first and the daytime study second.

Data Analysis

For each treatment, the color response data were divided into two categories: initial color response and final color response. The initial color response data included the subjects' responses at either 1000 ft or 500 ft. The final color response data included the subjects' responses at the beginning of the work zone. The percent of participants who correctly and incorrectly assessed the color of the RRPMs was calculated. In addition, researchers reviewed the subjects' responses to the questions to determine their perception of the meaning of the RRPM colors and if any of the RRPM colors caused confusion.

Daytime Results

Fluorescent Orange RRPMs

Even though both types of fluorescent orange RRPMs have fluorescent orange bodies, the Type 2 and Type 1 fluorescent orange markers were only initially seen at either the 1000-ft or 500-ft stations in one out of 24 trials and six out of 24 trials, respectively. Thus, the daytime initial color response data were not analyzed.

The final color responses for the fluorescent orange RRPMs are provided in Table 19. For the treatments with fluorescent orange and white RRPMs (treatments 2 and 5), 100 percent of the subjects thought the fluorescent orange markers were orange. When the Type 1 fluorescent orange RRPMs were mixed with red RRPMs (treatment 4), 84 percent of the subjects could distinguish between the two colors and only one subject (8 percent) thought fluorescent orange markers were yellow. In contrast, only 42 percent of the subjects could differentiate between the Type 2 fluorescent orange RRPMs and the red RRPMs (treatment 6). Instead, the majority of the subjects (58 percent) only saw orange markers. However, it is unknown whether these subjects misinterpreted the red RRPMs to be orange or just did not see the red RRPMs. Neither of the fluorescent orange RRPMs was misinterpreted to be red during the day.

Standard RRPM Colors

Since the standard yellow, white, and red RRPMs are designed to be used at night to delineate the travel path, it is not surprising that in a majority of the trials the subjects did not see these RRPMs at the 1000-ft and 500-ft stations during the day. Thus, again the daytime initial color response data were not analyzed.

Table 19. Final Daytime Color Responses for Fluorescent Orange RRPMs.

Treatment (RRPM Type)	Percent of Subjects That Chose Each Color				
	Orange	Red	Orange & Red	Red & Yellow	Did Not See
2 (Type 1)	100%	0%	0%	0%	0%
4 (Type 1)	8%	0%	84%	8%	0%
5 (Type 2)	100%	0%	0%	0%	0%
6 (Type 2)	58%	0%	42%	0%	0%

For all of the treatments, the color of the white RRPMs was correctly identified by 100 percent of the subjects. As seen in Table 20, for each treatment 75 to 92 percent of the subjects correctly interpreted the color of the yellow RRPMs (located adjacent the left edge line in all treatments). Collectively, the final color response for the yellow markers was correct in 62 out of 72 trials (86 percent). The yellow RRPMs were mistaken to be orange by two subjects and white by two subjects.

As discussed previously, the subjects were able to distinguish the red RRPMs from the Type 1 fluorescent orange RRPMs better than from the Type 2 fluorescent orange RRPMs (84 percent versus 42 percent). However, it is unknown whether the remaining subjects misinterpreted the red RRPMs to be orange or just did not see the red RRPMs. With respect to treatment 3 (white and red RRPMs adjacent the right edge line), 83 percent of the subjects correctly interpreted the color of the red RRPMs. The other 17 percent thought the red RRPMs were orange.

Table 20. Final Daytime Color Responses for Standard Yellow RRPMs.

Treatment	Percent of Subjects That Chose Each Color				
	Yellow	White	Orange	Yellow & Orange	Did Not See
1	84%	0%	8%	8%	0%
2	75%	17%	8%	0%	0%
3	92%	0%	8%	0%	0%
4	92%	0%	8%	0%	0%
5	84%	8%	8%	0%	0%
6	92%	0%	8%	0%	0%

Nighttime Results

Fluorescent Orange RRPMs

As expected, at night the initial color response rate improved. However, in nine out of the 24 Type 2 fluorescent orange RRPM trials (38 percent), subjects still could not see the fluorescent orange markers at either the 1000-ft or 500-ft stations. Table 21 and Table 22 contain the initial and final color responses for the fluorescent orange RRPMs at night, respectively.

Table 21. Initial Nighttime Color Responses for Fluorescent Orange RRPMs.

Treatment (RRPM Type)	Percent of Subjects That Chose Each Color						
	Orange	Red	Yellow	Orange & Red	Orange & Yellow	Red & Yellow	Did Not See
2 (Type 1)	50%	17%	17%	8%	8%	0%	0%
4 (Type 1)	67%	17%	8%	8%	0%	0%	0%
5 (Type 2)	33%	17%	0%	8%	0%	0%	42%
6 (Type 2)	25%	17%	17%	8%	0%	0%	33%

Table 22. Final Nighttime Color Responses for Fluorescent Orange RRPMs.

Treatment (RRPM Type)	Percent of Subjects That Chose Each Color						
	Orange	Red	Yellow	Orange & Red	Orange & Yellow	Red & Yellow	Did Not See
2 (Type 1)	84%	8%	8%	0%	0%	0%	0%
4 (Type 1)	42%	8%	0%	42%	8%	0%	0%
5 (Type 2)	75%	25%	0%	0%	0%	0%	0%
6 (Type 2)	33%	42%	0%	17%	0%	8%	0%

Initially, the Type 1 and Type 2 fluorescent orange RRPMs scored 50 percent and 33 percent correct, respectively, when shown in conjunction with white RRPMs (treatments 2 and 5). Both fluorescent orange markers were initially misinterpreted to be red by 25 percent of the subjects. In addition, initially the Type 1 fluorescent orange RRPMs were mistaken to be yellow by 25 percent of the subjects. The final correct color responses for the Type 1 and Type 2 fluorescent orange RRPMs improved to 84 percent and 75 percent, respectively (a 68 percent and 127 percent increase in correct color response, respectively). Even though the final correct color responses improved for the Type 2 fluorescent orange RRPMs (mainly because more subjects could see the markers), 25 percent of the subjects still thought the Type 2 fluorescent orange RRPMs looked red. For the Type 1 fluorescent orange RRPMs, the final incorrect color responses were reduced to 16 percent (one red response and one yellow response).

When both types of fluorescent orange markers were viewed with a mix of white and red RRPMs (treatments 4 and 6), initially only 8 percent of the subjects could decipher between the fluorescent orange RRPMs and the red RRPMs. The final correct responses (being able to differentiate between the fluorescent orange and red RRPMs) improved only to 42 percent and 17 percent for the Type 1 and Type 2 fluorescent orange RRPMs, respectively. The Type 1 fluorescent orange markers were only misinterpreted to be red by 8 percent of the subjects. In contrast, the Type 2 fluorescent orange markers were seen as red by 42 percent of the subjects and as yellow by 8 percent of the subjects.

Based on the final nighttime color responses, overall the Type 1 fluorescent orange RRPMs were incorrectly identified as red by only one subject in two out of 24 trials (8 percent), while the Type 2 fluorescent orange RRPMs were mistaken for red RRPMs by six subjects in eight out of 24 trials (33 percent). The tendency for the Type 2 fluorescent orange RRPMs to be seen as red more often than Type 1 fluorescent orange RRPMs is not surprising since the color of the Type 2 markers tended more toward the red color region in Figure 7. Both fluorescent orange markers were misinterpreted to be yellow in one out of 24 trials (4 percent).

Standard RRPM Colors

As expected, the subjects were able to see the standard color RRPMs (yellow, white, and red) at the 1000-ft and 500-ft stations at night. Thus, both the initial and final color responses for the yellow, white, and red RRPMs are discussed.

At all stations (1000 ft, 500 ft, and at the sign) the color of the white RRPMs was correctly identified by 100 percent of the subjects. Table 23 and Table 24 contain the initial and final color responses for the standard yellow RRPMs, respectively. Interestingly, for treatment 1 (yellow RRPMs adjacent to the left edge line and white RRPMs adjacent to the right edge line) the yellow RRPMs were initially mistaken to be orange by 42 percent of the subjects. As the subjects approached the work zone, the percent of subjects who thought the yellow RRPMs were orange was reduced to 25 percent. Still, only 75 percent of the subjects thought the yellow RRPMs looked yellow at the beginning of the work zone. The final correct responses improved to 92 percent for the treatments that included either fluorescent orange, red, or both fluorescent orange and red RRPMs (treatments 2-6).

Table 23. Initial Nighttime Color Responses for Standard Yellow RRPMs.

Treatment	Percent of Subjects That Chose Each Color					
	Yellow	White	Orange	Yellow & Red	White & Orange	Did Not See
1	58%		42%			
2	83%		17%			
3	76%		8%	8%	8%	
4	75%	8%	17%			
5	92%		8%			
6	75%	8%	17%			

Table 24. Final Nighttime Color Responses for Standard Yellow RRPMs.

Treatment	Percent of Subjects That Chose Each Color					
	Yellow	White	Orange	Yellow & Red	White & Orange	Did Not See
1	75%		25%			
2	92%		8%			
3	92%		8%			
4	92%		8%			
5	92%		8%			
6	92%		8%			

As discussed previously, less than half of the subjects could distinguish between the red RRPMs and the fluorescent orange RRPMs. The red RRPMs were mistaken to be orange by 42 percent of the subjects when shown with the Type 1 fluorescent orange RRPMs (treatment 4) and 33 percent of the subjects when shown with the Type 2 fluorescent orange RRPMs (treatment 6). With respect to treatment 3 (white and red RRPMs adjacent to the right edge line), initially half of the subjects thought the red RRPMs were orange. Even though the correct color response improved from 17 percent to 58 percent, 42 percent of the subjects still interpreted the red RRPMs as orange.

Comparison with Previous Color Recognition Studies

As previously discussed, there have been two previous research projects (*12*, *28*) that evaluated the color recognition of fluorescent orange RRPMs in order to identify the specific 'shade' of fluorescent orange that decreases the probability that daytime and nighttime drivers would confuse it with red. One shade of fluorescent orange RRPMs was evaluated in the first study and two shades of fluorescent orange RRPMs were evaluated in the second study. Thus, including the study documented herein (two shades) the color recognition of five shades of fluorescent orange RRPMs has been evaluated.

In order to see how these five shades of fluorescent orange RRPMs differ, researchers planned to have NIST measure the color of the three shades included in the two previous studies. However, researchers were unable to obtain a sample of the fluorescent orange RRPMs used in the first study (one shade), so NIST only measured the color of the two shades of fluorescent orange RRPMs from the second study. Figure 15 is a plot of the ASTM D4280 color regions and the average xy chromaticity coordinates of four shades of fluorescent orange RRPMs. As shown in this figure, the Type 1 fluorescent orange markers tend more toward the yellow color region, while the other three shades of fluorescent orange markers tend more toward the red color region.

Table 25 contains a summary of the results from all three color recognition studies (treatments where fluorescent orange RRPMs were seen in a simulated work zone). In all three studies, the final daytime correct color response was 100 percent. In contrast, the final nighttime correct color responses showed some variability between shades.

In the first study, researchers found that at night, only 60 percent of the subjects correctly identified the color of the fluorescent orange RRPMs. The other 40 percent all misinterpreted the fluorescent orange RRPMs to be red.

In the second study, researchers determined that at night 90 percent of the subjects (all but one) correctly identified the color of the shade 1 fluorescent orange RRPMs. However, at night only 50 percent of the subjects correctly identified the color of the shade 2 fluorescent orange RRPMs. All incorrect responses (10 percent for shade 1 and 50 percent for shade 2) were red. These findings are not surprising since according to the color measurements the shade 2 fluorescent orange RRPMs were located closer to the red color region than the shade 1 fluorescent orange RRPMs.

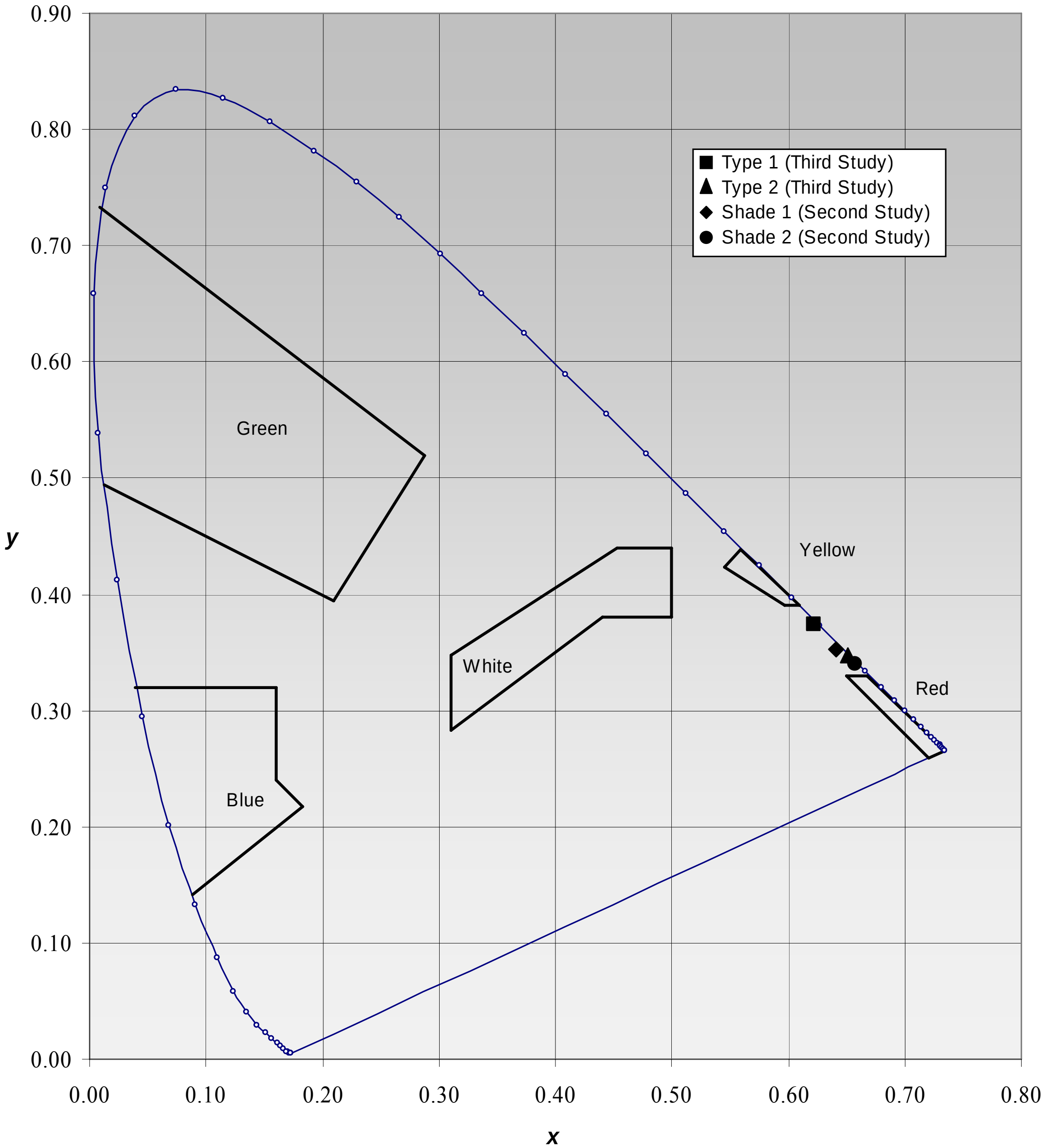


Figure 15. Chromaticity of Four Shades of Fluorescent Orange RRPMs.

Table 25. Comparison of Fluorescent Orange RRPM Color Recognition Study Results [a].

Fluorescent Orange RRPM Shade	Final Percent Correct	
	Daytime	Nighttime
First Study *(12)*	100%	60%
Second Study Shade 1 *(28)*	100%	90%
Second Study Shade 2 *(28)*	100%	50%
Third Study Type 1 [b]	100%	84%
Third Study Type 2 [c]	100%	75%

[a] Daytime and nighttime percent correct responses when fluorescent orange RRPMs were seen in a simulated work zone. In the first two studies, the yellow and white pavement markings, as well as the yellow RRPMs and white RRPMs, were not used.
[b] Study documented herein. The percentage is for treatment 2.
[c] Study documented herein. The percentage is for treatment 5.

In the third study (documented herein), the final correct color responses for the Type 1 and Type 2 fluorescent orange RRPMs were 84 percent and 75 percent, respectively. One subject (8 percent) identified the color of the Type 1 fluorescent orange RRPMs as yellow, which is not surprising since the measured color of these markers tends more toward the yellow color region. In addition, only one subject (8 percent) thought the color of the Type 1 fluorescent orange RRPMs was red. In contrast, 25 percent of the subjects thought the Type 2 fluorescent orange RRPMs looked red. This finding is also not surprising since the color of the Type 2 fluorescent orange RRPMs is closer to the red region than the Type 1 fluorescent orange RRPMs.

Meaning of RRPM Colors and Patterns

At the end of each study, the subjects were shown a white, yellow, red, and fluorescent orange RRPM. For each color of marker, the subjects were asked, "Where do you think you would see these at?" In general, the subjects stated that the standard yellow RRPMs were located in the middle of the road to separate two-way traffic and to indicate no passing zones. Some of the subjects indicated that the yellow RRPMs are used to indicate caution and might be found in work zones.

Typically, subjects thought the white RRPMs marked lane boundaries. More specifically, three subjects thought white RRPMs are used to separate lanes on two-lane roadways, and seven subjects thought that white RRPMs are located on the right edge of the roadway. However, it is unknown whether the later of these two uses was influenced by the location of the white RRPMs in this study.

Only three subjects stated that red RRPMs are used to indicate a wrong-way movement. Five subjects thought that red RRPMs are placed in locations where motorists need to stop or slow down. Other subjects commented that the red RRPMs are used in emergency situations, such as for accidents. A few subjects thought the red RRPMs would be utilized to keep motorists out of work zones. Again, this was most likely influenced by the use of the red RRPMs in the work zones for this study.

All of the subjects associated the fluorescent orange RRPMs with work zones. Specific locations within the work zone where the fluorescent orange RRPMs would be used included narrow lanes, separating temporary lanes, around flaggers, at curves, and at lane closures.

With respect to treatment 1 (yellow RRPMs adjacent to the left edge line and white RRPMs adjacent to the right edge line), in only two out of the 24 trials (8 percent) did subjects comment that the RRPMs were confusing. One subject felt both RRPM colors were confusing, while the second subject only thought the white RRPMs were confusing since you don't see them as often. Both of these comments were observed under daytime conditions.

During the day when the fluorescent orange RRPMs were added to the right edge line (treatments 2 and 5), subjects in 12 out of the 24 trials (50 percent) thought the fluorescent orange RRPMs were helpful in letting them know there was a lane closure since the fluorescent orange RRPMs were more visible than the white RRPMs. At night, subjects in only 8 out of the 24 trials (33 percent) thought the fluorescent orange RRPMs were helpful since they catch your attention and mean caution. Overall the fluorescent orange RRPMs were thought to be helpful in notifying the subjects that there was a lane closure ahead in only 20 out of 48 trials (42 percent). Only one subject felt the fluorescent orange RRPMs were confusing.

SUMMARY AND CONCLUSIONS

During the day, in a simulated work zone environment with standard yellow, standard white, and fluorescent orange RRPMs, 100 percent of the subjects were able to correctly identify the color of both types of fluorescent orange RRPMs. Thus, during the day none of the subjects misinterpreted the color of either of the fluorescent orange RRPMs to be red.

At night, the color of the Type 1 and Type 2 fluorescent orange RRPMs was identified correctly by 84 percent and 75 percent of the subjects, respectively, when shown in a simulated work zone environment with standard yellow and standard white RRPMs. At night, 25 percent of the subjects thought the Type 2 fluorescent orange RRPMs looked red compared to 8 percent of the subjects who thought the Type 1 fluorescent orange RRPMs were red.

Under all conditions, the Type 1 fluorescent orange RRPMs were incorrectly identified as red by only one subject (8 percent). In contrast, the Type 2 fluorescent orange RRPMs were mistaken for red RRPMs by six subjects (50 percent).

All of the subjects expected the fluorescent orange RRPMs to be used in work zones. Subjects identified the following specific locations within the work zone where the fluorescent orange RRPMs would most likely be used: at narrow lanes, separating temporary lanes, around flaggers, at curves, and at lane closures. Overall, during the day and at night approximately 50 percent of the subjects thought the fluorescent orange RRPMs were helpful in notifying them that there was a lane closure ahead.

Under all conditions (day and night), the color of the standard white RRPMs was correctly identified by 100 percent of the subjects. This was not the case for the standard yellow and standard red RRPMs. Only 75 to 92 percent of the subjects (varied among the treatments) correctly interpreted the color of the yellow RRPMs under both daytime and nighttime conditions. The majority of the incorrect responses were orange. With respect to the red RRPMs, during the day 83 percent of the subjects correctly interpreted their color. However, at night only 58 percent of the subjects correctly identified the color of the red RRPMs. All incorrect responses (17 percent during the day and 42 percent at night) were orange.

Based on the results of the color recognition study, researchers made the following conclusions:

- During the day in a simulated work zone environment with typical yellow and white pavement markings, both types of fluorescent orange RRPMs looked orange and were not confused with red RRPMs.
- At night in a simulated work zone environment with typical yellow and white pavement markings, the color of the Type 2 fluorescent orange RRPMs was misinterpreted as red more often than the color of the Type 1 fluorescent orange RRPMs.

- The standard white RRPMs appeared white under daytime and nighttime conditions.
- During the day and especially at night, the standard yellow and standard red RRPMs were commonly mistaken to be orange.
- Additional research is needed to identify the most effective application(s) of fluorescent orange RRPMs.

CHAPTER 6
EVALUATION OF "REMOVABLE" PAVEMENT MARKING PAINT

Typically, water-borne paint, thermoplastic, or temporary tape is used to delineate travel lanes during temporary situations such as work zones. However, some eradication methods damage the roadway surface leaving "ghost" markings, which can potentially confuse drivers. Also, sometimes temporary tape does not stay affixed to the pavement or chips. Recently, TxDOT became aware of a "removable" paint system that is applied like typical water-borne paint but uses a patented liquid remover to eradicate the marking. Researchers were charged with evaluating this new product by assessing the ease of application, durability, and ease of removal of the product.

DESCRIPTION OF "REMOVABLE" PAINT

Based on information obtained from the manufacturer (*30*), the "removable" paint system can be used on asphalt and concrete and comes in a variety of colors. Some of the paint products are water based and some are alcohol based. The "removable" paint is applied with current application technology and if needed, retroreflective beads can be used. The paint and remover are environmentally friendly as they exceed all volatile organic compound (VOC) recommendations and contain no toluene, lead, xylene, or naphtha solvents. Traditional paint equipment should be cleaned with lacquer thinner or methyl ethyl ketone (MEK).

DURABILITY EVALUATIONS

In June of 2004, TTI researchers applied approximately 2000 ft of the "removable" paint on the closed course at the Texas A&M University Riverside Campus in Bryan, Texas, with a self-propelled pavement marking applicator. This application included yellow and white paint on concrete and asphalt. Type II beads were used.

Once a month, for the next five months (thru November 2004), researchers measured the retroreflectivity and chromaticity of the paint. The retroreflectivity measurements were taken with a MX-30 handheld retroreflectometer with an observation angle of 1.05 degrees and an entrance angle of 88.76 degrees. The chromaticity measurements were taken with a BYK Gardner Colorimeter (D65 illumination and 10 degree observation angle). Researchers conducted this initial evaluation to assess the durability of the "removable" paint system under existing weather conditions since the markings experienced very little traffic exposure at this site.

As seen in Figure 16, the retroreflectivity of the yellow "removable" paint remained relatively constant over the five month period (averaging 200 mcd/m^2/lux on concrete and 180 mcd/m^2/lux on asphalt). In contrast, the retroreflectivity of the white "removable" paint decreased steadily over the five month period (97 to 35 mcd/m^2/lux on concrete and 168 to 78 mcd/m^2/lux on asphalt). This degradation in the retroreflectivity of the white "removable" paint was discussed with the manufacturer and a second version of the white "removable" paint was provided to TTI. As shown in Figure 16, the second white "removable" paint had a higher initial retroreflectivity value (325 mcd/m^2/lux) than the first white "removable" paint and maintained its retroreflectivity for approximately three months (averaging 337 mcd/m^2/lux).

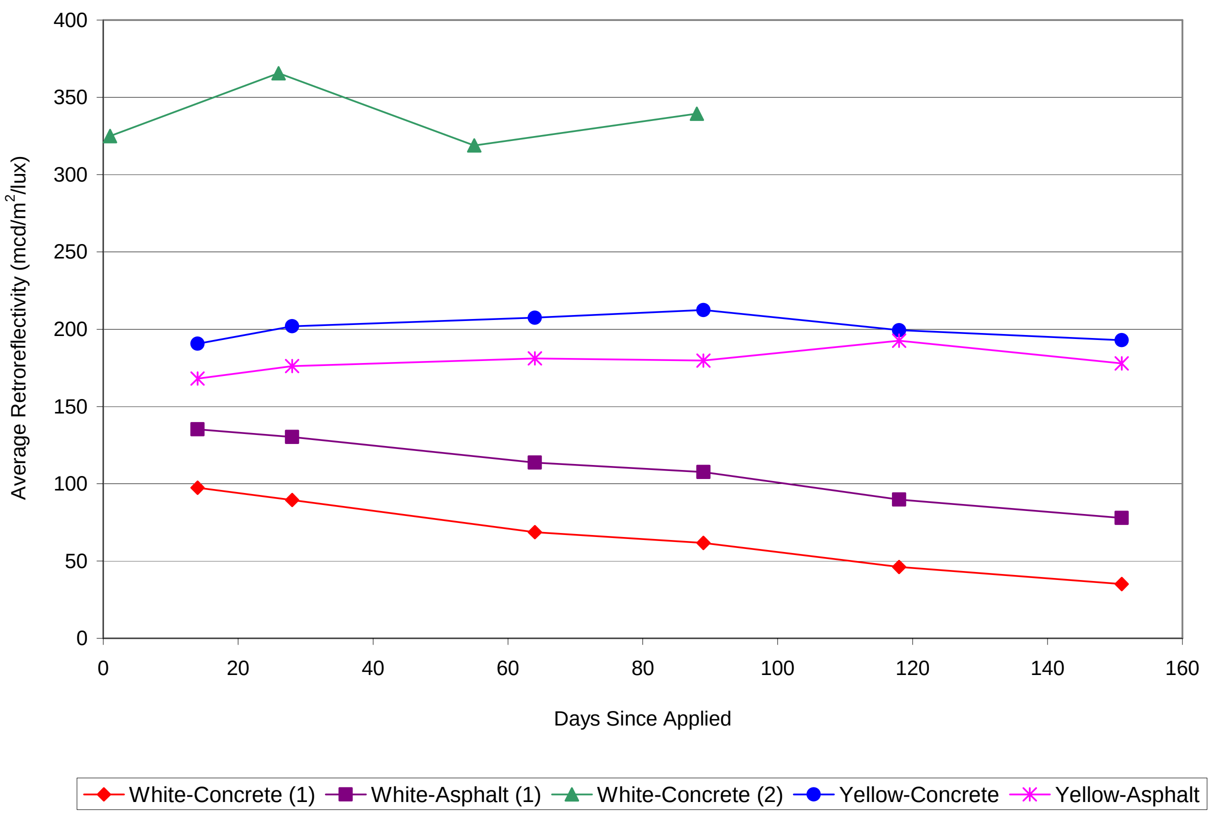


Figure 16. Retroreflectivity Results – Texas A&M University Riverside Campus.

Figure 17 shows the daytime color specifications for white and yellow pavement markings *(31)*, as well as the chromaticity coordinates of the white and yellow "removable" paint. The color of the white markings remained relatively constant over the five month period, remaining well inside the acceptable color region. The color of the yellow "removable" paint barely remained within the acceptable color region as it tended toward the white color region as time progressed.

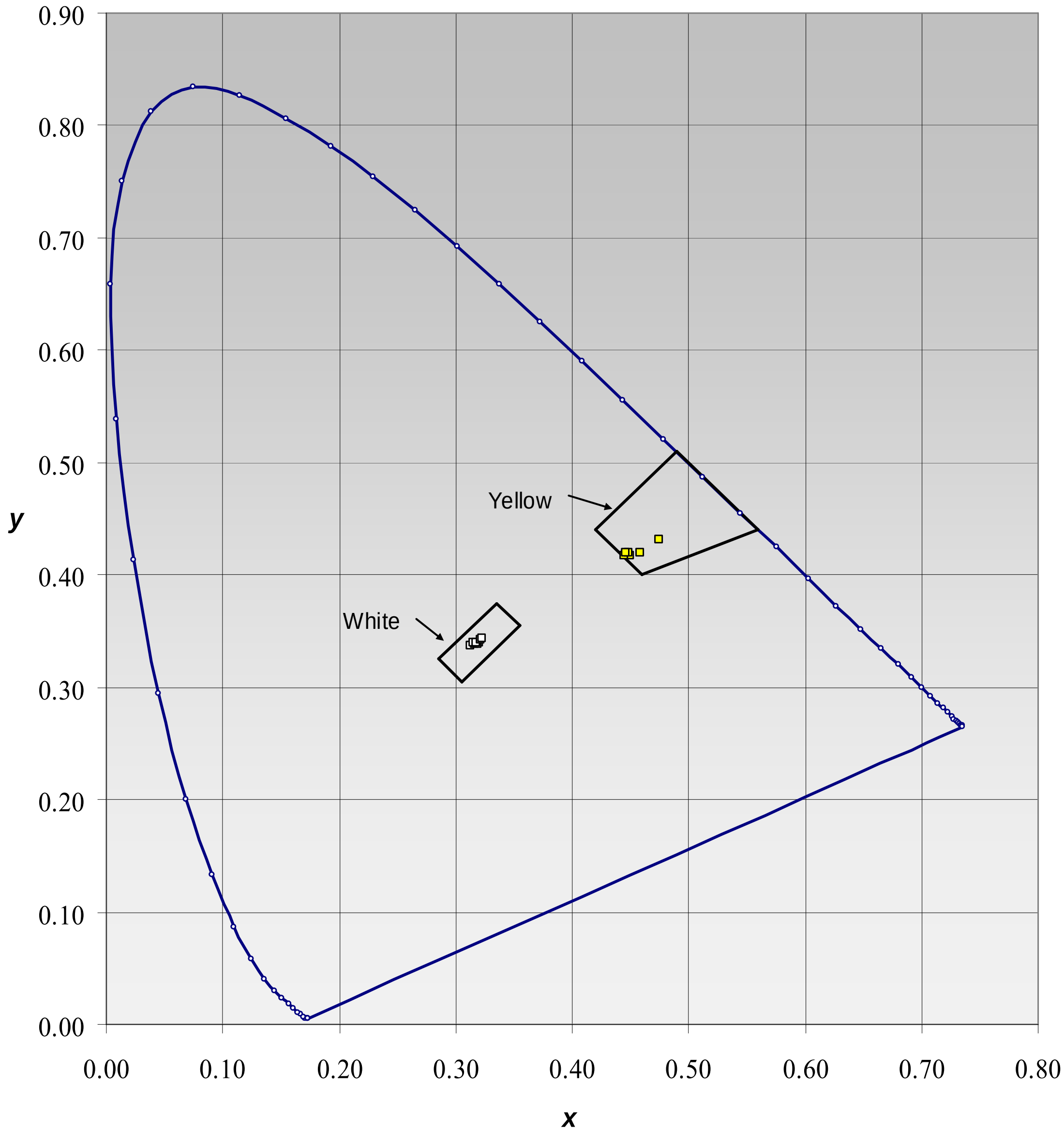


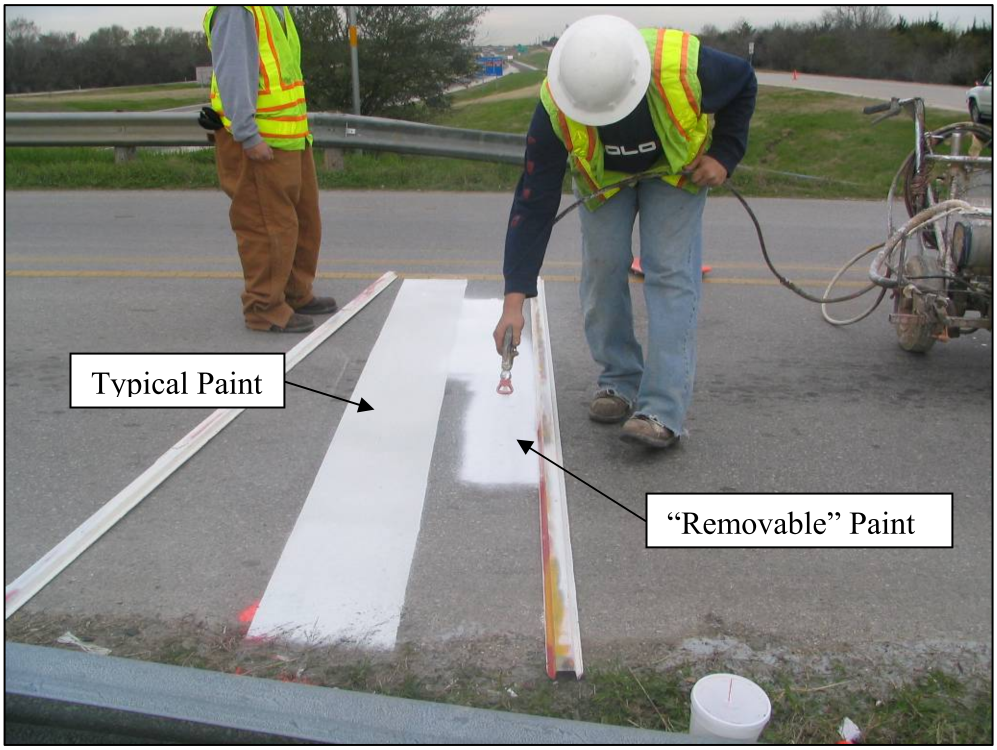
Figure 17. Chromaticity Results – Texas A&M University Riverside Campus.

In February 2005, researchers applied the second white "removable" paint and typical white water-borne paint adjacent to each other to form a stop bar on one approach to a two-way stop-controlled intersection (Figure 18a) and two transverse lines denoting the beginning and ending of a school zone (Figure 18b). All three of these applications were located on the frontage road of State Highway 6 in Bryan, Texas. Each product was 1-ft wide; thus, all three transverse markings were 2-ft wide overall. The roadway surface was asphalt and Type II beads were used.

Every two weeks, for 2.5 months (thru March 2005), researchers measured the retroreflectivity of both products. This evaluation was conducted to assess the durability of the "removable" paint system when exposed to actual traffic even though the "removable" paint system was not intended to be used in such applications. However, these were the only locations available to test the "removable" paint at that time.

Figure 19 is a plot of the retroreflectivity values for both products over the 2.5 month time period at all three locations. By the end of the first month, at the stop bar location the retroreflectivity of the "removable" paint had decreased from 141 to 80 mcd/m^2/lux and the retroreflectivity of the water-borne paint had decreased from 259 to 193 mcd/m^2/lux. As shown in Figure 20, by the end of the seventh week the "removable" paint section was almost completely obliterated. However, as mentioned previously, this was not an intended application for the "removable" paint. Also, at this site the stop bar was located approximately 50 ft upstream of the stop sign; thus, the markings were exposed to high levels of friction since drivers were decelerating to a stop while they traveled over the pavement markings.

Figure 19 also shows the retroreflectivity data for the school zone markings. The retroreflectivity of the "removable" paint sections was always less than the retroreflectivity of the water-borne paint sections. In addition, for the school zone markings the retroreflectivity of the "removable" paint was never above 75 mcd/m^2/lux. However, researchers believe that this might have been a result of the field crew's lack of experience applying this new product. Both products were applied with hand-operated applicators, but the second white "removable" paint was more viscous than typical water-borne paint, which the field crew usually applies with the hand-operated applicator. This resulted in a thicker than normal application of the "removable" paint at the stop bar location and a thinner than usual application of the "removable" paint at the school zone locations.



a) Stop Bar.

b) End School Zone.

Figure 18. Applications of “Removable” Paint on Frontage Road of State Highway 6.

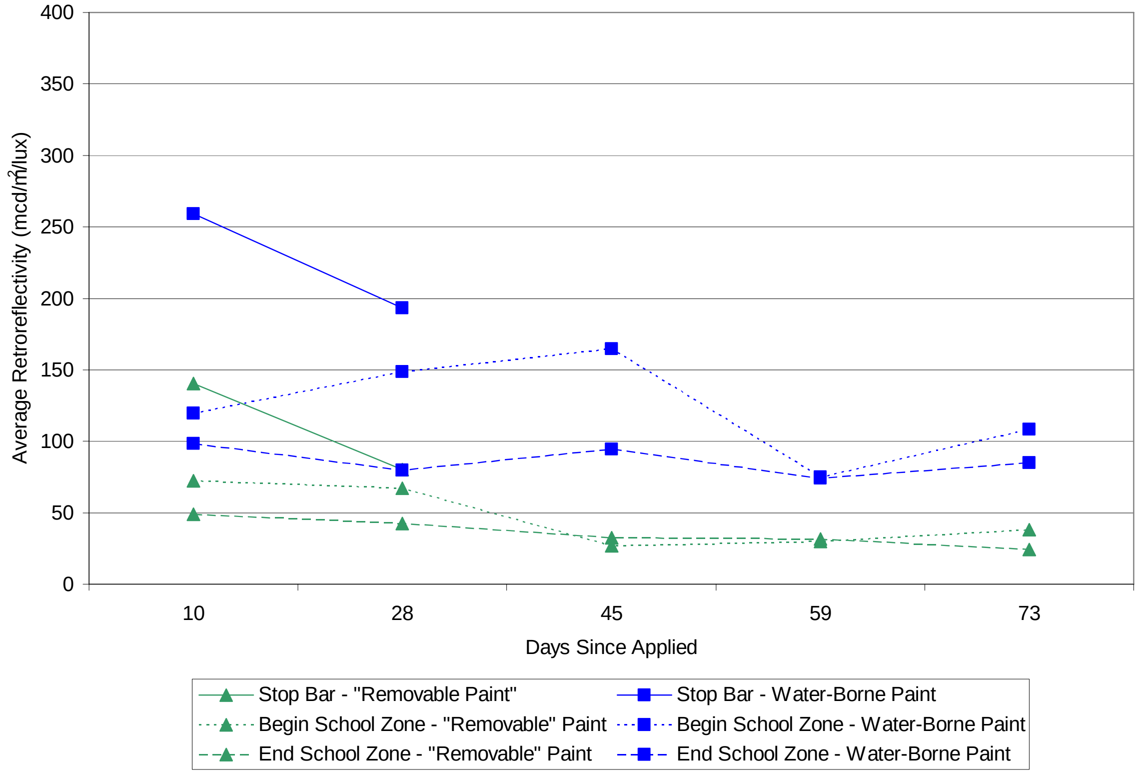


Figure 19. Retroreflectivity Results – State Highway 6 Frontage Road.

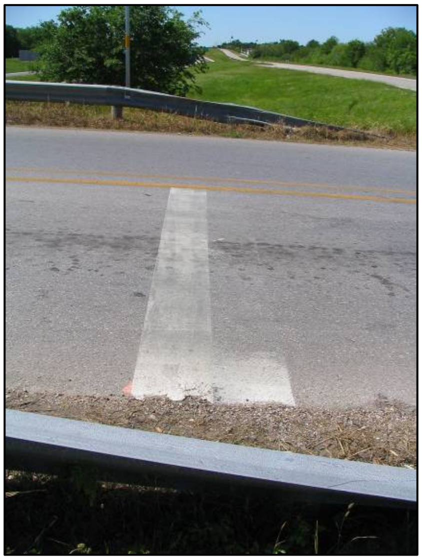


Figure 20. Stop Bar Application after 7 Weeks.

Based on the field experiences with the second white "removable" paint, researchers consulted the manufacturers, and they developed a third white "removable" paint that was less viscous. In June 2005, researchers applied 200 ft of this third white "removable" paint (edge line and lane lines) in a work zone on Texas Avenue in College Station, Texas (five-lane major arterial), with a self-propelled pavement marking applicator. Again the roadway surface was asphalt, and Type II beads were used. However, one week later a subcontractor applied thermoplastic pavement markings over the "removable" paint test section. The thermoplastic edge line markings were eradicated with a milling machine and the "removable" paint reapplied; however, the second application of the "removable" paint was not indicative of an ideal installation. As shown in Figure 21, the second installation resulted in a less consistent marking.

a) First Installation.

b) First Installation – Close-Up.

c) Second Installation.

d) Second Installation – Close-Up.

Figure 21. Comparison of Two "Removable" Paint Installations on Texas Avenue.

Researchers monitored the retroreflectivity of the second application of the "removable" paint (edge line only) for one month. Figure 22 shows the retroreflectivity data measured every week. One week after application, the retroreflectivity of the third white "removable" paint was 90 mcd/m^2/lux. After four weeks, the retroreflectivity of the "removable" paint was 45 mcd/m^2/lux (50 percent decrease). Again, the initial low retroreflectivity value and the quick degradation of the marking may be attributed to the less than ideal second application.

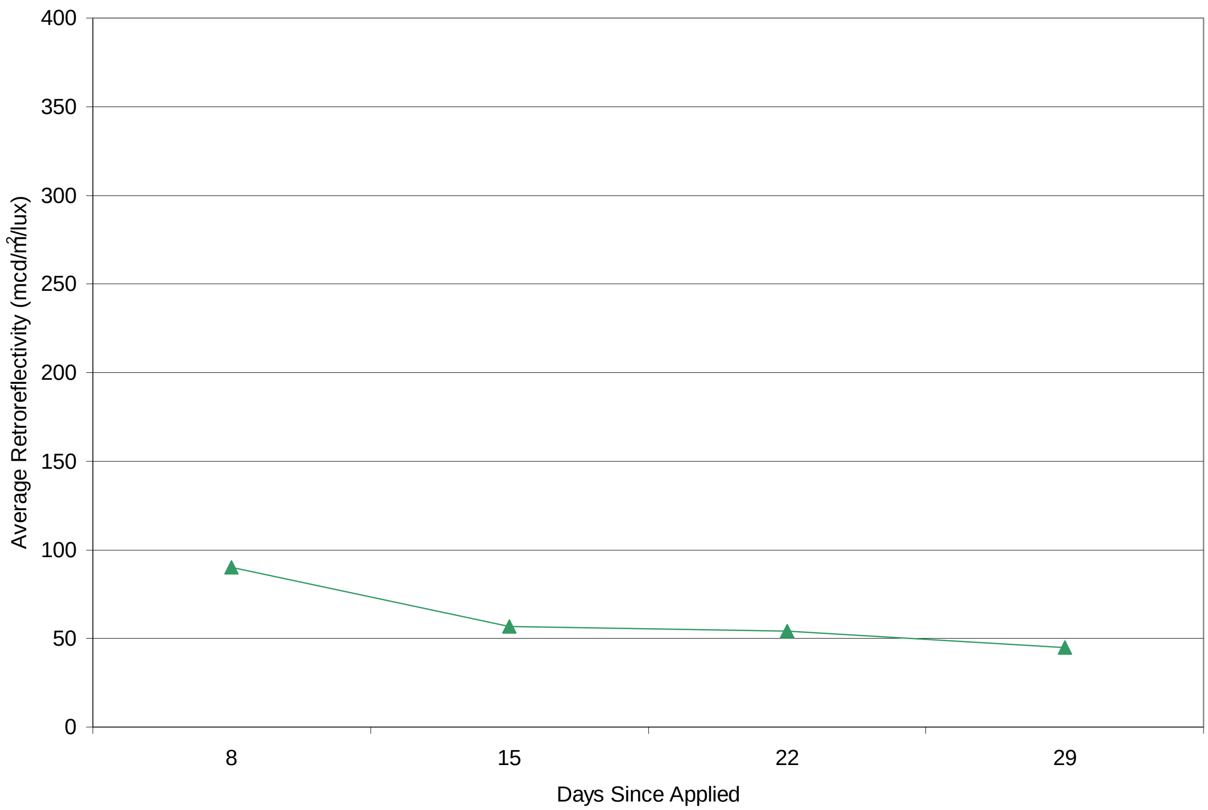


Figure 22. Retroreflectivity Results – Texas Avenue.

In addition to the previously discussed durability evaluations, TxDOT tested the chromaticity of four samples of the "removable" paint in their Xenon Weather-ometer® for 1480 hours. Two of the samples were the first white paint (one with Type II beads and one without beads) and two of the samples were yellow paint (one with Type II beads and one without beads). All of the samples were applied on concrete.

Figure 23 shows the chromaticity of the four samples over time. The chromaticity of both samples of the white "removable" paint remained constant over the 1480 hours of exposure.

The chromaticity of both of the yellow samples shifted over time toward the white color region, with the color of the yellow sample without beads falling outside of the yellow color region after 1480 hours. These results are similar to the measurements taken at the Texas A&M Riverside campus over a five month period (Figure 17).

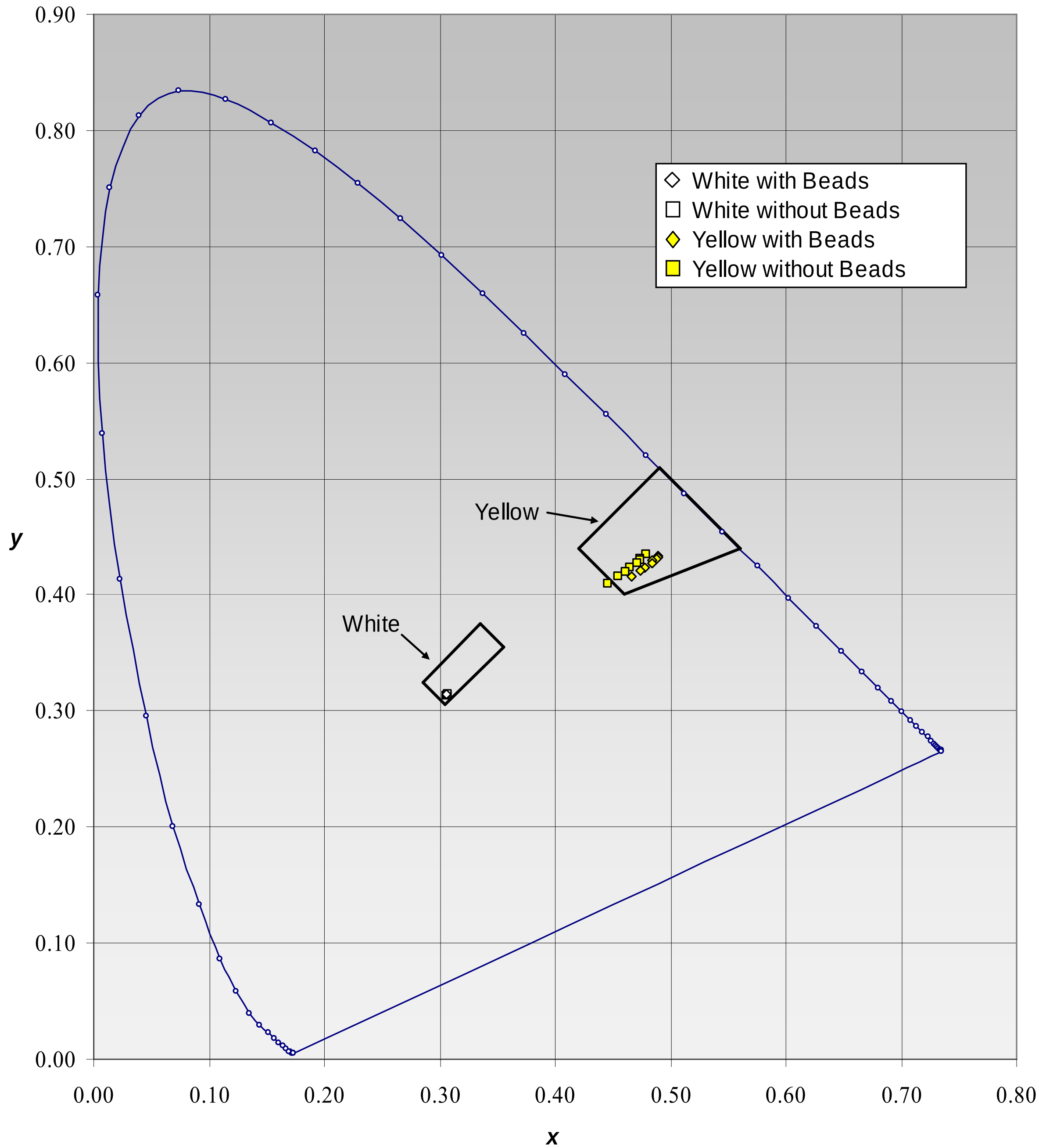


Figure 23. Chromaticity Results – TxDOT Weather-ometer®.

REMOVAL EVALUATIONS

Based on information received from the manufacturer, to eradicate the "removable" paint you apply the patented remover, wait 3 to 5 minutes, use a brush to agitate the surface, and then rinse with high-pressure water (120 pounds per square inch [psi] or greater).

In April 2005, TTI researchers tested the removal of the yellow and white paint on concrete and asphalt at the Texas A&M University Riverside campus. The following questions were investigated:

- How long do you have to leave the remover on the paint surface to completely remove the markings?
- Do you need to agitate the surface after you apply the remover to break up the paint?
- Do you need to use a high-pressure water rinse?
- Can you use a low-pressure water rinse instead?
- Does the high-pressure water rinse alone (no remover) remove the paint?

Figure 24 shows the equipment used during the removal testing. The remover was applied with a small motorized spray rig (60 psi), and push brooms were used to agitate the surface (when desired). A motorized high-pressure sprayer (3000 psi) and motorized low-pressure sprayer (less than 60 psi) were used to apply water in order to remove the paint and rinse the roadway surface, respectively.

For most of the trials, 90 to 100 percent of the "removable" paint markings were removed. Figure 25 shows two examples of the removal results (yellow on asphalt and white on concrete). The following are answers to the previously posed questions:

- Once the remover is applied a chemical breakdown of the paint starts to occur. The remover works best if it is allowed to work for at least 5 minutes, with 10 minutes preferred.
- Agitation is not needed as it did not improve the effectiveness of the remover. Agitation only smeared the clumped removed paint all over the roadway surface.
- A high-pressure water rinse is needed to help break up the removed paint from the surface. A high-pressure water rinse alone (no remover) does not remove the paint.

a) Motorized Spray Rig and Brooms.

b) High-Pressure Sprayer.

c) Low-Pressure Sprayer.

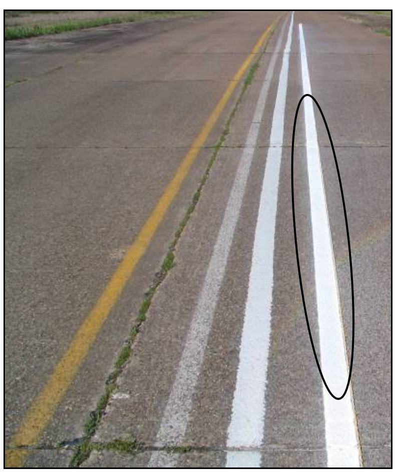
Figure 24. Equipment Used During the Removal Testing.

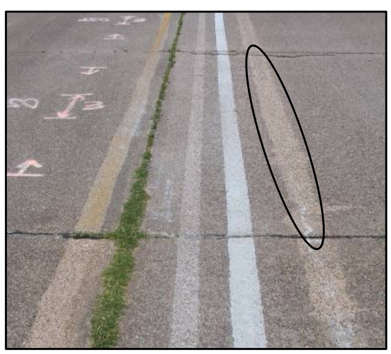
- A low-pressure water rinse cannot be used in place of a high-pressure water rinse. The low-pressure water rinse does remove some of the paint, but it is not as effective as the high-pressure water rinse.

a) Yellow Markings Prior to Removal.

b) Yellow Markings After Removal.

c) Yellow Markings After Removal – Close-Up.





d) White Markings Prior to Removal.

e) White Markings After Removal. [a]

f) White Markings After Removal – Close-Up. [a]

[a] The mark on the pavement in the highlighted area is not left over "removable" paint. The high-pressure water rinse cleaned the concrete as it removed the paint leaving behind the appearance of a marking.

Figure 25. Results of the Removal Testing.

Below are some issues that researchers identified during the removal effort:

- The removal effort is a multi-step process that requires several pieces of equipment. However, researchers believe that one to two trucks could be outfitted with the appropriate equipment (e.g., sprayer, tanks, etc.) in order to consolidate the equipment. This consolidation would also reduce the amount of labor needed.
- After rinsing with the high-pressure water, a liquid mixture of remover, paint residue, and water is left on the roadway. This mixture is slippery and sudsy (like soapy water) (Figure 26). Even though the manufacturer states that the products are environmentally friendly and will decompose in the soil, this mixture would need to be removed from the roadway surface prior to reopening the area to traffic. This removal could be accomplished with a vacuum truck.
- After the liquid mixture dried on the pavement, researchers noticed that the paint residue was left behind on the surface. (Prior to drying the paint residue was suspended in the liquid mixture.) Based on limited testing of a new remover product received from the manufacturer, it appears that this issue has been corrected (i.e., the paint is now dissolved by the remover).

Figure 26. Liquid Mixture Remaining after Removal.

SUMMARY AND CONCLUSIONS

Recently, TxDOT became aware of a "removable" paint system that is applied like typical water-borne paint but uses a patented liquid remover to eradicate the markings.

Researchers evaluated the durability of this new product and assessed the ease of application and removal of the product.

The retroreflectivity of the yellow "removable" paint remained relatively constant over a five month test period (averaging 190 $mcd/m^2/lux$). Three types of white "removable" paint were evaluated. The average retroreflectivity of the first white "removable" paint steadily decreased over a five month test period from 116 to 57 $mcd/m^2/lux$. The second white "removable" paint had a higher initial retroreflectivity value (325 $mcd/m^2/lux$) and maintained an average retroreflectivity of 337 $mcd/m^2/lux$ over a three month period. However, the viscosity of the second white "removable" paint (more fluid than typical water-borne paint) made it difficult to apply, yielding much lower retroreflectivity values at the stop bar (141 to 80 $mcd/m^2/lux$) and school zone locations (61 to 31 $mcd/m^2/lux$) over a 2.5 month period. The third white "removable" paint (which was less viscous) was applied as the edge line in a work zone located on a five-lane major arterial; however, again installation complications resulted in low retroreflectivity values over a one month period (90 to 45 $mcd/m^2/lux$).

The color of the white "removable" paint remained relatively constant over time, remaining well inside the acceptable color region for white pavement markings. In contrast, the color of the yellow "removable" paint drifted toward the white color region as time progressed and at the end of one test fell outside the acceptable color region for yellow pavement markings.

The initial versions of the white and yellow "removable" paint, as well as the third white "removable" paint were applied successfully with a self-propelled pavement marking applicator. The application of the second white "removable" paint with a hand-operated pavement marking applicator resulted in a thicker than normal application since the second white "removable" paint was more viscous than the initial version of the white "removable" paint and typical water-borne paint. For most of the removal trials, 90 to 100 percent of the "removable" paint markings were removed. Researchers recommend the following removal procedure:

1. Apply remover, completely covering the pavement marking.
2. Wait 10 minutes. This allows the remover to chemically break down the pavement marking paint.
3. Rinse the pavement marking with a high-pressure water sprayer in order to break up the removed paint from the roadway surface.
4. Use a vacuum truck to remove the remaining liquid from the pavement.

Overall, the “removable” pavement marking paint showed promise as it can be applied and removed with existing equipment. In addition, the patented remover does eliminate the markings without scarring the pavement like some other eradication methods. However, the durability of the white “removable” paint at the field locations was less than ideal (retroreflectivity values less than 100 $mcd/m^2/lux$ after one month). Thus, researchers recommend that further field testing of the “removable” pavement marking paint be conducted in work zones where temporary changes in alignment need to be delineated for a short period of time. The field testing should evaluate the retroreflectivity and chromaticity of both colors of paint and the ease of removal of the product on an actual roadway.

CHAPTER 7
RUMBLE STRIP SOUND AND VIBRATION ANALYSIS

Roughly 240,000 roadway departure or run-off-the-road (ROR) crashes (40 percent of all traffic crashes) occurred in the United States in 2001, resulting in 23,205 fatalities (55 percent of the total traffic fatalities) and in 740,000 injuries (35 percent of all traffic crash injuries). Two-thirds of these crashes occurred in rural areas (*32*). ROR crashes are the result of several factors including: driver fatigue, driver impairment, driver distraction, and poor visibility.

In an attempt to reduce ROR crashes, many state transportation agencies have installed rumble strips on roadways (*33*). Previous research (*32*, *33*, *34*) has shown an improvement in safety from installing rumble strips; however, there are still questions with regard to the level of sound and vibration needed to alert a driver and the sound impact on adjacent residences and businesses. As part of this research project, researchers conducted a literature review on the effects of rumble strip design on sound and vibration, measured the inside sound and vibration in three different types of vehicles under two different speeds, and measured the outside sound produced by two different types of vehicles under two different speeds. These tasks were completed in order to quantify the impact various types and designs of rumble strips installed in Texas have on drivers and the general public living and working near roadways with rumble strips.

RUMBLE STRIP DESIGN

Rumble strips are grooved or raised patterns that provide an audible and vibratory warning to the driver as the tires of the driver's vehicle traverse the rumble strips. There are several ways to apply rumble strips including milled, rolled, and raised rumble strips. Figure 27 contains pictures of milled, rolled, and two different types of raised rumble strips.

Milled rumble strips are cut into the road with a mechanical milling device that uses a rotary cutting head. These can be installed on both new and existing concrete and asphalt roadways. The cuts are typically 0.5 inches in depth (*35*).

Rolled rumble strips are depressions on asphalt roadways formed by steel pipes welded onto a roller at uniform lengths. These strips can be applied only on new or reconstructed asphalt surfaces. The resulting tire drop is approximately 0.03 inches, 1/26th of the drop from the milled strips (35). Metal forms are used to install what could be termed "rolled" rumble strips in new concrete.

a) Milled.

b) Raised (Profile).

c) Rolled.

d) Raised (Button).

Figure 27. Rumble Strip Applications.

Raised rumble strips are rounded or rectangular markers or strips adhered to the roadway. These include traffic buttons, profile markings, preformed thermoplastic, or raised sections of asphalt pavement. Raised rumble strips can be applied to any roadway; however, typically they are restricted to warmer climates, because cooler climate regions may require snowplowing that may damage the rumble strips and/or the snowplowing equipment. Heights vary from approximately 0.25 to 0.5 inches (36).

As shown in Figure 28, rumble strips are placed at different locations along the roadway to alert drivers to various changes in the roadway environment. These include the following:

- Centerline rumble strips (CRSs) alert drivers inadvertently crossing into opposing traffic to reduce head-on crashes, opposite direction side-swipe crashes, and ROR crashes *(35)*.
- Shoulder rumble strips (SRSs) or edge line rumble strips (ERSs) on extended highway sections, as well as work zones, off-ramps, and lane drops, alert drivers inadvertently leaving the roadway to reduce ROR crashes *(33)*.
- Laneline rumble strips (LRSs) are currently not installed to alert drivers to lane departures but instead they are installed to improve wet-night visibility.
- Transverse rumble strips (TRSs) alert drivers to upcoming changes or hazards including lane changes, reduced speed or stop, horizontal curves, work zones, toll ways, or intersections *(33)*.

a) CRSs.

b) ERSs (a form of SRSs).

c) LRSs.

d) TRSs.

Figure 28. Types of Rumble Strips.

Rumble strip designs do not only differ in type and application, but they also differ with respect to dimensions. Figure 29 depicts the various dimensions associated with rumble strips.

The width of a rumble strip is the dimension perpendicular to the direction of travel, while the length of a rumble strip is the dimension in the direction of travel. Spacing is the distance in the direction of travel from the leading edge of one rumble strip to the leading edge of the following rumble strip. For milled and rolled rumble strips, the depth is measured from the roadway surface to the bottom of the rumble strip. For raised rumble strips, the height is measured from the roadway surface to the top of the rumble strip.

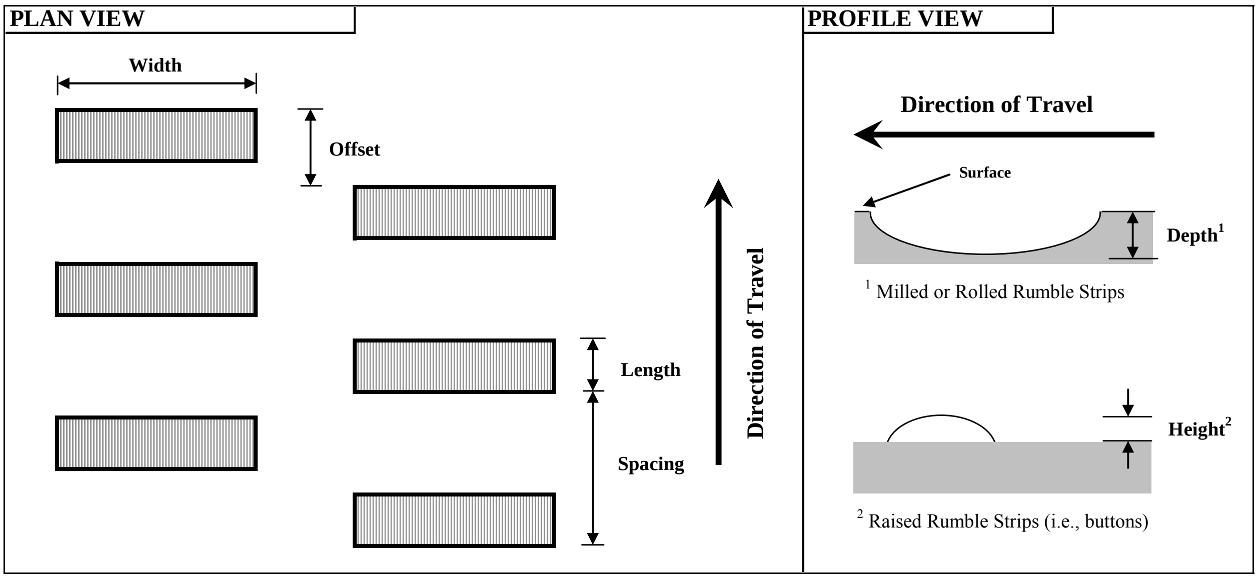


Figure 29. Rumble Strip Design Definitions.

PREVIOUS RESEARCH

Numerous research efforts have investigated the sound and vibration associated with rumble strips (*37*-*45*). These various projects helped quantify the sound and vibration associated with the installation of rumble strips for two primary purposes: 1) establish whether a particular design of rumble strip provided a noticeable increase in sound and vibration above ambient conditions; and 2) establish whether there is a design that provides adequate sound and vibration to drivers in automobiles while not diminishing other road users' (i.e., bicyclists) ability to use the roadway.

Before discussing any research related to sound, it is important to relate the concept of sound, which is typically measured in decibels (dB), to common sounds that occur in the environment. This relationship is shown in Figure 30. The sound measurements discussed later in this report are within the 60 to 100 dB range (a two-person conversation to the sound of a subway train, respectively).

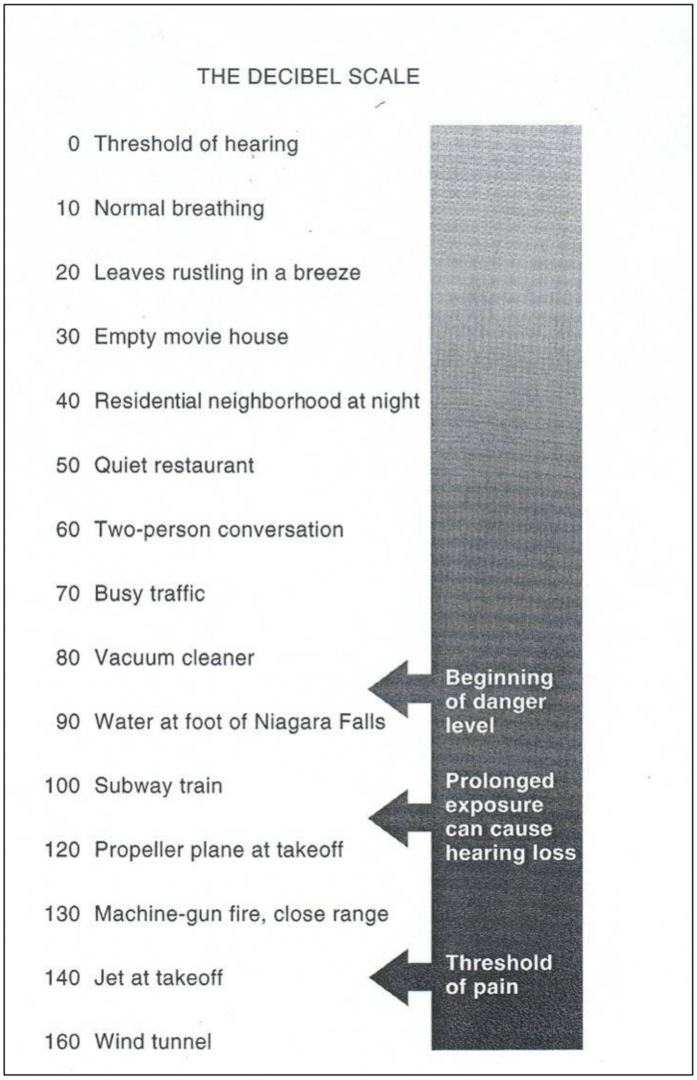


Figure 30. Decibel Scale (*46*).

A study by Meyer and Walton (*40*) focused on the effects of TRS pattern layout on sound and vibration. Fifteen different test sections were created to analyze the effects of thickness (i.e., height of raised TRSs), spacing, and offset. A compact car (1998 Ford Escort), a midsize car (1992 Honda Accord), and a dump truck were used during the project, and they were all driven at 40, 50, and 60 mph. At 60 mph, the average ambient sound reading was 77 dB for the cars and 84 dB for the dump truck. The average increase in sound was 10 dB and 4 dB for the cars and dump truck, respectively. It was found that an increase in height will increase the sound and vibration, 24-inch spacing appears to be optimal, and offsetting TRSs will reduce the sound and vibration. One additional finding of the study was that the removable rumble strip tested generated a larger increase in sound and vibration than the asphalt rumble strip tested. It is believed that the domed shape of the asphalt rumble strip may have impacted this difference.

Researchers at the Pennsylvania Transportation Institute (PTI) investigated how depth, spacing, and length affected the sound and vibration associated with milled rumble strips (*43*). In the PTI study, they drove a 1998 Plymouth Grand Voyager at 45 and 55 mph over six different sets of milled rumble strips. All of the rumble strips were 16 inches wide, but they varied in depth from 0.25 to 0.5 inches, length from 5 to 7 inches, and spacing from 11 to 12 inches. While these differences in dimensions were small, it was shown that as the length and depth of the rumble strip increased, so did the sound and vibration. The average ambient sound reading at 55 mph was 65 dB, and the average increase ranged from 13 to 24 dB. Furthermore, the researchers cited a 1977 report by Watts (*37*) that stated a 4 dB increase in sound for 0.35 seconds or 2 dB for 0.90 seconds was needed for drivers to be alerted to a change in the ambient sound. Overall, Watts recommended that a 4 dB increase be used as a threshold value.

The California Department of Transportation (Caltrans) conducted an evaluation of sound and vibration with 11 different installations of rumble strips which allowed them to look at differences in the manner of application and dimensions (*44*). Table 26 contains a list of the different installations tested. Three light private vehicles (i.e., Chevrolet Lumina, Dodge Spirit, and Dodge Ram 150) were driven at 50 and 60 mph over the rumble strips, and three heavy commercial vehicles (i.e., International semi-tractor trailer, Autocar 10 yard dump truck, and GMC single unit Topkick) were driven at 50 mph over the rumble strips. At the time of the research, rumble strip test section 1 was Caltrans' standard rumble strip design. At the completion of the study, it was recommended to reduce the width of the standard rumble strip to 12 inches and add a milled rumble strip (test section 3 but with a 12-inch width) to the state specifications.

Based on previous research (*39*, *40*, *42*, *43*, *44*) the following can be generalized: sound and vibration are the direct result of tire displacement from the normal road surface. The kinetic energy from the tires is converted into sound and vibration as it displaces, and as the displacement increases in magnitude and frequency, more energy is converted which results in more sound and vibration. Hence, as the width and length increase for milled or rolled rumble strips to the point at which a tire can completely drop to the bottom of the rumble strip, then the sound and vibration will increase. For raised rumble strips, tire displacement increases as the width of the rumble strip increases to the point where the entire cross section of the tire is lifted off the pavement. Furthermore, as the depth/height of a rumble strip increases, sound and vibration would increase provided that a tire was still permitted to obtain maximum displacement. As the spacing increases sound and vibration would decrease because the frequency of the tire displacement would decrease. Spacing, for raised rumble strips, affects the tire displacement in the same manner that length does for milled or rolled rumble strips. Subsequently, the spacing must be far enough to allow for maximum tire displacement, but again, any increase beyond the distance required to allow for maximum tire displacement will decrease sound and vibration because the frequency of the tire displacement decreases.

Table 26. Caltrans Rumble Strip Test Sections.

ID	Application	Dimensions (inch)				Sound Change(dB)		Vibration Change (g)	
		Length	Width	Height [a]	Spacing	Light [b]	Heavy [b]	Light [b]	Heavy [b]
1	Rolled	2	24	-1.00	8	14	5	0.28	0.34
2	Milled	5	16	-0.25	12	11	2	0.13	0.15
3	Milled	6	16	-0.38	12	17	4	0.41	0.23
4	Milled	7	16	-0.50	12	18	5	0.45	0.25
5	Milled	7.5	16	-0.63	12	20	5	0.57	0.29
6	Chipseal	NA	NA	NA	NA	7	2	0.31	0.12
7	Button	4	4	0.50	12	17	4	0.62	0.18
8	Button, Staggered	4	4	0.50	6	17	5	0.54	0.26
9	Carsonite Bar	4	24	0.50	24	17	4	0.72	0.24
10	Inverted Profile Thermo [c]	1 / 4	4	0.19 / 0.50	1 / 22	9	1	0.24	0.07
11	Profile Thermo	4	4	0.50	22	3	1	0.10	0.10

[a] Height is relative to the distance from the pavement surface to the maximum elevation of the rumble strip and, therefore, will be negative for rolled and milled applications.
[b] Light indicates the light private vehicles, and heavy indicates the heavy commercial vehicles.
[c] If there are two dimensions, the first dimension refers to the inverted portion of the marking, and the second dimension refers to the profile portion of the marking.
NA refers to not applicable, and in the case of the chipseal treatment, the chipseal is a standard design that would be louder than standard hot-mix asphalt (HMA) or concrete.

STUDY DESIGN

Equipment

The data collection equipment was borrowed from the North Carolina Department of Transportation (NCDOT). The equipment was developed by researchers from the North Carolina State University during a research project sponsored by the NCDOT. Figure 31 is a schematic of the instrumentation. The system is referred to as the Vibraline Sound and Vibration Measurement System, and consists of the following items:

- sound level meter (SL4001, Lutron);
    - 30 to 130 dB range
    - 10 mV/dB sensitivity
    - DC output
- piezoelectric ICP® shear accelerometer (353B03, PCB Piezotronics, Inc.);
- ICP® power unit, signal conditioner (480E09, PCB Piezotronics, Inc.);
- junction box (connects signal from accelerometer and sound level meter to data acquisition card);
- data acquisition card (PCM5516-D-16, ADAC);
    - 16-bit analog-to-digital converter
    - 100 kHz maximum throughput
- laptop computer (Solo 2550, Gateway); and
- Labtech Notebook software.

Data Collection

Data were collected under daytime, dry conditions, and the data collection effort was split into two tasks:

- collect sound and vibration data from inside vehicles, and
- collect sound data from outside vehicles.

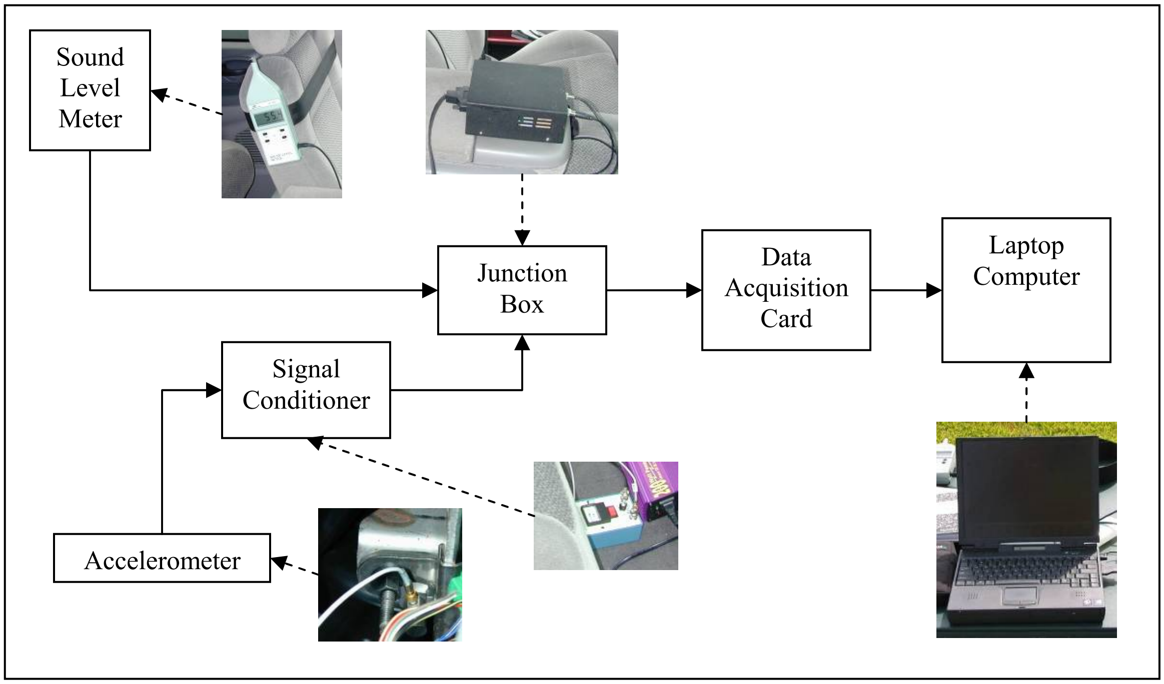


Figure 31. Instrumentation Schematic.

In order to quantify the stimulation experienced by the driver, sound and vibration data were collected from inside three different vehicles. The vehicles used were a sedan (2003 Ford Taurus), ½ ton truck (2001 Ford F-150), and a commercial vehicle (1999 Kenworth half-loaded such that it weighed approximately 46,520 lb). These vehicles are shown in Figure 32. The sedan and ½ ton truck were driven at 55 and 70 mph along the test roads provided that the speed limit was at least 70 mph. The commercial vehicle was driven at only 55 mph to ensure the safety of the driver and other vehicular traffic. The type and size of tires on the vehicles used in this study are listed in Table 27.

Sound and vibration measurements were recorded from the perspective of the driver. Sound was measured at shoulder level on the driver's right side (nearest to the center of the vehicle), and vibration was measured from a piece of metal attached directly to the floor of the vehicle (usually the bottom of the driver's seat). The data logging equipment and a researcher were located in the passenger seat. Figure 33 is a depiction of the setup of the data collection equipment in the ½ ton truck. A similar setup was used for the other two vehicles.

a) 2003 Ford Taurus. **b) 2001 Ford F-150.** **c) 1999 Kenworth.**

Figure 32. Study Vehicles.

Table 27. Tire Size Data.

Vehicle	Tire Size	Width (inches)	Radius (inches)
Sedan	P215/60/R16	8.5	13.0
½ Ton Truck	P255/70/R16	10.0	15.0
Commercial Vehicle	11R24	11.5	21.5

a) Sound Meter. **b) Vibration Sensor.** **c) Data Logger.**

Figure 33. Inside Vehicle Equipment Setup.

In order to quantify the impact of vehicle contact with rumble strips on the surrounding environment, sound measurements were recorded from the perspective of a pedestrian on the side of the road adjacent to the rumble strips. The sound measuring device and the data logging equipment were placed on a small, collapsible table set up 50 ft from the outside edge of rumble strip applications. Figure 34 is a picture of the standard equipment setup for collecting outside sound data. The outside sound measurements were collected for the sedan and commercial vehicle. The sedan was driven at 55 and 70 mph along the test roads provided that the speed limit was at least 70 mph. Again, for safety reasons the commercial vehicle was only driven at 55 mph.

a) Equipment Setup.   b) Centerline Measurements.   c) Shoulder Measurements.

Figure 34. Outside Equipment Setup.

For both inside and outside measurements, data were collected for the ambient and the rumble strip conditions. The ambient condition was defined as the sound and vibration associated with the test vehicle traveling at a specified speed (55 or 70 mph) along a designated roadway. The rumble strip condition was defined as the sound and vibration associated with the test vehicle traveling at a specified speed along a designated roadway while traveling with at least one tire contacting the rumble strips.

Sound was measured in decibels and vibration was measured in acceleration with respect to units of gravity or g's. At least two 30-second test trials were conducted for each condition, speed, and type of rumble strip. During data collection, the presence of another vehicle near the test vehicle or uneven pavement surfaces not associated with the installation of rumble strips was recorded with respect to time. This information was used to remove any anomalies in the data associated with such events. Table 28 contains a list of the 12 sites and the data collected at each location. Additional information concerning the applications (e.g., dimensions) is in Appendix F.

The number of test runs completed is listed in Table 29. The numbers differ because tests were not conducted at 70 mph with the commercial vehicle, and occasionally additional test runs were completed if something occurred that may have affected data collection, such as nearby vehicles affecting sound readings.

Table 28. Study Locations.

Roadway[a]	Pavement [b]	Type	Application	Inside	Outside
FM 50	HMA	TRS	Raised	Yes	Yes
FM 969	HMA	CRS	Button	Yes	Yes
FM 1179	HMA	TRS	Raised	Yes	Yes
FM 1431	HMA	CRS	Button	Yes	No
FM 2154	Chipseal	TRS	Raised	Yes	Yes
FM 2549	Chipseal	TRS	Raised	Yes	Yes
RM 32	HMA	CRS, ERS	Milled	Yes	No
RM 2222	HMA	CRS	Button	Yes	No
SH 6	HMA	CRS, ERS, SRS	Button, Profile	Yes	Yes
SH 21	HMA, Chipseal	CRS, LRS, ERS, SRS	Rolled, Milled	Yes	Yes
SH 47	HMA	SRS	Milled	Yes	Yes
SH 195	HMA	CRS, SRS	Button	Yes	No

[a] Farm-to-Market road (FM), Ranch-to-Market road (RM), State Highway (SH)
[b] Hot-Mix Asphalt (HMA)

Table 29. Number of Test Runs.

Vehicle	Number of Test Runs	
	Inside Sound and Vibration	Outside Sound
Sedan	172	127
½ Ton Truck	166	-
Commercial Vehicle	65	45

"-" Not collected.

Analysis

The purpose of the analysis was to: 1) quantify any change in sound and/or vibration associated with the installation of various rumble strips; and 2) investigate the effects of speed, vehicle, rumble strip application (i.e., button, profile, rolled, milled), and dimensions have on sound and/or vibration. These changes were calculated from the differences between the ambient condition and the rumble strip condition. Anomalies in the data caused by the presence of another vehicle near the test vehicle or uneven pavement surfaces not associated with the installation of rumble strips were removed from the data. There were two methods used to reduce the data for further analysis.

Method A was used to calculate the inside sound and vibration values for all rumble strip applications except TRSs. In Method A, the researchers calculated the frequency distributions of the data. The mean, and the 15th, 50th, and 85th percentile values were calculated for each set of sound and vibration data, and then, the 15th percentile values were used to establish the bins for the frequency distributions. For sound data, the bins were incremented in 1 dB whole numbers (i.e., 15 dB, 16 dB, etc.). Vibration data were binned in increments of 0.01 g. Normally, the bin with the largest frequency for a particular sound or vibration value was recorded. However, the researchers chose values with lower frequencies in some cases based on objective review of the data overall. Frequency values generated with Method A were recorded for all ambient conditions and all rumble strip conditions with the exception of TRSs.

Method B was used to calculate inside sound and vibration values for TRSs, as well as the outside sound values for all rumble strip applications studied. Method B consisted of finding the peak value associated with the data collected for traversing a set of rumble strips and the ambient condition. With respect to TRSs, in most cases a vehicle crossed three sets of TRSs during a single test. However, since many of the TRSs were located upstream of stop-controlled intersections, drivers had to reduce speed as they crossed the second and third sets of TRSs. Thus, the researchers only analyzed the results from the first set of TRSs, which were crossed prior to slowing below the test speed.

RESULTS

The analysis is discussed in general terms and then more specifically by rumble strip application, pavement type, and dimensions. Within each section, the inside sound and vibration results will be discussed, followed by a discussion of the outside sound results. Furthermore, to make the graphs more legible "car" was used in place of sedan, "truck" was used in place of ½ ton truck, and "CV" was used in place of commercial vehicle. Based on previous research *(37, 43)*, the researchers will consider increases of 4 dB or greater sufficient to alert drivers when contacting rumble strips. No research was found that specified a minimum increase in vibration needed to alert drivers, so the results will focus on documenting the change associated with vibration. Appendix G contains more detailed data.

General Trends

The analysis by rumble strip type must be viewed from a broad perspective, since a number of factors that influence sound and vibration, such as rumble strip application, pavement type, and dimensions of rumble strips, were collapsed. Subsequently, this section of the analysis focuses on investigating general trends and the magnitude of the sound and vibration data. For brevity, the results from the truck are not discussed in this section since the truck results generally fell between the results of the sedan and commercial vehicle. In addition, only the 55 mph data are discussed. The effect of speed is addressed later.

As shown in Figure 35, the ambient inside sound ranged between 65 and 77 dB and the inside sound increase ranged from 0 to 12 dB. The highest reading was 81 dB, and it was recorded for the commercial vehicle crossing the CRSs. The recorded increases in sound were above 4 dB in the sedan for CRSs, SRSs, and TRSs, while the sound increase in the commercial vehicle only reached the minimum 4 dB threshold while crossing CRSs. Neither the sedan nor the commercial vehicle elevated the sound inside the vehicle above 4 dB when crossing the LRSs. Again, LRSs were installed for the purposes of improving wet-night visibility of the laneline pavement marking and not to audibly or tactilely alert drivers to lane departures, so these findings were expected.

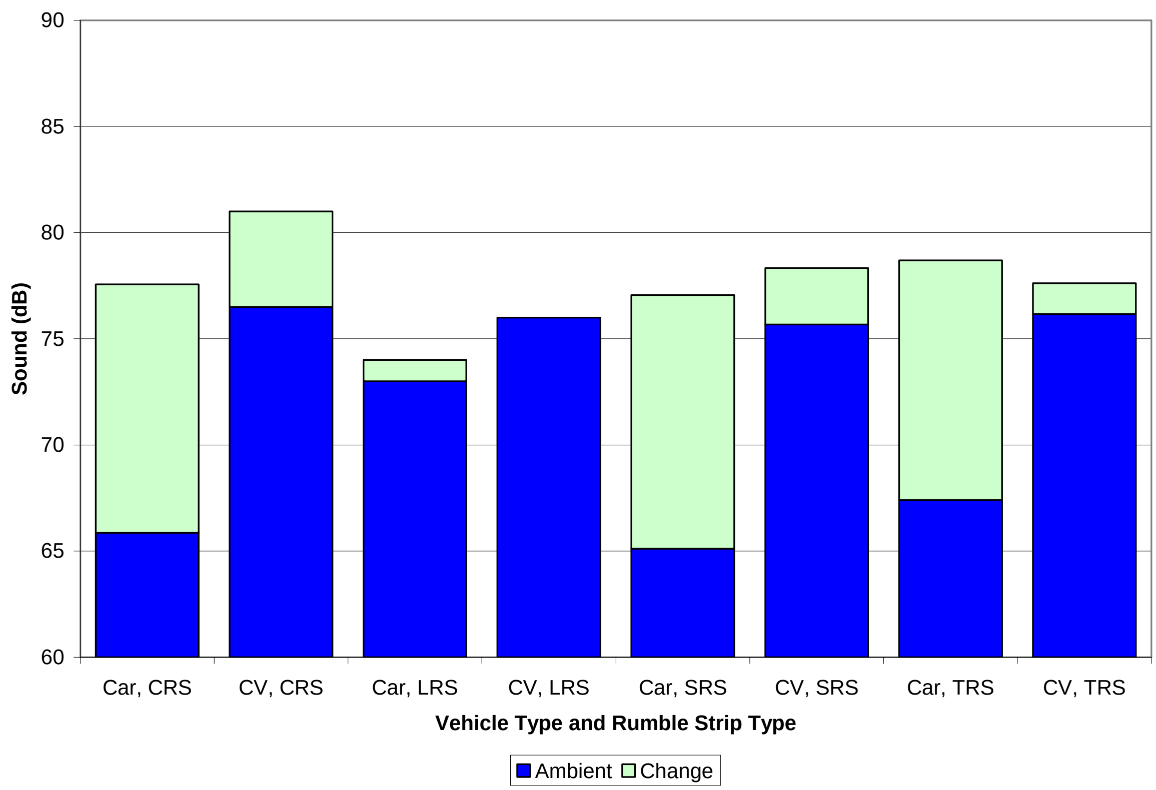


Figure 35. Change in Sound inside Vehicle at 55 mph by Rumble Strip Type.

The ambient vibration and the change in vibration caused by crossing rumble strips are shown in Figure 36. The sedan experienced greater ambient vibration and change in vibration than the commercial vehicle. For the sedan, the increase in vibration was between 0.03 g and 0.29 g (43 and 311 percent). The only observed change in vibration in the commercial vehicle occurred while it contacted TRSs, but the increase was only 0.006 g.

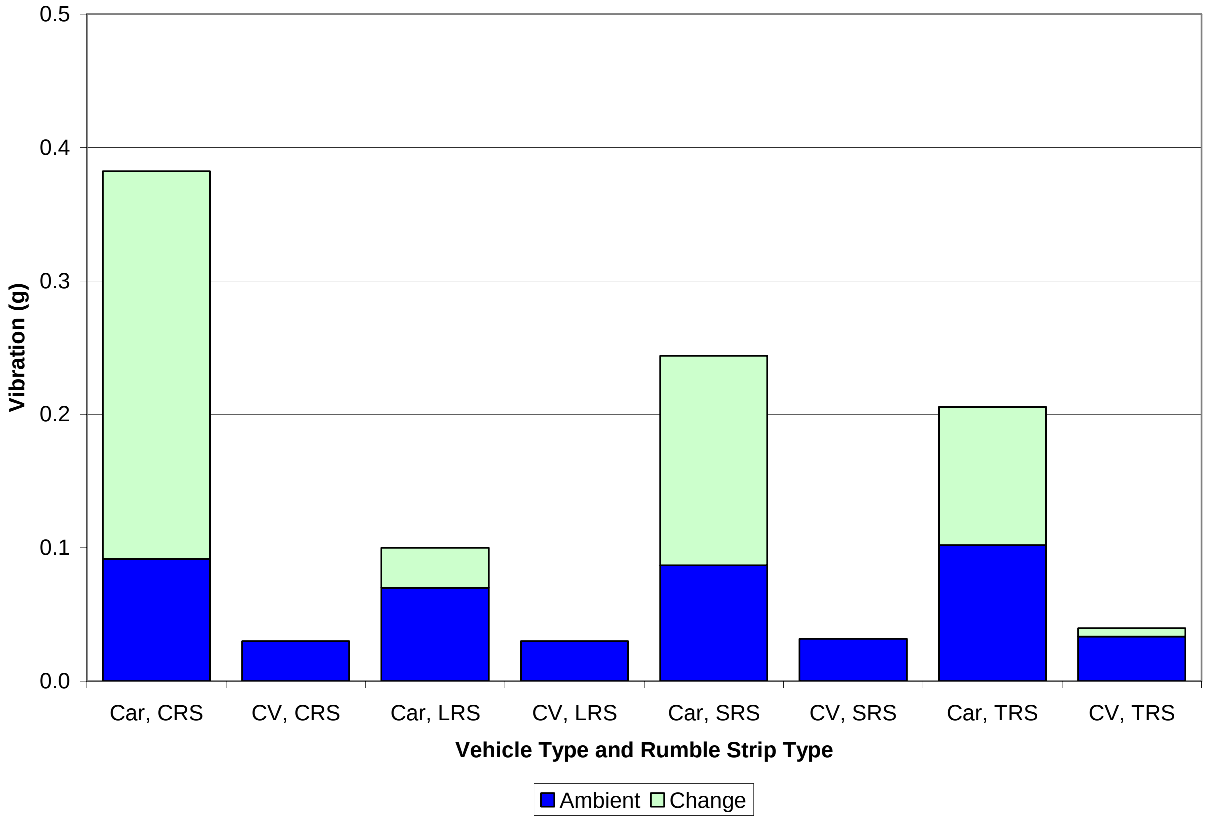


Figure 36. Change in Vibration inside Vehicle at 55 mph by Rumble Strip Type.

As shown in Figure 37, the outside sound was louder than the inside sound, but the overall change was less. The ambient outside sound ranged from 69 to 86 dB, and the increase ranged from 2 to 8 dB. The highest reading (88 dB) occurred when the commercial vehicle contacted CRSs and SRSs. It should be noted that the change was -1 dB for the LRS when crossed by the commercial vehicle. It is believed that this was an anomalous finding resulting from the difficultly associated with trying to keep the commercial vehicle tires situated over the LRS which were only 4 inches wide. The issue of width is discussed later in this chapter in further detail.

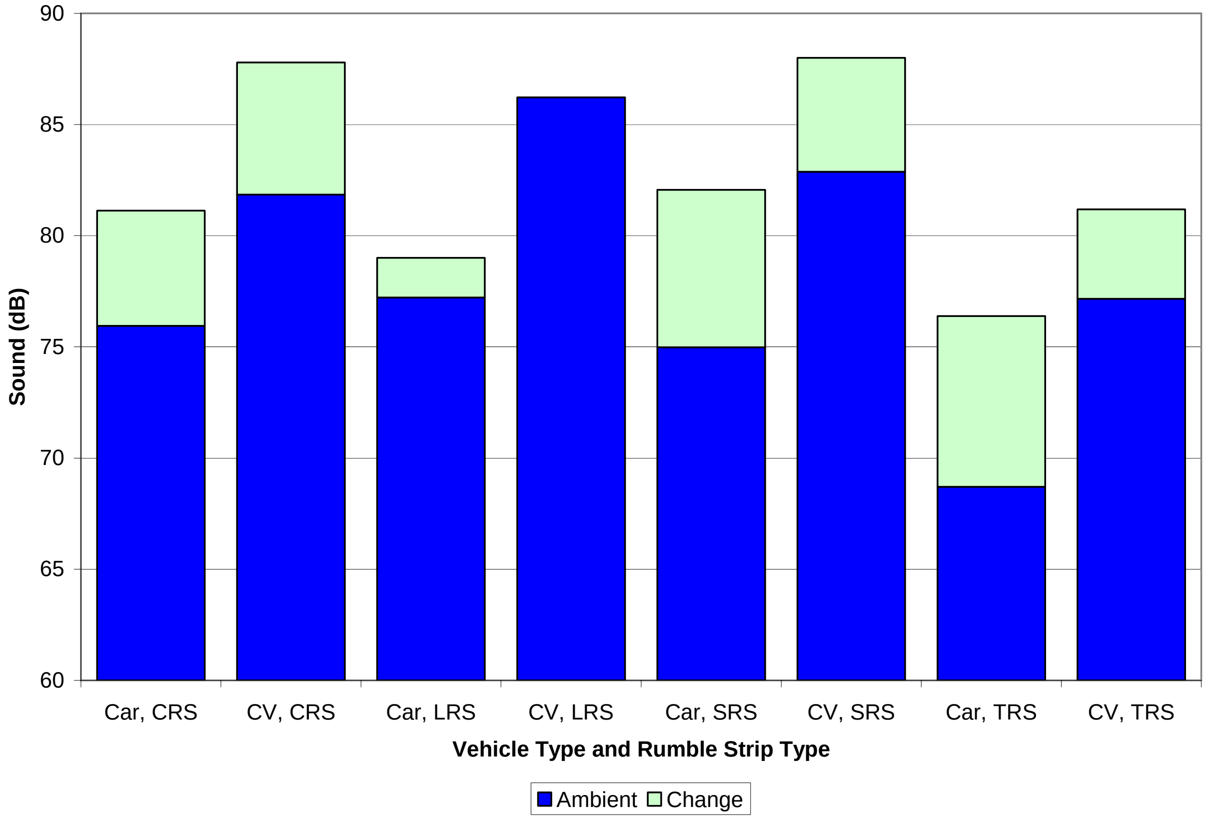


Figure 37. Change in Sound outside Vehicle at 55 mph by Rumble Strip Type.

Now that a general comparison of sound and vibration data under ambient and rumble strip conditions has been established, the remainder of this analysis is focused on the change between the two conditions by application, pavement type, and dimensions.

Application

With respect to rumble strip application, rumble strips were categorized as button, profile, rolled, milled, or transverse. For the profile and rolled applications, the pavement type and dimensions were constant across the sites. This was not the case for the other applications. The button applications varied in spacing, the TRSs varied by pavement type, length, and height, and the milled applications varied by pavement type, width, and spacing. The effect of pavement type, width, and spacing on the sound and vibration of milled rumble strips is discussed later. The button and TRSs relationships were not further investigated due to the limited amount of data.

For each vehicle and speed, all of the different applications provided a 2 dB increase or better, as shown in Figure 38, but a 4 dB or greater increase in sound was only observed inside the sedan and the ½ ton truck. Across all rumble strip applications and speeds, the sound increase inside the sedan and ½ ton truck ranged from 6 to 15 dB. In the case of the commercial vehicle, the increase inside the vehicle was the smallest (≤ 3 dB) with the differences between the different applications within 2 dB of each other.

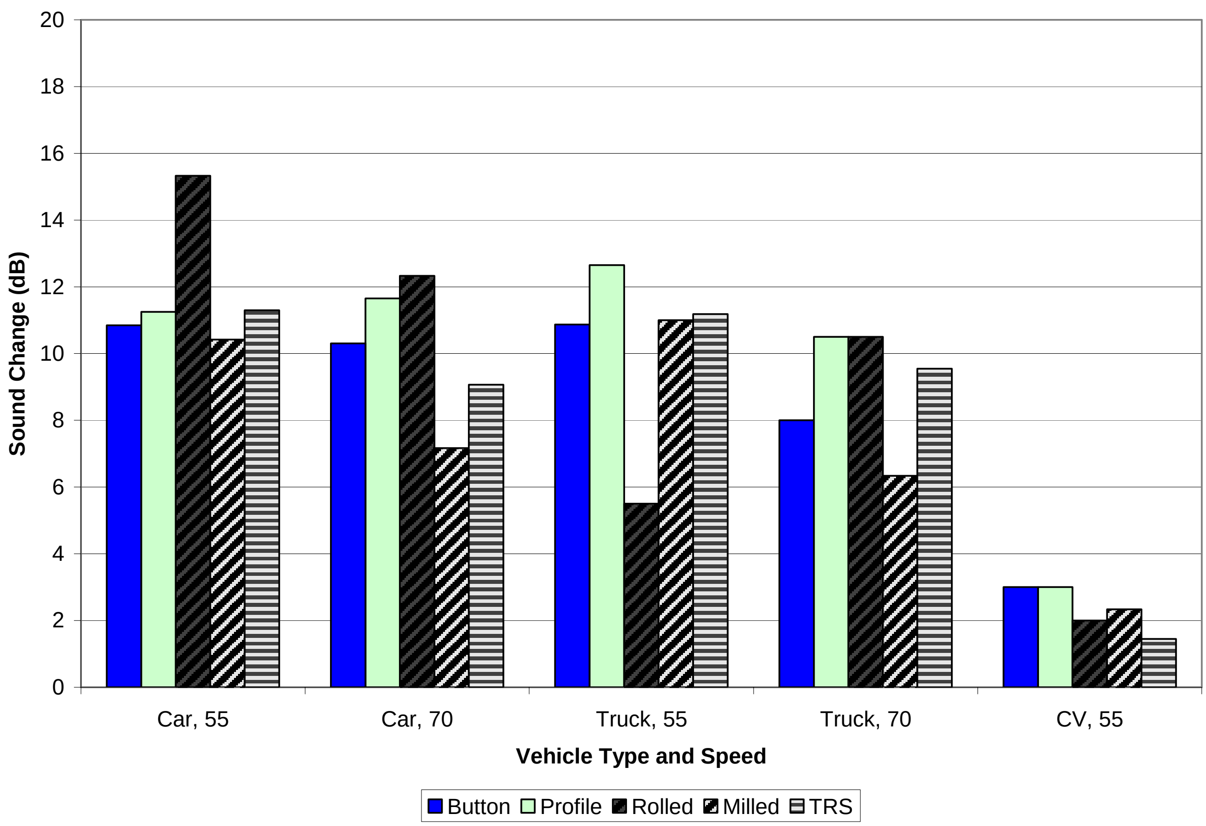
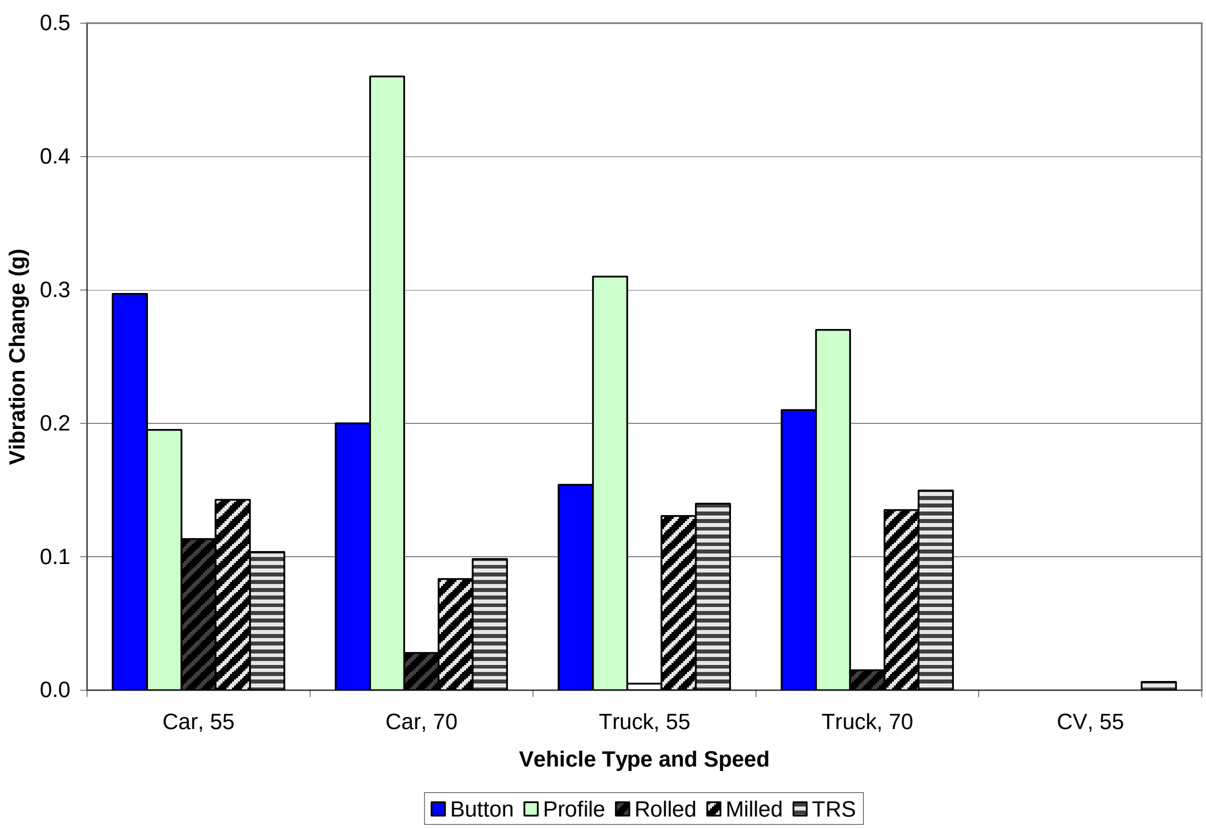


Figure 38. Change in Sound inside Vehicle by Rumble Strip Application.

Focusing on the sedan and ½ ton truck results, within each vehicle/speed condition, the button, profile, and TRS applications yielded similar changes in the inside sound (within 4 dB of each other). The rolled and milled applications did not result in such consistent results. At 70 mph, the sound increase caused by the rolled applications was similar to that of the button and profile applications. However, for the rolled applications at 55 mph, the sound increase in the sedan was 4 dB greater than the other types of rumble strip applications, and the sound increase in the truck was considerably less than the other applications (6 dB versus 12 dB). For the milled applications, the results were consistent with the button and profile applications at 55 mph, but at 70 mph the milled application generated the lowest increase in sound (6 to 7 dB).

From Figure 39, it appears that profile rumble strips typically generate the most vibration (0.20 to 0.46 g). Button, milled, and TRS applications seem to have similar and consistent performance, but in most cases, they generate less vibration than profile. Rolled rumble strips generate the least vibration. Vibration induced when crossing rumble strips does not seem to reach the cab of the commercial vehicle, because recorded vibration between the ambient and rumble strip condition was the same. Therefore, it would appear that a commercial driver would only have the stimulus of sound to alert him/her. However, assuming a 4 dB threshold is needed for drivers to be alerted to change in ambient sound, the sound increase provided by all the rumble strip applications examined in this project (when collapsed across other factors) would not be sufficient (Figure 38).



[a] For the commercial vehicle at 55 mph, the change in vibration between the ambient and rumble strip conditions was approximately zero for all of the rumble strip applications except TRSs.

Figure 39. Change in Vibration inside Vehicle by Rumble Strip Application. [a]

In Figure 40, rolled rumble strips create the largest increase in outside sound (9 to12 dB) resulting in outside sound levels between 84 and 91 dB. TRSs produced a 4 to 10 dB change in the outside sound, raising the outside sound between 76 and 81 dB. The other three applications preformed similarly (3 to 7 dB change generating 78 to 88 dB), with buttons typically yielding the lowest change across the applications, vehicles, and speeds. In general, the change in the outside sound was greater in the sedan than in the commercial vehicle and greater at higher speeds.

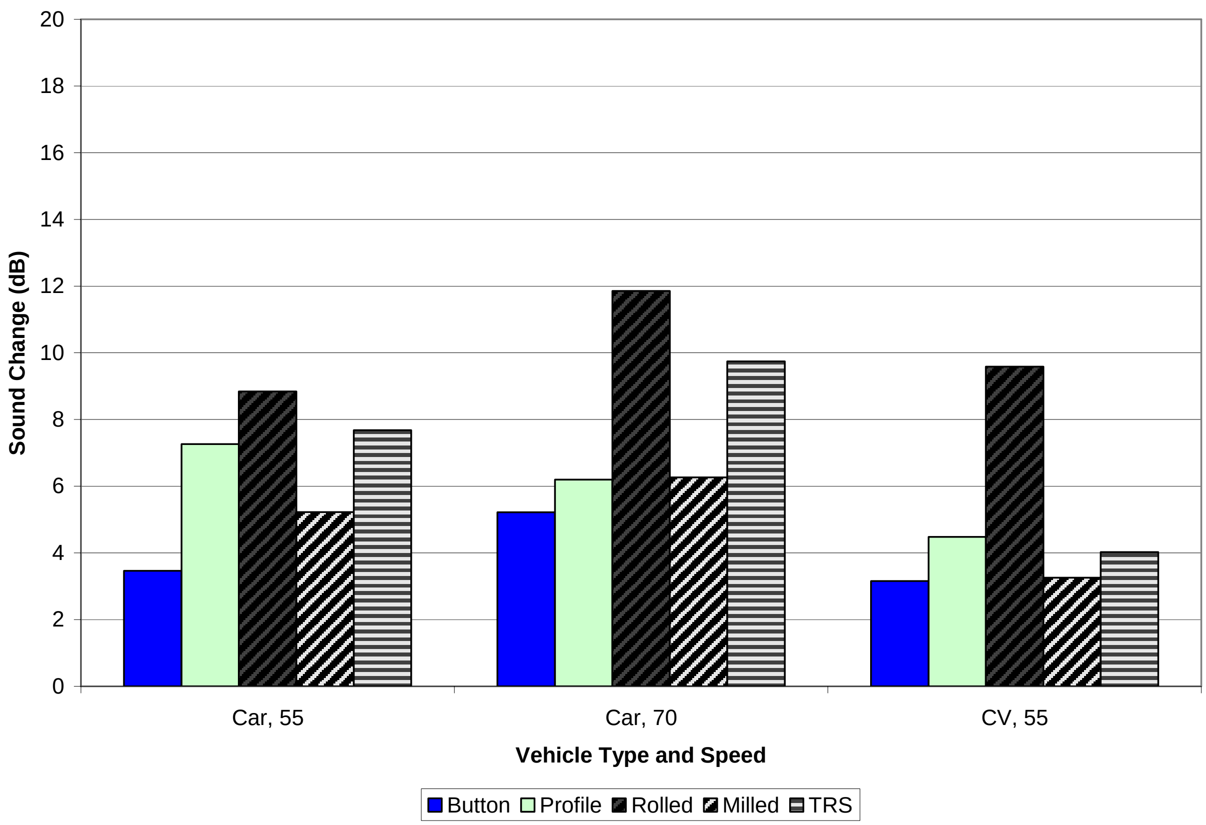
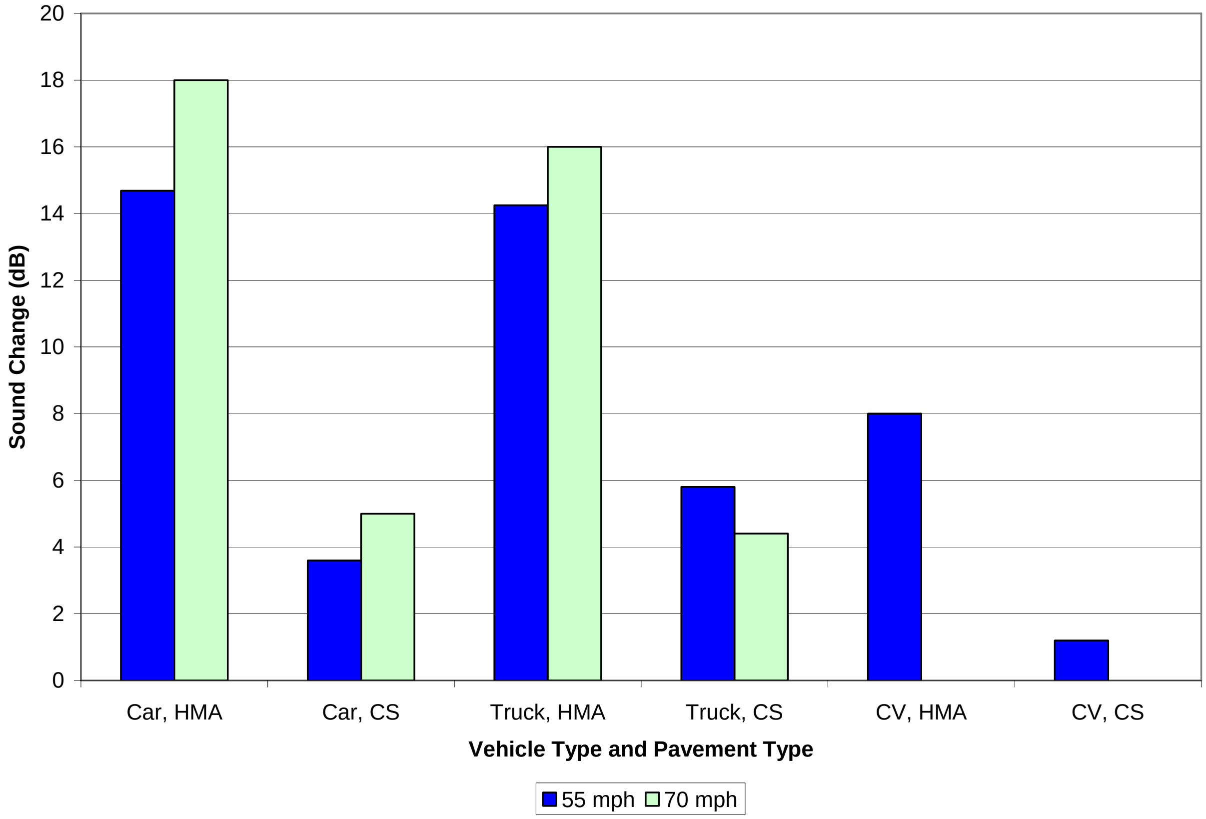


Figure 40. Change in Sound outside Vehicle by Rumble Strip Application.

Pavement

In order to examine the effect of pavement type, only the milled rumble strip application data were used. In general, the increase in sound and vibration was higher for rumble strips placed on hot-mix asphalt (HMA) versus chipseal (CS) (see Figure 41 through Figure 43). On HMA, an increase in speed appears to increase the sound (inside and outside) and vibration.

This was not the case on chipseal which produced mixed results. For all speeds and vehicles tested, the inside sound increase on HMA was above 4 dB. On chipseal, the increase in sound was only above 4 dB for the ½ ton truck at both speeds and the sedan at 70 mph.

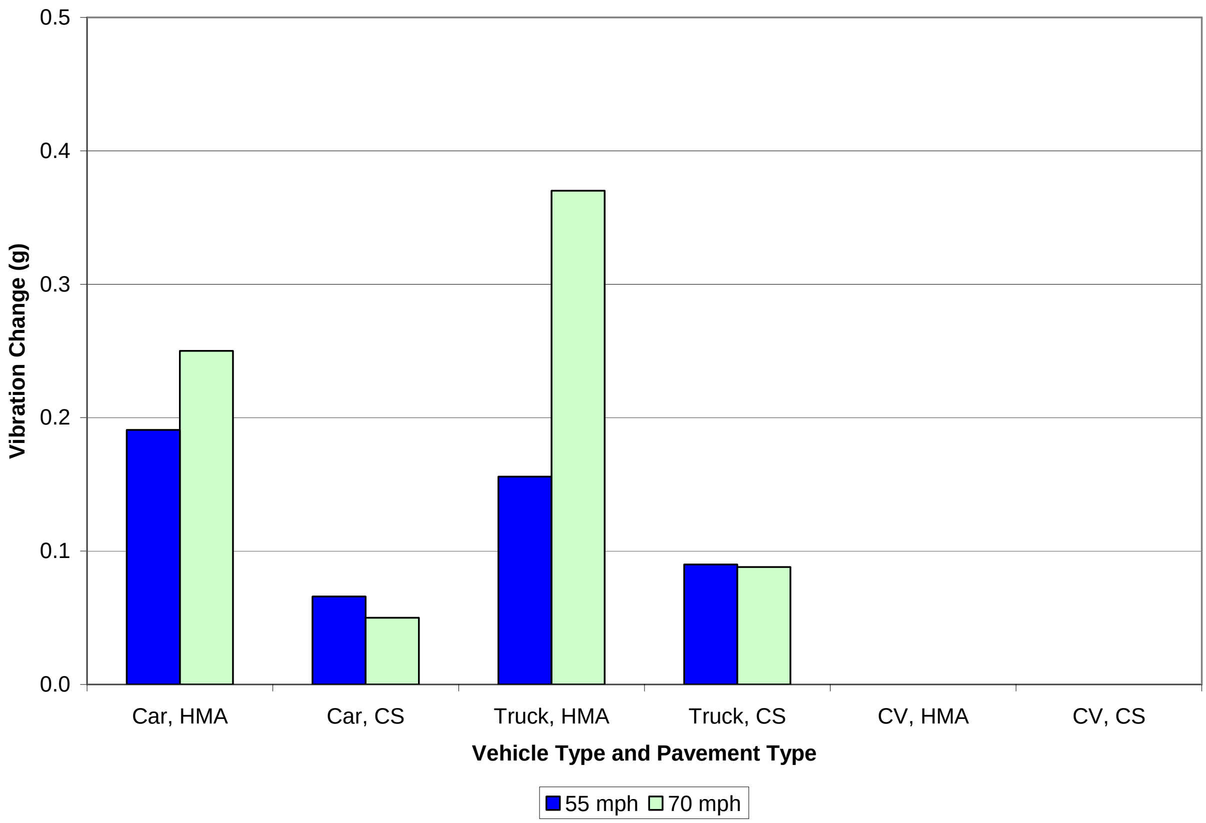


[a] Data were not collected for the commercial vehicle at 70 mph.

Figure 41. Change in Sound inside Vehicle for Milled by Pavement Type. [a]

On HMA between 55 and 70 mph, the vibration increase more than doubled (0.16 to 0.37 g) for the ½ ton truck and increased by 32 percent (0.19 to 0.25 g) for the sedan. The change in vibration on chipseal between the two speeds was minimal. For both pavement types, the milled applications did not produce a measurable change in vibration in the commercial vehicle.

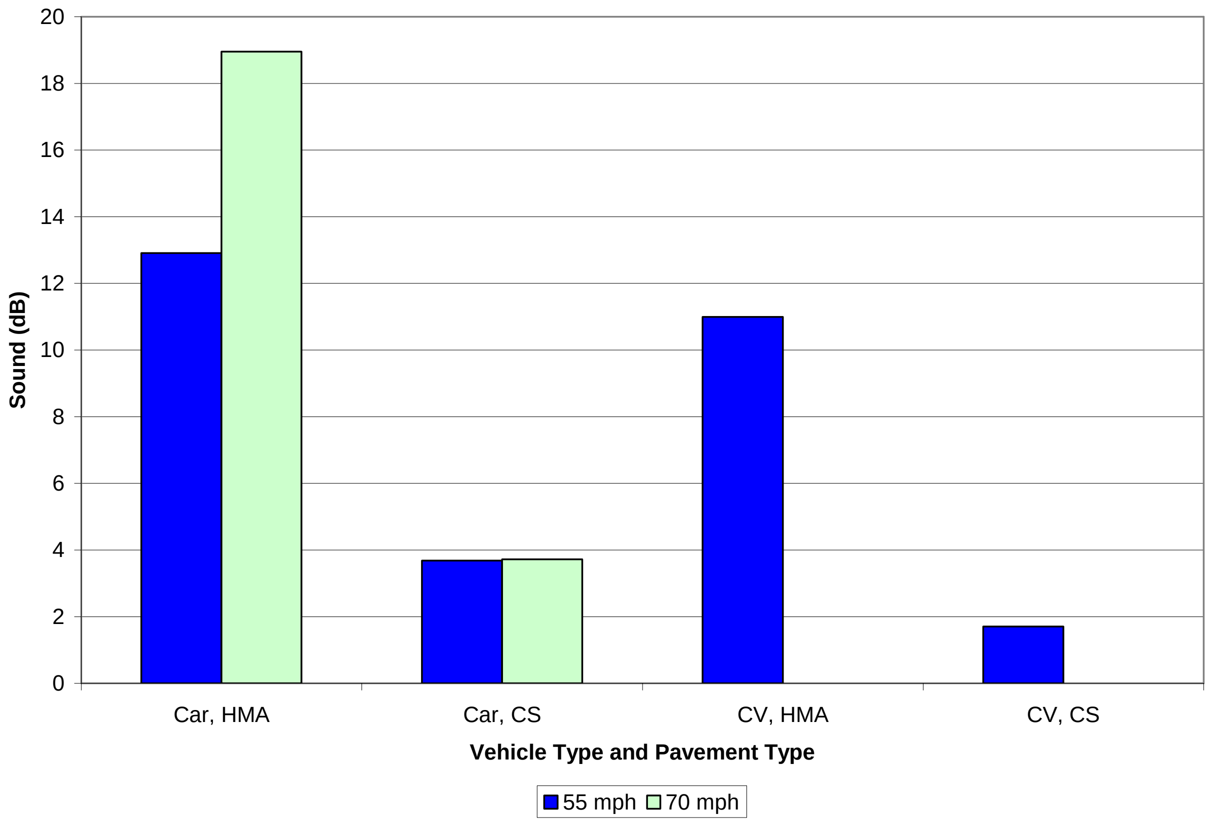
With respect to the outside sound, for all speeds and vehicles, HMA resulted in the largest increase (11 to 19 dB). When traversing the milled applications on HMA, the outside sound levels generated by the sedan were 84 and 94 dB (55 and 70 mph, respectively) and the commercial vehicle produced 93 dB (55 mph). The outside sound levels while traveling on the milled rumble strips on chipseal were lower than on HMA with the sedan producing 81 and 84 dB (55 and 70 mph, respectively) and the commercial vehicle generating 87 dB (55 mph).



[a] Data were not collected for the commercial vehicle at 70 mph. For the commercial vehicle at 55 mph, the change in vibration between the ambient and rumble strip conditions was approximately zero for both types of pavement.

Figure 42. Change in Vibration inside Vehicle for Milled by Pavement Type. [a]

It is believed that the larger changes for HMA are the result of the ambient chipseal conditions masking the additional sensory information created by the rumble strips. Under ambient conditions, chipseal generates more sound (inside and outside) than HMA. Auditory information is comprised of multiple sounds; thus, the sound generated by the car traversing over the chipseal pavement alone is competing with the additional sound created by traveling on the milled rumble strips. Since the ambient sound is greater on chipseal, the chipseal pavement tends to mask the additional sound created by the rumble strips more than HMA pavement which produces less ambient sound.



[a] Data were not collected for the commercial vehicle at 70 mph.

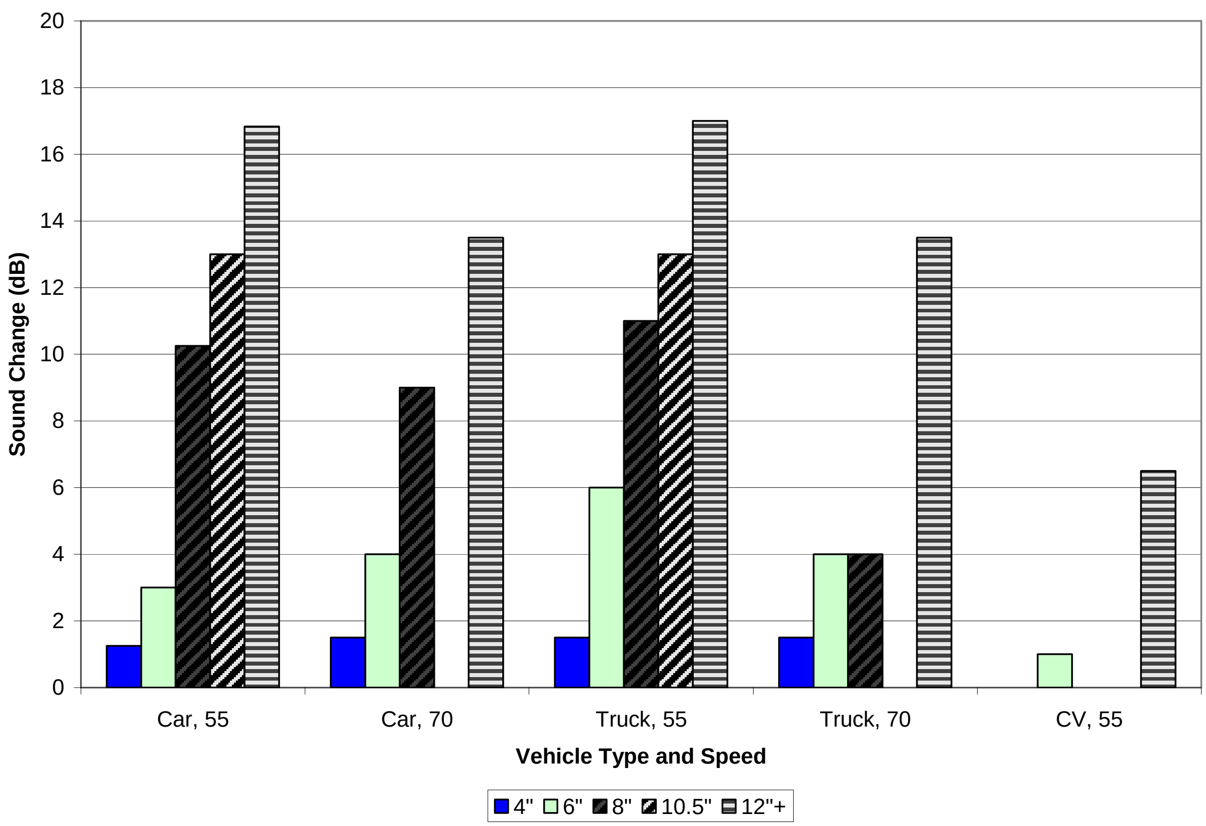
Figure 43. Change in Sound outside Vehicle for Milled by Pavement Type. [a]

Dimensions

There are four factors with respect to rumble strip dimensions that can affect the sound and vibration generated when crossing rumble strips, and they are width, length, depth/height, and spacing. Only the effect of width and spacing are analyzed in this section since most of the applications evaluated did not vary in length or depth/height. In order to investigate the effects of width and spacing on sound and vibration, the data analysis was limited to milled rumble strips because more data with respect to these two dimensions were available for milled rumble strips than any other application of rumble strips.

Width

Figure 44 and Figure 45 show that the change in sound and vibration inside the sedan more than doubled when the rumble strips went from 6 to 8 inches at 55 and 70 mph, and the increase in sound was more than 4 dB for 8 inches and wider. As the width increased beyond 8 inches, increases in the inside sound and vibration were still observed, but it appears the largest increase occurred at 8 inches when the tire was able to almost drop completely into the rumble strip. The largest increase in vibration occurred for widths 12 inches or greater.

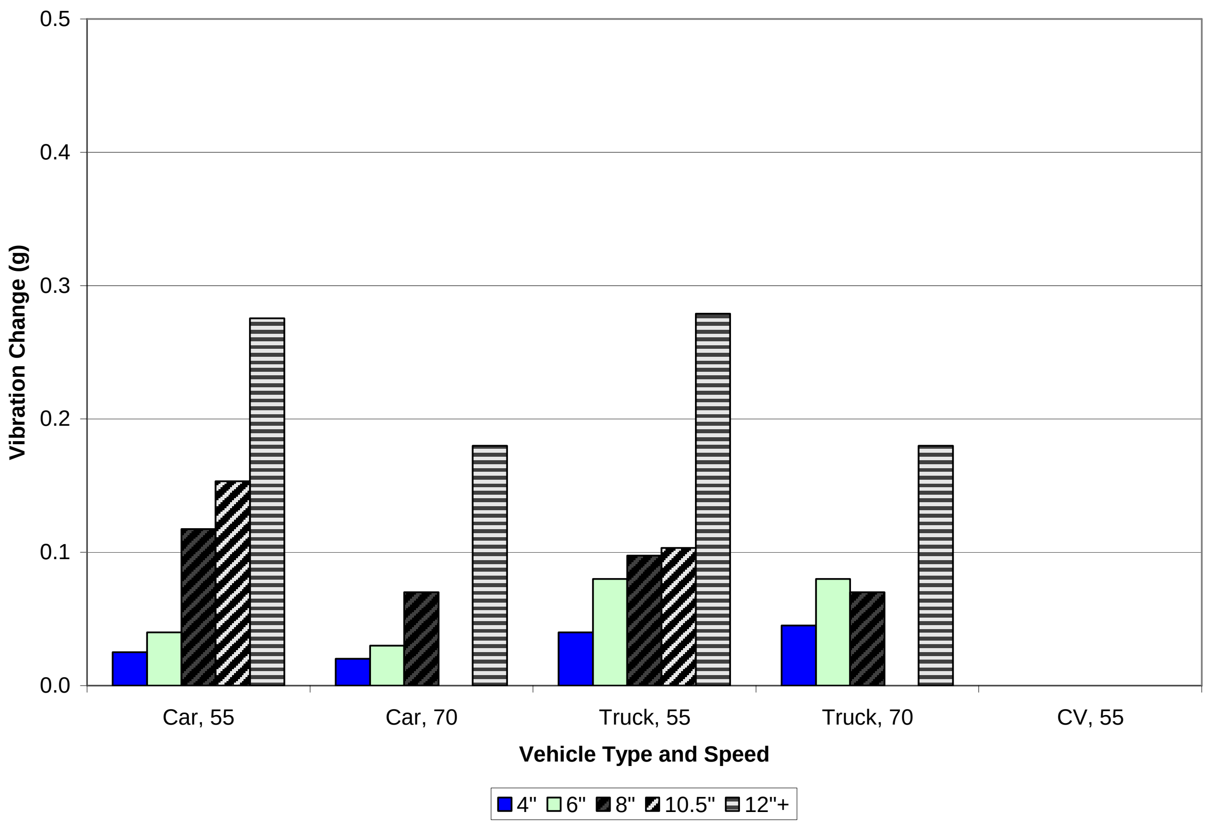


[a] Data were not collected for 10.5-inch width milled rumble strips in the sedan and truck at 70 mph and in the commercial vehicle at 55 mph. For the commercial vehicle at 55 mph, the change in sound between the ambient and rumble strip conditions was approximately zero for the 4-inch and 8-inch widths.

Figure 44. Change in Sound inside Vehicle for Milled by Width. [a]

For the ½ ton truck, the increase in sound inside the vehicle was at or above 4 dB for 6 inches and wider. The largest increase occurred at widths 12 inches or greater which was wider than the tire and thus allowed for maximum tire displacement. It was expected that the largest increase in sound and vibration would occur at 10.5 inches because the tire width was

10 inches; however, data could not be collected at 70 mph and so the results are limited. Similar to the sedan, the largest increase in vibration occurred for widths 12 inches or greater.



[a] Data were not collected for 10.5-inch width milled rumble strips in the sedan and truck at 70 mph and in the commercial vehicle at 55 mph. For the commercial vehicle at 55 mph, the change in vibration between the ambient and rumble strip conditions was approximately zero for all widths.

Figure 45. Change in Vibration inside Vehicle for Milled by Width. [a]

The trend for the commercial vehicle inside sound data is comparable to that of the ½ ton truck with the largest increase occurring at widths 12 inches or greater. However, no change was observed with regard to vibration at any width. It is believed that this is the result of the amount of dampening that may have occurred due to the weight and size of the vehicle; thus, it may have required more energy to transmit the vibration from the tires to the seat of the driver. Based on these results, drivers of commercial vehicles may not feel the change in vibration caused by crossing rumble strips, and hence, the change in sound from contacting rumble strips would play an even more important role in alerting commercial vehicle drivers. These findings support those stated previously with regard to application. It is important to note that this is the first instance that an increase in sound inside the commercial vehicle was at or above 4 dB, and it was for 12 inches and wider milled installations.

Figure 46 shows the change in sound outside the sedan and commercial vehicle was the largest (8 to 14 dB) when the width was 12 inches or greater. For widths less than or equal to 8 inches, the outside sound levels while traversing over the milled rumble strips ranged from 79 to 86 dB, compared to 84 and 91 dB for widths 12 inches or greater.

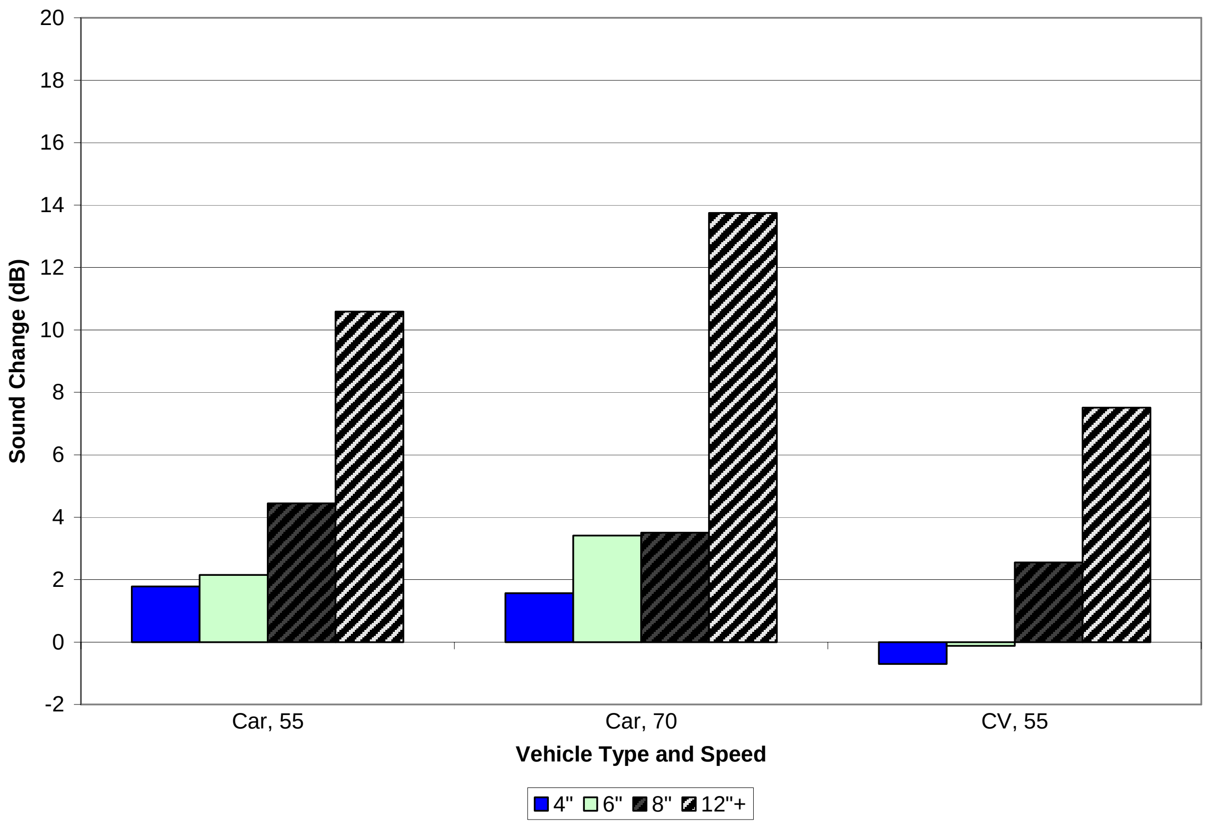
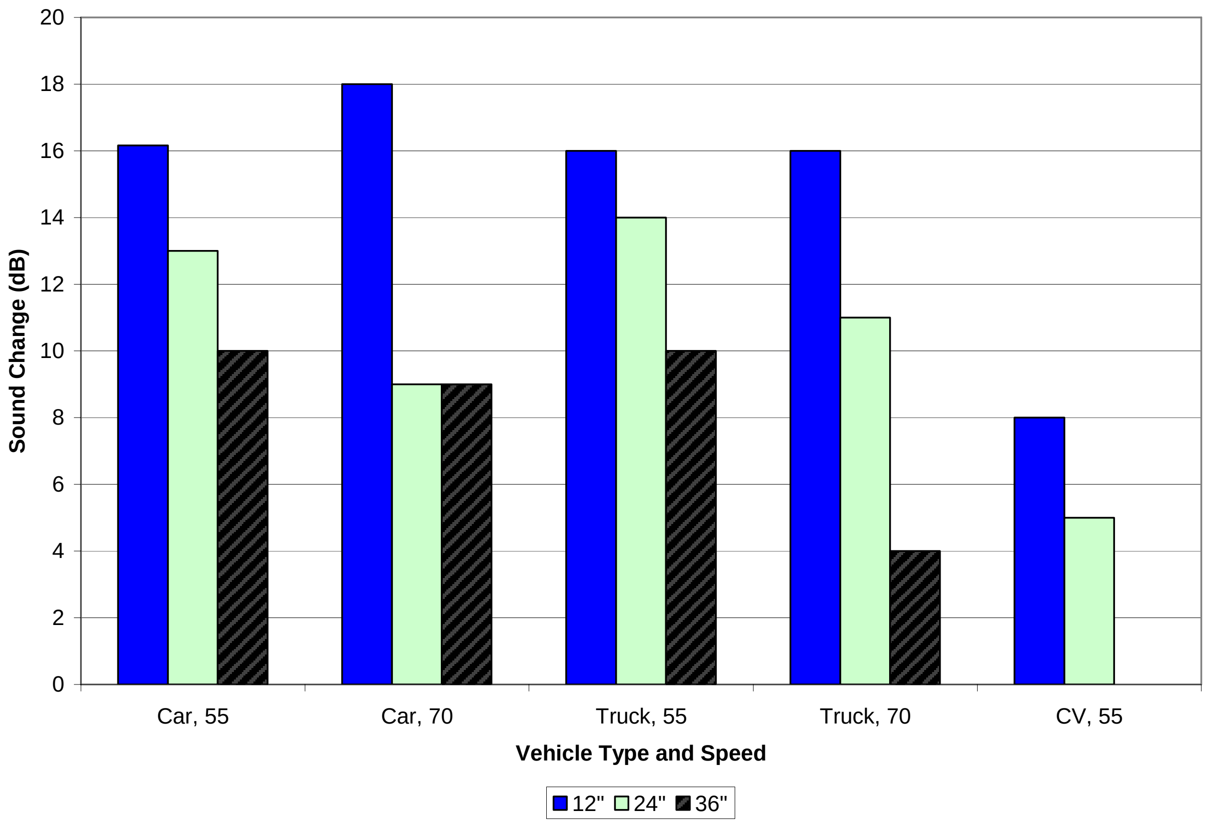


Figure 46. Change in Sound outside Vehicle for Milled by Width.

Spacing

Based on the findings with regard to width, the spacing analysis focused on data collected for milled rumble strips of an 8-inch width or greater. As shown in Figure 47 through Figure 49, sound (inside and outside) and vibration decrease as spacing increases. The inside sound was at or above 4 dB for all vehicles, speeds, and spacings with the exception of the 36-inch spacing for the commercial vehicle. The change in outside sound was greatest for the 12-inch spacing (13 to

19 dB) which produced between 84 and 94 dB when traveling over the milled rumble strips compared to the 36-inch spacing which generated between 82 and 85 dB.

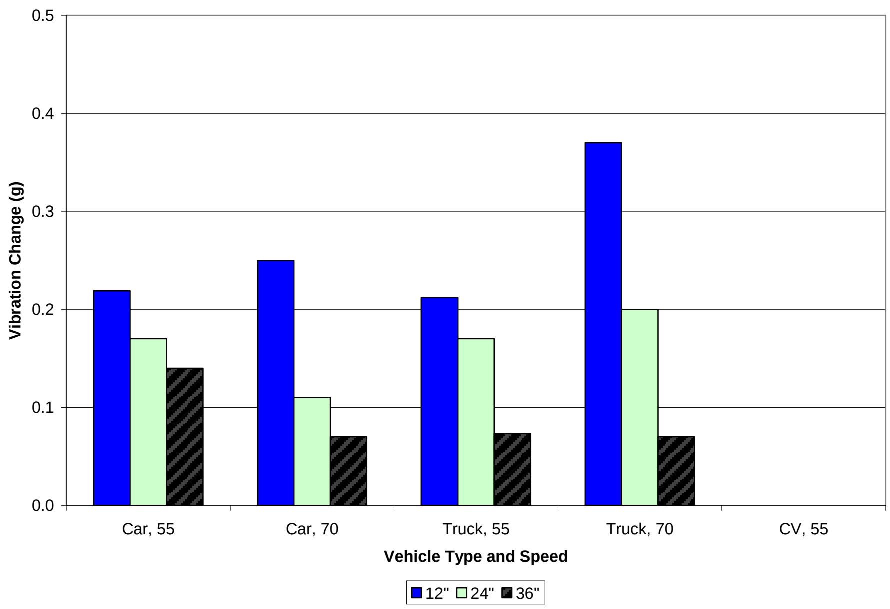


[a] For the commercial vehicle at 55 mph, the change in sound between the ambient and rumble strip conditions was approximately zero for 36-inch spacing.

Figure 47. Change in Sound inside Vehicle for Milled (8 inches or wider) by Spacing. [a]

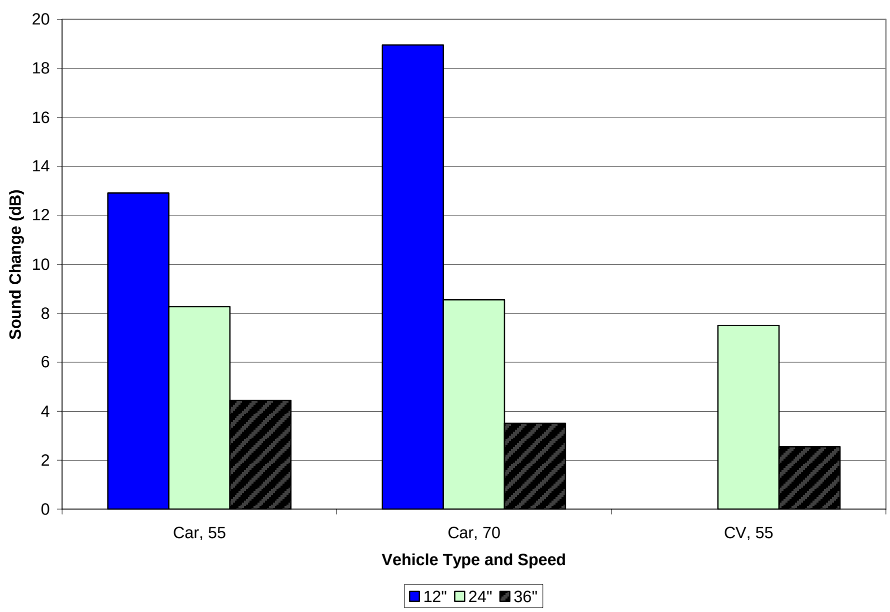
SUMMARY AND CONCLUSIONS

Researchers conducted a literature review on the effects of rumble strip design on sound and vibration, measured the inside sound and vibration in three different types of vehicles under two different speeds, and measured the outside sound produced by two different types of vehicles under two different speeds. These tasks were completed in order to quantify the impact various types and designs of rumble strips installed in Texas have on drivers and the public living and working near roadways with rumble strips.



[a] For the commercial vehicle at 55 mph, the change in vibration between the ambient and rumble strip conditions was approximately zero for all spacings.

Figure 48. Change in Vibration inside Vehicle for Milled (8 inches or wider) by Spacing. [a]



[a] Data were not collected for 12-inch spacing in the commercial vehicle.

Figure 49. Change in Sound outside Vehicle for Milled (8 inches or wider) by Spacing. [a]

It was found that there was adequate sound (increase of 4 dB or more generated to alert drivers in the sedan and ½ ton truck by all types and applications of rumble strips investigated with the exception of LRSs and milled rumble strips of less than 8-inch width. Only the milled rumble strip application of 12 inches or wider provided enough sound increase to alert drivers of commercial vehicles. The inside sound was at or above 4 dB for all of the spacings under all conditions examined with the exception of the 36-inch spacing for the commercial vehicle.

With regard to vibration, the researchers could not find justification for a particular level of vibration required to alert drivers, but the results of this report appear to be within reason of other reports *(44)*. None of the rumble strip designs investigated appeared to provide enough change in vibration for the commercial vehicle. Thus, the change in sound from contacting the rumble strips plays an even more important role in alerting commercial vehicle drivers.

In general, the increase in the sound outside of the vehicle generated by traversing over the rumble strips was greater in the sedan than in the commercial vehicle and was greater at 70 mph than 55 mph. The rolled rumble strips created the largest increase in outside sound 9 to 12 dB, closely followed by TRSs (4 to 10 dB). Button, profile, and milled applications yielded similar changes in the outside sound (3 to 7 dB). Milled rumble strip applications of 12 inches or wider resulted in an 8 to 14 dB increase in the outside sound, while those 8 inches or less in width only increased the outside sound by 4 dB or less. With respect to spacing, the increase in outside sound was the greatest for milled rumble strip applications with 12-inch spacing (13 to 19 dB). The 24-inch and 36-inch spacings yielded increases in the outside sound of 9 dB or less.

It was found that pavement type also affects the change in sound and vibration generated by traveling on milled rumble strips. In general, the increase in sound and vibration was higher for milled rumble strips placed on HMA versus chipseal. On HMA, all of the milled rumble strip applications generated a sound increase inside the vehicle above 4 dB. The sound increase inside the vehicle produced by traveling on the milled rumble strips on chipseal was only above 4 dB for the ½ truck at both speeds and the sedan at 70 mph. In addition, the change in vibration on chipseal was minimal for all conditions. The change in the sound outside of the vehicle was less than 4 dB on chipseal and ranged from 11 to 19 dB on HMA.

Considering the need for drivers to be alerted and the impact on the public living and working near roadways with rumble strips, researchers developed the recommendations below with respect to the application of rumble strips. These recommendations are based on the findings of this research project and thus do not consider other issues such as cost and maintenance.

- For longitudinal applications, button, profile, and milled rumble strips are recommended over the use of rolled rumble strips since these three types of rumble strips produce adequate sound change inside the vehicle to alert a driver, while minimizing the sound increase in the surrounding environment.
- In order to alert drivers of passenger vehicles, milled rumble strips should be 8 inches or greater in width and spaced no more than 36 inches apart.
- When possible, the width of milled rumble strips should be at least 12 inches and the spacing should be no more than 24 inches in order to accommodate commercial vehicle drivers.
- Practitioners should consider the pavement type when deciding on the design of milled rumble strips. In general, milled rumble strips on chipseal produce smaller increases in the sound (inside and outside the vehicle) and vibration than those on HMA. Thus, practitioners should consider more aggressive designs when installing rumble strips on chipseal. More specific recommendations with respect to minimum width and maximum spacing on HMA and chipseal could not be made due to a limited amount of data.

In addition, researchers recommend that future research projects investigate the following:

- minimum sound and vibration thresholds required to alert a driver and required to enable inattentive drivers to differentiate between the location of the rumble strip to ensure the appropriate corrective action is taken,
- durability of button and profile rumble strip applications with respect to reductions in sound and vibration over time and maintenance requirements for replacement,
- frequency of hits received and the duration of these events for various types and applications of rumble strips, and
- minimum sound thresholds in the surrounding environment required before alternatives need to be considered.

CHAPTER 8
SUMMARY OF RECOMMENDATIONS

The following sections summarize the researchers' recommendations with respect to each of the pavement marking materials investigated as part of this research project.

YELLOW-GREEN CROSSWALK MARKINGS

Based on the phone survey, only a limited number of the ongoing YG crosswalk marking evaluations have been completed. Thus, at this time researchers did not develop recommendations concerning the use of YG markings at school crosswalks. Instead, researchers recommend that guidelines be developed after the ongoing evaluations are completed. In addition, researchers recommend that a driver behavior study utilizing motorist compliance (percent of motorists yielding/stopping for pedestrians) as a measure of effectiveness be conducted. Researchers also recommend conducting a motorist survey downstream of the location where the motorist compliance data are collected. This survey could include questions concerning the following:

- whether the motorist noticed the crosswalk;
- the design of the crosswalk (e.g., what color was the crosswalk?);
- whether the motorist noticed the pedestrian; and
- why the motorist did or did not yield/stop for the pedestrian.

IN-ROADWAY WARNING LIGHTS

The installation of IRWLs is addressed in the MUTCD (*1*) and Texas MUTCD (*2*); however, these manuals do not provide practitioners with specific criteria for determining when and where IRWLs are needed or justified. As part of an ongoing TCRP/NCHRP project, researchers are planning to develop one set of quantitative guidelines that provides advice on the use of a number of pedestrian crossing treatments including IRWLs. However, in the interim TxDOT needs guidance with respect to installation of IRWLs to ensure statewide uniformity. Based on the review of previous research, researchers recommended that TxDOT utilize the following criteria to determine if IRWLs should be considered as a potential crosswalk enhancement:

- An engineering study should be conducted to determine if there is a pedestrian safety problem (*22*, *23*, *25*).
- The location must have a marked crosswalk with applicable warning signs (*1*, *2*).
- Alternative measures to mitigate the pedestrian safety problem should have been tried and proven unsuccessful or engineering judgment should have determined that other alternative measures are not feasible (*25*).
- The 85th percentile speed of vehicles approaching the crosswalk from either direction should not be more than 45 mph (*23-25*).
- The average daily traffic on the street being crossed should be between 5000 and 30,000 vpd (*6*, *24*, *25*), or vehicular volume through the crossing should exceed 200 vph in urban areas or 140 vph in rural areas during peak-hour pedestrian usage (*23*, *25*).
- The daily pedestrian crossing volume should be at least 100 ppd (*6*, *12*, *13*, *24*, *25*) or at least 40 pedestrians should regularly use the crossing during each of any two hours (not necessarily consecutive) during a 24-hour period *(23*, *25*).
- The existing stopping sight distance from both directions should not be less than the stopping sight distance criteria in the current version of the TxDOT *Roadway Design Manual* (*27*).

These guidelines do not address all situations. Thus, the final decision as to whether to install IRWLs at a location should be left to engineering judgment.

FLUORESCENT ORANGE RRPMS

During this project, researchers conducted a color recognition study to determine whether drivers can correctly distinguish the color of the fluorescent orange RRPMs from traditional RRPM colors, especially red RRPMs. Under all conditions, the Type 1 fluorescent orange RRPMs were only incorrectly identified as red by one subject (8 percent). In contrast, the Type 2 fluorescent orange RRPMs were mistaken for red RRPMs by six subjects (50 percent). Researchers recommend additional research to determine whether motorists understand the meaning of fluorescent orange RRPMs and to identify the most effective application(s) of fluorescent orange RRPMs.

"REMOVABLE" PAVEMENT MARKING PAINT

The "removable" pavement marking paint showed promise as it can be applied and removed with existing equipment. In addition, the patented remover does eliminate the markings without scarring the pavement like some other eradication methods. However, the durability of the white "removable" paint at the field locations was less than ideal (retroreflectivity values less than 150 mcd/m^2/lux) but researchers believe that this was due to installation complications. Thus, researchers recommend that further field testing of the "removable" pavement marking paint be conducted in work zones where temporary changes in alignment need to be delineated for a short period of time. The field testing should evaluate the retroreflectivity and chromaticity of both colors of paint (yellow and white) and the ease of removal of the product on an actual roadway.

RUMBLE STRIPS

Considering the need for drivers to be alerted and the impact on the public living and working near roadways with rumble strips, researchers developed the recommendations below with respect to the application of rumble strips. These recommendations are based on the sound and vibration evaluations conducted as part of this research project and thus do not consider other issues such as cost and maintenance.

- For longitudinal applications, button, profile, and milled rumble strips are recommended over the use of rolled rumble strips since these three types of rumble strips produce adequate sound change inside the vehicle to alert a driver, while minimizing the sound increase in the surrounding environment.
- In order to alert drivers of passenger vehicles, milled rumble strips should be 8 inches or greater in width and spaced no more than 36 inches apart.
- When possible, the width of milled rumble strips should be at least 12 inches and the spacing should be no more than 24 inches in order to accommodate commercial vehicle drivers.
- Practitioners should consider the pavement type when deciding on the design of milled rumble strips. In general, milled rumble strips on chipseal produce smaller increases in the sound (inside and outside the vehicle) and vibration than those on HMA. Thus, practitioners should consider more aggressive designs when installing

rumble strips on chipseal. More specific recommendations with respect to minimum width and maximum spacing on HMA and chipseal could not be made due to a limited amount of data.

In addition, researchers recommend that future research projects investigate the following:

- minimum sound and vibration thresholds required to alert a driver and required to enable inattentive drivers to differentiate between the location of the rumble strip to ensure the appropriate corrective action is taken,
- durability of button and profile rumble strip applications with respect to reductions in sound and vibration over time and maintenance requirements for replacement,
- frequency of hits received and the duration of these events for various types and applications of rumble strips, and
- minimum sound thresholds in the surrounding environment required before alternatives need to be considered.

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APPENDIX A
SURVEY OF TXDOT DISTRICT CROSSWALK DESIGN PRACTICES

SURVEY OF CROSSWALK DESIGN PRACTICES

The Texas Transportation Institute (TTI) is currently conducting research for the Texas Department of Transportation (TxDOT). The objectives of this research are to evaluate experimental pavement marking materials and identify the most effective application(s). Your help is needed to make this project a success.

Two of the experimental pavement markings being investigated are designed to be used at crosswalks in school zones. As a preliminary task, TTI is surveying districts to identify current practices and solicit feedback. The information collected will be used to develop potential applications for the experimental pavement markings and identify locations for future evaluations.

The person responding to the survey should be familiar with your district's crosswalk design practices. Our intent is for you to spend less than 10 minutes on the survey.

Please return the completed survey **by June 18, 2004** to Melisa Finley. Please contact Melisa if you have any questions or comments. Thank you in advance for your time!

Melisa D. Finley, P.E.
Assistant Research Engineer
Texas Transportation Institute
3135 TAMU
College Station, Texas 77843-3135
Phone: 979-845-7596
Fax: 979-845-6006
Email: m-finley@tamu.edu

SECTION 1: CONTACT INFORMATION

Name: ______________________________ Date: ______________________________

Title: ______________________________ District: ______________________________

Phone: ______________________________ Fax: ______________________________

Address: ______________________________ City/Zip Code: ______________________________

Email: ______________________________

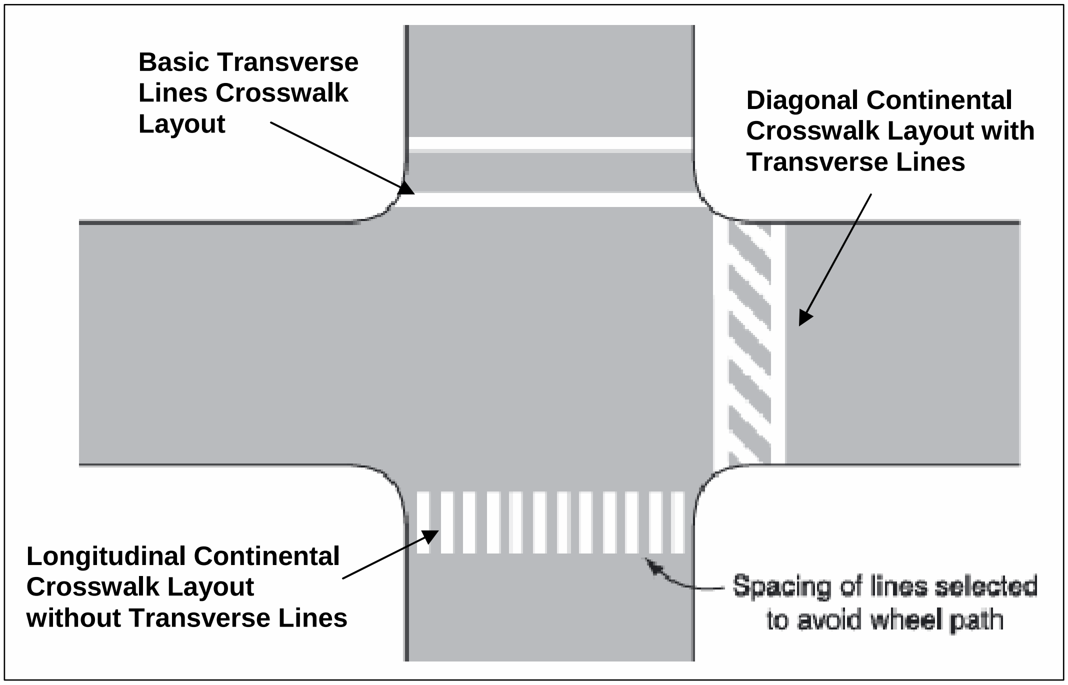
SECTION 2: SURVEY QUESTIONS

1) In your district, approximately how many school zones are located on state roadways? _____

2) Approximately how many of these school zones include crosswalks? ___________________

3) In your district, approximately how many crosswalks are located in school zones on state roadways? ____

The 2003 Texas MUTCD documents three typical crosswalk designs: transverse (basic layout), diagonal continental, and longitudinal continental. These three designs are shown in the figure below. Transverse crosswalk markings are between 6 inches and 24 inches wide, and should not be spaced less than 6 ft apart. For added visibility, diagonal lines at a 45 degree angle or longitudinal lines parallel to traffic may be used. When diagonal or longitudinal lines are used, the transverse markings may be omitted.



4) What type(s) of crosswalk design(s) does your district use <u>in school zones</u>? Please explain why. Feel free to attach sketches.

____
____
____
____
____
____

5) If you had to choose one design for crosswalks <u>located in school zones</u>, what would it be? (Does not matter if crosswalk design is in MUTCD.) Please explain why.

____
____
____
____
____
____

6) In your district, does the design of crosswalks <u>located in school zones</u> differ from those <u>located outside of school zones</u>? Please explain why.

____
____
____
____
____
____

7) What types of devices (e.g., beacons, pavement word or symbol markings, signs, etc.) does your district use to enhance crosswalks <u>located in school zones</u>? Please explain why.

____
____
____
____
____
____

8) What types of new devices or innovative designs should the researchers consider within the study? How would these devices or designs enhance TxDOT's current practices? Please explain.

____
____
____
____
____

Table A1. District Survey Contacts.

District	Participant	Position
Abilene	Roy Wright	Director of Transportation Operations
Amarillo		
Atlanta	Carlos Ibarra	Director of Transportation Operations
Austin	Scott Cunningham	Traffic Engineer
Beaumont	Ted East	Traffic System Supervisor III
Brownwood	Howard Holland	Director of Operations
Bryan	Michael Jedlicka	Transportation Engineer
Childress	Bart Sherrill	Traffic Supervisor
Corpus Christi	Ernie De La Garza	Transportation Engineer
Dallas	Linden Burgess	Traffic Systems Manager
El Paso	Edgar Fino	Traffic Engineer
Fort Worth	Matthew Hendricks	Engineering Specialist II
Houston	Stuart Corder	District Traffic Engineer
Laredo	Guillermo Dougherty	Engineering Assistant
Lubbock	Teddy Copeland	Transportation Operations Engineer
Lufkin	Herbert Bickley	Director of Transportation Operations
Odessa	Mike McAnally	Director of Operations
Paris	Karl Puckett	Engineering Tech V
Pharr	Jesus Leal	Director of Transportation Operations
San Angelo	Angie Ortegon	Transportation Operations Engineer
San Antonio		
Tyler	Peter Eng	Director of Transportation Operations
Waco	Larry Colclasure	Director of Transportation Operations
Wichita Falls	Matthew Smith	Engineering Specialist II
Yoakum	Marla Jasek	Director of Transportation Operations

Blank areas show the districts that did not respond.

APPENDIX B
YELLOW-GREEN PAVEMENT MARKING SURVEYS

YELLOW-GREEN PAVEMENT MARKING QUESTIONNAIRE

CONTACT INFORMATION

Contact Person: ____

Agency: ______________________ Position: ______________________

Telephone Number: ______________ Email: ______________________

Date and Time of Survey: ____

Introduction

Hello. My name is ____________________ and I am with the Texas Transportation Institute. We are currently conducting a research project for the Texas Department of Transportation concerning the evaluation of new pavement marking applications. With this in mind, we contacted FHWA to obtain a list of agencies that are currently experimenting with yellow-green (YG) pavement markings. Do you have a few minutes to answer a few questions about your evaluations? *If not, set up a time to call back and conduct the survey.*

☐ Call back When? (set date and time)____________________________________

QUESTIONS

1) Where have you used the YG markings? *Find out the number of sites, type of roadway (i.e., # of lanes, functional classification, etc.), and what type of crossing (i.e., school or non-school [regular pedestrian crossing]).*______________________________________

____

____

2) What prompted you to try the YG markings?______________________________

____

____

3) How have you applied the YG markings? *Get a detailed description of the layout of the markings. Also note whether all markings are YG or a combination of white and YG is used.*

____

____

4) Do you use FYG signs with the YG markings? *Try to get a description of the layout of the crossing (i.e., other traffic control devices used, especially other YG devices).* ____________

____

____

5) What kind of evaluation are you conducting? *Identify the type of study (e.g., before/after study, control site, etc.) and what data (MOEs) are being collected.*______________________

____

____

6) Where are you at in your evaluation? *Identify the timeline of the evaluation and if there are any data, results, or conclusion/recommendations available.* ___________________________

____

____

7) Do you feel that the YG markings are effective? _____________________________________

____

____

YELLOW-GREEN PAVEMENT MARKING FOLLOW-UP QUESTIONNAIRE

CONTACT INFORMATION

Contact Person: ____
Agency: ______________________ Position: ______________________
Telephone Number: ______________ Email: ______________________

Date and Time of Survey: ______________________________________

QUESTIONS

1) Have you installed yellow-green crosswalks at any additional locations since the first time we spoke? *Find out the number of sites, type of roadway (i.e., # of lanes, functional classification, etc.), and what type of crossing (i.e., school or non-school [regular pedestrian crossing]).* ____
____
____

2) What prompted you to try the YG markings at these new sites?
____
____

3) Do the new sites use the same material and layout as the original sites? If not have you found one material or layout to be better than another? ______________________
____
____

4) Where are you in your evaluation of YG markings? *Identify the timeline of the evaluation and if there are any data, results, or conclusion/recommendations available.* __________
____
____

5) Do you feel that the YG markings are effective? ______________________
____
____

6) Can you email me any preliminary findings you have?
____
____

7) Do you have any pictures you can email me? ______________________
____
____

8) Have you been happy with the performance of the material? (i.e., have you had any issues or concerns with the durability, retroreflectivity, or color stability of the product?) ___________
____
____

APPENDIX C
CITY OF KIRKLAND, WA, CRITERIA FOR LOCATING IRWLS

I. Threshold criteria:

Location must have a marked crosswalk and stopping sight distance must be adequate for approach speed.

II. Engineering (30 points max)

Approach speed 85th percentile (MPH)

Speed	*Points*
<20 or >45	0
20-29 or 41-45	4
30-35	8
36-40	12

ADT (000)

Volume	*Points*
<5 or >30	0
>5-<15 or >25-<30	8
>15-<25	16

Cost
(Above standard costs)

Cost	*Points*
Other	0
Small or no additional cost	2

III. Connections (35 points max)

Distance in feet to nearest crosswalk

Distance	*Points*
<500	0
>500-<1000	4
>1000-<1500	6
>1500	9

What type of facilities does the crosswalk cross and/or continue?
(Priority 1 and 2 Pedestrian facilities are defined in the Non-Motorized Plan.)

Continues/Crosses	*P1*	*P2*	*Other*
P1	8	6	4
P2	6	4	2
Other	4	2	0

Is the crosswalk on school Walk Route?

Yes	6

Is the crosswalk near schools, community facilities, etc.?

	Distance to Center	
Activity Ctr.	*< 1/4 mi*	*<1/2 mi*
School	3 pts	2 pts
Com. Facility	2 pts	1 pt
Business Dist	2 pts	1 pt
Transit/HOV	1-2 pts	0.5-1 pt
Regional Ctr	1 pt	0.5 pt
Connect w/in Business Dist		1 pt

IV. Safety (35 points maximum)

Does the crosswalk serve a vulnerable population?

Yes	13

What is the accident history at the crosswalk?

Experience	*Points*
Less than Average	0
Average	6
More than Average	12

What improvements exist?

Improvements	*Points*
Striped crosswalk	10
Striped+Median or +O'head sign	6
Striped+O'head+Median	2

APPENDIX D
CITY OF FOUNTAIN VALLEY, CA, CRITERIA FOR LOCATING IRWLS

Criteria	Yes or No
1. Type of Pedestrian Crossing The crosswalk must be uncontrolled, marked, and accompanied by applicable warning signs. (The crosswalk cannot be controlled by STOP signs, YIELD signs, or traffic signals.)	________
2. Speed on the Main Street The vehicular approach speed (85th percentile) on the main street to be crossed must be 45 mph or less.	________
3. Average Daily Traffic (ADT) The traffic volume or ADT on the main street to be crossed must be between 5,000 and 30,000 vehicles per day.	________
4. Safe Stopping Distance If the vehicular approach speed on the main street is less than 35 mph, the stopping sight distance must be at least 400 feet prior to the crosswalk. If the vehicular approach speed on the main street is between 35 mph and 40 mph, the stopping sight distance must be at least 500 feet prior to the crosswalk. If the vehicular approach speed on the main street is between 40 mph and 45 mph, the stopping sight distance must be at least 600 feet prior to the crosswalk.	________
5. Pedestrian Volume The crossing must be used by at least 100 pedestrians per day.	________
6. Adjacent Crosswalks or Traffic Control There must be no marked crosswalks or controlled intersections within 300 feet in advance of or following the crosswalk.	________
7. Roadway Cross Section The cross section of the main street to be crossed must be a minimum of three lanes.	________
8. Other Treatments Considered Other treatments for facilitating pedestrians have been considered and the use of in-pavement flashers is most appropriate for site conditions.	________

The installation warrant is satisfied if the requirements for all criteria are met, i.e. all answers are "Yes."

APPENDIX E
ARNOLD RECOMMENDATIONS (*25*)

The following was extracted from a report by E.D. Arnold titled, *Development of Guidelines for In-Roadway Warning Lights* (25).

II. APPROPRIATE LOCATIONS TO INSTALL IN-ROADWAY WARNING LIGHTS

The location being considered for an IRWL must have an identified pedestrian safety problem (pedestrian accidents, near misses, high pedestrian volumes, a sight distance problem, excessive speeding, etc.). The location must have a marked crosswalk with applicable warning signs (*1*). It may be at either an intersection or mid-block. IRWLs shall not be used at crosswalks controlled by a yield or stop sign or traffic control signal (*1*). If these criteria are met, further consideration of IRWLs should be based on the following step-by-step analysis:

1. *If the location does not currently have a marked crosswalk,* VDOT's most recent *Guidelines for the Installation of Marked Crosswalks* (*2*) shall be applied. See Attachment A.
   - *If a marked crosswalk is not justified* according to Figure B3 in Attachment A, do not consider an IRWL.
   - *If a marked crosswalk is justified,* Table B1 in Attachment A must identify an IRWL (a Level 4 device) as a potential special treatment at the crossing.

2. *If the location currently has a marked crosswalk,* VDOT's most recent *Guidelines for the Installation of Marked Crosswalks* (*2*) shall be consulted to determine if the crosswalk is justified. See Attachment A.
   - *If the existing marked crosswalk is not justified,* do not consider an IRWL.
   - *If the marked crosswalk is justified,* Table B1 in Attachment A must identify an IRWL (a Level 4 device) as a potential special treatment at the crossing.

3. If the *Guidelines for the Installation of Marked Crosswalks* (*2*) identify an IRWL as a potential special treatment at the crossing, the following additional guidance is suggested.
   - *Alternative measures to mitigate the pedestrian safety problem should have been tried and proven unsuccessful or engineering judgment should have determined that other alternative measures are not feasible. A typical example is some arrangement of the standard flashing beacon, either on continuous flash or pedestrian actuated.*
   - *The 85th percentile speed of vehicles approaching the crosswalk from either direction should not be more than 45 mph* (*3, 4*).
   - *The average daily traffic (ADT) on the street being crossed should be between 5,000 and 30,000 vehicles per day* (*3, 5*)*, or vehicular volume through the crossing should exceed 200 vehicles per hour in urban areas or 140 vehicles per hour in rural areas during peak-hour pedestrian usage* (*4*).
   - *The daily pedestrian crossing volume should be at least 100 pedestrians per day* (*3, 5*) *or at least 40 pedestrians should regularly use the crossing during each of any 2 hours (not necessarily consecutive) during a 24-hour period* (*4*).
   - *The existing stopping sight distance from both directions should not be less than the minimums shown here.*

Stopping Sight Distance (Feet)
(Height of Eye 3.5 ft; Height of Object 2. 0 ft)

Design Speed* (mph)	25	30	35	40	45	50	55	60	65	70
Minimum Sight Distance	155	200	250	305	360	425	495	570	645	730

* If the design speed is unknown, it may be assumed to be the posted speed limit unless the operating speed is lower at that point.
Source: *Sight Distance*, Appendix C, Design Data, Vol. 1. Virginia Department of Transportation, Richmond, p. C-11, Revised 10/02.

4. *Although these guidelines were crafted to be as comprehensive as possible, they do not address all situations.* Therefore, the final decision as to whether to install an IRWL should be left to engineering judgment, and this decision should most likely be made by the district traffic engineer.

APPENDIX F
RUMBLE STRIP STUDY LOCATIONS

Table F1. Rumble Strip Study Locations.

Roadway [a]	Speed Limit (mph)	Pavement [b]	Rumble Strip		Rumble Strip Dimensions (inches)			
			Type [c]	Application	Length	Width	Elevation [d]	Spacing
FM 50	70	HMA	TRS	Raised	6	48	0.4	24
FM 969	55	HMA	CRS	Button	4	4	0.5	48
FM 1179	55	HMA	TRS	Raised	24	132	0.125	24
FM 1431	55	HMA	CRS	Button	4	4	0.5	Unknown
FM 2154	70	Chipseal	TRS	Raised	6	48	0.4	24
FM 2549	65	Chipseal	TRS	Raised	6	48	0.4	24
RM 32	60	HMA	CRS	Milled	7	16	0.5	24
RM 32	60	HMA	ERS	Milled	7	10.5	0.5	36
RM 32	60	HMA	ERS	Milled	7	8	0.5	36
RM 32	60	HMA	ERS	Milled	7	10.5	0.5	24
RM 32	60	HMA	ERS	Milled	7	8	0.5	24
RM 32	60	HMA	ERS	Milled	7	10.5	0.5	12
RM 32	60	HMA	ERS	Milled	7	8	0.5	12
RM 2222	45	HMA	CRS	Button	4	4	0.5	Unknown
SH 6	70	HMA	CRS	Profile	4	6	0.25	18
SH 6	70	HMA	ERS	Profile	4	6	0.25	18
SH 6	70	HMA	SRS	Button	4	4	0.5	60
SH 21 (1)	70	HMA	SRS	Rolled	2	24	0.5	12
SH 21 (2)	70	Chipseal	CRS	Milled	7	16	0.5	24
SH 21 (2)	70	Chipseal	ERS	Milled	7	8	0.5	36
SH 21 (2)	70	Chipseal	ERS	Milled	7	6	0.5	24
SH 21 (2)	70	Chipseal	LRS	Milled	7	4	0.5	18
SH 21 (2)	70	Chipseal	LRS	Milled	7	4	0.5	36
SH 47	70	HMA	SRS	Milled	7	16	0.5	12
SH 195	65	HMA	CRS	Button	4	4	0.5	Unknown
SH 195	65	HMA	SRS	Button	4	4	0.5	Unknown

[a] Farm-to-Market (FM), Ranch-to-Market (RM), State Highway (SH)
[b] Hot-Mix Asphalt (HMA)
[c] Transverse Rumble Strips (TRS), Centerline Rumble Strips (CRS), Edge line Rumble Strips (ERS), Shoulder Rumble Strips (SRS)
[d] For milled and rolled rumble strips this is depth. For button and profile rumble strips this is height.

APPENDIX G
RUMBLE STRIP DATA

Table G1. Button Rumble Strip Data.

Roadway [a]	Rumble Strip Type [b]	Speed Driven (mph)	Vehicle [c]	Inside Sound (dB)		Inside Vibration (g)		Outside Sound (dB)	
				Ambient	Change	Ambient	Change	Ambient	Change
FM 969	CRS	55	Sedan	63	10	0.09	0.21	73	5
			½ Truck	62	10	0.08	0.10	-	-
FM 1431	CRS	55	Sedan	67	10	0.12	0.53	-	-
			½ Truck	65	10	0.09	0.19	-	-
RM 2222	CRS	45	Sedan	63	12	0.08	0.26	-	-
			½ Truck	-	-	-	-	-	-
SH 6	SRS	55	Sedan	65	10	0.09	0.21	75	2
			½ Truck	66	10	0.10	0.20	-	-
			CV	75	3	0.03	0.00	82	3
		70	Sedan	68	10	0.11	0.20	78	5
			½ Truck	69	8	0.13	0.21	-	-
SH 195	CRS	55	Sedan	65	12	0.09	0.33	-	-
			½ Truck	64	13	0.09	0.16	-	-
		65	Sedan	67	11	0.1	0.4	-	-
			½ Truck	66	13	0.09	0.16	-	-
	SRS	55	Sedan	65	12	0.09	0.21	-	-
			½ Truck	64	11	0.09	0.12	-	-
		65	Sedan	67	10	0.10	0.24	-	-
			½ Truck	66	11	0.09	0.12	-	-

[a] Farm-to-Market (FM), Ranch-to-Market (RM), State Highway (SH)
[b] Centerline Rumble Strips (CRS), Shoulder Rumble Strips (SRS)
[c] Commercial Vehicle (CV)
"-" Not collected.

Table G2. Profile Rumble Strip Data.

Roadway [a]	Rumble Strip Type [b]	Speed Driven (mph)	Vehicle [c]	Inside Sound (dB)		Inside Vibration (g)		Outside Sound (dB)	
				Ambient	Change	Ambient	Change	Ambient	Change
SH 6	CRS	55	Sedan	65	11	0.09	0.16	78	3
			½ Truck	66	12	0.10	0.28	-	-
			CV	76	4	0.03	0.00	81	4
		70	Sedan	68	10	0.11	0.65	81	3
			½ Truck	69	8	0.12	0.29	-	-
	ERS	55	Sedan	65	12	0.09	0.23	75	12
			½ Truck	66	13	0.10	0.34	-	-
			CV	75	2	0.03	0.00	82	5
		70	Sedan	68	13	0.11	0.27	78	9
			½ Truck	69	13	0.13	0.25	-	-

[a] State Highway (SH)
[b] Centerline Rumble Strips (CRS), Edge Line Rumble Strips (ERS)
[c] Commercial Vehicle (CV)
"-" Not collected.

Table G3. Rolled Rumble Strip Data.

Roadway [a]	Rumble Strip Type [b]	Speed Driven (mph)	Vehicle [c]	Inside Sound (dB)		Inside Vibration (g)		Outside Sound (dB)	
				Ambient	Change	Ambient	Change	Ambient	Change
SH 21 (1)	SRS	55	Sedan	64	15	0.09	0.11	75	9
			½ Truck	63	6	0.08	0.01	-	-
			CV	75	2	0.03	0.00	82	10
		70	Sedan	67	12	0.10	0.03	75	12
			½ Truck	68	11	0.10	0.02	-	-

[a] State Highway (SH)
[b] Shoulder Rumble Strips (SRS)
[c] Commercial Vehicle (CV)
"-" Not collected.

Table G4. Transverse Rumble Strip Data.

Roadway [a]	Rumble Strip Type [b]	Speed Driven (mph)	Vehicle [c]	Inside Sound (dB)		Inside Vibration (g)		Outside Sound (dB)	
				Ambient	Change	Ambient	Change	Ambient	Change
FM 50	TRS	55	Sedan	66	14	0.06	0.08	64	9
			½ Truck	66	14	0.10	0.21	-	-
		70	Sedan	69	11	0.07	0.03	65	12
			½ Truck	69	11	0.12	0.26	-	-
FM 1179	TRS	55	Sedan	66	14	0.06	0.08	73	5
			½ Truck	66	14	0.10	0.21	-	-
			CV	77	2	0.04	0.00	79	2
FM 2154 (NB)	TRS	55	Sedan	69	9	0.15	0.08	69	9
			½ Truck	68	9	0.11	0.07	-	-
			CV	76	3	0.03	0.01	75	6
		70	Sedan	72	10	0.16	0.18	74	7
			½ Truck	71	11	0.13	0.10	-	-
FM 2154 (SB)	TRS	55	Sedan	69	8	0.15	0.23	-	-
			½ Truck	68	8	0.11	0.09	-	-
			CV	76	0	0.03	0.01	-	-
		70	Sedan	72	6	0.16	0.09	-	-
			½ Truck	71	7	0.13	0.09	-	-
FM 2549	TRS	55	Sedan	68	11	0.09	0.05	-	-
			½ Truck	67	11	0.14	0.11	-	-
		65	Sedan	68	11	0.09	0.05	-	-
			½ Truck	68	9	0.15	0.07	-	-

[a] Farm-to-Market (FM), Northbound (NB), Southbound (SB)
[b] Transverse Rumble Strips (TRS)
[c] Commercial Vehicle (CV)
"-" Not collected.

Table G5. Milled Rumble Strip Data.

Roadway [a]	Rumble Strip Type [b]	Rumble Strip Dimensions (inches)		Speed Driven (mph)	Vehicle [c]	Inside Sound (dB)		Inside Vibration (g)		Outside Sound (dB)	
		Width	Spacing			Ambient	Change	Ambient	Change	Ambient	Change
RM 32	CRS	16	24	55	Sedan	63	18	0.09	0.33	-	-
					½ Truck	62	19	0.08	0.17	-	-
RM 32	ERS	10.5	36	55	Sedan	63	14	0.09	0.26	-	-
					½ Truck	62	13	0.08	0.09	-	-
RM 32	ERS	8	36	55	Sedan	63	12	0.09	0.12	-	-
					½ Truck	62	11	0.08	0.05	-	-
RM 32	ERS	10.5	24	55	Sedan	63	13	0.09	0.04	-	-
					½ Truck	62	13	0.08	0.17	-	-
RM 32	ERS	8	24	55	Sedan	63	12	0.09	0.12	-	-
					½ Truck	62	10	0.08	0.13	-	-
RM 32	ERS	10.5	12	55	Sedan	63	12	0.09	0.16	-	-
					½ Truck	62	13	0.08	0.05	-	-
RM 32	ERS	8	12	55	Sedan	63	13	0.09	0.19	-	-
					½ Truck	62	17	0.08	0.13	-	-
SH 21 (2)	CRS	16	24	55	Sedan	73	9	0.07	0.19	77	8
					½ Truck	69	14	0.09	0.21	-	-
					CV	77	5	0.03	0.00	83	8
				70	Sedan	75	9	0.08	0.11	79	9
					½ Truck	73	11	0.10	0.20	-	-
SH 21 (2)	ERS	8	36	55	Sedan	73	4	0.07	0.04	77	4
					½ Truck	69	6	0.09	0.08	-	-
					CV	76	0	0.03	0.00	83	3
				70	Sedan	75	9	0.08	0.07	81	4
					½ Truck	73	4	0.10	0.07	-	-

[a] Ranch-to-Market (RM), State Highway (SH)
[b] Centerline Rumble Strips (CRS), Edge Line Rumble Strips (ERS), Laneline Rumble Strips (LRS), Shoulder Rumble Strips (SRS)
[c] Commercial Vehicle (CV)
"-" Not collected.

Table G5. Milled Rumble Strip Data (continued).

Roadway [a]	Rumble Strip Type [b]	Rumble Strip Dimensions (inches)		Speed Driven (mph)	Vehicle [c]	Inside Sound (dB)		Inside Vibration (g)		Outside Sound (dB)	
		Width	Spacing			Ambient	Change	Ambient	Change	Ambient	Change
SH 21 (2)	ERS	6	24	55	Sedan	73	3	0.07	0.04	77	2
					½ Truck	69	6	0.09	0.08	-	-
					CV	76	1	0.03	0.00	86	0
				70	Sedan	75	4	0.08	0.03	80	3
					½ Truck	73	4	0.10	0.08	-	-
SH 21 (2)	LRS	4	18	55	Sedan	73	2	0.07	0.04	76	3
					½ Truck	69	2	0.09	0.04	-	-
					CV	76	0	0.03	0.00	87	-1
				70	Sedan	75	2	0.08	0.02	81	2
					½ Truck	73	2	0.10	0.06	-	-
SH 21 (2)	LRS	4	36	55	Sedan	73	0	0.07	0.02	78	1
					½ Truck	69	1	0.09	0.04	-	-
					CV	76	0	0.03	0.00	86	-1
				70	Sedan	75	1	0.08	0.02	82	1
					½ Truck	73	1	0.10	0.03	-	-
SH 47	SRS	16	12	55	Sedan	64	24	0.09	0.31	71	13
					½ Truck	65	18	0.07	0.46	-	-
					CV	77	8	0.04	0.00	82	11
				70	Sedan	66	18	0.09	0.25	76	19
					½ Truck	69	16	0.09	0.37	-	-

[a] Ranch-to-Market (RM), State Highway (SH)
[b] Centerline Rumble Strips (CRS), Edge Line Rumble Strips (ERS), Laneline Rumble Strips (LRS), Shoulder Rumble Strips (SRS)
[c] Commercial Vehicle (CV)
"-" Not collected.