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# Evaluation of Audible Lane Departure Warning Treatments for Seal Coat Road Surfaces

Technical Report 0-6888-R1

Cooperative Research Program


TEXAS A&M TRANSPORTATION INSTITUTE

COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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16. Abstract

In an effort to reduce the number of single vehicle run-off-road and two-lane two-way crossover crashes, TxDOT has implemented various audible lane departure warning systems on seal coat road surfaces. This 20-month research project explored the effectiveness of these various treatments using several performance metrics and provided recommendations on implementation of these types of treatments. The researchers conducted performance evaluations at 24 unique field sites that had 51 treatments, and at a test deck that had 12 different variations of audible markings. The field sites consisted of varying designs and spacing of audible markings, rumble bars, and milled rumble strips. A crash study was conducted that considered 77 treatment sites and appropriate comparison sites.

The field performance study found that the performance was somewhat variable, but the alternative treatments could produce noise and vibration levels similar to milled rumble strips. The crash study showed that the installed treatments reduced total crashes by about 19 percent across all the sites considered (30 percent reduction in fatal and injury crashes). These sites had a minimum of at least one treatment on either the edge line or the center line. Audible markings and rumble bars are viable alternative lane departure warning treatments from a noise and vibration performance standpoint, from a crash reduction standpoint, and a benefit-cost ratio (at least 11:1) standpoint. Recommendations to improve standards and specifications, and how to implement these treatments were provided.

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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.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Adam M. Pike, P.E. #105117.

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# CHAPTER 1: OVERVIEW

In an effort to reduce the number of single vehicle run-off-road and two-lane two-way crossover crashes, the Texas Department of Transportation (TxDOT) has implemented various audible lane departure warning systems on seal coat road surfaces. These audible lane departure warning systems are typically profiled pavement markings and, recently, have included rumble bars (preformed thermoplastic strips). These countermeasures are typically used on, but not limited to, seal coat road surfaces where milled rumble strips cannot be used or on roadways where shoulders are too narrow for milled rumble strips.

TxDOT does not currently have a performance requirement, from a noise, vibration, or visibility standpoint for these types of treatments. Contractors and material producers are using different designs to meet current specifications, and some contracts call for non-standard treatment spacing. This may result in treatments with varying levels of performance. This 20-month research project was conducted to explore the effectiveness of these various treatments using several performance metrics and to provide recommendations on implementation of these types of treatments. The researchers evaluated the following aspects of audible lane departure warning treatments to meet the project goals:

- What are the safety benefits?
- What is the delivered performance (noise, vibration, visibility)?
- What are the costs?
- What is(are) the best design(s)?
- When and where should audible lane departure warning treatments be implemented?
- What level of performance remains after the treatments are seal coated over?

# CHAPTER 2:
# STATE OF THE PRACTICE – AUDIBLE LANE DEPARTURE WARNING

The research project is focusing on treatments that can serve as an alternative to rumble strips so that the alternate treatment can be used in situations where rumble strips cannot (e.g., on many seal coat road surfaces and roads with narrow shoulders). The objectives of the state of the practice review were to conduct a thorough literature review and to conduct a survey of each TxDOT district.

## LITERATURE REVIEW

To reduce the number of single vehicle run-off-road and two-lane two-way crossover crashes, states have implemented various treatments to alert drivers that they are leaving their lane. Rumble strips are the most common audible and tactile warning that is provided to drivers to indicate that they are leaving their lane. Rumble strips are typically milled into the road surface and require adequate road surface depth and shoulder space. Alternative treatments to milled rumble strips are becoming more common because of the safety benefits that milled rumble strips have continually shown. Alternate systems are typically profiled (audible) pavement markings and, recently, have included rumble bars (preformed thermoplastic bars). These countermeasures are typically used on seal coat road surfaces where milled rumble strips cannot be used or on roadways where shoulders are too narrow for milled rumble strips. While these treatments are mostly intended for sealcoat road surfaces and roads where milled rumble strips cannot be used, they are being used on concrete and asphalt surfaces with adequate construction for milled rumble strips. Little research has been conducted to determine if these alternative systems provide a similar safety benefit to milled rumble strips, or if the systems can be considered a cost-effective countermeasure.

The literature review gathered information to better understand the current practices and performance of these alternative rumble strip treatments. Specific areas addressed are:

- What treatments are available.
- What are current DOT practices.
- Installation locations.
- Specifications.
- Costs.
- What studies have been conducted.
- What are the safety benefits.
- What is the delivered performance (noise, vibration, visibility).

**Types of Treatments**

There are numerous audible lane departure warning treatments on highways to help prevent run-off-road and two-lane two-way crossover crashes. These treatments create varying levels of noise and vibration to alert the driver that they are leaving the travel lane. The most common lane departure warning system on the road are rumble strips. Rumble strips are typically milled into the centerline area, edge line area, or on the shoulder of a road. Rumble strips require adequate pavement depth (typically 2 in. or more) and an adequate shoulder width. In situations where rumble strips cannot be applied, practitioners can implement several other treatments that can get the attention of inattentive drivers that may be leaving their travel lane.

The second most common treatment behind rumble strips is audible pavement markings. Audible pavement markings refer to any pavement marking designed with the intent to provide audible and tactile feedback that the driver is driving on the line. The most common audible pavement marking is a profiled pavement marking. Another form of pavement marking is inverted profile markings with or without an audible bump. The standard inverted profile marking produces a hum when driven over. The inverted profile marking with audible bump produces a more pronounced noise. Figure 1 provides an example of an inverted profile marking with audible bump (left image) and a profile pavement marking (right image).

**Figure 1. Inverted Profile Marking (Audible) and Profile Edge Line Markings.**

In addition to pavement markings, other forms of on the road audible lane departure warning treatments are being used. Rumble bars, also referred to as preformed thermoplastic strips, or preformed raised rumble strips are used as a replacement for milled rumble strips. These preformed products are affixed to the roadway with the intent that they will perform similarly to rumble strips. Non-reflective raised traffic buttons in white, yellow, and black have also been used in a similar fashion. Figure 2 provides images of two different rumble bar installations. The left image in Figure 2 has the rumble bar installed in conjunction with rumble stripes. A rumble stripe is a rumble strip that has been placed along a marking location and then striped with a pavement marking. The right image in Figure 2 has the rumble bar installed on the shoulder.

Figure 3 provides images of two different rumble bar setups along a centerline. The right image in Figure 3 has the rumble bars and inverted profile marking with audible bump.

**Figure 2. Rumble Bars on Edge Line and Shoulder.**

**Figure 3. Rumble Bars and Audible Markings on Centerlines.**

The durability of these treatments is relatively unknown. Rumble strips can last as long as the road surface does. Profile pavement makings may not last any longer than standard pavement markings. Being that profile pavement markings and rumble bars are typically applied on seal coat road surfaces, their service life may be limited by the service life of the road surface. The durability, cost, and performance of the various treatments need to be considered when deciding which treatments to use and where to use them.

**Current DOT Practices**

There is currently no guidance on a national level for when and where to use alternative rumble strip treatments. Several states have standards and specifications that outline specific layouts and designs of the treatments. Figure 4 provides a detailed view of the profile pavement markings. The general rumble strip standards for TxDOT [RS(1)-13 through RS(4)-13] address the usage of profile pavement markings and centerline rumble bars. Figure 5 provides the typical layouts for centerline rumble strips and alternatives. Profile pavement markings are allowed at any location where typical markings would be used, as long as the speed limit exceeds 45 mph. Rumble bars are only listed in the standards as being allowed for centerline treatments on two-lane two-way roadways where the speed limit exceeds 45 mph. The TxDOT statewide Special Specification 8020 addresses the design of reflectorized profile pavement markings, whereas Special Specification 6071 addresses inverted profile pavement marking (audible). Special Specification 8020 was recently combined with the standard pavement marking Item 666 with the standards update in 2014. Currently TxDOT contractors and material producers are using slightly different designs to meet current TxDOT specifications, which may yield varying levels of performance. Project plans are also calling for different spacing criteria and combinations of treatments. The TxDOT roadway design manual indicates that profile thermoplastic markings should be limited to roadways where milled rumble strips cannot be used and where speeds are greater than 45 mph.

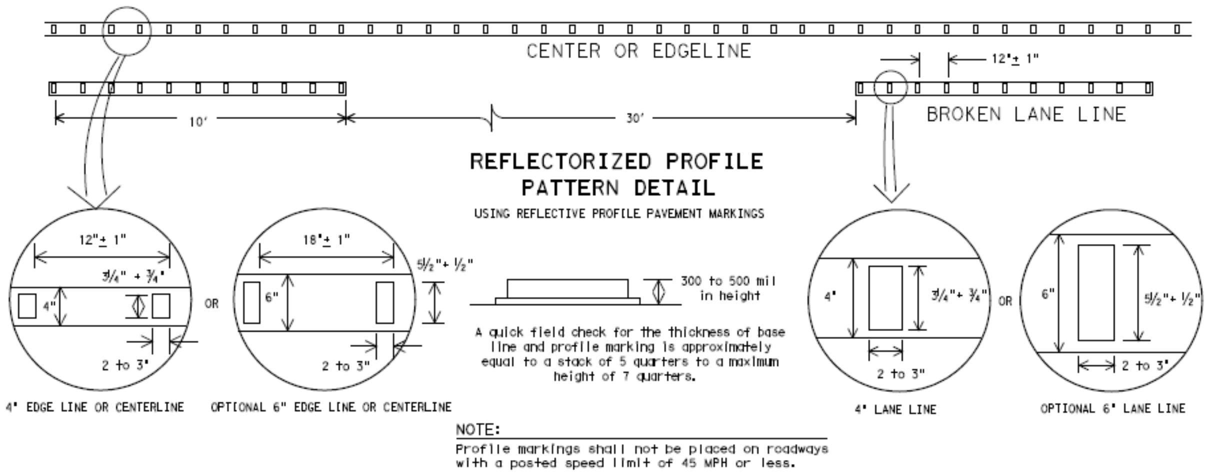


**Figure 4. TxDOT PM (2)-12 Standard, Reflectorized Profile Pattern Details.**

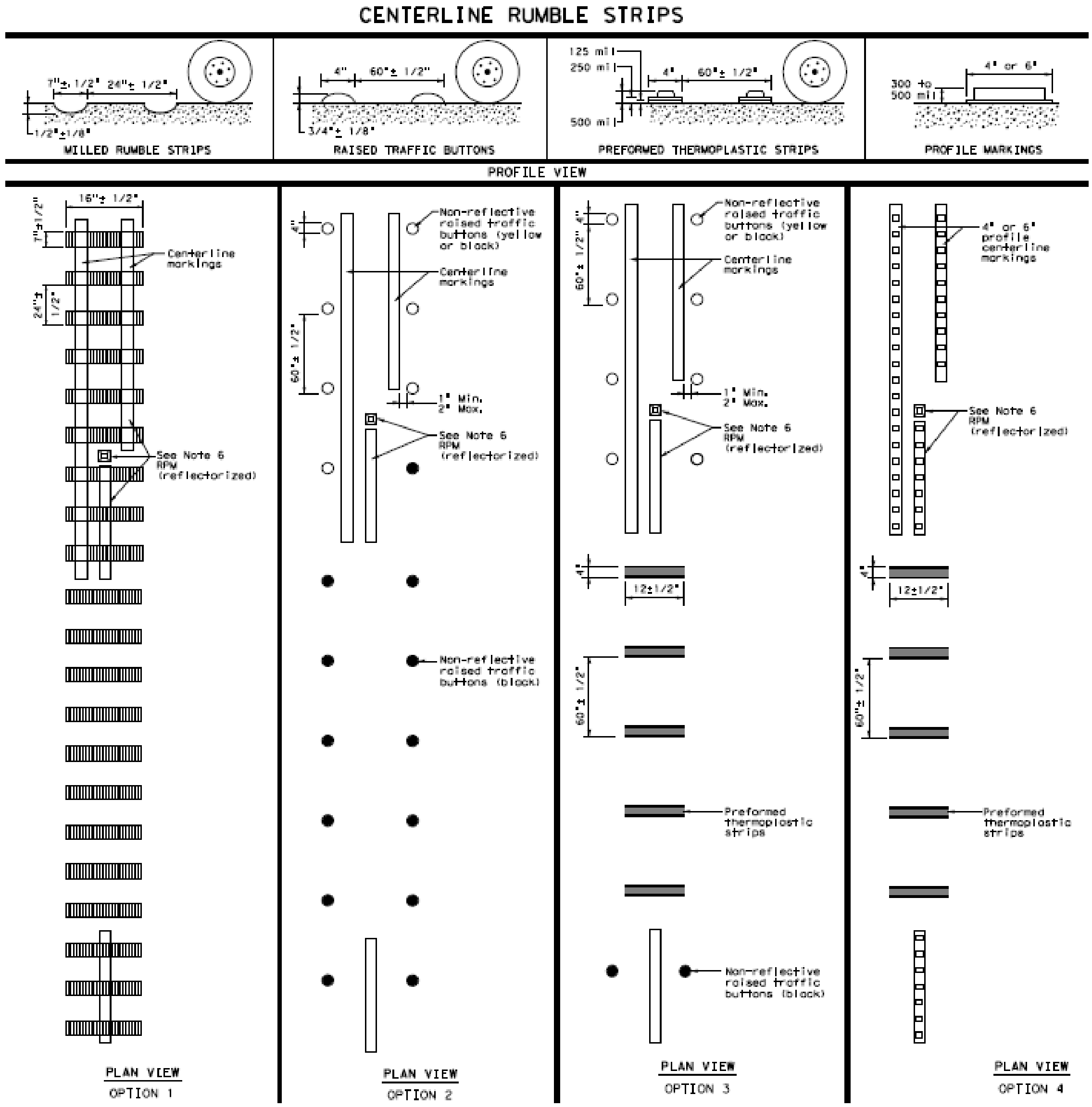


**Figure 5. TxDOT RS (3)-13 Standard, Centerline Rumble Strips.**

From a cost stand point, the different treatments vary greatly based on average bid prices. TxDOT bid price information was used to develop the following costs. Standard rumble strips are the most common and do not have durability issues. The average unit price for rumble strips ranges from \$0.15–0.24/ft. For profile markings, 4-in. markings range in cost from \$0.55–0.75/ft, and 6-in. marking are around \$1.00/ft. Inverted profile marking (audible) were only listed in the bid documents at 6-in. width at a typical cost of \$3.00–4.00/ft. Standard pavement markings generally cost \$0.25–0.40/ft for 4-in. markings and around \$0.50/ft for 6-in. markings. Rumble bars were only listed for centerlines at an average unit cost of \$3.00–4.00 per unit. The wide range of costs for the different treatments may or may not be justified based on their performance.

The Florida Department of Transportation (FDOT) greatly increased the usage of audible and vibratory markings after implementing new policy in 2008. The policy called for the audible and vibratory markings to be installed on all rural projects excluding limited access facilities, specifically edge lines on two-lane and multilane rural undivided roads, inside and outside edge lines on two-lane and multilane rural divided roads, and only on centerlines of two-lane rural roads with a history of centerline cross over crashes. The markings should also be considered for FDOT classified Urban 2 and 3 areas with flush shoulders. FDOT had required the usage of rumble strips since the 1990s on limited access facilities.

In 2015, Florida updated their audible and vibratory markings standard and now calls them profiled thermoplastic markings. Profiled thermoplastic is now the only audible and vibratory method to be used on concrete pavements. Profiled thermoplastic is to be used on center lines of all two-lane two-way roadways and the inside and outside edge lines of two-lane and multilane roadways. Profiled thermoplastic edge lines are to be used on concrete limited access facilities that have concrete shoulders. Rumble strips are the only audible and vibratory markings to be used on asphalt pavement. Rumble strips are to be used on the center lines of all two-lane roads and on the inside and outside edge lines of two lane and multilane roads. Specifically stating the type of audible and vibratory markings used for each road surface is a step toward more defined usage of these types of treatments. A notable difference between the TxDOT and FDOT specifications is the spacing of the profiled bumps. TxDOT uses a 12 in. spacing for 4-in. wide markings and an 18-in. spacing for 6-in. wide markings. FDOT states that spacing should be 30 in. for all profiled thermoplastic makings (FDOT Standard Specifications Section 701).

**Past Research**

Limited research has been conducted that has specifically looked at the safety impact and performance of profile pavement markings and rumble bars. Most research has focused on rumble strips as they are the most common and most cost-effective form of audible lane departure warning systems. Results and methodologies from these rumble strip specific studies can still be beneficial to better understand how profile pavement markings and rumble bars may perform and the best ways to study their performance. A summary of a few studies concerning audible lane departure warning treatments is provided in this section.

National Cooperative Highway Research Program report 641 looked at all aspects of centerline and shoulder rumble strips (*1*). The report indicated a safety impact of centerline rumble strips to produce between 30 and 40 percent reduction on target crash types, and a total reduction in crashes of about 9 percent. The report indicated a safety impact of shoulder rumble strips to reduce target crashes between 11 and 22 percent. For both centerline and shoulder rumble strips a larger reduction in crashes when specifically looking at fatal and injury crashes was observed. The research recommended an interior noise level increase between 6 and 15 A-weighted decibels (dBA) above ambient conditions depending on the situation. The research also developed a methodology to predict the noise level difference in the passenger compartment to help with future designs.

The California Department of Transportation conducted a research study to evaluate the noise and vibration performance of milled rumble strips, rolled rumble strips, and audible edge stripe (*2*). Noise and vibration performance were collected on different treatments in several different vehicles including heavy vehicles. The study results included recommendations to improve the Caltrans specifications and recommendations that raised/inverted profile pavement markings be allowed to substitute for rumble strips where rumble strips cannot be installed, such as bridge decks and roads with narrow shoulders (<1.5 m). The research also recommends site installation requirements for the various rumble strip designs that considered road surface, milling depth, bicycle usage, and shoulder width.

The Texas A&M Transportation Institute (TTI) has conducted several studies concerning rumble strips (*3, 4*). One of these studies included profile pavement markings and raised buttons as alternatives to rumble strips (*3*). Noise and vibration were collected on various rumble strips and rumble strip alternatives. The research found that all treatments tested except for the rolled rumble strip provided adequate noise inside the vehicle while minimizing exterior noise levels. The recommendations included that the design of rumble strips may need to change to provide adequate noise level changes over the ambient condition. In particular, chip seal roads were indicated as a surface that may require a more aggressive design since the road surface itself produces more ambient noise than other road surfaces. The research also suggested additional areas of study including minimum noise and vibration needed to alert drivers, durability of raised buttons and profile markings and if their performance changes over time, and the minimum exterior noise at which alternative (quieter) treatments need to be considered in sensitive areas.

A second TTI study evaluated the operational effects of shoulder and centerline rumble strips on two-lane undivided roadways (*4*). This research looked at how the placement (lateral offset) of centerline and shoulder rumble strips impacted vehicular operations on roads of varying widths. The research found that operations did not appear to be impacted on roadways with only a centerline rumble strip and lane widths of 10 ft or greater. The research also found that operations did not appear to be impacted on roadways with centerline and shoulder rumble strips and lane widths of 11 ft or greater. The research indicated that driver’s reaction time to take corrective action after hitting the shoulder rumble strips was 0.6 s (85$^{th}$ percentile). The lateral distance traveled away from the edge line was 13.24 inches (85$^{th}$ percentile). Recommendations were made as to the maximum lateral offset for shoulder rumble strips, and for when to use centerline rumble strips in conjunction with shoulder rumble strips. The research also suggested that a crash study be conducted to assess safety implications of shoulder and centerline rumble strips on two-lane, undivided roadways.

TTI conducted a three-year study to identify factors that influence the number and severity of roadway departure crashes on rural two-lane highways in Texas (*5*). Based upon the findings, the research team provided engineering countermeasures to reduce crashes. The study was completed by analyzing crash, traffic flow, and geometric data between 2003 and 2008. The study results showed that the proportion of roadway departures varied from 25 percent to 52 percent for all crashes occurring on the rural two-lane highway network. Proportionally more crashes occur on horizontal curves than on tangents and during nighttime. Distracted driving and speeding were found to be important contributing factors. Profile pavement markings were one of the recommended countermeasures to consider. Audible lane departure warning systems such as profile pavement markings would help combat distracted driving crashes as they would alert a driver that they are leaving the travel lane.

A wide range of crash modification factors (CMFs) exist for rumble strips individually along the centerline or on the shoulder or in combination where both are implemented at the same time. The CMF range is due to varying study designs, study locations, and crash types included among other factors. For the most part, the CMFs show crash reductions when rumble strips are implemented. Currently, there are no published CMFs for profile pavement markings or rumble bars. A CMF for audible pavement markings is on the most wanted list of CMFs on the CMF Clearinghouse website (*6*). The most wanted list represents areas or countermeasures of interest for which the CMF Clearinghouse does not have much good quality information.

The Alabama Department of Transportation sponsored a study to compare flat thermoplastic markings with inverted profiled pavement markings (*7*). The goals of the study were to compare service life, life-cycle costs, crash rates, and wet-night visibility of the two different marking types. The crash study evaluated 48 flat marking sites (357 centerline miles) and 55 profiled marking sites (378 centerline miles). In total, 6,000 crashes were evaluated. The crash period included 3 years of before data and 2 years of after data. The crash study did not find any significant evidence to support lower crash rates are associated with the profiled markings. The profiled markings cost 3–4 times as much as the flat markings. The service life analysis was based on the retroreflective decay of the markings. The markings were evaluated with a mobile retroreflectometer up to three times during the study. The researchers then modeled the decay for the flat and profiled markings retroreflectivity. Both marking types decay at a similar rate, but that the flat markings started at and maintained a higher retroreflectivity level than the profiled markings. If replacement of the markings were based on retroreflectivity, the flat markings would last longer. With a minimum retroreflectivity level of 100 mcd/m$^2$/lux the flat markings were estimated to last between 23 and 60+ months, whereas the profiled markings were expected to last between 17 and 60+ months. The profiled marking provided approximately twice the wet retroreflectivity level of the flat marking. The life cycle costs of the profiled marking were much higher than the flat marking due to the higher costs and overall shorter expected lifespan. With no indications of a crash benefit and the profiled markings costing more, the researchers recommended to not consider widespread use of the profiled markings.

In Germany, and most of Europe, structured markings are common. Structured markings provided added wet-night visibility by allowing the rain to run off the marking keeping the glass beads exposed. Structured markings also provide low levels of noise when driven on by vehicles. These noise levels are not as high as markings designed for audible performance, but the audible levels may be significant enough to cause issues for nearby residents. A German study from 2012 sought to identify the roadside noise levels produced by some typical structured and unstructured pavement markings at varying speeds (*8*). Six different markings including a profiled tape, a flat marking, an agglomerate marking, and dot patterned structured markings. Multiple noise level pressure meters were installed on the roadside adjacent to the markings to evaluate the noise levels at speeds ranging from 30 to 120 km/hr. The noise levels increased as speeds increased. Compared to the noise from the road surface, the profiled tape and flat marking actually reduced the noise level. The other structured markings produced noise level increases between 1.8 and 7.6 dBA.

A study conducted in Australia evaluated the impact of shoulder widening and audible pavement markings (*9*). The study used a before and after design to determine the impact on crashes and the corresponding economic impact of the treatments. The study used 123 treatment sites that consisted of 6 sites that had audible markings as the only treatment and 7 sites that had both audible markings and a wider shoulder. Crashes were collected at the 13 treatment sites and 13 control sites for 5 years prior to installation and between 6 months and 5 years after the treatments were installed. All crash types were included in the analysis. The results showed significant safety improvements for both treatment types. All sites combined showed a 58 percent reduction in crashes in the after period. Sites that received both treatments showed a 71 percent reduction in crashes. When property damage only (PDO) crashes were excluded a reduction of 80 percent was found for all treatment sites, with an 88 percent reduction for the sites that received both treatments. The benefit cost ratio across all treatment sites was found to be 40.3 to 1.

New Zealand has conducted numerous studies on audible pavement markings (*10, 11, 12, 13*). The New Zealand Transport Agency refers to the pavement marking treatment as audio tactile profiled road markings. New Zealand has seen an increase in the usage of audio tactile profiled road markings since 2004. Transit New Zealand implemented a major safety initiative in 2004 and funded approximately $4 million in new installations of audio tactile profile markings each year (*10*). Their expectation is a service life of 3 to 8 years with these markings. As more markings were applied, questions arose as to the best means of applying these systems to maximize cost effectiveness, how to evaluate their performance, how to maintain them, and what installation tolerances were acceptable.

The New Zealand research project focused on ways to evaluate the performance of the audio tactile markings and to evaluate the relationship between different markings designs (*10*). The study used an instrumented vehicle to evaluate the noise and vibration produced from the proprietary vibraline pavement marking. The test vehicle drove at 100 km/hr and found increases in noise level over the ambient noise from the open graded porous asphalt of 9 dBA and 2 dBA, and differences on grade 3 chip seal of 2 dBA and 0 dBA. The higher noise level values on each road surface were for vibraline in good condition, and the lower noise level values were for vibraline in a worn condition. The noise frequencies also differed indicating the driver would hear a different tone in addition to the different noise level. The vibration was also found to be higher for the vibraline in good condition compared to the worn condition. The study of the impact of differing dimensions did not yield satisfactory results. A major issue was the variance of the markings in each test area. The height of the markings was not always consistent, which made evaluating the other factors difficult. The vibration data were also difficult to subjectively evaluate but was strongly related to the more easily identified noise level differences.

A study was conducted in New Zealand to determine whether the audio and vibration characteristics of audio tactile edge line markings were compromised after various maintenance treatments (*11*). The researchers wanted to better understand the impact of applying various seal coat materials over existing audio tactile markings. Would these markings maintain any level of audio or vibration after standard roadway maintenance? Could a normal flat line be reapplied directly over the location of the previous audio tactile marking and yield benefits or would a new audio tactile marking need to be applied? A subjective study was conducted to determine the performance of old audio tactile markings. Sites up to 10 years old were included in the study and the effectiveness of the markings from an audio and vibration perspective were found to be reasonable, medium, or poor. The results directly related to the condition of the markings. At sites where a 7 mm seal was placed over the marking, the audio and vibrator results were reasonable. The bars could still be seen after the seal coat and restripe. At sites where a 10 mm seal was used, the audio tactile markings tended to get buried and performance rated as poor and, in some conditions, where the marking was originally in good condition, the performance fell to medium. For some surface treatment types, it was recommended to remove the audio tactile marking to ensure the new surface can be installed properly.

New Zealand was concerned with the ongoing costs of maintaining the audio tactile markings and wanted to evaluate the impact on fatal and serious injury crashes. A study was conducted to analyze 10 years of before and after crash data for audio tactile marking installations around New Zealand (*12*). A minimum of three years of before data was used. The study found that across New Zealand where audio tactile markings have been installed there was a 23 percent reduction in in injury crashes, a 39 percent reduction in fatal crashes, and a 25 percent reduction in serious crashes. A comparison was made between rural state highways with and without audio tactile markings installed over a similar time frame. The rural state roads without audio tactile markings saw a 15 percent reduction in injury crashes, a 2.4 percent reduction in fatal crashes, and a 2.7 percent reduction in serious crashes. The rural state roads with audio tactile markings saw a 24 percent reduction in injury crashes, a 25 percent reduction in fatal crashes, and a 17 percent reduction in serious crashes. The benefit cost ratio for the audio tactile markings over the studied time frame was approximately 25 to 1. If the audio tactile markings were to be replaced every four years and the crash reductions continue the overall benefit cost ratio over a 30-year span would be 17 to 1. It was recommended to continue installation and maintenance of audio tactile markings. A separate study recommended that audio tactile markings should be considered on all state highways and strategic local government owned roads (*13*).

### Literature Review Summary

There is limited research into the performance of alternative audible pavement markings and other rumble strip alternatives. Much of the current literature is not from the United States. The research that is out there still lacks answers to several questions concerning the performance of varying designs. The various designs and performance levels of the audible lane departure warning systems are an area that needs additional research. The impact on crashes is not consistent with a U.S.-based study indicating no impact, whereas several foreign studies indicate a significant safety improvement. There is limited research on these treatments that can currently be used to identify the best designs and best locations for implementation to maximize the benefit. With the added cost over standard pavement markings and rumble strips, an optimal design needs to be applied in the best locations to provide a cost-effective treatment.

## TXDOT DISTRICT SURVEY

The purpose of the survey was to better understand the current practices of each TxDOT district on the use of alternative lane departure warning treatments. The researchers sought to better understand which districts were implementing these treatments, what specific treatments were being implemented, and where they were being implemented. Specific questions were included in the survey to help the research team achieve the goals of the project.

The research team developed three documents for the survey. The primary document was the survey questionnaire; see Appendix A. The other two documents were the email that was sent to each district and the survey consent information sheet. The questionnaire and survey consent information were attached to the email. The questionnaire contains the questions that the districts were to respond to. The survey consent information sheet provided the respondents information about the purpose of the survey and their rights as a survey participant. All three of the documents had to be approved by the Texas A&M University Institutional Review Board because the survey was collecting information from respondents.

Prior to distributing the survey, the TxDOT project team had the chance to review and comment on the survey documents. The comments received did not result in changes to the survey but helped to better direct the TTI research team when conducting any follow-up phone calls to specific districts that may take part in other parts of the research study. The research team also worked with the TxDOT Traffic Operations Division to establish the survey distribution list. The survey distribution list included the director of traffic operations and/or the traffic engineer for each district.

The survey was distributed to all 25 districts on Friday, January 25, 2016. It was estimated that the survey would take 10 minutes to complete, plus additional time if the districts looked up specific information on costs and/or quantity of materials. The questionnaire requested a response within 15 business days. After being distributed for 15 business days, the research team had heard back from 7 districts and had received 5 completed responses. The research team sent a reminder email to the non-responding districts on February 18, 2016. The districts were requested to respond to the survey within 10 business days if they wanted to take part. In total, 11 responses were received.

Most of the questions were answered in each of the 11 responses to the survey. Due to some districts not using the treatments and some questions not answered in all surveys, the number of responses for each question may vary. The responses to the survey allowed the research team to gather a significant amount of information about the usage of these treatments that can be used as alternatives to milled rumble strips. The summary of the survey responses is provided following the survey questions that are provided in italics.

1. *Is your district currently using any audible lane departure warning system (ALDWS) that is a focus of this study?*

Nine of the 11 responses were ‘yes’, 2 of the 11 responses were ‘no’.

2. *Is there a reason your district is not using any ALDWS? If yes, please provide additional information.*

Both of the ‘no’ responses indicated the potential for the treatments to be plowed off during snow plowing activities.

3. *Is your district using audible pavement markings? If yes, please input the quantity of centerline miles.*

All nine yes responses indicated the use of audible pavement markings. The response to the quantity of the installed treatments varied. Three responses did not have that information available. Table 1 lists districts that estimated quantities of installed centerline mile.

**Table 1. TxDOT Survey: Audible Marking Quantity Response.**

| |
|---|
| 320 centerline miles, 210 audible centerline, 198 audible edge line |
| 60.663 miles |
| 50–100 miles |
| We have mainly used them on the edge line striping. We only have a couple of roads that have centerline markings. We have approximately 100 centerline miles at this time. We have around 50 roads that will be done by contract in the next year or so. |
| 550 since 2013 |
| ~ 500+ CL miles |

4. *Is your district using rumble bars? If yes, please input the quantity of centerline miles.*

Three of the nine yes responses indicated the use of rumble bars. Table 2 lists the estimated quantities of installed centerline mile.

**Table 2. TxDOT Survey: Rumble Bar Quantity Response.**

| |
|---|
| 332 centerline miles, 287 centerline bars, 147 edge line bars |
| 48.39 MI |
| 30 |

5. *Does your district have records indicating which roads have these systems and when they were installed? If yes, please provide additional information on the details of your records.*

Seven of the nine districts indicated they have some level of records indicating the locations and dates of installations. Table 3 lists the responses.

**Table 3. TxDOT Survey: Installation Records.**

| |
|---|
| In process of compiling list, but not completed. |
| We use project information from DCIS, in Excel, to keep track and map this information in ArcMap. |
| We have one job currently under construction (0054-01-104, etc). This is the first job we have used profile striping and centerline rumble strips. We are in the process of building a spread sheet to track the completed roadways. |
| We can access the recent plans where these rumble strips were added. |
| It would take some research and time to accumulate the info. |
| I will attach the plan sheets. |
| We have just started collecting the data. |
| Have design plans since 2013; will need CST input on installation dates |

6. *Would your district be willing to provide additional information over the phone or via email about specific installations of ALDWS?*

Each of the nine districts indicated they would be willing to provide additional information to the research team about specific installations of ALDWS in their districts.

The research team followed up with many of the responding districts to gather more information about specific installations and other information needed for the field evaluation and the crash study. The research teams' goal was to identify districts that know when and where they installed the treatments. Knowing the dates and location of installations would allow for those roadway segments to be included in the crash study. If districts only know the locations of the treatments but may be unsure of the installation dates, those segments could still be used in the field performance evaluation.

7. *Does your district have criteria for when to install these systems? If yes, please provide additional information on specific criteria. If no, provide information on the motivation behind installation of the systems?*

Four districts responded that they have specific criteria for when to install these treatments. Two districts responded that they do not have specific criteria for when to install these treatments. Table 4 lists the additional information that the respondents provided.

**Table 4. TxDOT Survey: Criteria for Treatment Usage.**

| |
|---|
| District is currently working on this. |
| We use HSIP funds, so the locations are based on accidents. |
| We prefer to use milled in rumble strips due to the ice being bladed off in the winter, however if the pavement is too thin to have milled in rumble strips applied we choose profile striping with centerline rumble strips. |
| We use the HSIP program call to find roads that need to be done. This program call looks at accident data. |
| Centerline for head-on crashes. |
| We are considering milling in all cases and sealing over them to protect from moisture damage. This is to extend the life cycle and have more effective decibel deltas. The decibel delta between the two systems being studied and the road-noise on seal coated roads is disappointing and maybe even wasteful. |

Of particular note in the response is the last response listed. The respondent noted disappointment in the noise level change for the audible markings on seal coat road surfaces. This district is being contacted to find specific locations that can be studied to determine why the noise levels produced may not be adequate.

*8. Are these systems limited to certain roadway classifications? If yes, please provide additional information on specific roadway classifications where these systems may or may not be used.*

Seven respondents indicated these treatments were not limited to any specific roadway class. One respondent indicated that they limit the treatments to interstate, U.S., and state highways.

*9. Are these systems limited to certain roadway surface types? If yes, please provide additional information on specific roadway surface types where these systems may or may not be used.*

One respondent indicated that these treatment types are limited to hot mix asphalt and concrete road surfaces. Three respondents indicated that these treatments are limited to roadways with less than 2 in. of roadway structure, if more than 2 in. exists then they use milled rumble strips. Five respondents indicated that these treatments were not limited by roadway surface type.

*10. What are the typical project sizes and unit costs associated with the installed systems?*

The responses to the typical project sizes and unit costs varied, and specific costs for specific treatment types were not always mentioned. Table 5 lists the responses.

**Table 5. TxDOT Survey: Project Size and Cost.**

| |
|---|
| Typically 5–10 mile project lengths. Centerline bars ($18,000/mile) edgeline bars ($22,000/mile) edgeline Audible ($32,000/mile) centerline and edgeline bars ($40,000/mile) centerline bars and edgeline audible ($50,000/Mile) |
| Our first contract was for about 9 roads, but we have two contracts coming out in the next year or so that will have around 25 roads on each. The cost was $0.51 a foot. |
| 125 centerline miles, 4" profile stripe 60 mil is around $0.55/lf, 4" profile stripe 90 mil is around $0.65, and a preformed centerline rumble strips are around $6.00/lf. |
| Currently on safety which length vary and unit price is profile $X and milled-in $X |
| Over $1 million |

*11. What specification was used for the design/installation of the systems? If no specific specification was used, or a specification was modified, please indicate the length, width, height, and spacing of the treatments.*

The respondents indicated that the standard specifications were used for the installations. One district did provide a specific rumble strip detail for the rumble bars that they had used. This document provided additional detail over the information contained in the standard rumble strip sheets RS(1-5)-1.

*12. Does your district have any experience or feedback on the performance of the systems (e.g., sound, vibration, visibility, durability, ease of installation, service life, maintenance, safety)?*

Four respondents indicated that they did not have any experience or feedback on the systems. The noted response from question 7 would also be a good response to this question. Table 6 lists the other responses.

**Table 6. TxDOT Survey: Feedback on Treatment Performance.**

| |
|---|
| Most feedback is positive, except for motorcycle and bicycle rides do not like any of the audible treatments. The rumble bars provide better sound and vibrations after initial installation and also continues to sound and vibrate well after at least one seal coat application. Audible normally last one seal coat cycle. After a seal coat there is really no noticeable audible value left. |
| They have not been in place long enough. Far as sound, there is adequate sound on seal coat to alert road user of their deviation from the travel lane. |
| We put our first ones out about two years ago, so we are still new to the use of them. So far they have worked very well. |
| Maintenance during plowing of ice and snow. |

*13. Does your district have any concerns with previous, existing, or future installations of these systems?*

Two respondents answered no. Table 7 lists the other responses.

**Table 7. TxDOT Survey: Concerns with these Treatment Types.**

| |
|---|
| We are concerned with ALDWS and how it fits into the sealcoat maintenance operations. We have several roadways that have rumble bars with one seal coat application which are still performing well. However, after the next seal coat application, we are concerned with how and when these ALDWS system will need to be replaced. We are not sure if we will simply need to place the new ones on top of the old ones or place them in between the old ones. We feel like we will need to try several ways before we can be sure of a standard way of handling the situation. |
| We do a lot of seal coat on our roadway in this district and we are not sure if we will have to replace these each time we do a seal or it they will still work. |
| We are very curious how they will hold up after the first ice and blading. |
| Concerns with ability of contractor to install profile pavement markings according to specs. |
| Yes, when plowing roadways due to snow and ice, many of the profiles marking will be removed. |
| Yes, The decibel delta between the two systems being studied and the road-noise on seal coated roads is disappointing and maybe even wasteful. |

*14. Does your district plan on implementing ALDWS in the future? If Yes, please indicate when. If No, please indicate why.*

Of the 11 respondents 7 answered, yes that they plan to use them in the future. One answered maybe, 2 answered no, and 1 did not respond. Table 8 provides specific responses.

**Table 8. TxDOT Survey: Future Implementation.**

| | |
|---|---|
| Yes | We have HSIP funding currently through FY 2019. |
| Yes | We have another profile striping/center line rumble strip job coming up in April 2016 (0054-02-032, etc.) and another one in March of 2017 (0231-01-053, etc.). |
| Yes | As safety needs arise. |
| Yes | 2016. |
| Yes | Our goal is to have profile pavement markings or milled rumble strips on every roadway. |
| Maybe | Maybe, if funding is an issue and we cannot afford to install the milled in version. |
| No | We can't afford to maintain them. |
| No | The potential to get plowed off every year. |

15. *Would your district be willing to serve as a host district for an ALDWS test area(s) to be installed in spring/summer 2016? The focus of the test area(s) will be on the evaluation of the sound and vibration of the ALDWS. It is anticipated that the individual test areas will be no longer than 1 mile in length. Ideally the test areas can be incorporated into a planned ALDWS project.*

Eight of the nine districts that indicated the use of ALDWS indicated that they would be willing to serve as a test location. One of those districts has already hosted a test area for the project. The one district that did not indicate they would serve as a host site was unsure.

# CHAPTER 3: FIELD PERFORMANCE EVALUATIONS

This chapter describes the field performance evaluations. Data were collected at various sites to evaluate the performance of the various treatments. Noise, vibration, and visibility data were collected. Specific design characteristics of the treatments were also collected, so the treatments could be identified by their type, size, spacing, and the road surface upon which they were applied.

## STUDY LOCATIONS

The research team wanted to focus data collection efforts on locations where numerous treatments were located to reduce data collection costs and increase efficiency. After conducting the survey in Task 1 the research team found that the Atlanta District was the only District that had numerous types of audible marking and rumble bar treatments within close proximity to each other. Therefore, the data collection efforts were focused in the Atlanta District. Data collection also took place at several sections along SH 21 and at a test deck installed near Brenham.

### Atlanta District Test Areas

The research team received a list of treatments and a map of their locations from the Atlanta District to help determine where data collection would take place. Figure 6 provides a map of the locations included in the evaluation. The different colors and patterns on the roads indicate different treatments and installation dates (provided by TxDOT). The segments circled in red are the locations where the research team collected data during the first year of the project, Atlanta Trip 1. The segments circled in black are the locations where the research team collected data during the second year of the project, Atlanta Trip 2. The sections on SH 300 and SH 154 are circled in both red and black as they were evaluated during both data collection trips.

In total, 13 roadways were evaluated during the first Atlanta District trip. These 13 roadways had a total of 27 treatments on them. Table 9 provides a list of each of the roadways and treatments in each test section. Treatments consisted of audible profiled markings, rumble bars, milled rumble strips, inverted profiled markings with audible, milled rumble strips with rumble bars, and audible markings or rumble bars that had been seal coated over one time. These treatments were located on the edge line, on the center line, or on the shoulder of the roads. Most of the roads were seal coat, with two being asphalt. The spacing and general design of each treatment was noted.

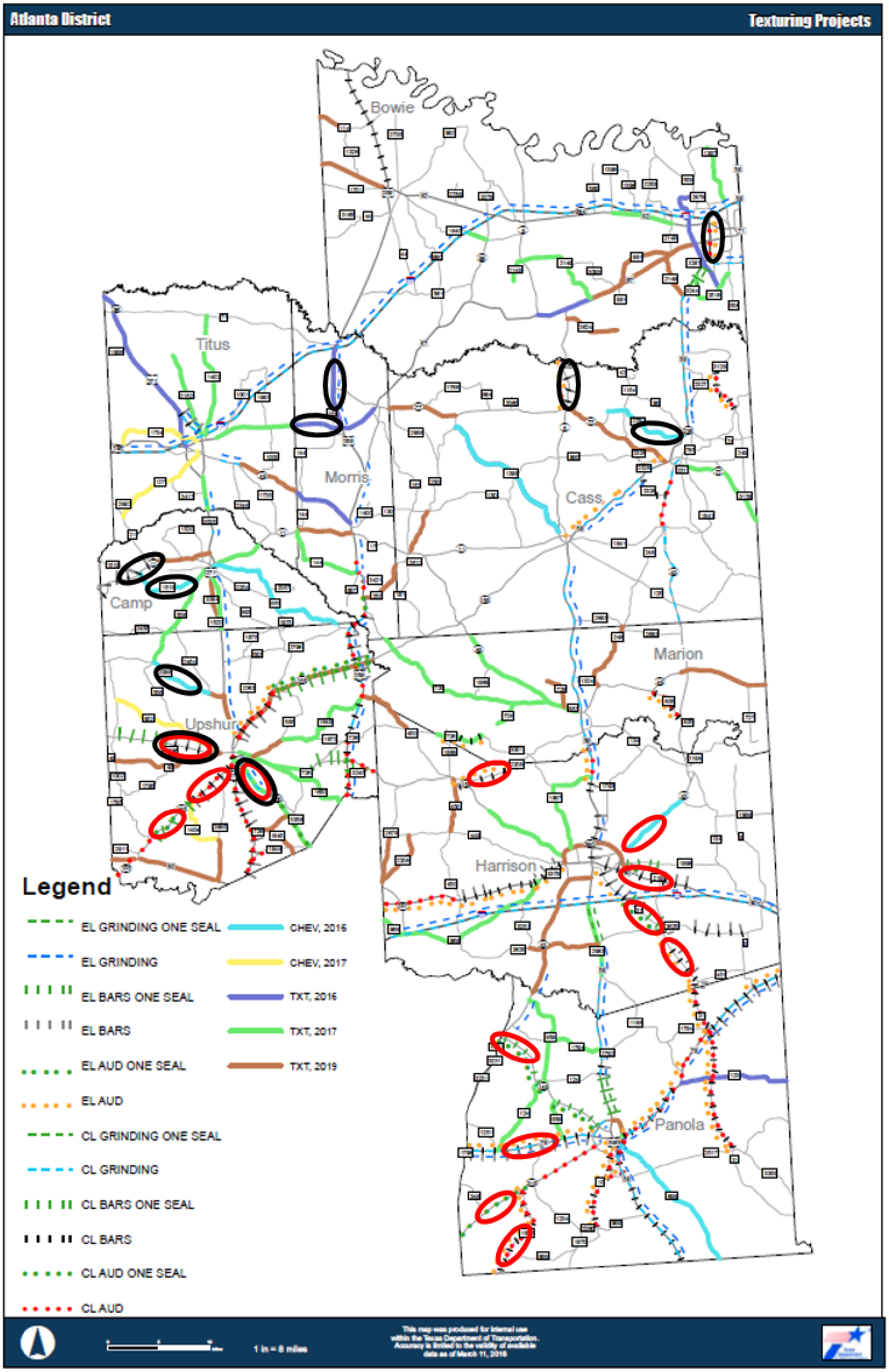


Figure 6. Atlanta District Map.

## Table 9. Atlanta District Trip 1 Site Information.

| Roadway | Location | Road Surface | Rumble Design | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Location | Style | Spacing (in.) | Length (in.) | Width (in.) | Height (in.) |
| US 79 | West of Carthage | Seal Coat | Edge Line | Inverted Profile w/ Audible | 16 | 2 | 6 | 0.3 |
| | | | Shoulder | SRS + Rumble Bars | 12, Bars @ 60 | 7.5 | 16 | 0.375 |
| | | | Center | CLRS + Rumble Bars | 24, Bars @ 60 | 7.5 | 16 | 0.375 |
| US 80 | East of Marshall | Seal Coat | Shoulder | Rumble Bars | 55 | 2 | 10.75 | 0.5 |
| | | | Center | Rumble Bars | 60 | 2 | 10.75 | 0.5 |
| SH 43 | East of Marshall | Seal Coat | Edge Line | Audible Dot Marking | 14 | 3 | 6 | 0.3 |
| | | | Center | Rumble Bars | 48 | 3 | 12.5 | 0.3 |
| SH 149 | West of Carthage | Seal Coat | Edge Line | Inverted Profile w/ Audible | 16 | 2 | 6 | 0.3 |
| | | | Center | Rumble Bars | 50 | 2 | 10.75 | 0.5 |
| SH 154 | West of Gilmer | Seal Coat | Edge Line | Rumble Bars | 43 | 2 | 10.75 | 0.5 |
| | | | Center | Rumble Bars | 48 | 2 | 10.75 | 0.5 |
| SH 155a | South West of Gilmer | Seal Coat | Shoulder | Rumble Bars w/ 1 seal coat | 50 | 2 | 10.75 | about even with seal coat |
| | | | Center | Rumble Bars w/ 1 seal coat | 50 | 2 | 10.75 | about even with seal coat |
| SH 155b | South West of Gilmer | Asphalt Overlay | Shoulder | Rumble Bars | 50 | 2 | 10.75 | 0.5 |
| | | | Center Line | Audible Marking + Rumble bars | 18, Bars @ 56 | 2 | 6 | 0.3 |
| SH 300 | South East of Gilmer | Asphalt | Edge Line | ERS | 12 | 6.5 | 16 | 0.375 |
| | | | Center Line | CLRS | 12 | 6.5 | 16 | 0.3 |
| SH 315 | South West of Carthage | Seal Coat | Center Line | Audible Marking w/ 1 seal coat | 12 | 2 | 4 | about even with seal coat |
| FM 31a | South East of Marshall | Seal Coat | Shoulder | Rumble Bars | 66 | 2 | 10.75 | 0.5 |
| | | | Edge Line | Inverted Profile w/ Audible | 16 | 2 | 6 | 0.3 |
| | | | Center | Rumble Bars | 48 | 2 | 10.75 | 0.5 |
| FM 31b | South East of Marshall | Seal Coat | Shoulder | Rumble Bars w/ 1 seal coat | 60 | 2 | 10.75 | about even with seal coat |
| | | | Center | Rumble Bars w/ 1 seal coat | 50 | 2 | 10.75 | about even with seal coat |
| FM 1971 | South West of Carthage | Seal Coat | Edge Line | Audible Marking | 12 | 2 | 6 | 0.4 |
| | | | Center Line | Audible Marking + Rumble bars | 12, Bars @ 56 | 2 | 6 | 0.4 |
| FM 2208 | North West of Marshall | Seal Coat | Edge Line | Inverted Profile w/ Audible | 16 | 1.5 | 6 | 0.25 |
| | | | Center | Rumble Bars | 50 | 2 | 10.75 | 0.5 |

Goals of the second Atlanta trip were to evaluate some of the same study locations from the first trip to determine if the performance had changed and to include new study locations that had new treatments. In total, 10 roadways were evaluated during the second Atlanta District trip. These 10 roadways had a total of 23 treatments on them. Table 10 provides a list of each of the roadways and treatments in each test section. Treatments consisted of audible profiled markings, rumble bars, rumble strips, inverted profiled markings with audible, dot markings with audible bumps, and audible checkerboard patterned markings. These treatments were located on the edge line, center line, or on the shoulder of the roads. Most of the roads were seal coat, with three being asphalt. The spacing and general design of each treatment was noted.

The test sections on SH 300 and SH 154 were the same areas that were evaluated in the first year of the project. The test sections on FM 2088, FM 1519, US 67, US 259, and FM 2791 were installed during spring 2016 and included new styles and application techniques for the treatments. These five sections were similar to those evaluated on SH 43 during the first year of the project. The audible checkerboard marking style on US 259 is a unique pattern that had not been previously tested.

Figure 7 through Figure 14 provide examples of the treatments evaluated in the Atlanta District.

**Table 10. Atlanta District Trip 2 Site Information.**

<table>
<tr><th rowspan="2">Roadway</th><th rowspan="2">Location</th><th rowspan="2">Road Surface</th><th colspan="6">Rumble Design</th></tr>
<tr><th>Location</th><th>Style</th><th>Spacing (in.)</th><th>Length (in.)</th><th>Width (in.)</th><th>Height (in.)</th></tr>
<tr><td rowspan="2">SH 300</td><td rowspan="2">South East of Gilmer</td><td rowspan="2">Asphalt</td><td>Edge Line</td><td>ERS</td><td>12</td><td>6.5</td><td>16</td><td>0.375</td></tr>
<tr><td>Center Line</td><td>CLRS</td><td>12</td><td>6.5</td><td>16</td><td>0.3</td></tr>
<tr><td rowspan="2">SH 154</td><td rowspan="2">West of Gilmer</td><td rowspan="2">Seal Coat</td><td>Edge Line</td><td>Rumble Bars</td><td>43</td><td>2</td><td>10.75</td><td>0.5</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>48</td><td>2</td><td>10.75</td><td>0.5</td></tr>
<tr><td rowspan="2">FM 2088</td><td rowspan="2">North of Gilmer</td><td rowspan="2">Seal Coat</td><td>Edge Line</td><td>Audible Dot Marking</td><td>50</td><td>3</td><td>4.5</td><td>0.4</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>48</td><td>2.5</td><td>12</td><td>0.1</td></tr>
<tr><td rowspan="2">FM 1519</td><td rowspan="2">West of Pittsburg</td><td rowspan="2">Seal Coat</td><td>Edge Line</td><td>Audible Dot Marking</td><td>50</td><td>3</td><td>4.5</td><td>0.4</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>48</td><td>2.5</td><td>12</td><td>0.3</td></tr>
<tr><td rowspan="2">SH 11</td><td rowspan="2">West of Pittsburg</td><td rowspan="2">Seal Coat</td><td>Edge Line</td><td>Rumble Bars</td><td>54</td><td>2</td><td>11</td><td>0.5</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>60</td><td>2</td><td>11</td><td>0.5</td></tr>
<tr><td rowspan="2">US 67</td><td rowspan="2">West of Omaha</td><td rowspan="2">Seal Coat</td><td>Edge Line</td><td>Audible Dot Marking</td><td>49</td><td>2.5</td><td>4.5</td><td>0.4</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>48</td><td>2.5</td><td>12</td><td>0.5</td></tr>
<tr><td rowspan="4">US 259</td><td rowspan="4">North of Omaha</td><td rowspan="4">Asphalt</td><td>Shoulder</td><td>SRS</td><td>12</td><td>6</td><td>16</td><td>0.375</td></tr>
<tr><td>Edge Line</td><td>Audible Dot Marking</td><td>48</td><td>3.5</td><td>6</td><td>0.4</td></tr>
<tr><td>Center Line</td><td>Audible Checkerboard Marking</td><td>2.5</td><td>2</td><td>6</td><td>0.15</td></tr>
<tr><td>Center Line</td><td>Rumble Bar</td><td>48</td><td>2.5</td><td>12</td><td>0.4</td></tr>
<tr><td rowspan="2">I-369</td><td rowspan="2">West of Texarkana</td><td rowspan="2">Asphalt</td><td>Edge Line</td><td>Audible Marking</td><td>18</td><td>2.5</td><td>6</td><td>0.5</td></tr>
<tr><td>Center Line</td><td>Audible Marking</td><td>15</td><td>4</td><td>6</td><td>0.5</td></tr>
<tr><td rowspan="2">FM 2791</td><td rowspan="2">West of Atlanta</td><td rowspan="2">Seal Coat</td><td>Edge Line</td><td>Audible Dot Marking</td><td>50</td><td>2.5</td><td>4</td><td>0.3</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>48</td><td>2.5</td><td>12</td><td>0.25</td></tr>
<tr><td rowspan="3">SH 8</td><td rowspan="3">North of Douglassville</td><td rowspan="3">Seal Coat</td><td>Shoulder</td><td>Rumble Bars</td><td>54</td><td>2</td><td>11</td><td>0.3</td></tr>
<tr><td>Edge Line</td><td>Inverted Profile w/ Audible</td><td>16</td><td>2</td><td>4</td><td>0.2</td></tr>
<tr><td>Center</td><td>Rumble Bars</td><td>60</td><td>2</td><td>11</td><td>0.3</td></tr>
</table>

**Figure 7. FM 1971 Edge Line Profile Audible Marking.**

**Figure 8. US 79 Edge Line Inverted Profile Marking with Audible, Milled Rumble Strips, and Rumble Bars.**


**Figure 9. SH 155a Center Line Rumble Bars with One Seal Coat.**


**Figure 10. SH 43 Edge Line Profile Audible Marking with Dot Line.**

**Figure 11. I-369 Edge Line Profile Audible Marking.**

**Figure 12. SH 8 Edge Line Inverted Profile Marking with Audible, and Shoulder Rumble Bars.**

**Figure 13. FM 2088 Center Line Rumble Bars (Bars Are Somewhat Flattened Out).**

**Figure 14. US 259 Checkerboard Pattern Audible Marking with Rumble Bars.**

### State Highway 21 Test Areas

In total, three sections were evaluated on SH 21 in the Bryan and Austin Districts. These three sites had a total of five treatments on them. Table 11 provides a list of each of the treatments in each test section. Treatments consisted of audible profiled markings, and milled rumble strips that had been seal coated over one time. The profile markings on these sections were of the standard design that most districts use. The Atlanta District has several styles of profile marking designs, and other districts have used circular profile bumps. These treatments were located on the edge line, on the center line, or on the shoulder of the roads. Two of the road surfaces were asphalt and the other seal coat. The spacing and general design of each treatment was noted. Figure 15 through Figure 17 provide examples of the treatments evaluated along SH 21.

**Table 11. State Highway 21 Test Area Site Information.**

| Roadway | Location | Road Surface | Rumble Design | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Location | Style | Spacing (in.) | Length (in.) | Width (in.) | Height (in.) |
| SH 21 | Near Bastrop | Asphalt | Edge Line | Audible Marking | 14 | 3 | 3.5 | 0.35 |
| | | | Center Line | Audible Marking | 13 | 3 | 3.5 | 0.35 |
| SH 21 | Near Lincoln | Asphalt | Edge Line | Audible Marking | 11.5 | 2.5 | 4 | 0.35 |
| SH 21 | Near Bryan | Seal Coat | Shoulder | SRS w/ 1 seal coat | 12 | 7 | 16 | 0.35 |
| | | | Center Line | CRS w/ 1 seal coat | 12 | 7 | 16 | 0.35 |

**Figure 15. Aged Profile Pavement Marking near Bastrop.**

**Figure 16. New Profile Pavement Marking near Lincoln.**

**Figure 17. Seal Coat over Milled Rumble Strip near Bryan.**

### Brenham Test Area

A test area was installed near Brenham as part of the project to evaluate new treatments/designs. A newly seal coated road was selected so that the striping could be applied to meet the needs of the project. The Brenham test deck was installed with cooperation from the Bryan District and a pavement marking contractor, Stripe-A-Zone. The Brenham test deck consisted of numerous variations of audible profiled pavement markings on the new seal coat road surface. Standard audible profiled markings were installed along with variations that consisted of different spacing's that were intended to produce unique noises that would be more noticeable to drivers. Table 12 provides a summary of the different treatments installed at the Brenham test deck. The Brenham test deck was approximately 2 miles in length. Each individual test section was approximately one-third of a mile long.

**Table 12. Brenham Test Area Site Information.**

| Roadway | Location | Section | Rumble Design | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Location | Style | Spacing (in.) | Length (in.) | Width (in.) | Height (in.) |
| FM 389 | Near Brenham | WB 1 | Edge Line | Audible Marking | 12 | 2 | 4 | 0.35 |
| | | WB 2 | | Audible Marking | 18 | 2 | 4 | 0.35 |
| | | WB 3 | | Audible Marking | 12,12,12,12,18,18,18, 18 | 2 | 4 | 0.35 |
| | | WB 4 | | Audible Marking | 8,8,8,16,16,16 | 2 | 4 | 0.35 |
| | | WB 5 | | Audible Marking | 12,18,24,24,18,12 | 2 | 4 | 0.35 |
| | | WB 6 | | Audible Marking | 12,18,24,24,18,12 | 4 | 4 | 0.35 |
| | | EB 1 | | Audible Marking | 12 | 2 | 4 | 0.35 |
| | | EB 2 | | Audible Marking | 18,18,24,36 | 2 | 4 | 0.35 |
| | | EB 3 | | Dot Marking | No profile bumps | 2 | 4 | 0.35 |
| | | EB 4 | | Audible Marking | 12,18,24,24,18,12 | 2 | 4 | 0.35 |
| | | EB 5 | | Audible Marking | 8,8,12,12,16,16,24,16 ,16,12,12 | 2 | 4 | 0.35 |
| | | EB 6 | | Audible Marking | 8,8,8,16,16,16 | 2 | 4 | 0.35 |

Many profiled markings applications have the bump placed on top of the solid line. Due to the nature of this installation and the available equipment, it was decided to place the bumps first and then cover them with the solid line. The resulting noise and vibration will still provide typical levels and allow the research team to compare the different designs of the treatments. Figure 18 provides an image of the installation of the profiled bumps. The striping equipment was preprogrammed with the specific designs of each treatment. The spacing, length, and width of the bumps were all computer controlled.

**Figure 18. Profile Bump Installation.**

Initially the bumps were placed at each of the test areas prior to striping over the entire test deck with the solid lines. Figure 19 shows the standard spacing of the profiled bumps, with 12-in. spacing. Figure 20 shows a variable spacing test area with three bumps spaced at 8 in. followed by three bumps spaced at 16 in.

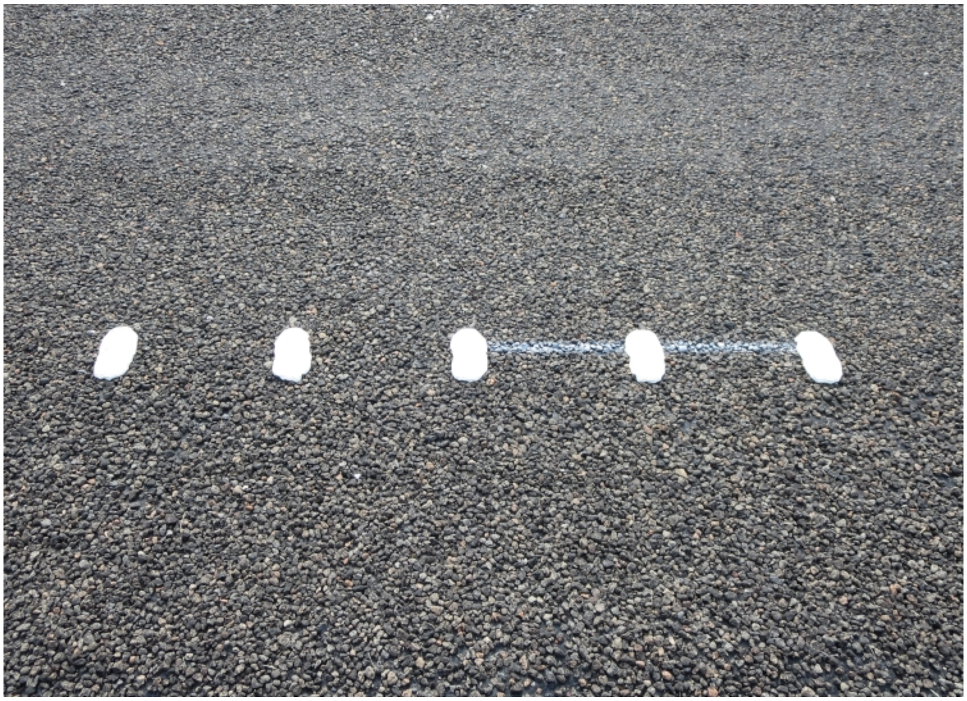

**Figure 19. Profile Bumps prior to Solid Line Installation (Standard Spacing, Section WB1).**

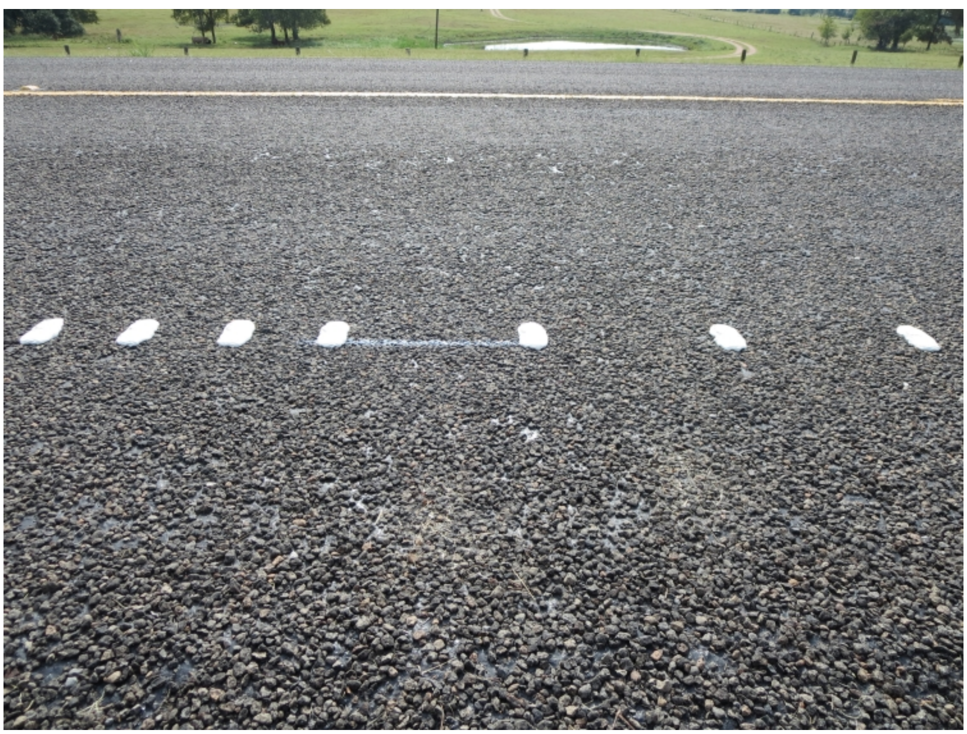

**Figure 20. Profile Bumps prior to Solid Line Installation (Variable Spacing, Section WB4).**

After the bumps were placed, the long lines were placed over the top. Test areas heading westbound received an extruded solid line with a high refractive index drop on glass bead. This bead type typically results in higher retroreflectivity levels. Test areas heading eastbound received a dot line with standard drop on glass beads. The dot line is anticipated to provide better wet weather visibility due to its structure. When looking directly down on the marking or at short distances ahead, the gaps in the marking are visible. When looking farther down the road at typical driver viewing distances, the marking appears to be a solid line. Figure 21 shows the standard 12-in. spacing profiled bumps covered with the solid extruded line immediately after application. Figure 22 shows test area three eastbound where only the dot marking was applied. Figure 23 shows a test area with a combination of the dot marking and profiled bumps.

**Figure 21. New Profiled Marking with Solid Line over Bump (WB1).**

**Figure 22. Dot Marking Only (EB3).**

**Figure 23. Profiled Bumps with Dot Marking (Standard Spacing, EB1).**

## NOISE PERFORMANCE EVALUATION

The primary performance metric for audible lane departure warning treatments is how much noise they generate when driven on. The researchers collected noise data inside and outside the vehicle. The interior noise was measured with a free-field microphone positioned to the right of the driver's head. The exterior noise was measured with an on-board sound intensity (OBSI) system in general conformance with AASHTO TP 76 (Test Method for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity Method). Divergence from the standard involved measuring noise only at the tire leading edge and using a non-standard tire when testing with a pick-up truck. The exterior noise measurements were only valid for edge line and shoulder located treatments, because the equipment only mounts on the passenger side of the vehicle. At select test sections on FM 389, wayside noise measurements were collected using a controlled pass-by technique with the vehicles traveling at 55 mph. The microphone was placed at 25 ft from the edge line marking at a height of 5 ft above the road surface. Figure 24 provides images of the noise measurement equipment setup. Measurements were made with both a passenger car and a truck at 55 mph and in select locations at 70 mph.

The raw signals were processed with fast-Fourier transform (FFT) analysis, then the narrow-band and 1/3-octave band sound intensity was calculated. The overall a-weighted noise level, dBA, was then calculated (Figure 25).

(a) (b)

(c)

**Figure 24. Noise Measurement Equipment: (a) Interior Microphone, (b) OBSI System (Only Leading Edge Enabled), and (c) Wayside Noise System.**

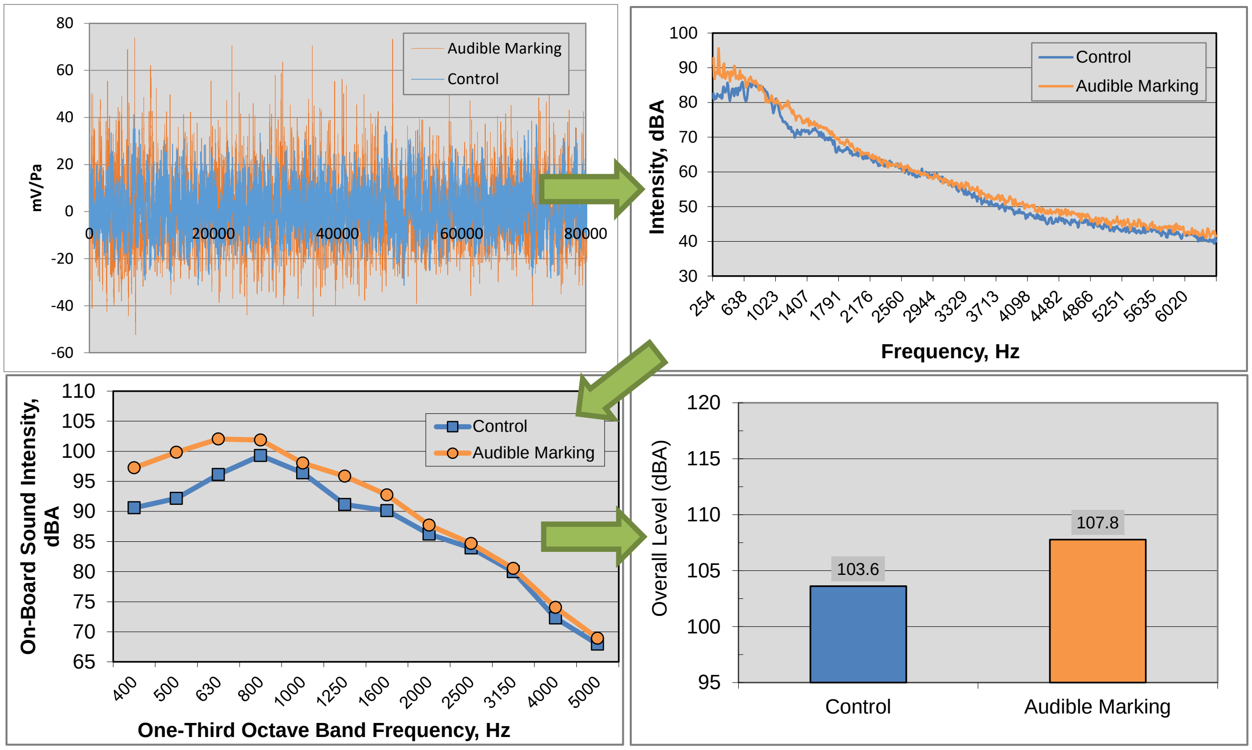


**Figure 25. Progression of Noise Data Processing.**
**(Raw Data >> Narrow Band >> 1/3 Octave Band >> A-Weighted Noise Level)**

Treatment performance was characterized by 1) the overall a-weighted noise level, 2) the overall change in noise level from the control (ambient noise while driving in the travel lane), and 3) the change in the peak frequency (Figure 26). The change in frequency is an important aspect of alerting drivers.

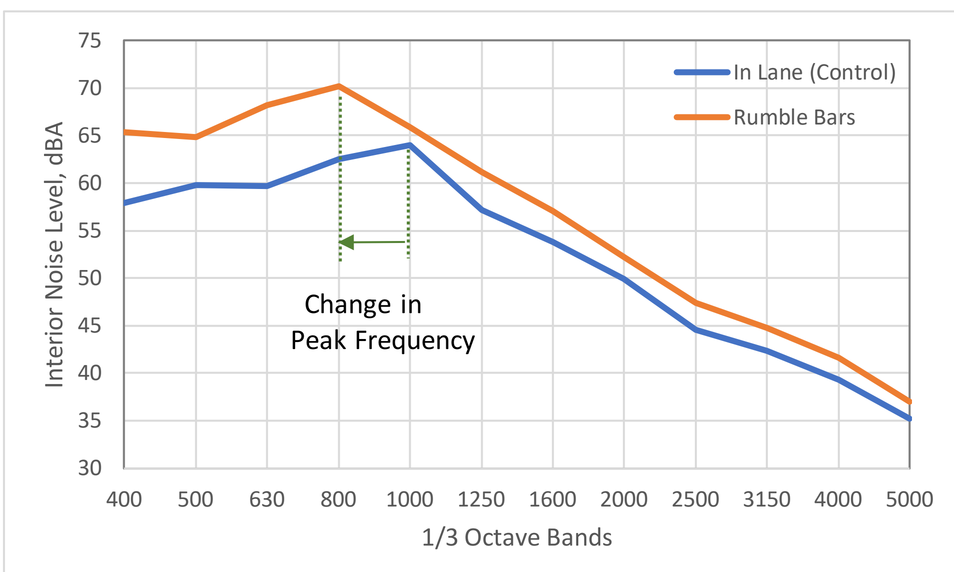


**Figure 26. Calculation for Change in Peak Frequency.**

Various methods were used to evaluate the impact of the factors on treatment performance. Table 13 summarizes the factors evaluated and the methods used to evaluate them. Statistical methods were used for all evaluations except when comparing treatment types that were not on the Brenham test deck. Due to numerous designs evaluated of the various treatment types, so small sample sizes, a statistical analysis would not be appropriate. Appendix B contains details for each analysis, including the data set and sample size.

**Table 13. Methods for Analyzing Test Factors.**

| Factor | Analysis Method |
|---|---|
| Vehicle Type | MANOVA |
| Vehicle Speed | MANOVA |
| Treatment Type<br>(Brenham test deck)<br>(Other sections) | MANOVA<br>Boxplot comparison |
| Exterior (OBSI) Noise<br>vs.<br>Interior Noise by Vehicle Type | Linear Regression |
| Wayside Noise<br>vs.<br>Exterior (OBSI) Noise | Linear Regression |

**Results**

Based on the statistical analysis, both speed and vehicle type affect the interior noise level and the change in noise level. To analyze the effect of speed, only data where tests were done at both 55 and 70 mph were included. Data for both the car and the truck were averaged together. In the vehicle analysis, all locations were used and the data from different test speeds were averaged together. Figure 27 shows the overall effect of speed on noise level and change in noise level. The research team considered changes in noise level of less than 6 dBA as being negligible (i.e., not a great enough change to be easily noticeable to the driver). Anything greater than 10 dBA was considered excellent. Overall, faster speeds result in an increased noise level. Also, faster speeds results in a smaller change in noise from the ambient condition. While this difference in noise level change is statistically significant, the practical significance is negligible. Figure 28 indicates that the truck had lower interior noise than the car and less change in noise. Because of the wide variation among all vehicles in terms of body design, suspension, tires, and wear, this trend may not translate to every car and every truck but is the case for the two test vehicles. The data clearly show that different vehicle types can result in different levels of noise generation.

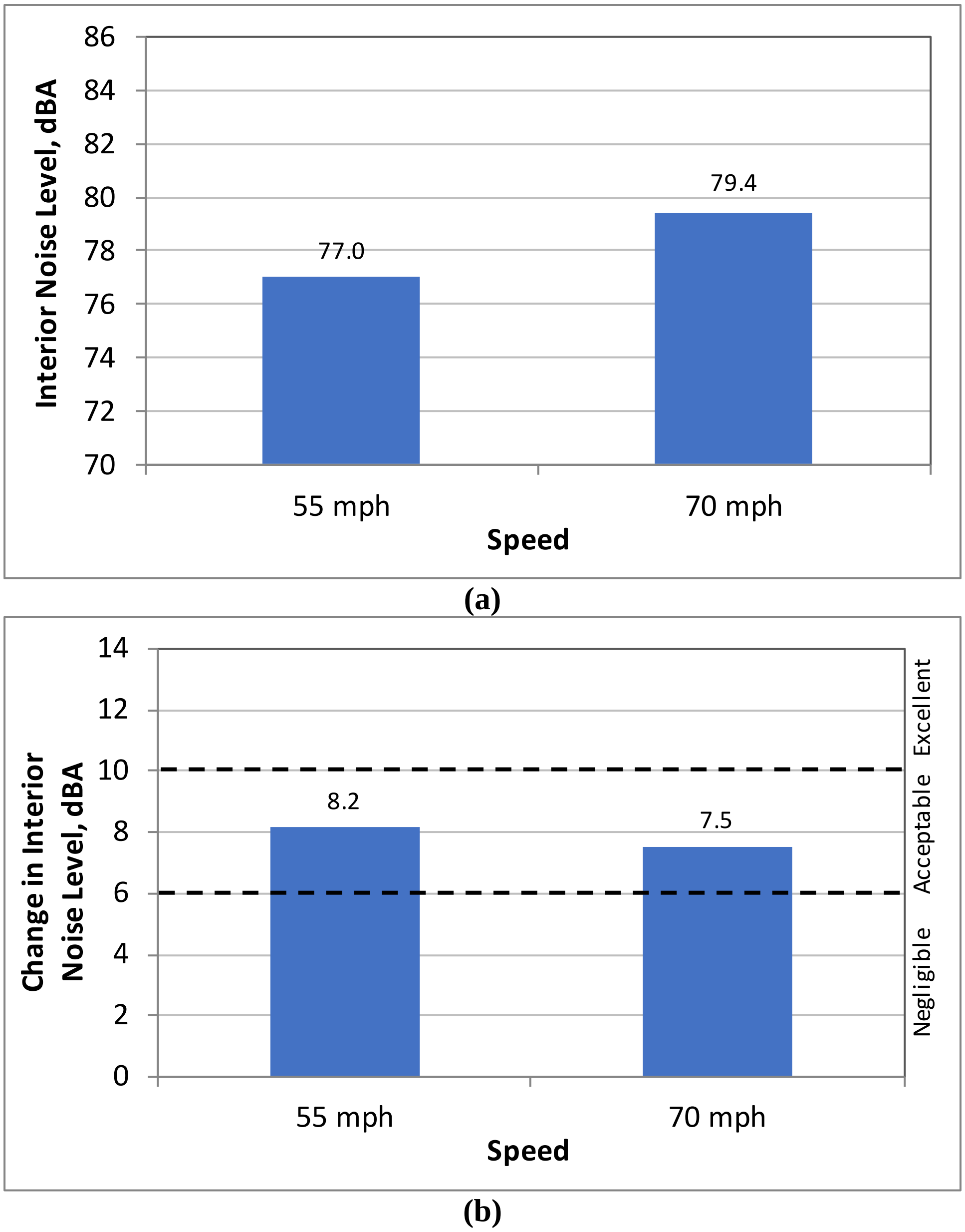


**Figure 27. Statistical Effect of Vehicle Speed: (a) Interior Noise Level and (b) Change in Interior Noise Level.**

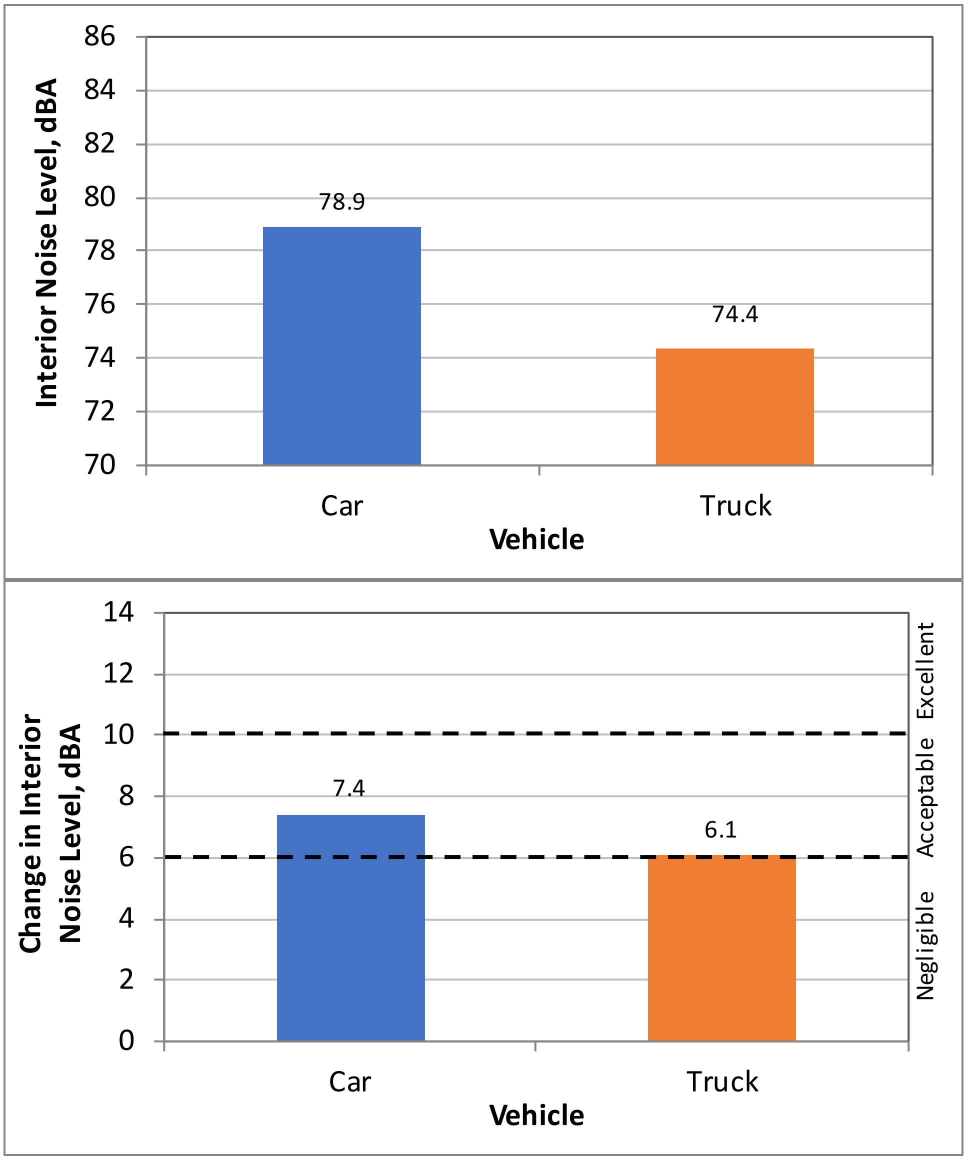


**Figure 28. Statistical Effect of Vehicle Type: (a) Interior Noise Level and (b) Change in Interior Noise Level.**

Figure 29 and Table 14 display the effect of treatment type on the Brenham test deck. The effect of treatment type was statistically significant for all three performance metrics. According to the change in noise level, the design that had the clearest performance advantage was the dot stripe with 12-in. spacing (EB 1). Five other test areas were not statistically different than the best performer with noise changes in the upper 7 dBA range, which would be considered acceptable. Most of the other designs showed little statistical distinctions with noise changes ranging from 5.4 to 6.6 dBA. The dot stripe without audible markings was not statistically different than the control. As seen in the third graph, driving on the audible treatments decreased the peak frequency around 200 to 300 Hz, and as much as 400 Hz.

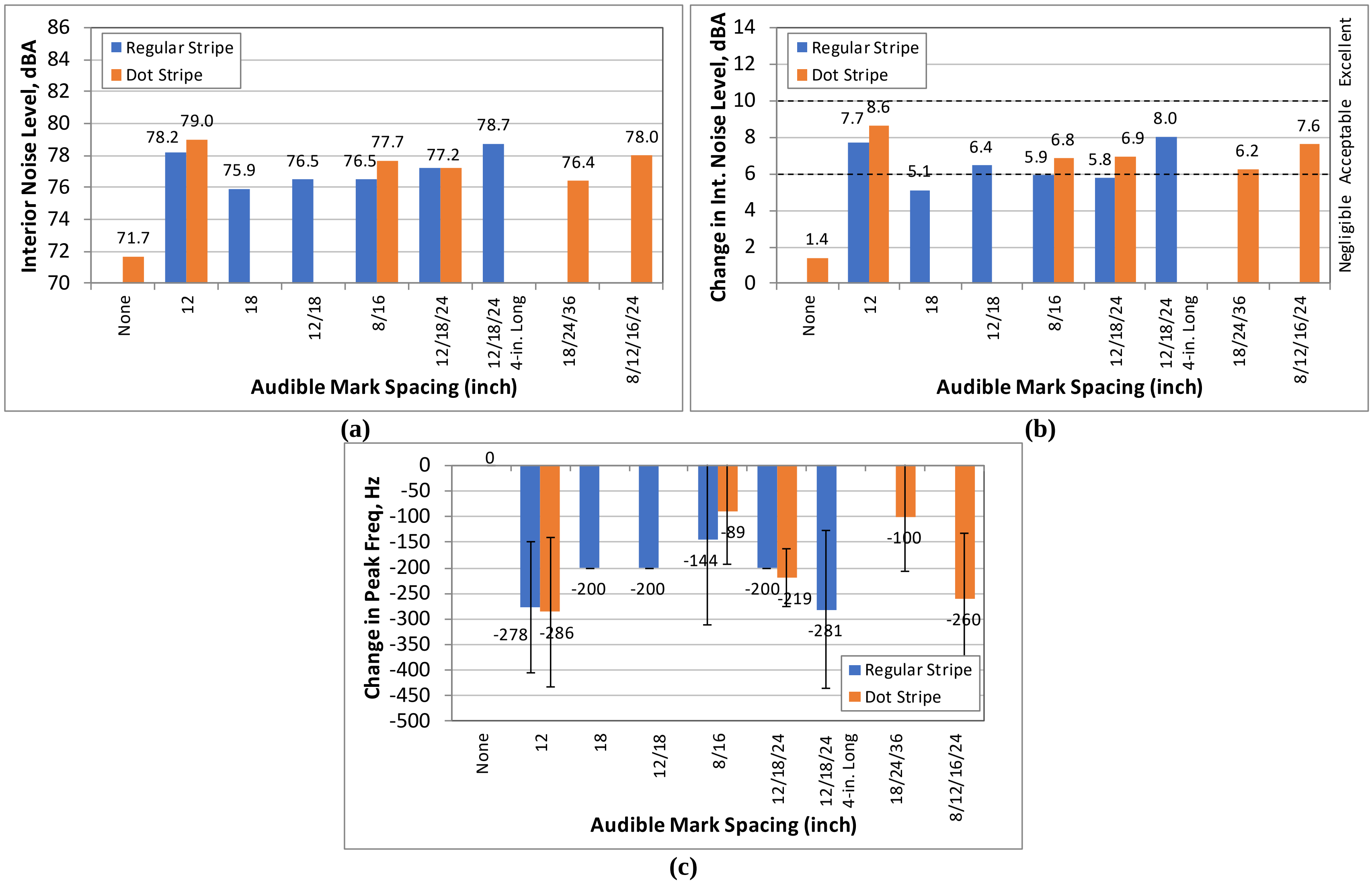


**Figure 29. Effect of Treatment Type on the Brenham Test Deck: (a) Interior Noise Level, (b) Change in Interior Noise Level, and (c) Change in Peak Frequency.**

**Table 14. Interior Noise Change by Treatment Design and Statistical Grouping.**

| Treatment with Audible Marker Spacing (in.) | | Change in Interior Noise Level, dBA | Statistical Grouping* | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dot Stripe | 12 | 9.0 | A | | | | | |
| Regular Stripe | 12/18/24<br>4" Long | 8.5 | A | | | | | |
| Regular Stripe | 12 | 7.9 | A | B | | | | |
| Dot Stripe | 12/18/24 | 7.8 | A | B | C | | | |
| Dot Stripe | 8/12/16/24 | 7.7 | A | B | C | | | |
| Regular Stripe | 12/18 | 7.6 | A | B | C | D | | |
| Dot Stripe | 8/16 | 6.6 | | B | C | D | E | |
| Dot Stripe | 18/24/36 | 6.5 | | B | C | D | E | |
| Regular Stripe | 8/16 | 6.2 | | B | | D | E | |
| Regular Stripe | 12/18/24 | 5.9 | | | | D | E | |
| Regular Stripe | 18 | 5.4 | | | | | E | |
| Dot Stripe | None | 1.8 | | | | | | F |

*Tukey's HSD, Levels not connected by the same letter are significantly different.

Figure 30 through Figure 33 summarize the performance of all treatments aside from the Brenham test deck. The data represent 24 different roadway sections with 51 total treatments. Only data collected at 55 mph were analyzed, as 55 mph data were collected on each treatment. As previously mentioned, there are not enough samples for certain treatment types to perform hypothesis testing, so the data are assessed visually with box plots.

Based on car observations, typical audible markings and the milled rumble strip designs produced the most noise, greater than 10 dBA on average. The noise change for many of the other audible marking designs and most rumble bar designs was negligible (less than 6 dBA increase). The rumble bars with audible markings produced an acceptable change in noise level. The results are slightly different for the truck measurements. The best performers (>10 dBA change) were the milled rumble strip designs. The group of treatments with the next highest mean change was typical audible markings and rumble bars+audible lane markings. These designs had a mean change greater than 6 dBA. Other designs had a mean change less than 6 dBA.

Many of the treatments measured had a wide spectrum of performance between sites. Rumble bar designs, for example, had negligible performance on some sites and excellent performance on others. Audible markings as a whole have a similar spread, though the typical audible marking design has more consistently acceptable to excellent performance.

In nearly every case, the treatments produced a lower peak interior noise frequency, but there was little consistency among the frequency changes for the car and the truck data.

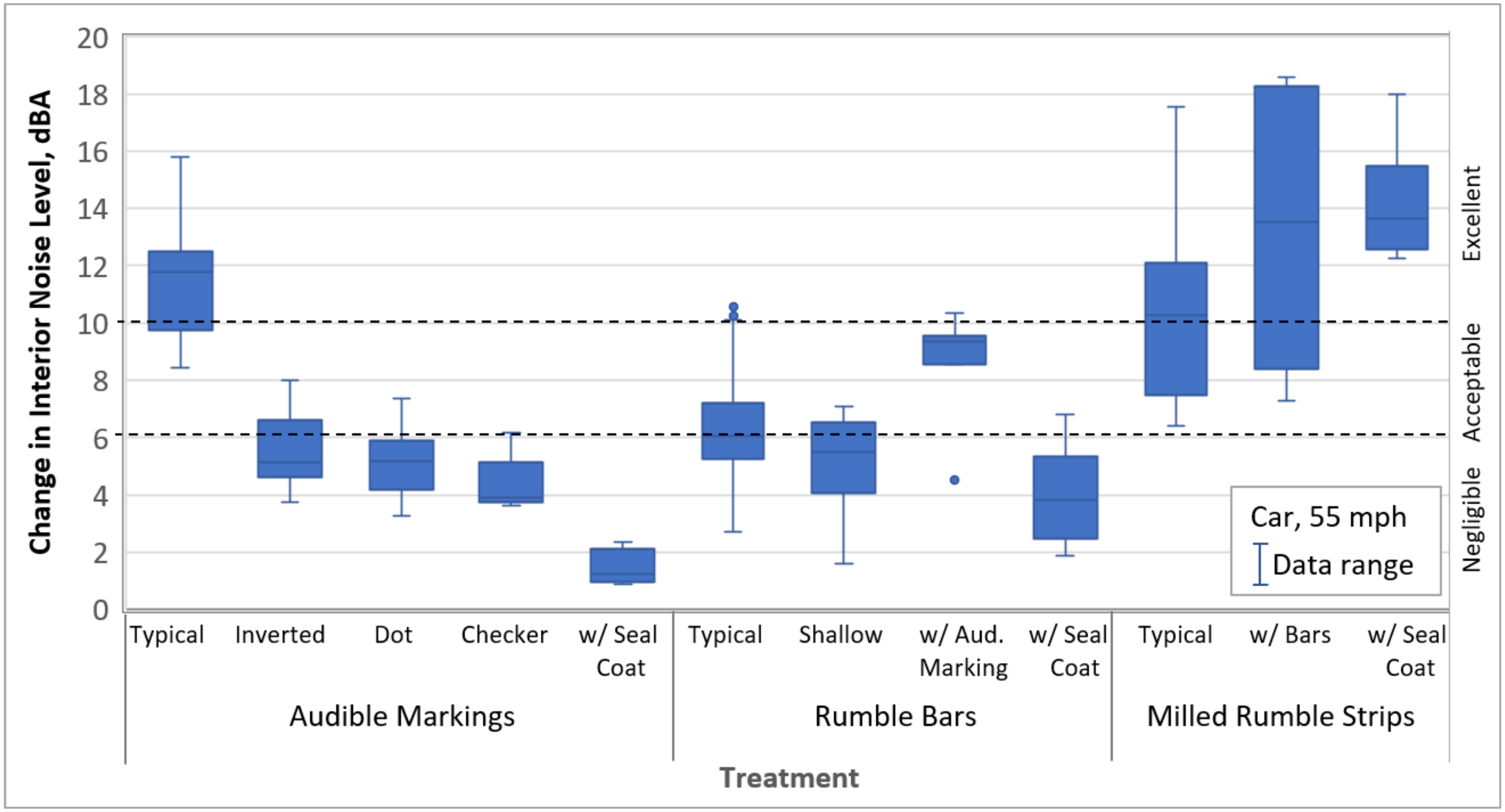


**Figure 30. Change in Interior Noise Level by Treatment Type (Car, 55 mph).**

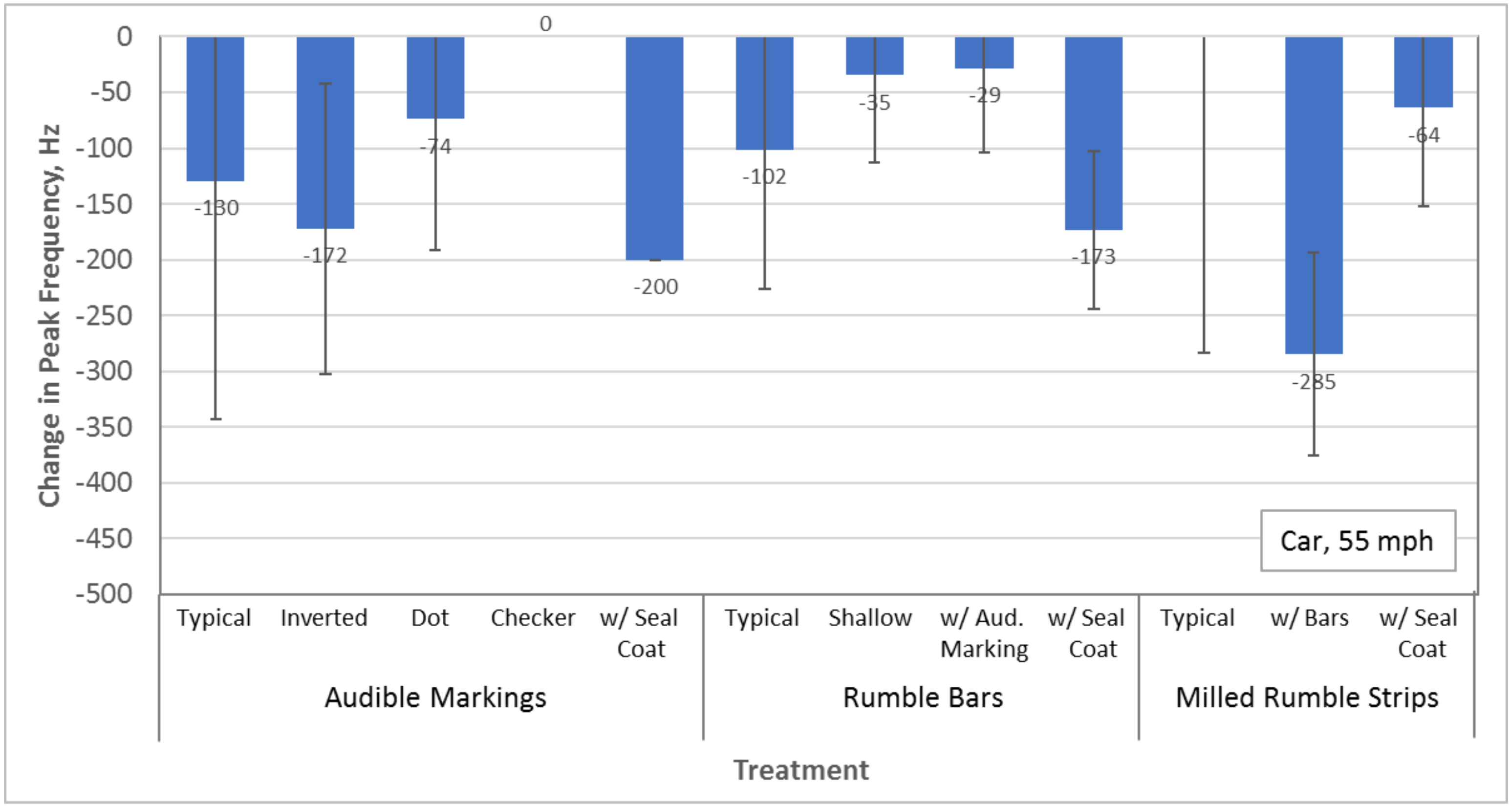


**Figure 31. Change in Peak Frequency by Treatment Type (Car, 55 mph).**

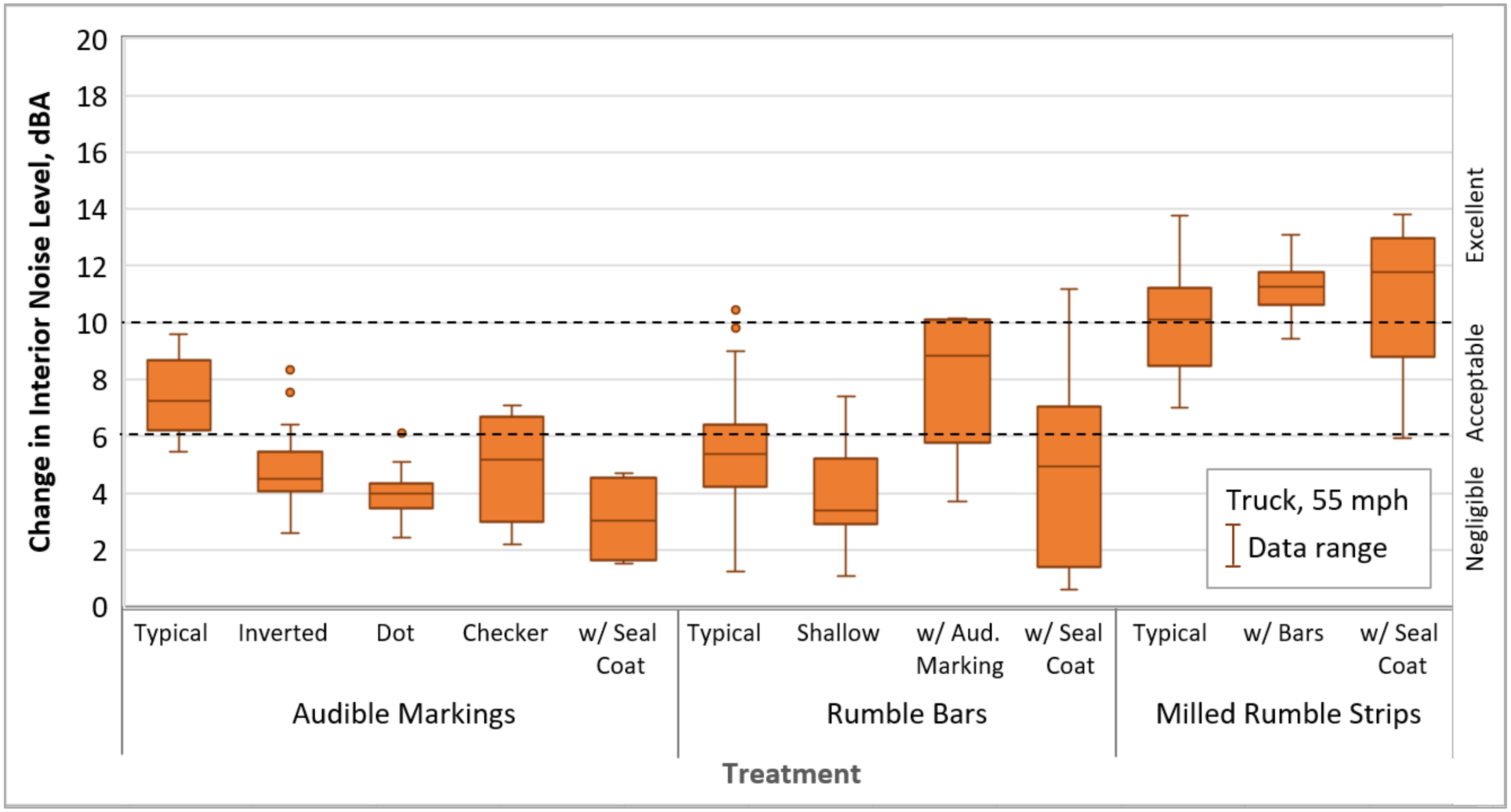


**Figure 32. Change in Interior Noise Level by Treatment Type (Truck, 55 mph).**

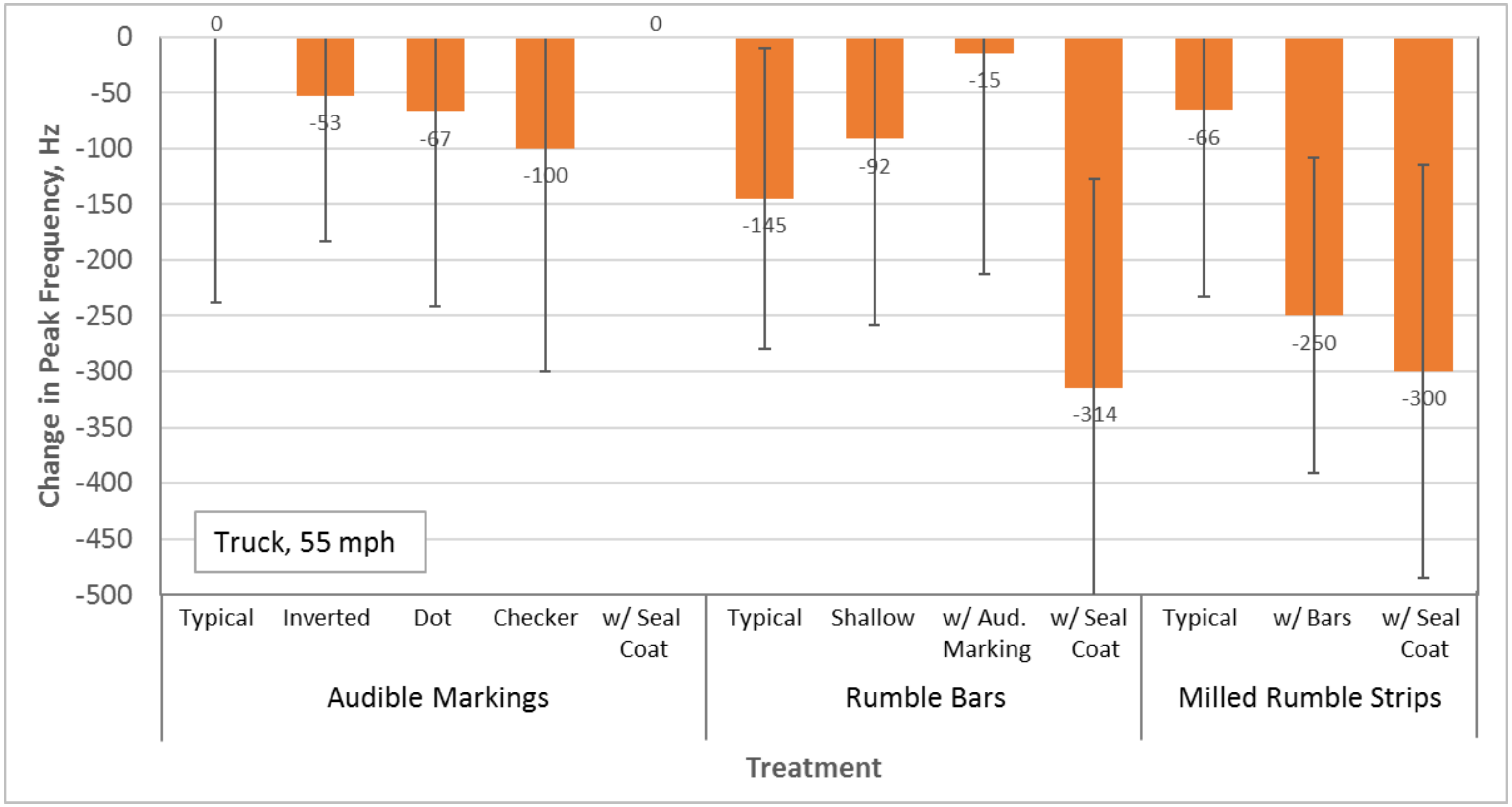


**Figure 33. Change in Peak Frequency by Treatment Type (Truck, 55 mph).**

The correlation of exterior noise (OBSI) and interior noise is given in the following correlation equation and illustrated in Figure 34. The effect of vehicle type was significant, so the car data have an additional shift factor in the equation. If any other vehicle were considered, a new shift factor would be required. The feasibility of predicting interior noise from the OBSI is moderate. For a given measured OBSI value, the predicted value is within ±10 dBA with 95 percent confidence, which is too wide a range to use as a decision-making tool.

$$dBA_{Interior} = dBA_{OBSI} * 0.769 + 5.235 * IsCar - 11.849 \qquad \text{Correlation Equation}$$

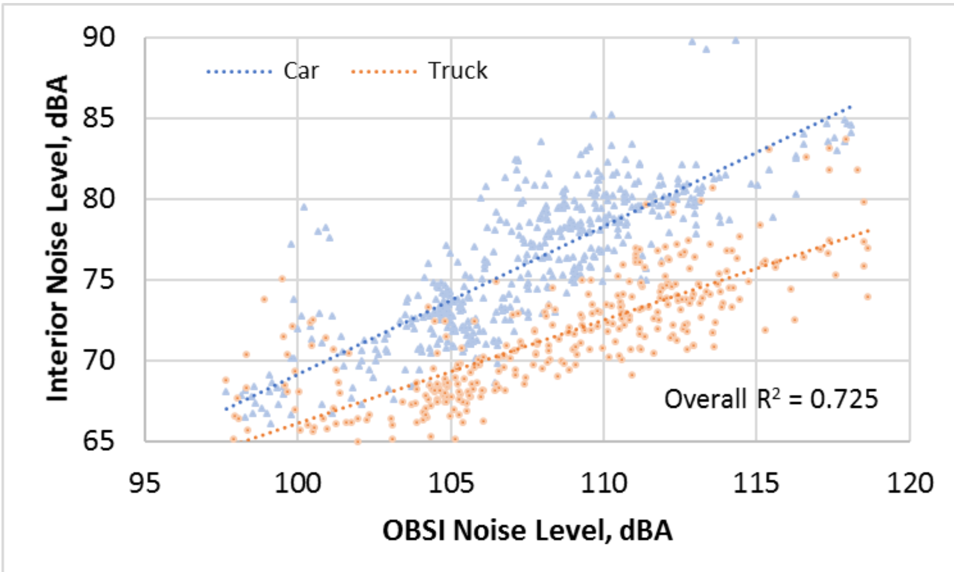


**Figure 34. OBSI Noise Level vs Interior Noise Level.**

One concern with audible lane departure warning systems is the problem with noise pollution. The occasional vehicle driving on the treatment can cause annoyance to nearby residences, especially when the change in noise is large. Figure 35 shows the exterior noise change for the car on different treatment types as measured by the OBSI system. The loudest treatment is the typical audible lane marking, with an average noise increase of about 8 dBA. Next are two other audible marking designs and the milled rumble strips. The rumble bar designs have less than half the decibel increase as the audible markings or milled rumble strips. When considering which treatments have both high interior performance and low exterior noise generation, the milled rumble strips and rumble bars+audible markings did very well.

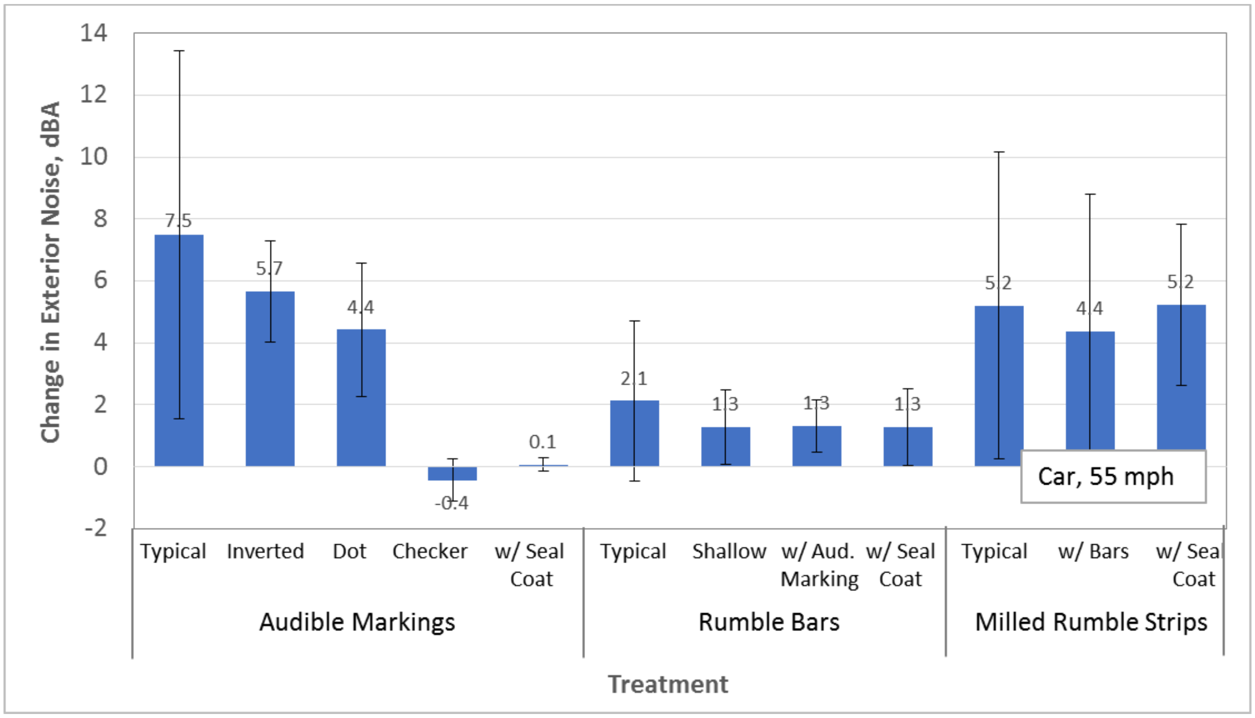


**Figure 35. Change in Exterior Noise.**

Figure 36 shows a comparison of OBSI noise to wayside noise. The regression has an $R^2$ value of 0.84. The noise level at the source (OBSI) is in the range of 105 to 112 dBA and at an offset of 25 ft (distance to wayside measurement location); the noise level is reduced to between 78 and 85 dBA. The wayside noise level increased by approximately 5 dBA when on the treatment compared to the ambient noise when just driving in the lane (control).

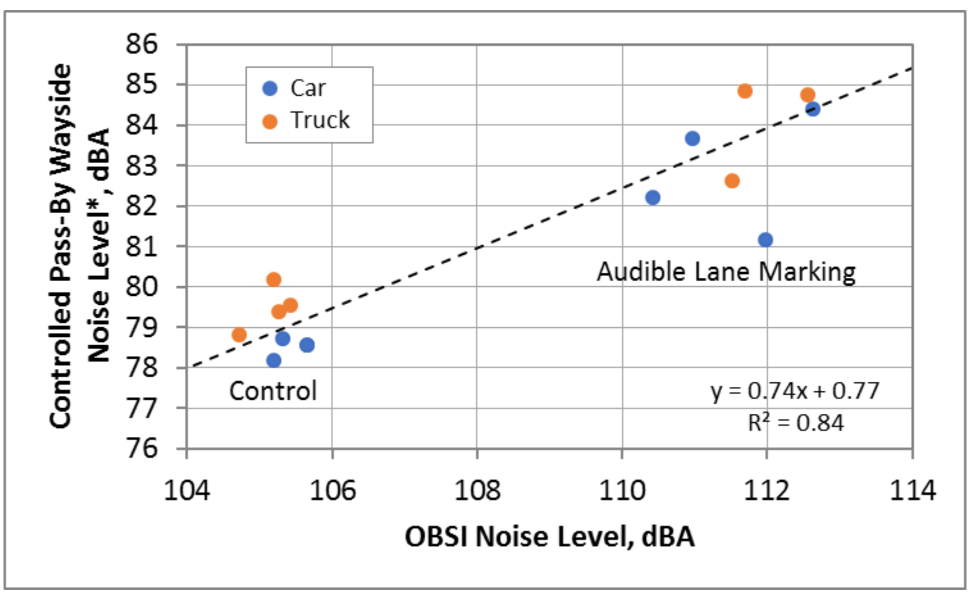


**Figure 36. OBSI Noise Level vs. Wayside Noise Level.**

## Findings

The following are key findings from the noise study:

- Noise level increases with vehicle speed.
- The pick-up truck had lower interior noise than the passenger car.
- The treatments on the Brenham test deck increased the noise level by 5.4 to 9.0 dBA. The most effective treatments were the 12-in. bump spacing design and the variable spacing design with 4-in. long bumps. Other designs had little statistical or practical difference in terms of performance.
- For other treatments tested with the car, typical audible markings and milled rumble strip designs had the best interior noise performance, with an increase of more than 10 dBA on average. Other audible marking and rumble bar designs had less than a 6 dBA increase on average. Most treatment types had significant performance variability.
- For measurements with the truck, the milled rumble strip designs had the best performance (>10 dBA increase). Typical audible markings and rumble bars+audible markings had acceptable performance (>6 dBA), and other designs, on average, had less than 6 dBA noise increase. Most treatment types had significant performance variability.
- Essentially all treatments decreased the noise frequency compared to driving in the wheel path.
- Interior noise and outside noise are related, but the prediction is vehicle dependent and not accurate enough for reliable decision making (±10 dBA).
- As noise pollution is concerned, the lane departure treatments generate more noise at the source, between 1 and 8 dBA increase on average.
- At 25 feet, the treatments generate roughly 5 more decibels compared to just the vehicle noise.

From a noise perspective, the current milled rumble strip design is most effective at alerting drivers of lane departure. The typical audible marking design is also highly effective. Variable marker spacing does not need to be considered as there was no consistent benefit. Rumble bars designs may also have acceptable performance. If lower exterior noise volumes are required rumble bars may be the best option. Using exterior (OBSI) noise measurement for assessing interior noise performance is not recommended.

## VIBRATION PERFORMANCE EVALUATION

Vibration data were collected on the interior of the vehicle at each of the data collection sites. In addition to the Brenham test deck, which had 12 different treatments, a total of 24 sites with a total of 51 treatments were evaluated. Treatments that produce higher levels of vibration will generally be more effective at alerting drivers that they are leaving their lane. The vibration was measured with an accelerometer mounted to the base frame of the driver's seat. This position was selected because the treatments need to be able to transmit the vibration to the driver and through the seat is a major source of the vibration transmission. The base mounting point is also a solid mounting point where the vibration can be effectively monitored. Figure 37 shows the accelerometer mounted to the driver's seat frame, the power source for the accelerometer, and the data acquisition system that was used to transfer the data to the laptop computer.


**Figure 37. Vibration Data Collection Setup.**

**Results**

The vibration was analyzed differently than the noise data. The noise data (especially the interior value) are the primary metric for judging the performance of audible lane departure warning treatments. The vibration data are more difficult to collect and analyze. When a vehicle drives over a treatment, the wheel is displaced and the suspension tries to absorb the impact to minimize vibration. When both wheels are on a treatment, the vibration in a vehicle can be very random with positive and negative forces acting upon occupants. To analyze the data, the absolute values of the vibration were averaged to get an average force acting upon the sensor. The treatment designation in the figures and tables is as follows: center line audible marking (CAM), edge line audible marking (EAM), shoulder milled rumble strip (SRS), center line milled rumble strip (CRS), center line rumble bar (CRB), edge line rumble bar (ERB), shoulder rumble bar (SRB), and with one layer of seal coat (wSC).

Appendix C contains the tabular results for each test area and results of a mixed effects ANOVA analysis of the results from each Atlanta District trip and the three sites along SH 21. The results indicate a rank order of the treatments and which treatments are statistically different from one another. Figure 38 provides a plot of the predicted mean absolute vibration value for the different treatment types obtained by ANOVA during the first Atlanta data collection trip. The car experiences significantly more vibration than the truck. Data collected at 70 mph were typically higher than at 55 mph. The treatment combination of the milled rumble strips and bars produced the highest vibration levels. The rumble bars and audible markings had similar performance.

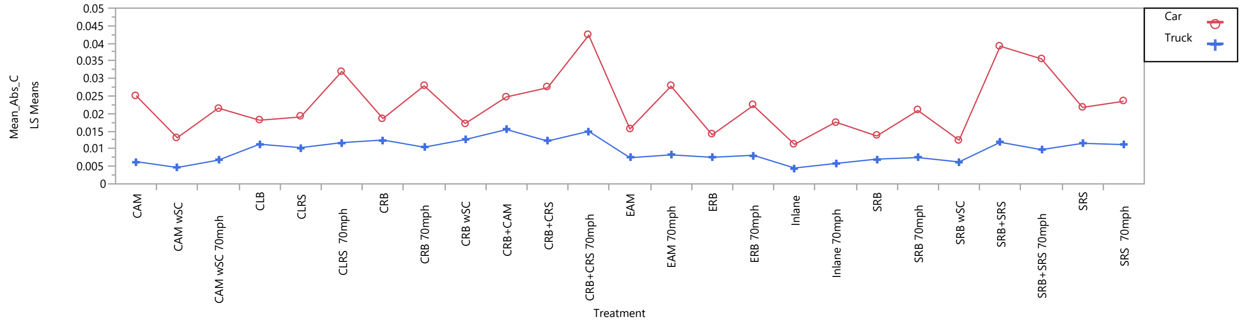


**Figure 38. Atlanta District Trip 1 Vibration Summary.**

Figure 39 and Figure 40 display the predicted mean absolute vibration values from the second Atlanta District trip and the test sections on SH 21. Both data sets show a significant difference between the truck and car results, with the car producing higher vibration levels. The center line rumble bar at 70 mph was one of the top performers, but the same treatment at 55 mph was a middle of the pack performer. This treatment shows the impact of speed greatly increased the performance, whereas other test areas do not show as large of an impact from speed. This is likely due to the specific design of the treatment such as its spacing and how it interacts with the vehicle wheelbase, speed, and suspension components. The results also show that centerline treatments result in higher vibration levels than shoulder or edge line treatments. This is likely due to the accelerometer being mounted to the outside rail of the driver's seat, which is on the same side of the vehicle as the centerline treatments.

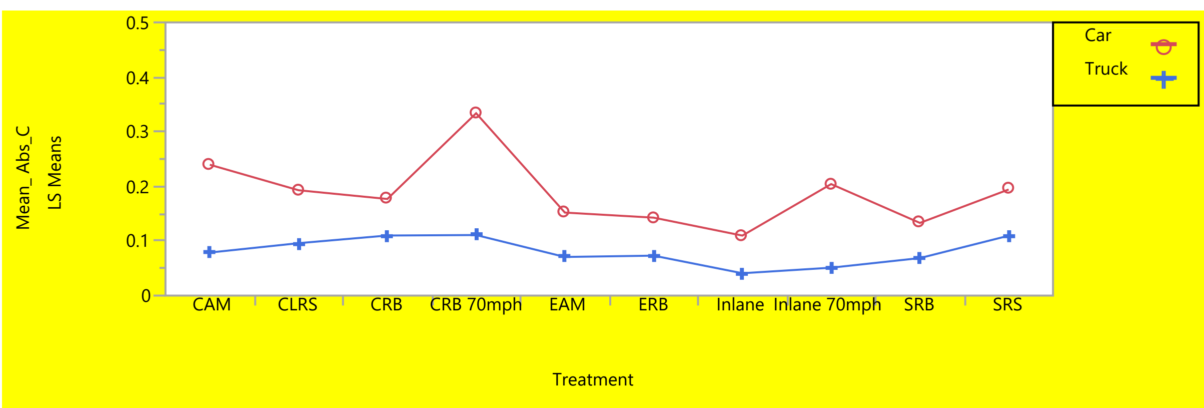


**Figure 39. Atlanta District Trip 2 Vibration Summary.**

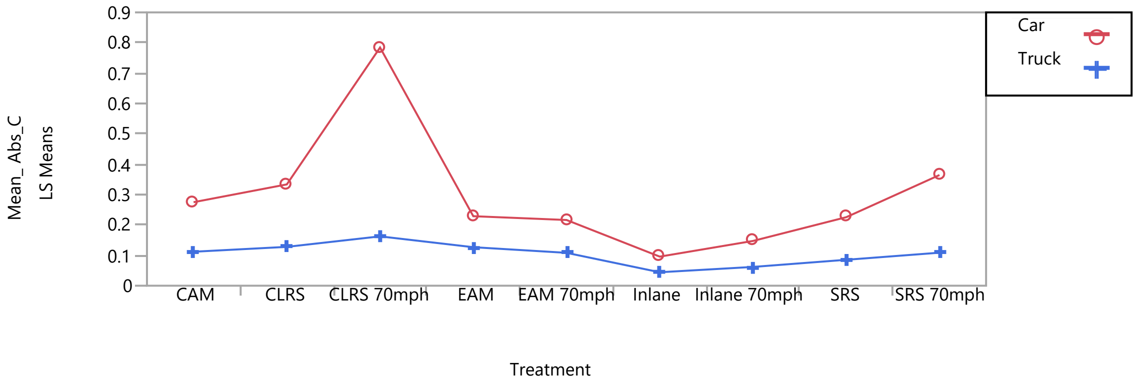


**Figure 40. SH 21 Vibration Summary.**

The Brenham test area allowed researchers to determine the impact of variable spacing on vibration levels. Data were collected soon after the treatments were installed and then a year later to determine if there was any loss in performance. The change in vibration level from a control run where the test vehicle stayed in the center of the lane to test run when the vehicle was on the treatment was also calculated. Figure 41 and Figure 42 provide the first-year vibration levels and changes in vibration levels for the car. The regular stripe indicates the westbound tests where the bumps were topped with a standard flat line marking. The dot stripe indicates the eastbound tests where the bumps were topped with a dot patterned structured marking. The results are similar to the noise results. The 12-in. spacing of the treatment and the variable spacing with the 4-in. long bump were the top performers.

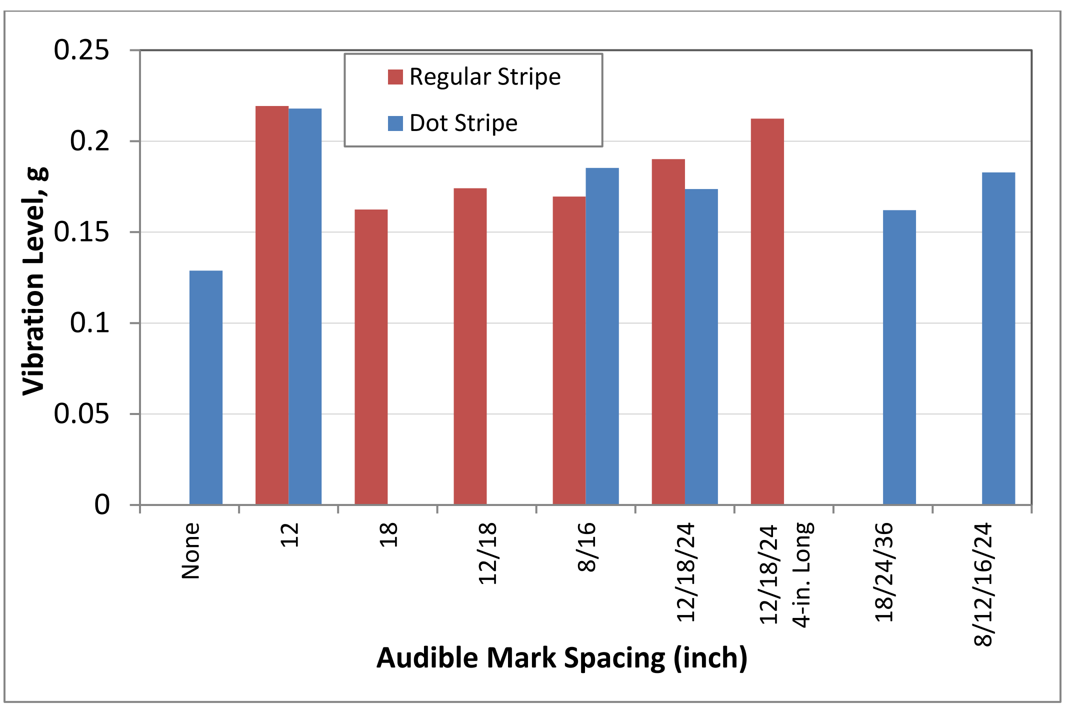


**Figure 41. Brenham Vibration Level, Car 2016.**

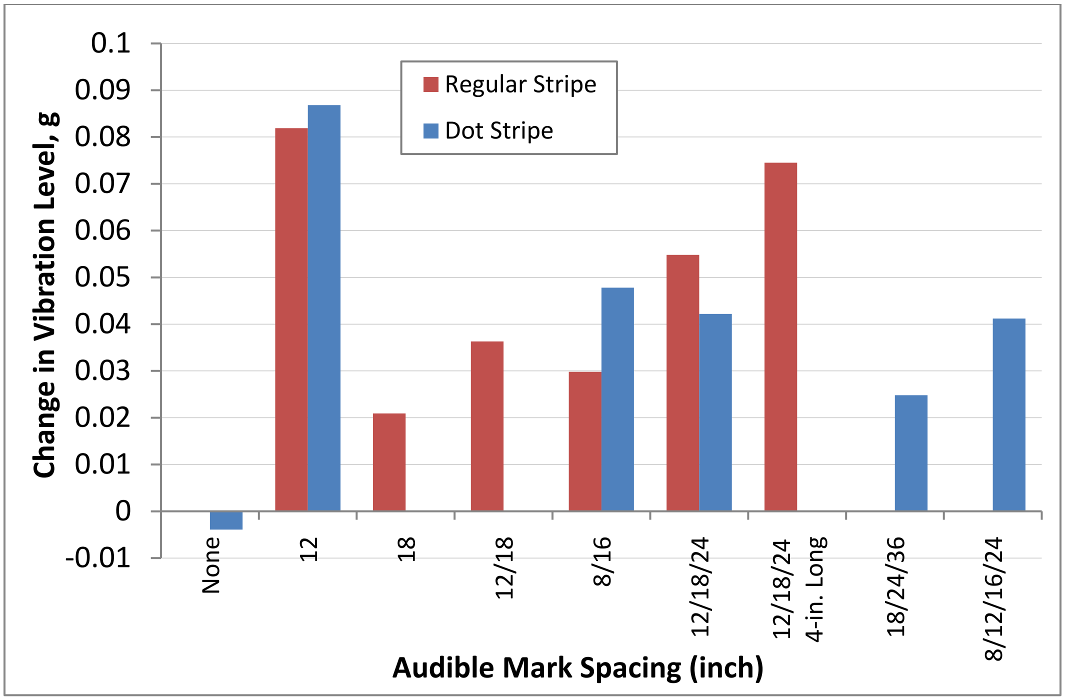


**Figure 42. Brenham Change in Vibration Level, Car 2016.**

Figure 43 provides all the 2017 data graphically for both the car and the truck. The ambient data are the control data where the test vehicle drove in the center of the lane, not on the treatment. Figure 44 and Figure 45 provide the second-year vibration levels and changes in vibration levels for the car. The results are very similar to the first-year results with the 12-in. spacing providing the largest change in vibration level. Figure 46 and Figure 47 provide the second-year vibration levels and changes in vibration levels for the truck. The truck results are different than the car results. The 12-in. spaced treatment was no longer a stand out performer. The variable spaced treatment with the 4-in. long bumps was the best performer, with near twice the vibration level of any other treatment. These results, similar to the noise results, show the differences between the vehicle types. The impact of vehicle type is a significant factor and needs to be considered if monitoring programs were implemented to ensure adequate performing treatments were being installed.

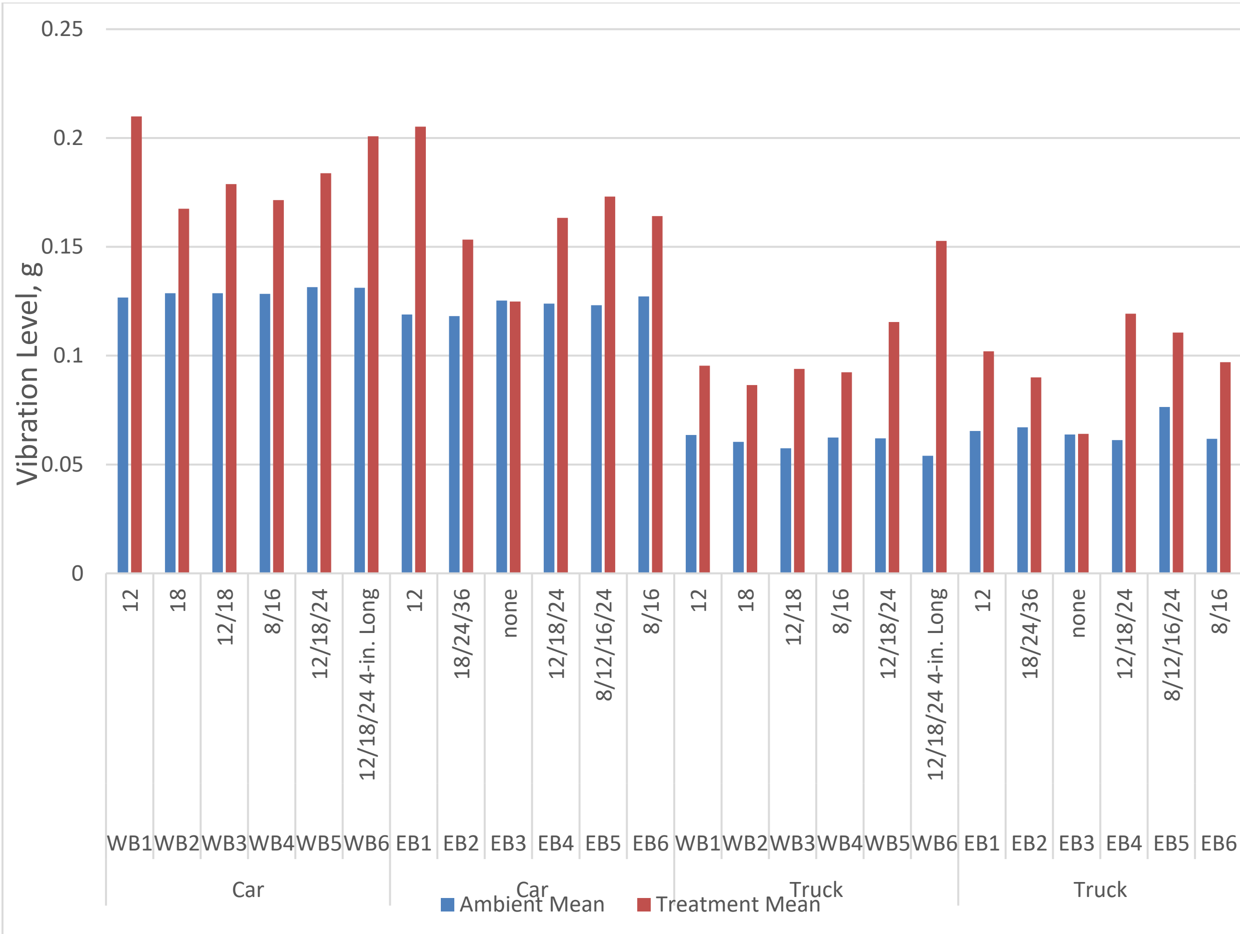


Figure 43. Brenham 2017 Summary Vibration Data.

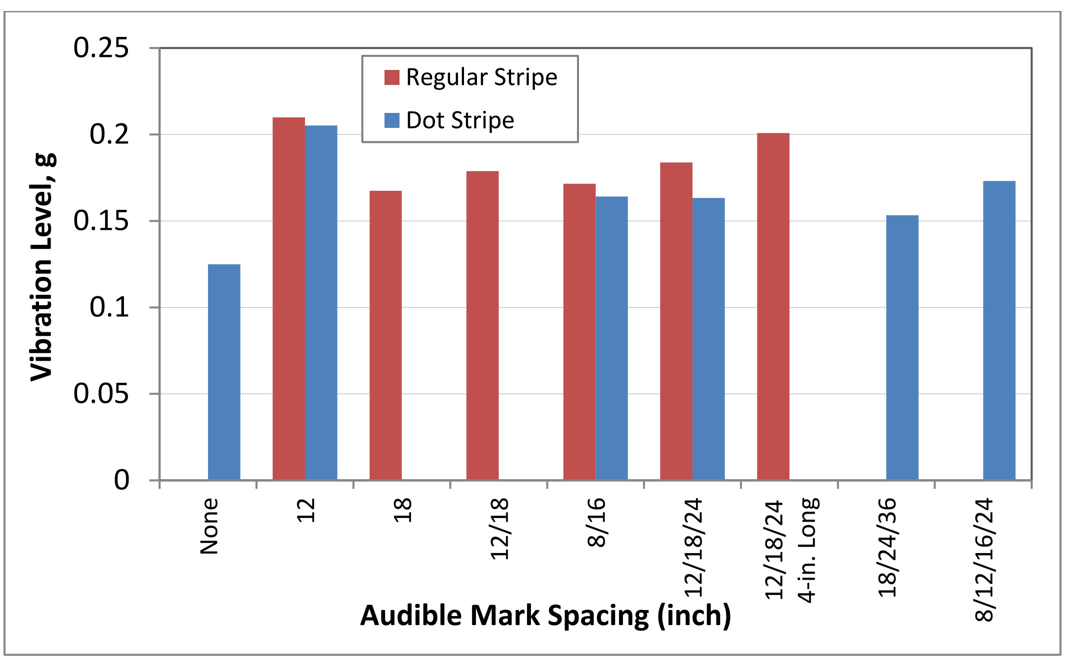


Figure 44. Brenham Vibration Level, Car 2017.

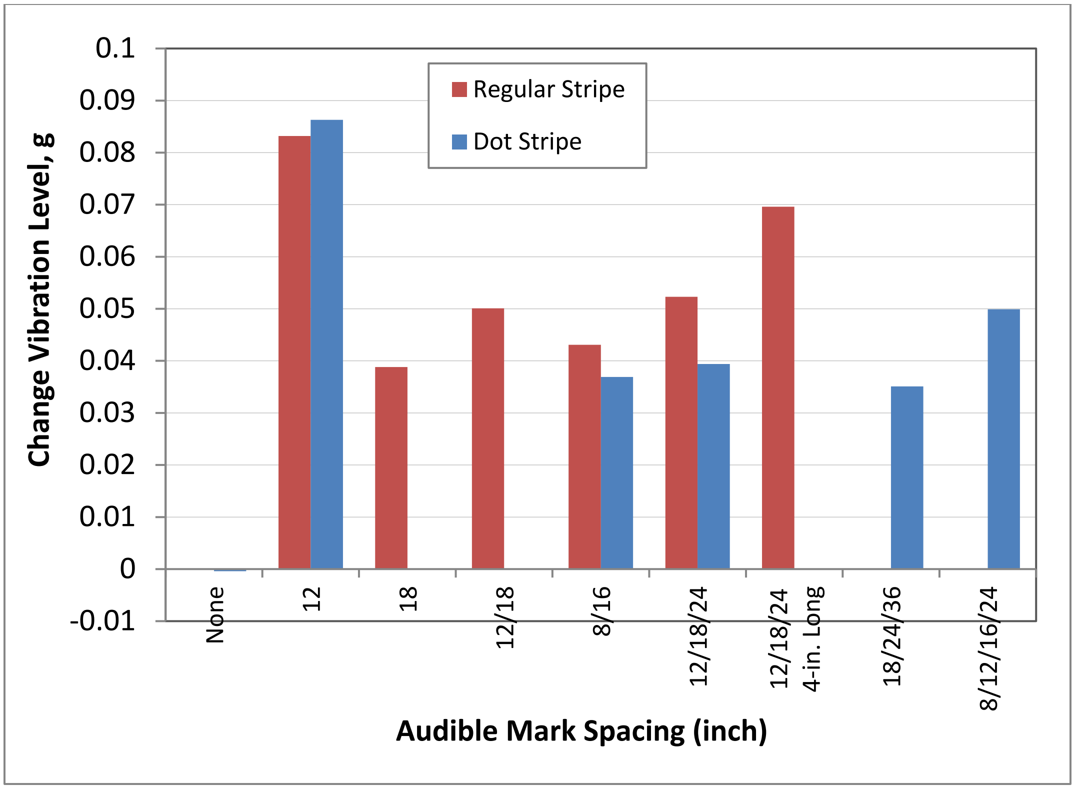


**Figure 45. Brenham Change in Vibration Level, Car 2017.**

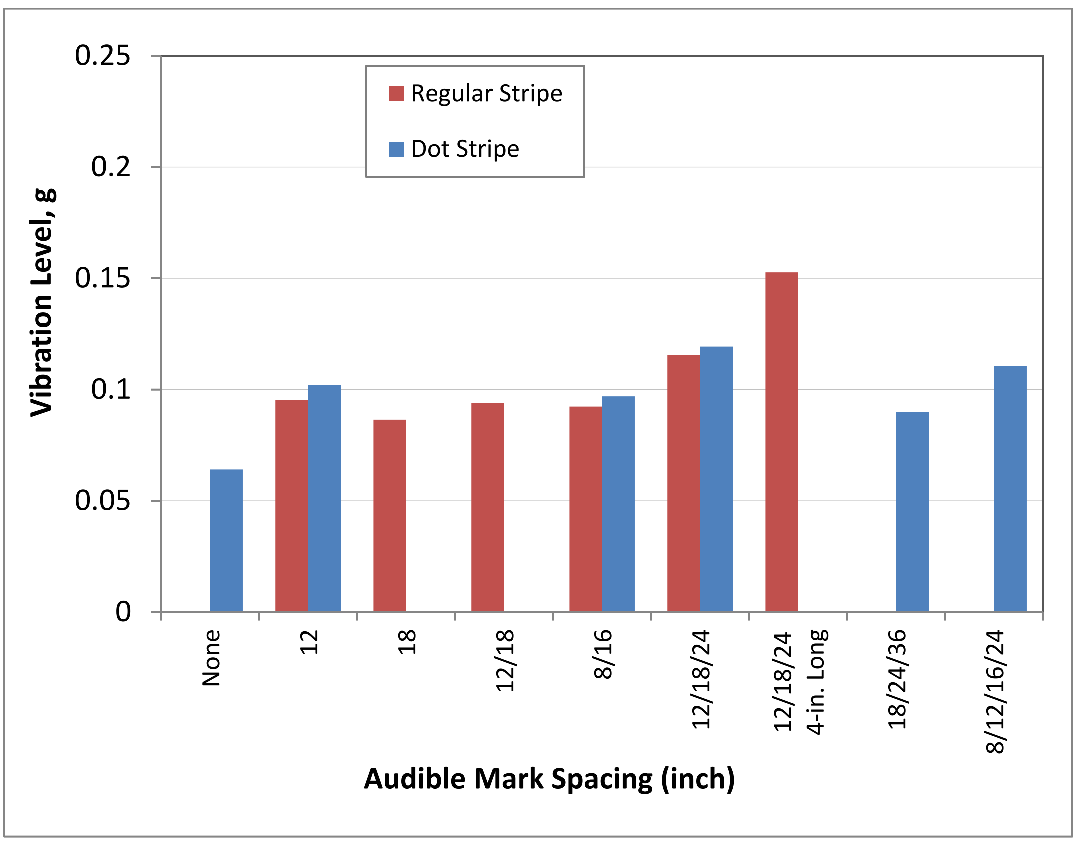


**Figure 46. Brenham Vibration Level, Truck 2017.**

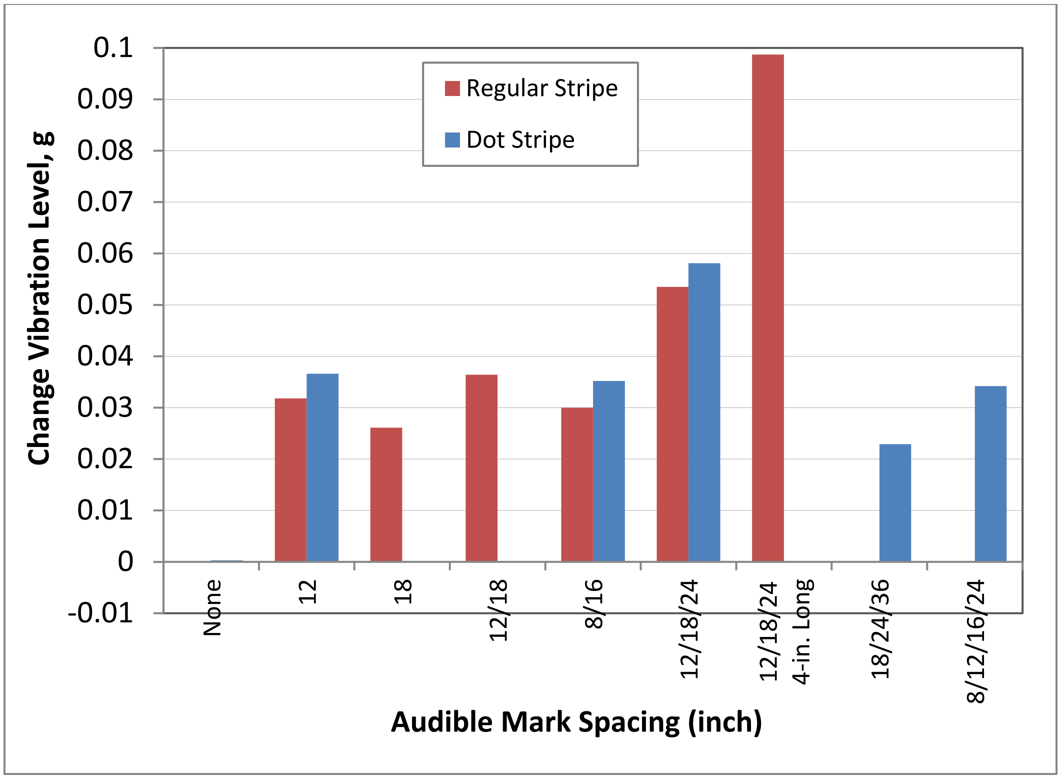


**Figure 47. Brenham Change in Vibration Level, Truck 2017.**

## Findings

The following are key findings from the noise study:

- Vibration level increases with vehicle speed.
- The pick-up truck had lower vibration levels than the passenger car.
- On the Brenham test deck, the most effective treatments were the 12-in. bump spacing design and the variable spacing design with 4-in. long markers.
- The Brenham test deck did not show a decrease in performance between the two sets of data taken approximately 1 year apart.
- The treatment combination of the milled rumble strips and bars produced the highest vibration levels.
- The rumble bars and audible markings had similar performance.
- The results also show that centerline treatments result in higher vibration levels than shoulder or edge line treatments. This is likely due to the accelerometer being mounted to the outside rail of the driver's seat, which is on the same side of the vehicle as the centerline treatments.

From a vibration perspective, the current milled rumble strip design by itself or in combination with rumble bars produced consistently high vibration levels. The typical audible marking and rumble bar designs produced similar results but were not as effective as the milled treatments.

Variable marker spacing does not need to be considered as there was no consistent benefit, but a longer profile bump did produce high vibration levels, especially for the truck.

## RETROREFLECTIVITY PERFORMANCE EVALUATION

The profile pavement markings have visibility benefits that are not present with rumble bars or milled rumble strips. It was expected that profiled markings would achieve visibility levels similar to those of a standard flat markings in dry conditions but yield superior visibility levels in wet and rainy conditions. This section describes the retroreflectivity evaluation of the profile pavement markings that were installed on the Brenham test area.

The researchers collected data three times at the Brenham test area. The initial readings were approximately 5 months after the markings were installed and only considered dry conditions. Approximately seven months later, both dry and wet retroreflectivity data were collected. Approximately 1 year after the initial readings, another set of retroreflectivity data was collected, where both dry and wet retroreflectivity were evaluated.

The dry retroreflectivity readings were evaluated along the entire length of each test area using a properly calibrated mobile pavement marking retroreflectometer. Table 15 and Table 16 provide the average retroreflectivity ($R_L$ in mcd/m$^2$/lux) levels for each test area and each adjacent section of standard applied markings, for each data collection period. The westbound markings were installed with a higher quality drop on bead than the eastbound markings. The westbound profiled marking test areas showed approximately a 50 percent reduction in retroreflectivity between the first and last data collection periods, but the retroreflectivity levels remain higher than the typical flat markings that are adjacent to the test area. The flat markings showed less than a 10 percent reduction in retroreflectivity over the one-year period. The eastbound test areas showed lower retroreflectivity compared to westbound but showed similar percent reductions (approximately 45 percent). The eastbound standard flat markings showed little reduction in retroreflectivity between the data collection periods.

**Table 15. Westbound Dry Retroreflectivity Data.**

| Westbound Sections | March 2016 | October 2016 | April 2017 | Percent Reduction (March 2016 to April 2017) |
|---|---|---|---|---|
| | Average | Average | Average | |
| Standard Marking | 249 | 247 | 237 | −5 |
| Section 1 | 728 | 538 | 373 | −49 |
| Section 2 | 720 | 530 | 384 | −47 |
| Section 3 | 834 | 587 | 412 | −51 |
| Section 4 | 716 | 484 | 327 | −54 |
| Section 5 | 712 | 450 | 348 | −51 |
| Section 6 | 774 | 566 | 395 | −49 |
| Standard Marking | 257 | 248 | 237 | −8 |

**Table 16. Eastbound Dry Retroreflectivity Data.**

| Eastbound Sections | March 2016 | October 2016 | April 2017 | Percent Reduction (March 2016 to April 2017) |
|---|---|---|---|---|
| | Average | Average | Average | |
| Standard Marking | 137 | 190 | 159 | 17 |
| Section 1 | 213 | 164 | 137 | −36 |
| Section 2 | 254 | 176 | 140 | −45 |
| Section 3 | 319 | 189 | 139 | −56 |
| Section 4 | 318 | 207 | 165 | −48 |
| Section 5 | 272 | 184 | 159 | −42 |
| Section 6 | 254 | 180 | 151 | −41 |
| Standard Marking | 249 | 245 | 235 | −6 |

The research team took continuous wetting retroreflectivity measurements at some of the test areas in addition to the previously mentioned dry retroreflectivity measurements. The research team conducted measurements using the ASTM E2832 standard test method for evaluating pavement marking retroreflectivity in a continuous wetting condition. This test method requires a calibrated wetting device and an external beam handheld retroreflectometer. Prior to conducting the continuous wetting measurements, the research team collected dry retroreflectivity readings with the handheld device in the same location. Readings were spaced over the length of several intervals of the profiled spacing and averaged to provide a more accurate value. Figure 48 provides an image of the continuous wetting box and retroreflectometer while taking measurements on a profiled marking. Figure 49 shows the wetted marking after taking measurements.

**Figure 48. Continuous Wetting Test Setup on Profiled Marking.**


**Figure 49. Continuous Wetting Setup after Test.**

Table 17 provides a summary of the dry and continuous wetting handheld retroreflectivity ($R_L$ in mcd/m$^2$/lux) data collected. Wet data were collected on the standard flat marking, the dot marking by itself, the dot marking with standard profile spacing, and the standard profile spacing with the solid extruded marking. The dot marking, and standard flat marking had similar dry retroreflectivity but the dot marking had a higher continuous wetting retroreflectivity value. This was expected due to the structure of the marking. The dot marking with profile bumps had similar continuous wet retroreflectivity to just the dot marking, but its dry retroreflectivity was quite a bit lower. This indicated that the profiled bumps may also provide some benefit to wet retroreflectivity. The profiled marking with the solid extruded marking over it had the highest dry and wet retroreflectivity levels. The initial readings were approximately 1 year after installation on a low volume seal coat road surface. The final readings were after the markings were in-service for about 1.5 years.

**Table 17. Continuous Wetting Retroreflectivity Values.**

| Measurement Date | Section Name | Eastbound 0 | Eastbound 3 | Eastbound 1 | Westbound 1 |
|---|---|---|---|---|---|
| | Marking Type | Flat Marking | Dot Marking Only | Dot marking with Profile @ 12" | Profiled @ 12" |
| October 2016 | Average Dry | 170 | 242 | 167 | 456 |
| | Average Wet | 42 | 69 | 68 | 116 |
| April 2017 | Average Dry | 150 | 214 | 157 | 512 |
| | Average Wet | 29 | 46 | 47 | 94 |
| Percent Reduction (October 2016 to April 2017) | Average Dry | −12 | −11 | −6 | 12 |
| | Average Wet | −31 | −33 | −31 | −19 |

# CHAPTER 4:
# SAFETY PERFORMANCE ASSESSMENT

This chapter covers the safety performance evaluations of the audible lane departure warning treatments. Site information where these treatments were installed was collected. Crash, traffic, and roadway geometric data were also collected for treatment and comparison sites. Two types of before-after study methods were used: 1) comparison group method and 2) Empirical Bayes (EB) method. The comparison group method attempts to consider unrecognized factors which cannot be modeled easily. The key assumption for comparison group methodologies is that the ratio of before-to-after target crashes is the same for treatment and comparison groups (in the absence of the treatment). This suggests that unobserved changes, such as driving population, traffic, weather, etc., affect the target crashes in the same way as crashes in the comparison group. The EB method uses statistical models and combines the information from both observed counts of crashes at the site and the predicted crash frequency based on the safety performance of similar sites. This successfully accounts for the regression-to-the-mean bias. Regression-to-the-mean is the statistical tendency for locations chosen because of high crash histories to have lower crash frequencies in subsequent years even without treatment. Safety performance functions (SPFs) documented in the *Highway Safety Manual* (HSM) and *Texas Roadway Safety Design Workbook* (RSDW) were used to predict the crashes.

## METHODOLOGY

The methodology is divided into two parts. The first part describes the definition of the CMF. The second part presents the characteristics of different types of before-after studies.

### Crash Modification Factor

A CMF is a multiplicative factor that can be used to reflect or capture changes in the expected number of crashes when a given countermeasure or a modification in geometric and operational characteristics of a specific site is implemented (*14, 15*). In this project, it reflects the safety benefit of audible lane departure warning treatments. For example, assuming the CMF for installing a particular lane departure warning treatment is 0.95 and the expected number of crashes occurring at a roadway segment without the treatment is 10 per year. After installing the treatment, the expected number of crashes at the segment can be calculated as 10×0.95 = 9.5 per year, given there is no significant changes in other situations (e.g., traffic volume and component, weather, roadway users).

CMFs play a significant role in roadway safety management, including safety effect evaluation, crash prediction, hotspot identification, countermeasure selection, and economic evaluation. Several methods have been proposed for developing CMFs, such as before-after methods, cross-sectional studies (e.g., regression models and case-control), and expert panel studies among others (*16*). Amid these methods, before-after studies are always preferred whenever available, since this approach produces more reliable CMFs (*17, 18*). There are three common types of before-after studies for developing CMFs (i.e., naïve or simple before-after, before-after with comparison group, and EB method). A naïve before-after study simply assumes the number of crashes occurred before the treatment is a good estimate of the number of crashes that may occur in the after period if the sites had not been treated, without accounting for the regression-to-the-mean bias and other changes. It is generally believed that naïve before-after studies are unable to generate reliable CMFs due to the limitations. This approach is not recommended for developing CMFs. The other two approaches (before-after with comparison group and EB method) are robust and address most of the problems associated with naïve studies. The EB method has been recognized as the state-of-the-art approach for developing CMFs. However, the EB method requires a lot of data, which is sometimes difficult to collect. This project used the latter two methods for estimating the safety effects of installing audible rumble lane departure warning treatments on highways in TxDOT's Atlanta District. The following section mainly focuses on the characteristics of before-after studies with comparison group and EB method. Their limitations are also discussed.

**Before-After Studies**

Independent of the method used, before-after studies are usually accomplished using two tasks (*19*):

- *Task 1*: Predict what the safety of a site in the after period would have been, had the treatment not been implemented.
- *Task 2*: Estimate the safety of the treatment at the site after implementation.

For accomplishing these two tasks, the following terms need to be explained.

The variable $\pi$ is defined as the expected number of crashes at a specific site in the after period if the treatment has not been implemented. This variable only applies for the targeted crashes (e.g., all crashes, single-vehicle run off road, opposite direction, rear end) and/or their severity (e.g., fatal, incapacitating injury, property damage only). $\pi$ is referred to as the predicted value.

The variable $\lambda$ is used to define the expected number of crashes in the after period (after the implementation of the treatment). $\lambda$ is referred to as the estimated value.

The effects of a treatment are estimated by comparing both variables above in the following manner:

- The reduction (or increase) in the expected number of crashes is given as $\delta = \pi - \lambda$. A positive number indicates a decrease in the expected number of crashes.
- The ratio or the Index of Safety Effectiveness is defined as $\theta = \lambda / \pi$. If the number of crashes analyzed is below 500 for the before period, $\theta$ needs to be adjusted by the

following factor: $1+Var\{\pi\}/\pi^2$. This adjustment is used to minimize the bias caused by a small sample size. The Index of Safety Effectiveness therefore becomes the following: $\theta = \frac{\lambda/\pi}{\left[1+Var\{\pi\}/\pi^2\right]}$. A value below 1.0 indicates a reduction in the number of crashes.

The variable $Var\{\pi\}$ is referred to as the variance of $\pi$, while the variable $Var\{\lambda\}$ is referred to as the variance of $\lambda$. The variance is a measure of uncertainty associated with the estimated value.

The variance of the reduction, $\delta$, is calculated as follows:

$$Var\{\delta\} = Var\{\pi\} + Var\{\lambda\} \tag{1}$$

The variance of the Index of Safety Effectiveness is equal to:

$$Var\{\theta\} = \theta^2 \left[ \frac{\left(Var\{\lambda\}/\lambda^2\right) + \left(Var\{\pi\}/\pi^2\right)}{\left(1+Var\{\pi\}/\pi^2\right)^2} \right] \tag{2}$$

Table 18 lists the variables used when a reference group is used. The Latin characters represent the number of crashes that occurred at the sites under study. The Greek letters represent the expected or estimated number of crashes at those sites. How these variables are used is described below.

**Table 18. Observed and Expected Number of Crashes.**

| | **Treatment Group** | **Reference Group** |
|---|---|---|
| **Before** | K, $\kappa$ | M, $\mu$ |
| **After** | L, $\lambda$ | N, $\nu$ |

The safety effectiveness of an intervention is estimated using a 4-step process (*19*):

*Step 1*: Estimate $\lambda$ and $\pi$.
*Step 2*: Calculate the variance of $\lambda$ and $\pi$. As discussed above, they are defined as $Var\{\lambda\}$ and $Var\{\pi\}$, respectively.
*Step 3*: Estimate the difference $\delta$ and the Index $\theta$.
*Step 4*: Calculate the variance of $\delta$ and $\theta$. They are defined as $Var\{\delta\}$ and $Var\{\theta\}$, respectively.

The steps above are done for each site individually and the estimated and predicted values, as well as their variances, are summed for all the sites that are analyzed simultaneously. Additional discussion on this topic is presented below.

The first step in any before-after study involves selecting the target crash type(s). The target crashes are used as the absolute measure of safety. The target crashes for the research purposes are defined as those types of crashes that can be prevented by the installation of audible lane departure warning treatments. The team combined the findings from a comprehensive literature review and their expertise with Texas crash databases to form a viable definition of target crashes that was used to assess the safety performance of audible rumble strips. In general, the target crashes include: 1) single vehicle run-off-the-road (SVROR), and 2) opposite direction (OD) crashes.

The next sections present the characteristics of the two before-after study methods used for this study.

*Before-After Study with Comparison Group*

This method uses a comparison group to capture local and regional changes. The procedure for using the before-after study with comparison group is described using the following steps.

**Step 1: Select the Comparison Sites**

The comparison sites should be as identical as possible to the treatment sites. For a given treatment site, the comparison sites should be of the same functional class and have the same number of lanes as the treatment site. The total length of the chosen comparison site(s) must be greater than the treated site.

**Step 2: Estimate the Expected Number of Crashes in the After Period**

Estimating expected crashes and variances in the after period is necessary to account for influences that affect safety other than the treatment itself. Since other factors may cause an effect on predicting after-period crash frequency and variances that are either not measured or produce an influence on safety, they must be considered. The analytical procedure used in this study was described in detail by Hauer (*19*). The expected number of after-period crashes and their variances for site *i* had the treatment not been implemented at the treated site is given as:

$$\hat{\pi} = \hat{r}_T K \text{ and } V\hat{A}R(\hat{\pi}) = \hat{\pi}^2 \left(1/K + V\hat{A}R\{\hat{r}_T\}/r_T{}^2\right) \quad (3)$$

with, $\hat{r}_T = (N/M)/(1+1/M)$ and $V\hat{A}R\{\hat{r}_T\}/r_T{}^2 \cong 1/M + 1/N$

where,

$K$ = Total crash counts during the before period in treated group.
$M$ = Total crash counts during the before period in comparison group.
$N$ = Total crash counts during the after period in comparison group.

**Step 3: Compute the Sum of the Predicted Crashes over All Treated Sites**

The safety effect of a treatment varies from one site to another. Instead of a single site, the average safety effect of the treatment for a group of sites must be calculated. To account for this, the expected number of after-period crashes and their variances for a group of sites had the treatment not been implemented at the treated sites is given as:

$$\hat{\pi} = \sum_{i=1}^{J} \hat{\pi}_i \quad \text{and} \quad Var(\hat{\pi}) = \sum_{i=1}^{J} Var(\hat{\pi}_i) \tag{4}$$

where,
$J$ = Total number of sites in the treatment group.
$\hat{\pi}$ = The expected after-period crashes at all treated sites had there been no treatment.

**Step 4. Compute the Sum of the Actual Crashes over All Treated Sites**

For a treated site, crashes in the after period are influenced by the implementation of the treatment. The safety effectiveness of a treatment is known by comparing the actual crashes with the treatment to the expected crashes without the treatment. The actual number of after-period crashes for a group of treated sites is given as:

$$\hat{\lambda} = \sum_{i=1}^{N} L_i \tag{5}$$

where,
$L_i$ = Total crash counts during the after period at site ***i***.

**Step 5. Compute the Safety-Effectiveness of the Treatment**

The index of effectiveness ($\theta$) (also referred to as CMF) is defined as the ratio of what safety was with the treatment to what it would have been without the treatment.

The parameter θ gives the overall safety effect of the treatment and is given by:

$$\hat{\theta} = \frac{\left(\frac{\lambda}{\pi}\right)}{\left(1 + \frac{Var(\hat{\pi})}{\hat{\pi}^2}\right)} \tag{6}$$

The percent change in the number of target crashes due to the treatment is calculated by $100(1-\hat{\theta})$ %. If $\hat{\theta}$ is less than 1, then the treatment has a positive safety effect. The estimated variance and standard error of the estimated safety effectiveness are given by:

$$Var(\hat{\theta}) = \hat{\theta}^2 \frac{\left(1/\lambda + Var(\hat{\pi})/\hat{\pi}^2\right)}{\left(1 + Var(\hat{\pi})/\hat{\pi}^2\right)^2} \tag{7}$$

$$s.e.(\hat{\theta}) = \sqrt{Var(\hat{\theta})} \tag{8}$$

The approximate 95 percent confidence interval for $\theta$ is given by adding and subtracting $1.96 \times s.e.(\hat{\theta})$ from $\hat{\theta}$. If the confidence interval contains the value 1, then no significant effect has been observed.

Although the reference group method is superior to the naïve method, it still does not account for the regression-to-the-mean and the site selection effects (unless the reference group is characterized by the same effects as the treatment group, see Lord and Kuo (*20*). This method also requires more resources since data need to be collected at a large number of sites. Hence, it is not popular due to the increase in data collection costs and database management.

*Before-After Study with Empirical Bayes Method*

This method consists of incorporating the before-after study with the EB method in order to minimize the regression-to-the-mean described above (*19, 21*). For this method, the data collection requirements may be larger than for the reference group since a very large amount of data need to be collected for developing reliable regression models (*22*). This method allows the estimation of the safety benefits at treated sites using information from reference sites. The expected crash frequency ($E[k|K]$) at a treated site is a result of the combination of the predicted crash count ($E[k]$) based on the reference sites with similar traits and the crash history ($K$) of that site. The terms $\kappa$ and $E[\kappa]$ are technically the same, but the latter is usually used for statistical models. Hence, for the EB method, researchers used $E[\kappa]$ rather than $\kappa$. The expected crash frequency and its variance are shown in Equations (9) and (10), respectively:

$$E[k|K] = w \cdot E[k] + (1 - w) \cdot K \tag{9}$$

$$Var[k|K] = (1 - w) \cdot E[k|K] \tag{10}$$

where $w$ is a weight factor between 0 and 1.

The parameter $E[k]$ is estimated from the SPFs usually developed using a negative binomial (NB) regression (also known as Poisson-gamma) model under the assumption that the covariates in the SPFs represent the main safety traits of the reference sites (*23*). The procedure for using the before-after study with the EB method is described using the following steps.

**Step 1: Estimate the Expected Number of Crashes in the Before Period**

The foremost step in this method involves developing a new SPF or using an existing and reliable SPF. In this study, SPFs developed in the HSM (*24*) and RSDW (*25*) were used.

The SPFs for base conditions in the HSM for all crashes on two-lane roads is given as:

$$\mathrm{E[k]} = \mathrm{ADT} \times \mathrm{L} \times 365 \times 10^{-6} \times e^{-0.312} \tag{11}$$

The SPFs for base conditions in the RSDW for fatal and injury crashes on two-lane roads is given as:

$$\mathrm{E[k]} = 0.0537 \times (0.001\mathrm{ADT})^{1.30} \times \mathrm{L} \tag{12}$$

Using the base SPF, CMFs and calibration factor, estimate the expected number of crashes ($E[k_i]$ ) for the before period at each treatment site. Using the target crash proportion, estimate the target crash frequency. Obtain an EB estimate of the expected number of crashes ($E[\hat{k}_i|K_i]$) before implementation of the countermeasure at each treatment site and an estimate of variance of $E[\hat{k}_i|K_i]$. Recall that "^" refers to an estimate of a variable.

The estimate $E[\hat{k}_i|K_i]$ is given by combining the SPF predictions for the before period ($E[k]_i$ ) with the total count of crashes during the before period ($K_i$ ) as follows:

$$E[\hat{k}_i|K_i] = \hat{w}_i \cdot E[\hat{k}_i] + (1 - \hat{w}_i) \cdot K_i \tag{13}$$

The weight $\hat{w}_i$ is given by:

$$\hat{w}_i = \frac{1}{1+\frac{E[\hat{k}_i]}{\phi}} \tag{14}$$

where $\phi$ is the inverse dispersion parameter of a NB regression model (i.e., $Var[Y_i] = E[k_i] + E[k_i]^2/\phi$ ).

The variance of the estimate is given as:

$$Var\left[E[\hat{k}_i|K_i]\right] = (1 - \hat{w}_i) \cdot E\left[\hat{k}_i|K_i\right] \tag{15}$$

**Step 2: Calculate the Proportion of the After Period Crash Estimate to the Before Period Estimate**

Using the SPFs developed in Step 1, estimate the expected number of crashes ($E[z_i]$) in the after period at each treatment site. The proportion of the after period crash estimate to the before period estimate ($P_i$) is calculated as:

$$P_i = \frac{E[\hat{Z}_i]}{E[\hat{k}_i]} \tag{16}$$

**Step 3: Obtain the Predicted Crashes ($\hat{\pi}_i$) and its Estimated Variance**

Calculate the predicted crashes during the after period that would have occurred without implementing the countermeasure (i.e., audible lane departure warning treatments).

The predicted number of crashes ($\hat{\pi}_i$) is given by:

$$\hat{\pi}_i = P_i \times E[\hat{k}_i|K_i] \tag{17}$$

The estimated variance of $\hat{\pi}_i$ is given by:

$$Var[\hat{\pi}_i] = {P_i}^2 Var\left[E[\hat{k}_i|K_i]\right] = {P_i}^2 (1 - \hat{w}_i) \cdot E\left[\hat{k}_i\middle|K_i\right] \tag{18}$$

**Step 4: Compute the Sum of The Predicted and Observed Crashes over all Sites in the Treatment Group**

The after-period crashes and their variances for a group of sites had the treatment not been implemented at the treated sites is given as:

$$\hat{\pi} = \sum_{i=1}^{J} \hat{\pi}_i \tag{19}$$

where *J* represents the total number of sites in the treatment group, and $\hat{\pi}$ is the expected after-period crashes at all treated sites had there been no treatment, as described above.

**Step 5: Compute the Sum of the Actual Crashes over All Treated Sites**

For a treated site, crashes in the after period are influenced by the implementation of the treatment. The safety effectiveness of a treatment is known by comparing the actual crashes with the treatment to the expected crashes without the treatment. The actual number of after-period crashes for a group of treated sites is given as:

$$\hat{\lambda} = \sum_{i=1}^{j} L_i \tag{20}$$

where $L_i$ is the crash frequency during the after period at site *i*. The estimate of $\hat{\lambda}$ is equal to the sum of the observed number of crashes at all treated sites during the after study period.

**Step 6: Estimate $\mathbf{Var}[\hat{\boldsymbol{\lambda}}]$ and $\mathbf{Var}[\hat{\boldsymbol{\pi}}]$.**

Based on the assumption of a Poisson distribution, the estimate of variance of $\hat{\lambda}$ is assumed to be equal to L. The estimate of variance of $\hat{\pi}$ can be calculated from the equation as follows:

$$Var[\hat{\lambda}_i] = L_i \tag{21}$$

$$Var[\hat{\lambda}] = \sum_{i=1}^{J} Var[\hat{\lambda}_i] \tag{22}$$

$$Var[\hat{\pi}_i] = (1 - \hat{w}_i) \cdot E[\hat{k}_i | K_i] = (1 - \hat{w}_i) \cdot \hat{\pi}_i \quad (23)$$

$$Var[\hat{\pi}] = \sum_{i=1}^{j} Var[\hat{\pi}_i] \quad (24)$$

**Step 7. Compute the Safety-Effectiveness of the Treatment.**

The index of effectiveness ($\theta$) (also referred to as CMF) is defined as the ratio of what safety was with the treatment to what it would have been without the treatment.

The parameter θ gives the overall safety effect of the treatment and is given by:

$$\hat{\theta} = \frac{\left(\frac{\lambda}{\hat{\pi}}\right)}{\left(1 + \frac{Var(\hat{\pi})}{\hat{\pi}^2}\right)} \quad (25)$$

The percent change in the number of target crashes due to the treatment is calculated by $100(1-\hat{\theta})$ percent. If $\hat{\theta}$ is less than 1, then the treatment has a positive safety effect. The estimated variance and standard error of the estimated safety effectiveness are given by:

$$Var(\hat{\theta}) = \hat{\theta}^2 \frac{\left(1/\lambda + Var(\hat{\pi})/\hat{\pi}^2\right)}{\left(1 + Var(\hat{\pi})/\hat{\pi}^2\right)^2} \quad (26)$$

$$s.e.(\hat{\theta}) = \sqrt{Var(\hat{\theta})} \quad (27)$$

The approximate 95 percent confidence interval for $\theta$ is given by adding and subtracting $1.96 \times s.e.(\hat{\theta})$ from $\hat{\theta}$. If the confidence interval contains the value 1, then no significant effect has been observed.

Previous studies have indicated that before-after studies with EB method are the most robust approach in terms of developing CMFs and hotspot identification (*16*, *26*, *27*, *28*). A large portion of CMFs in the CMF Clearinghouse were developed with this approach (*14*). The safety effectiveness of many treatments are being estimated with this method (*29*, *30*, *31*).

However, EB method is not free of limitations. Similar to the comparison group method, EB method also suffers from the mixed safety effects and possibly the low sample size issue. Recently, Lord and Kuo (*20*) documented the limitations of EB method. One of the limitations is the presence of the site selection bias. This is similar to the regression-to-the-mean, but its effects are different in that the sites are selected based on a known or unknown entry criteria (e.g., five crashes per year).

## IDENTIFY TREATED SITES

The audible lane departure warning treatment installation locations were provided by TxDOT's Atlanta District. In total, there are 107 sites that have been treated with one or multiple types of audible lane departure warning treatment (up to five) in the Atlanta District. Specifically, they are center line grinding (CL Grinding, any form of center line milled rumble strips), edge line grinding (EL Grinding, any form of edge line or shoulder milled rumble strips), edge line audible pavement marking (EL AUD, any edge line profiled marking), center line audible pavement markings (CL AUD, any center line profiled marking), center line bars (CL BAR, center line rumble bars), and edge line bars (EL BAR, edge line or shoulder rumble bars). The treatment implementing dates were matched through TxDOT's project daily work report. The dates of 30 sites were not available, so they were excluded from the analyses. A 3-year period prior to the installation project beginning date is used as the before period for each treated site. The after period considered is the day after project ended to three years later or October 31, 2016 (this is the latest date of crash data availability to the research team), whichever is earlier. Not all sites had three years of after data because some of them were treated more recently. In total, there are 77 treated sites. Table 19 shows the summary statistics.

**Table 19. Summary Statistics of Treated Sites (77 Sites).**

| Variable | Min | Max | Mean | SD |
|---|---|---|---|---|
| Length (mi) | 0.5 | 18.7 | 5.1 | 3.2 |
| Annual Daily Traffic (ADT) | 205.8 | 23,140.5 | 6,940.7 | 4,984.6 |
| Annual Daily Traffic (After*) | 222.3 | 23,364.3 | 6,859.9 | 4,974.9 |
| Number of SVROR+OD Crashes (Before) | 0 | 30 | 9.22 | 6.6 |
| Number of SVROR+OD Crashes (After*) | 0 | 19 | 5.43 | 4.62 |

Note: * the after period for each site varies.

## DATA COLLECTION

Once the information of treated sites was obtained, comparison sites were identified that are as identical as possible to the treatment sites. The identification criteria were based on highway functional class, number of lanes, and traffic volume (i.e., ADT). For a given treatment site, the comparison sites should be of the same functional class and have the same number of lanes as the treatment site. In addition, the ADT of the comparison site was preferred to be within ±500 of that of the treatment site.

The total length of the chosen comparison site(s) must be greater than the treated site. In the case the total length of comparison sites was less than the treatment site, a relaxation coefficient k (0 < k < 1) was used for ADT. This way, a site with ADT between "k × ADT of treatment site" and "$\frac{1}{k}$ × ADT of treatment site" may be considered as a comparison site. In this study, k of 0.8 had been used in the site selection process. For a few treatment sites, comparison sites were still insufficient. For these sites, a relaxed criterion for functional class was used. Sites from a slightly different functional class are used for selecting the comparison sites. In total, 338 comparison sites were identified. Table 20 shows the summary statistics of the comparison sites.

**Table 20. Summary Statistics of Comparison Sites (338 Sites).**

| Variable | Min | Max | Mean | SD |
|---|---|---|---|---|
| Length (mi) | 0.001 | 7.9 | 1.2 | 1.4 |
| Annual Daily Traffic (Before) | 150.3 | 28,384.3 | 7,618.8 | 4,772.2 |
| Annual Daily Traffic (After*) | 44.0 | 34,750.0 | 7,436.6 | 5,165.7 |
| Number of SVROR+OD Crashes (Before) | 0 | 27 | 2.34 | 3.67 |
| Number of SVROR+OD Crashes (After*) | 0 | 22 | 1.48 | 2.60 |

Note: * the after period for each site varies.

### Crash Data

The research team collected crash data from TxDOT's Crash Records Information System (CRIS) maintained by the Traffic Operations Division. Three types of information are available in the CRIS database: crash, unit, and person level information. The crash file contains detailed information on the highway area type, accident type, location, severity, lighting and weather condition, and time of crash, among others. The unit data include information about vehicle type, vehicle model, crash contributing factors, and so forth. The person file contains data on the driver/passenger age, gender, crash causing factors such as driving under the influence, fatigue, and driver vision defects.

In addition to total target crashes, crash frequency by different severities was collected. This is important because it helps in understanding what severities are mostly influenced. Also, the SPF in the RSDW estimates fatal and injury crashes only. The following five crash severity levels were considered:

- Fatal (K).
- Incapacitating injury (A).
- Non-incapacitating injury (B).
- Minor injury (C).
- PDO.

### Roadway and Traffic Data

TxDOT's Road-Highway Inventory Network (RHiNo) database was used to extract variables such as ADT, surface width, shoulder width, number of lanes, and functional classification. Some specific roadway characteristics that are not included in the RHiNo Database were identified using Google Earth, including roadside clearance, shoulder rumble strips, center rumble strips, presence of passing lane, and density of driveways.

The collected data were assembled into a database with spatial and temporal cross reference across crash, traffic, and geometric records. The control section numbers and the distance from origin were used for this purpose.

## DATA ANALYSIS

This section documents the results from both comparison group and EB methods.

### Comparison Group Analysis

Among the 77 treated sites, 40 of them were treated with CL BARS, EL AUD, and EL BARS, simultaneously. For most of the other 33 sites, the treatment of each site is not identical and the treatments are usually a combination of two or more single countermeasures. This makes it difficult to estimate the safety effect of single treatment, so the comparison group analysis mainly focused on the combined safety effects of installing CL BARS, EL AUD, and EL BARS, simultaneously.

Using the comparison group method, the combined CMFs for installing CL BARS, EL AUD, and EL BARS for different crash types and severity are analyzed, and Table 21 shows the results.

Total target crashes show no change after installing CL BARS, EL AUD, and EL BARS simultaneously. However, KAB crashes decreased by 17 percent, marginally significant at 5 percent level. The severity C target crashes increased by 19 percent, statistically insignificant. An analysis by including SVROR crashes only shows that none of the changes are significant at 5 percent level. The before-after analyses show OD crashes reduced greatly for all levels of severity. The reduction in crashes is statistically significant. The CMF for all OD crashes is 0.526, which means the OD crashes would be reduced by 48 percent after installing the three treatments simultaneously.

**Table 21. Results of Comparison Group Analysis.**

| Crash Type (Severity) | Time Period | Treatment Group (40 Sites) | | | Comparison Group (143 Sites) | | | CMF (SD) |
|---|---|---|---|---|---|---|---|---|
| | | Crash Count | VMT | Crash Rate | Crash Count | VMT | Crash Rate | |
| SVROR+OD (All) | Before | 307 | 359 | 0.86 | 333 | 367 | 0.91 | 0.995(0.110) |
| | After* | 308.5 | 361 | 0.85 | 333.3 | 373 | 0.89 | |
| SVROR+OD (KAB) | Before | 86 | 359 | 0.24 | 98 | 367 | 0.27 | 0.831(0.166) |
| | After* | 84.1 | 361 | 0.23 | 111.9 | 373 | 0.30 | |
| SVROR+OD (C) | Before | 56 | 359 | 0.16 | 65 | 367 | 0.18 | 1.188(0.315) |
| | After* | 46.0 | 361 | 0.13 | 42.5 | 373 | 0.11 | |
| SVROR+OD (PDO) | Before | 165 | 359 | 0.46 | 170 | 367 | 0.46 | 1.010(0.151) |
| | After* | 178.5 | 361 | 0.49 | 178.9 | 373 | 0.48 | |
| SVROR (All) | Before | 278 | 359 | 0.77 | 309 | 367 | 0.84 | 1.052(0.122) |
| | After* | 280.8 | 361 | 0.78 | 293.8 | 373 | 0.79 | |
| SVROR (KAB) | Before | 74 | 359 | 0.21 | 86 | 367 | 0.23 | 0.904(0.192) |
| | After* | 76.9 | 361 | 0.21 | 95.5 | 373 | 0.26 | |
| SVROR (C) | Before | 52 | 359 | 0.14 | 63 | 367 | 0.17 | 1.228(0.338) |
| | After* | 41.4 | 361 | 0.11 | 38.5 | 373 | 0.10 | |
| SVROR (PDO) | Before | 152 | 359 | 0.42 | 160 | 367 | 0.44 | 1.051(0.164) |
| | After* | 162.5 | 361 | 0.45 | 159.8 | 373 | 0.43 | |
| OD (All) | Before | 29 | 359 | 0.08 | 24 | 367 | 0.07 | 0.526(0.177) |
| | After* | 27.7 | 361 | 0.08 | 39.6 | 373 | 0.11 | |
| OD (KAB) | Before | 12 | 359 | 0.03 | 12 | 367 | 0.03 | 0.357(0.176) |
| | After* | 7.2 | 361 | 0.02 | 16.4 | 373 | 0.04 | |
| OD (C) | Before | 4 | 359 | 0.01 | 2 | 367 | 0.01 | 0.283(0.157) |
| | After* | 4.5 | 361 | 0.01 | 4.0 | 373 | 0.01 | |
| OD (PDO) | Before | 13 | 359 | 0.04 | 10 | 367 | 0.03 | 0.522(0.229) |
| | After* | 16.0 | 361 | 0.04 | 19.2 | 373 | 0.05 | |

VMT= vehicle miles traveled. Note: Values of crash count and VMT for the sites with less than 3 years in the after period have been projected to match a 3-year period; the unit of VMT is in 100,000 vehicle-miles; the crash rate is in number of crashes per 100,000 vehicle-miles.

To summarize, the comparison group method analyses indicate that after installing CL BARS, EL AUD, and EL BARS simultaneously, OD crashes will be reduced by about 48 percent, but no change in SVROR crashes. These findings should be interpreted with caution. Given the existence of regression-to-the-mean bias and comparison group method’s inability to handle the regression-to-the-mean bias, the results may be biased and lead to potentially significant underestimates of the treatments. In addition, as documented previously, it is almost impossible to identify a true comparison site. This will also lead to biased estimation of treatment effectiveness.

### EB Analysis

To address the limitations associated with the comparison group method, an analysis was conducted with the EB method. Given the extensive data requirements, the EB analysis focused on two-lane roads where the milled rumble strip alternative audible lane departure warning treatments are frequently installed. There are 37 treated sites on two-lane roads that had one centerline treatment or one edge line treatment or both (referred to as Group 1 hereafter). Of which, 33 sites had at least one centerline and one edge line treatments (Group 2). CL BARS, EL AUD, and EL BARS were installed simultaneously at 16 sites (Group 3). The treated sites were categorized into three groups based on the type of specific treatment at each site. Table 22 presents the summary statistics of the three groups. Group 3 is a subgroup of Group 2, and Group 2 is a subgroup of Group 1.

**Table 22. Summary Statistics of Treated Site Groups on Two-Lane Highways.**

| **Variable** | **Min** | **Max** | **Mean** | **SD** |
|---|---|---|---|---|
| **Group 1: At Least One Centerline or One Edge Line Treatment (37 Sites)** | | | | |
| Length (mi) | 1.45 | 12.55 | 6.01 | 2.71 |
| ADT (Before) | 237.0 | 12,681.4 | 3,629.7 | 3,053.8 |
| ADT (After) | 213.3 | 12,112.0 | 3,494.0 | 2,918.5 |
| Number of SVROR+OD Crashes (Before) | 1 | 30 | 9.2 | 6.0 |
| Number of SVROR+OD Crashes (After*) | 0 | 16 | 4.8 | 3.3 |
| **Group 2: At Least One Centerline and One Edge Line Treatments (33 Sites)** | | | | |
| Length (mi) | 1.45 | 12.55 | 5.75 | 2.50 |
| ADT (Before) | 237.0 | 12681.4 | 3879.7 | 3135.5 |
| ADT (After) | 213.3 | 12112.0 | 3736.3 | 2999.1 |
| Number of SVROR+OD Crashes (Before) | 1 | 30 | 9.4 | 6.1 |
| Number of SVROR+OD Crashes (After*) | 0 | 16 | 4.7 | 3.4 |
| **Group 3: CL BARS, EL AUD and EL BARS Installed Simultaneously (16 Sites)** | | | | |
| Length (mi) | 1.45 | 7.22 | 4.66 | 1.50 |
| ADT (Before) | 386.8 | 12681.4 | 4009.4 | 3362.5 |
| ADT (After) | 254.6 | 12112.0 | 3922.0 | 3369.6 |
| Number of SVROR+OD Crashes (Before) | 1 | 17 | 7.9 | 4.6 |
| Number of SVROR+OD Crashes (After*) | 0 | 12 | 4.1 | 3.1 |

Note: * the after period for each site varies.

Table 23 presents the average safety effect of installing at least one centerline or edge line treatment (Group 1) on two-lane roads based on the EB method. The first three columns were estimated with HSM SPF and CMFs for two lane highways for total SVROR+OD, fatal and injury (FI) SVROR+OD, and PDO SVROR+OD, respectively. Note that FI and KABC are equivalent, the two terms are used interchangeably in this report. This table shows that there are 177 total crashes reported during the after study period at these 37 sites. The analysis results indicate that if the treatment had not been installed, the expected number of the crashes would have been 219.0 during the after study period based on HSM SPF and CMFs. In other words, it is estimated that audible lane departure warning treatments decreased the crashes by 19 percent. The standard deviation is 7 percent, which makes the estimate statistically significant at 5 percent level. The estimated CMF for FI crashes is 0.70, and the standard deviation is 0.09, meaning the crash reduction factor (CRF) is 30 percent. This result is statistically significant at 5 percent level. For PDO crashes, the CRF is 11 percent, and this is statistically insignificant at 5 percent level. With the SPF provided in the RSDW, the CMF for FI crashes was estimated as 0.63 (CRF = 37 percent), statistically significant at the 5 percent level. This is close to the results obtained with HSM SPF (i.e., 0.70).

**Table 23. Results of the EB Analysis for Group 1 (37 Sites).**

| **Variables** | **HSM SPF** | | | **RSDW SPF** |
|---|---|---|---|---|
| | **Total crashes** | **FI crashes** | **PDO crashes** | **FI crashes** |
| Predicted Crashes ($\hat{\pi}$) | 219.0<br>(56.7) | 103.2<br>(15.7) | 117.7<br>(20.5) | 114.3<br>(7.9) |
| Estimated Crashes ($\hat{\lambda}$) | 177<br>(13.3) | 72<br>(8.5) | 105<br>(10.2) | 72<br>(8.5) |
| Safety Index ($\hat{\theta}$) | <u>0.81</u><br><u>(0.07)</u> | <u>0.70</u><br><u>(0.09)</u> | 0.89<br>(0.09) | <u>0.63</u><br><u>(0.08)</u> |
| Reduction in Crashes ($\hat{\delta}$) | 42.0<br>(15.3) | 31.2<br>(9.4) | 12.7<br>(11.2) | 42.3<br>(8.9) |

Underlined: statistically significant at the 5% level. Value in the parenthesis is the standard error of the estimate.
FI = Fatal and injury crashes, includes all KABC.

Table 24 presents the average safety effect of installing at least one centerline and one edge line treatments (Group 2) on two-lane roads. As can be seen, the results are nearly identical to that of Group 1 (i.e., Table 6) based on both HSM and RSDW SPFs. CMFs for total crashes and FI crashes are statistically significant at 5 percent level. The main reason for almost the same finding is that the Group 2 just excludes four sites with single treatment from Group 1.

**Table 24. Results of the EB Analysis for Group 2 (33 Sites).**

| **Variables** | **HSM SPF** | | | **RSDW SPF** |
|---|---|---|---|---|
| | **Total crashes** | **FI crashes** | **PDO crashes** | **FI crashes** |
| Predicted Crashes ($\hat{\pi}$) | 196.7<br>(53.5) | 93.1<br>(15) | 106<br>(19.5) | 104.7<br>(7.7) |
| Estimated Crashes ($\hat{\lambda}$) | 155<br>(12.4) | 63<br>(7.9) | 92<br>(9.6) | 63<br>(7.9) |
| Safety Index ($\hat{\theta}$) | <u>0.79</u><br><u>(0.07)</u> | <u>0.68</u><br><u>(0.09)</u> | 0.87<br>(0.10) | <u>0.60</u><br><u>(0.08)</u> |
| Reduction in Crashes ($\hat{\delta}$) | 41.7<br>(14.4) | 30.1<br>(8.8) | 14<br>(10.6) | 41.7<br>(8.4) |

Underlined: statistically significant at the 5% level. Value in the parenthesis is the standard error of the estimate.
FI = Fatal and injury crashes, includes all KABC.

Table 25 presents the average safety effect of installing CL BARS, EL AUD, and EL BARS simultaneously (Group 3) on two-lane roads. Note that the same treatments were also considered while evaluating the safety effectiveness with the comparison group method. This table shows that there are 66 total crashes reported during the after study period at these 16 sites, while the predicted number of crashes is 93.1 if the three treatments had not been installed based on HSM SPF and CMFs. So, it is estimated that installing the three treatments simultaneously decreased the crashes by 27 percent. The standard deviation of this estimate is 10 percent, which makes the estimate statistically significant at 5 percent level. The CMFs for FI crashes are 0.61 and 0.54, using HSM SPF and RSDW SPF, respectively. Both are statistically significant at 5 percent level. The CMF for PDO crashes is 0.73, but this result is statistically insignificant at 5 percent level.

**Table 25. Results of the EB Analysis for Group 3 (16 Sites).**

| **Variables** | **HSM SPF** | | | **RSDW SPF** |
|---|---|---|---|---|
| | **Total crashes** | **FI crashes** | **PDO crashes** | **FI crashes** |
| Predicted Crashes ( $\hat{\pi}$ ) | 93.1<br>(30.1) | 45.8<br>(9.1) | 51.8<br>(11.6) | 51.5<br>(4.6) |
| Estimated Crashes ( $\hat{\lambda}$ ) | 66<br>(8.1) | 28<br>(5.3) | 38<br>(6.2) | 28<br>(5.3) |
| Safety Index ( $\hat{\theta}$ ) | <u>0.71</u><br><u>(0.10)</u> | <u>0.61</u><br><u>(0.12)</u> | 0.73<br>(0.14) | <u>0.54</u><br><u>(0.10)</u> |
| Reduction in Crashes ( $\hat{\delta}$ ) | 27.1<br>(9.8) | 17.8<br>(6.1) | 13.8<br>(7.0) | 23.5<br>(5.7) |

Underlined: statistically significant at the 5% level. Value in the parenthesis is the standard error of the estimate.
FI = Fatal and injury crashes, includes all KABC.

To summarize, the EB analyses indicate that after installing audible lane departure warning treatments on two-lane highways, total SVROR+OD crashes are expected to be reduced by about 19 percent, and FI SVROR+OD crashes would be reduced by about 29 to 40 percent. The safety effect of installing CL BARS, EL AUD, and EL BARS simultaneously is slightly higher (as shown in Table 25). Except for PDO crashes, all other results are statistically significant at the 5 percent level. In short, installing audible lane departure warning treatments are expected to reduce SVROR+OD crashes on two-lane highways.

## ECONOMIC EVALUATION

In this section, the economic impacts of various combinations of the audible lane departure warning treatments are evaluated.

### Crash Benefits

Shown in the previous section, the installation of audible lane departure warning treatments generally has a positive effect on traffic safety. The economic impacts resulting from these treatments are calculated as follows:

$$\text{Benefits (B)} = \sum_{i=1}^{5}\left(\hat{\delta}_i . C_i\right) \quad (28)$$

where,
$C_i$= average crash cost of the $i^{th}$ severity category ($i$=1, 2,.., 5).
$\hat{\delta}_i$= expected change in crashes by severity *i*.

The average crash costs by each crash severity are needed to conduct the evaluation. The average comprehensive cost by injury severity is obtained from the National Safety Council for the year 2015, as shown in Table 26.

**Table 26. Average Comprehensive Cost by Severity.**

| Injury Severity | Cost |
|---|---|
| Death | $10,082,000.00 |
| Incapacitating injury | $1,103,000.00 |
| Non-incapacitating injury | $304,000.00 |
| Possible injury | $141,000.00 |
| PDO | $46,600.00 |

Table 27 presents the crash proportion and fatalities or injuries per crash by severity based on the SVROR and OD crashes observed on two-lane rural roads in Texas.

**Table 27. Crash Proportion and Number of Fatalities or Injuries per Crash.**

| Crash Severity | Proportion | Fatalities/injuries per crash |
|---|---|---|
| Fatal (K) | 0.04 | 1.15 |
| Incapacitating Injury (A) | 0.09 | 1.39 |
| Non-Incapacitating Injury (B) | 0.19 | 1.46 |
| Minor Injury (C) | 0.14 | 1.46 |
| PDO (O) | 0.55 | 1.00 |

### Treatment Costs

Based on the information received from the TxDOT and after review of previous studies, the researchers have calculated the average cost and service life per treatment, shown in Table 28.

**Table 28. Installation Costs and Service Life by Treatment Type.**

| Treatment | Cost (per Mile) | Service Life (Year) |
|---|---|---|
| Edge Line Bars (ELB) | $22,000 | 6 |
| Center Line bars (CLB) | $16,685 | 6 |
| Edge Line Grinding (EL Grind) | $1,690 | 8 |
| Center Line Grinding (CL Grind) | $1,003 | 8 |
| Edge Line Audible (EL Aud) | $3,696 | 4 |
| Center Line Audible (CL Aud) | $2,217 | 4 |

**Benefit-Cost Ratio**

The results in Table 23 shows that, in total, about 42 crashes were reduced in the after period at 37 treated sites that had one centerline treatment or one edge line treatment or both. The average after period duration per site is 25 months. Based on the information provided in Table 27 and Table 28, the overall crash benefit at these sites over the service life of the treatment is $80.3 million. The treatment cost is $6.85 million. The benefit-cost ratio is 11.7. This means, for each dollar spent on the treatment, a benefit of $11.70 can be achieved.

Similarly, the results in Table 24 shows that, in total, about 42 crashes were reduced in the after period at 33 treated sites that had at least one centerline and one edge line treatment. The average after period duration per site is 24 months. Based on the information provided in Table 27 and Table 28, the overall crash benefit at these sites over the service life of the treatment is $82.4 million. The treatment cost is $6.6 million. The benefit-cost ratio is 12.4. This means, for each dollar spent on the treatment, a benefit of $12.40 can be achieved.

Finally, the results in Table 25 shows that, in total, about 27 crashes were reduced in the after period at 16 treated sites that had CL BARS, EL AUD, and EL BARS installed simultaneously. The average after period duration per site is 24.8 months. Based on the information provided in Table 27 and Table 28, the overall crash benefit at these sites over the service life of the treatment is $50.8 million. The treatment cost is $3.2 million. The benefit-cost ratio is 16.1. This means, for each dollar spent on the treatment, a benefit of $16.10 can be achieved.

# CHAPTER 5:
# SUMMARY AND RECOMMENDATIONS

This chapter summarizes the findings of the research and provides recommendations. The recommendations from this research cover three main areas: 1) Determine the most effective treatments, 2) Recommend modifications to standards and specifications to reflect the most effective treatments and their designs, and 3) Determine when and where to implement the treatments. Each of these areas are covered in individual sections. The recommendations are based off the field data collected for the noise (interior near driver position, exterior at road surface level, and wayside 25 ft from the travel lane), vibration (at driver seat location), and visibility (dry and wet retroreflectivity). The recommendations are also based off a crash study that looked at numerous sites across TxDOTs Atlanta District. A survey of TxDOT districts and a literature review were conducted to supplement field data and to help determine the current state of usage of milled rumble strip alternative treatments.

## DETERMINATION OF MOST EFFECTIVE TREATMENTS

To determine the most effective treatments, researchers considered the field data collection and the crash study. In total, researchers conducted performance evaluations at 24 unique field sites that had 51 treatments and at a test deck that had 12 different variations of audible markings. The field sites consisted of varying designs and spacing of audible markings, varying spacing of rumble bars, and milled rumble strips. Some sites had each of the previously mentioned treatments, but they had been seal coated over one time. The crash study considered up to 77 treatment sites and appropriate comparison sites. Many treatment sites had multiple treatments present. Researchers evaluated the performance of the various treatments separately when considering noise and vibration. For the crash study, researchers were unable to separate out the individual treatments at the sites, so they were considered as a system instead of individual treatments.

The crash study showed that the installed treatments reduced total crashes by about 19 percent across all the sites considered (30 percent reduction in fatal and injury crashes). These sites had a minimum of at least one treatment on either the edge line or the center line. A subset of the data that included only sites with multiple treatments (center line and shoulder rumble bars, along with edge line audible markings) showed total crash reductions of about 21 percent (32 percent reduction in fatal and injury crashes). These crash reductions were considered statistically significant. Based on the crash study, installation of these alternate treatments results in crash reductions that are in-line with those of standard milled rumble strips. Based on this, the installation of the combinations of treatments studied should be considered as a viable option when milled rumble strips cannot be used.

Due to the inability of the crash study to isolate treatment types, researchers cannot make specific recommendations on the most effective individual treatment or specific designs of the treatments. The noise, vibration, and visibility data can be considered safety surrogates in that researchers expect that higher performance levels will result in a more effective treatment that will have a greater impact on reducing crashes. The noise and vibration data collection found that the most effective spacing was the standard audible marking with 12-in. spacing and the variable spacing with the longer profiled bumps. In general, closer spacing, higher profile, or a longer treatment, results in higher noise and vibration levels. Generally, the audible markings produced higher interior noise levels than the rumble bars. The standard audible marking performed better than the inverted profile audible marking. The vibration performance was similar for the audible markings and rumble bars. All treatments tested increased noise pollution outside the vehicle when driving on the treatment. Increase in noise levels were less than 10 dBA at the source and approximately 5 dBA for the audible markings tested 25 ft from the roadway. The profile marking and profile marking with the dot pattern both increased the wet visibility of the markings compared to standard flat markings. Benefit-cost ratios in excess of 11 to 1 were found for the treatments included in the crash study, which indicates a positive investment. Researchers recommend that the standard spacing for audible markings remain in place (12 in. for 4-in. wide marking and 18 in. for 6-in. wide markings). Rumble bar spacing should not exceed 48 in., with shorter distances preferred if higher noise and vibration levels are desired. The height for both treatments should be near the maximum allowable 0.5 in. above the road surface.

Test areas where the treatment had been seal coated over had mixed results. The milled rumble strip tested area still had excellent noise and vibration performance. Some audible marking and rumble bar test areas had marginal performance, other test areas had little performance remaining. Similar to the standard treatments, the performance of the treatments under a seal coat was variable. After a seal coat is applied over existing treatments, milled rumble strips are expected to produce acceptable noise and vibration levels. Audible markings and rumble bars, however, are unlikely to be able to produce adequate noise and vibration performance levels. Researchers recommend not relying on the performance of audible markings or rumble bars after they have been seal coated over. If the visibility of an audible marking is not sufficient then the marking may be restriped over with standard application techniques to regain visibility without much of an impact on the noise or vibration performance.

## RECOMMENDED MODIFICATIONS TO STANDARDS AND SPECIFICATIONS

Several TxDOT standard sheets and specifications are used when considering profiled (audible) pavement markings and rumble bars (preformed thermoplastic strips). These standards and specifications have seen minor changes over the years. A significant change that was recently made with the 2014 version of the specification book was that the special specification for the reflectorized profile pavement markings (Special Specification 8020) was combined into the new TxDOT Standard Item 666 Retroreflectorized Pavement Markings Specification. Also incorporated into the 2014 Item 666 was Special Specification 8251 for Reflectorized Pavement Markings with Retroreflectivity Requirements. Not long after adopting the 2014 specifications, a memo was sent to all district engineers requiring all longitudinal markings paid under Item 666, except for profiled pavement markings, to meet minimum retroreflectivity requirements. The research team recommends requiring retroreflectivity performance on profiled pavement markings as well. The profiled markings need to be as visible as standard markings in all conditions. Special Specification 6085 for Inverted Profile Pavement Marking (audible) has retroreflectivity requirements, and these are significantly higher than standard markings. In general, it is more difficult to achieve good retroreflectivity in a profile marking due to the viscosity of the material being higher so that it will maintain its vertical structure. This decreased the ability to adequately imbed the reflective glass beads into the material. Adequate embedment of a quality glass bead is necessary to achieve good retroreflectivity initially and over time. To increase consistency in performance, the research team recommends TxDOT consider including noise performance levels into the specification. A minimum of a 6 dBA change in the interior noise should be required for audible marking installations. This can be measured with an inexpensive sound level meter affixed inside a vehicle. The research team does not recommend any other changes to Item 666 concerning the profile pavement markings or to the special specification.

The research team worked with a contractor to install a test bed of varying profile pavement marking designs. One of the designs consisted of a structured (dot or square pattern) pavement marking with the option of audible profile bumps incorporated on the marking. From above, this marking does not look like a solid marking, but from a distance (drivers perspective and beyond) the marking looks like a solid marking. These structured markings have the ability to help the marking drain water resulting in better wet retroreflectivity performance. When using standard marking practices, it is difficult to achieve and maintain good wet retroreflectivity levels. Structured markings, like the design studied in this project or the inverted profile pavement marking, are good options to achieve added wet visibility. There is not a special specification that currently covers structured markings. The development of a special specification for structured markings with the option for audible capabilities is recommended. This special specification should allow options to achieve the structure, while maintaining performance requirements, similar to those in Special Specification 6085.

The standard sheet for position guidance using raised markers and reflectorized profile markings is PM (2)-12. This document has the standard spacing and sizes for 4-in. and 6-in. wide profile pavement markings. The research team does not recommend any changes to this document. The research team evaluated several test markings with variable spacing, but the overall noise was not different. The advantage of the variable spacing is the oscillating frequency of the noise, but this may not be realized by most drivers as they do not drive on the markings for an extended period of time.

The standard sheets for edge line and center line rumble strips are in RS (1)-13 through RS (4)-13. These standard sheets cover various applications of milled rumble strips, raised rumble strips, profile markings, and preformed thermoplastic strips. For the profile pavement markings, these standard sheets provide similar design information as to what was provided in PM (2)-12. Information on the preformed thermoplastic strips is provided on page RS (3)-13. The preformed rumble strips are only shown as being used along the center line in-between the markings in passing areas. While this is one of the ways this type of treatment is used, the standard sheet should be updated with additional uses of the preformed thermoplastic strips. The two areas to address are the usage along the edge line or shoulder and continuously along the center line. For shoulder usage, the offset from the marking can follow the same guidelines as milled rumble strips. The suggested longitudinal spacing of 60-in. spacing is 1/5$^{th}$ the spacing as standard milled rumble strips. To increase the noise level and to provide a higher likelihood of being detected by a driver, a spacing of 48 in. is recommended. In areas with higher crash frequencies, a shorter spacing of 36 in. should be an option. The more frequent spacing will be more expensive but the noise and vibration performance will be increased and the associated crashes should decrease. To increase consistency in performance, the research team recommends TxDOT consider including noise performance levels into plans using rumble bars. A minimum of a 6 dBA change in the interior noise should be required for rumble bar installations.

## WHEN AND WHERE TO IMPLEMENT AUDIBLE LANE DEPARTURE WARNING TREATMENTS

To have a cost-effective crash countermeasure, the treatment needs to be installed at the appropriate locations where the crash reduction benefits will surpass the costs of installing and maintaining the treatment. Most divided highways have adequate pavement conditions were milled rumble strips can be implemented. These milled rumble strip alternatives are good options on seal coat road surfaces and other areas where the pavement surface may not have adequate depth for the installation of milled rumble strips. These alternative treatments may also be good options in areas where milled rumble strip usage may be limited due to the impact of noise pollution, since these treatments tend to produce lower noise levels. In areas where noise pollution is a concern, but roadway departure warning is desired, the rumble bars may be the best option. Numerous factors need to be considered when implementing these types of treatments. These factors include the following; crash history, highway speed, traffic volumes, shoulder width, amount of bicycle traffic, presence of nearby homes, and expected roadway service life.

The site selection for the installation of milled rumble strip alternatives should follow similar criteria that would be used for the selection of milled rumble strip locations. The biggest difference being that the roadway surface depth is no longer a consideration due to the alternative treatments being surface applied. Another consideration is that by being surface applied, winter maintenance activities may pose a threat to the treatments, by scraping them off of the roadway. Any roadway with a history of opposite direction or runoff the road crashes should be a candidate for installation of rumble strip alternatives. Roadways with speed limits of 50 mph or above should be considered if the average daily traffic is of sufficient volume.

Roadways with a short surface life left may not be a viable candidate for these treatments due to the installation cost and expected service life of the treatment. Roadways with these alternative treatments that have been seal coated over may no longer produce adequate performance levels. A quantitative performance evaluation or subjective evaluation should take place after the seal coat has been applied to determine if a treatment needs to be reapplied.

## SUMMARY

The research team found that in many cases the alternative treatments to milled rumble strips can produce adequate performance and result in crash reductions and a positive benefit-cost ratio. The results were somewhat variable in that not all treatment types within a similar category resulted in similar performance. This indicates the need for added inspection and performance monitoring. After seal coating over the treatments, the performance was reduced and may no longer be acceptable.

Using different vehicles and traveling at different speeds can impact the performance levels of the markings. Traveling at higher speeds and in a vehicle with a stiffer suspension results in higher noise and vibration levels. The specific treatment design also impacts the performance. Treatments with closer spacing, longer bumps, and higher profiles produced higher noise and vibration levels. The alternative treatments were able to produce noise and vibration levels that approached levels similar to milled rumble strips. In areas where milled rumble strips cannot be used, these alternative treatments are viable options. Even in areas where milled rumble strips can be used, these alternatives may be attractive options if the reduction in noise pollution is desired. In general, the audible marking had higher performance levels than the rumble bars. The audible markings also provide additional wet night visibility, whereas the rumble bars provide no visibility benefit.

Audible markings and rumble bars are viable alternative lane departure warning treatments from a noise and vibration performance standpoint, from a crash reduction standpoint, and from a benefit-cost ratio (at least 11:1) standpoint. These treatments should be considered when traffic volumes, speeds, and crash history indicate a need for increased attention to reduce single vehicle run-off-road and two-lane two-way crossover crashes.

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# APPENDIX A:
# TXDOT SURVEY QUESTIONNAIRE

### Texas A&M Transportation Institute: Audible Lane Departure Warning for Seal Coat Surfaces (TxDOT 0-6888)

The Texas A&M Transportation Institute (TTI) is currently working on TxDOT project 0-6888 to evaluate Audible Lane Departure Warning Systems (ALDWS) for Seal Coat Surfaces. One of the first steps of the study is to gather information about the current usage of these systems in each TxDOT district. TTI is gathering this information via a telephone interview, and/or e-mail questionnaire from each individual TxDOT district. Participation in this survey is optional, and respondents are not required to answer all questions to take part in the survey.

For this research project the focus is on audible pavement marking systems such as profile pavement markings and on preformed thermoplastic strips also referred to as rumble bars. These systems are the focus of the research because they can be used in areas where milled rumble strips cannot be used, i.e. many seal coat road surfaces. The research is not focusing on milled rumble strips. Please see the images below for examples of the ALDWS that are the focus of this research.

Profile pavement markings (left), rumble bars (right).

Please answer the questions honestly to the best of your knowledge. If you cannot respond to a question please indicate so or leave it blank. We are looking to get a general district opinion on the questions that do not have defined answers. Please note that participation in the study is confidential and the records of this study will be kept private; responses used in the research will not be linked to individual respondents. Our goal is to get some form of a response from all 25 districts so that TxDOT can better understand the ALDWS practices around the state.

If you have any questions regarding this study, please feel free to contact Adam Pike using the contact information at the end of the survey. If possible please schedule a telephone interview with Adam, or return the questionnaire within 15 working days. Your support of this important research study is greatly appreciated! We look forward to hearing back from you.

**RESPONDENT CONTACT INFORMATION**

Contact Person: ______________________________________________

TxDOT District: ____________________ Position: ______________________

Telephone Number: ___________________________________________

Email: ______________________________________________________

1. Is your district currently using any audible lane departure warning system (ALDWS) that is a focus of this study?
   _Yes (If Yes, go to question 3)
   _No (If No, go to question 2)

2. Is there a reason your district is not using any ALDWS? If yes, please provide additional information.
   _Yes _No

   | |
   |---|
   | |

   *Please continue on to question 14.*

3. Is your district using audible pavement markings? If yes, please input the quantity of centerline miles.
   _Yes _No

   | |
   |---|
   | |

4. Is your district using rumble bars? If yes, please input the quantity of centerline miles.
   _Yes _No

   | |
   |---|
   | |

5. Does your district have records indicating which roads have these systems and when they were installed? If yes, please provide additional information on the details of your records.
   _Yes _No

   | |
   |---|
   | |

6. Would your district be willing to provide additional information over the phone or via email about specific installations of ALDWS?
   _Yes _No

   | |
   |---|
   | |

7. Does your district have criteria for when to install these systems? If yes, please provide additional information on specific criteria. If no, provide information on the motivation behind installation of the systems?
   _Yes _No

8. Are these systems limited to certain roadway classifications? If yes, please provide additional information on specific roadway classifications where these systems may or may not be used.
   _Yes _No

9. Are these systems limited to certain roadway surface types? If yes, please provide additional information on specific roadway surface types where these systems may or may not be used.
   _Yes _No

10. What are the typical project sizes and unit costs associated with the installed systems?

11. What specification was used for the design/installation of the systems? If no specific specification was used, or a specification was modified, please indicate the length, width, height, and spacing of the treatments.

12. Does your district have any experience or feedback on the performance of the systems (e.g., sound, vibration, visibility, durability, ease of installation, service life, maintenance, safety, etc.)?

13. Does your district have any concerns with previous, existing, or future installations of these systems?

14. Does your district plan on implementing ALDWS in the future? If yes, please indicate when. If no, please indicate why.
    _Yes _No

15. Would your district be willing to serve as a host district for an ALDWS test area(s) to be installed in spring/summer 2016? The focus of the test area(s) will be on the evaluation of the sound and vibration of the ALDWS. It is anticipated that the individual test areas will be no longer than 1 mile in length. Ideally the test areas can be incorporated into a planned ALDWS project.
    _Yes _No

# APPENDIX B:
# NOISE RESULTS

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB1 | Edge Line | Aud Marking | 81.7 | 500 | 107.2 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB1 | Wheel Path | Control | 73.1 | 900 | 104.6 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB2 | Edge Line | Aud Marking | 79.2 | 770 | 107.7 | 783 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB2 | Wheel Path | Control | 73.0 | 1000 | 104.7 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB3 | Edge Line | Aud Marking | 74.6 | 967 | 104.8 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB3 | Wheel Path | Control | 73.2 | 1000 | 105.1 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB4 | Edge Line | Aud Marking | 79.6 | 645 | 108.7 | 785 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB4 | Wheel Path | Control | 73.2 | 900 | 104.8 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB5 | Edge Line | Aud Marking | 80.9 | 700 | 109.2 | 772 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB5 | Wheel Path | Control | 73.3 | 1000 | 104.9 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB6 | Edge Line | Aud Marking | 80.6 | 733 | 109.8 | 833 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | EB6 | Wheel Path | Control | 73.2 | 1000 | 104.8 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB1 | Edge Line | Aud Marking | 80.7 | 829 | 110.6 | 1000 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB1 | Wheel Path | Control | 72.9 | 1000 | 104.3 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB2 | Edge Line | Aud Marking | 78.6 | 804 | 109.2 | 925 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB2 | Wheel Path | Control | 73.5 | 1000 | 104.7 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB3 | Edge Line | Aud Marking | 78.0 | 750 | 108.8 | 867 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB3 | Wheel Path | Control | 72.9 | 1000 | 104.4 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB4 | Edge Line | Aud Marking | 78.9 | 857 | 109.2 | 914 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB4 | Wheel Path | Control | 73.1 | 1000 | 104.8 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB5 | Edge Line | Aud Marking | 79.7 | 720 | 110.3 | 1000 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB5 | Wheel Path | Control | 73.9 | 1000 | 104.8 | 800 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB6 | Edge Line | Aud Marking | 81.2 | 713 | 109.0 | 1000 |
| 2016 | Apr | FM389 | Sealcoat | Car | 55 | WB6 | Wheel Path | Control | 73.3 | 1000 | 104.8 | 800 |
| 2016 | May | FM1971 | Sealcoat | Car | 55 | | Center Line | Bars+Aud Marking | 79.0 | 950 | 106.0 | 800 |
| 2016 | May | FM1971 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 81.0 | 500 | 112.4 | 1000 |
| 2016 | May | FM1971 | Sealcoat | Car | 55 | | Wheel Path | Control | 70.9 | 1000 | 104.3 | 850 |
| 2016 | May | FM1971 | Sealcoat | Truck | 55 | | Center Line | Bars+Aud Marking | 73.2 | 800 | 104.7 | 800 |
| 2016 | May | FM1971 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 73.4 | 800 | 112.8 | 630 |
| 2016 | May | FM1971 | Sealcoat | Truck | 55 | | Wheel Path | Control | 66.9 | 950 | 103.7 | 1000 |
| 2016 | May | FM2208 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 76.7 | 850 | 104.0 | 800 |
| 2016 | May | FM2208 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 74.9 | 850 | 107.7 | 800 |
| 2016 | May | FM2208 | Sealcoat | Car | 55 | | Wheel Path | Control | 70.4 | 1000 | 102.8 | 1000 |
| 2016 | May | FM2208 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 71.0 | 800 | 104.1 | 900 |
| 2016 | May | FM2208 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 69.4 | 933 | 106.8 | 800 |
| 2016 | May | FM2208 | Sealcoat | Truck | 55 | | Wheel Path | Control | 65.8 | 1000 | 102.1 | 1000 |
| 2016 | May | FM31 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 77.5 | 933 | 105.1 | 800 |
| 2016 | May | FM31 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 78.6 | 800 | 110.3 | 1000 |
| 2016 | May | FM31 | Sealcoat | Car | 55 | | Shoulder | Rumble Bars | 77.8 | 800 | 107.7 | 800 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2016 | May | FM31 | Sealcoat | Car | 55 | | Wheel Path | Control | 72.6 | 950 | 104.9 | 800 |
| 2016 | May | FM31 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 74.0 | 600 | 105.3 | 800 |
| 2016 | May | FM31 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 71.8 | 800 | 113.1 | 800 |
| 2016 | May | FM31 | Sealcoat | Truck | 55 | | Shoulder | Rumble Bars | 71.9 | 800 | 108.8 | 800 |
| 2016 | May | FM31 | Sealcoat | Truck | 55 | | Wheel Path | Control | 67.2 | 900 | 105.4 | 1000 |
| 2016 | May | FM31b | Sealcoat | Car | 55 | | Center Line | Bars w/ Seal Coat | 77.5 | 800 | 104.9 | 800 |
| 2016 | May | FM31b | Sealcoat | Car | 55 | | Shoulder | Bars w/ Seal Coat | 76.6 | 933 | 105.0 | 800 |
| 2016 | May | FM31b | Sealcoat | Car | 55 | | Wheel Path | Control | 71.5 | 950 | 103.0 | 900 |
| 2016 | May | FM31b | Sealcoat | Truck | 55 | | Center Line | Bars w/ Seal Coat | 74.1 | 800 | 105.8 | 800 |
| 2016 | May | FM31b | Sealcoat | Truck | 55 | | Shoulder | Bars w/ Seal Coat | 72.0 | 700 | 107.5 | 800 |
| 2016 | May | FM31b | Sealcoat | Truck | 55 | | Wheel Path | Control | 67.4 | 1000 | 104.4 | 1000 |
| 2016 | May | Idle | NA | Car | 0 | | NA | NA | 52.8 | 400 | 62.6 | 1250 |
| 2016 | May | Idle | NA | Truck | 0 | | NA | NA | 48.4 | 500 | 60.8 | 758 |
| 2016 | May | SH149 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 77.2 | 900 | 104.4 | 1000 |
| 2016 | May | SH149 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 76.7 | 758 | 111.9 | 963 |
| 2016 | May | SH149 | Sealcoat | Car | 55 | | Wheel Path | Control | 71.3 | 1000 | 104.3 | 1000 |
| 2016 | May | SH149 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 71.4 | 800 | 105.0 | 1000 |
| 2016 | May | SH149 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 71.8 | 800 | 112.6 | 800 |
| 2016 | May | SH149 | Sealcoat | Truck | 55 | | Wheel Path | Control | 66.2 | 900 | 103.0 | 1063 |
| 2016 | May | SH154 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 78.2 | 800 | 103.3 | 900 |
| 2016 | May | SH154 | Sealcoat | Car | 55 | | Edge Line | Rumble Bars | 76.6 | 800 | 107.5 | 800 |
| 2016 | May | SH154 | Sealcoat | Car | 55 | | Wheel Path | Control | 70.5 | 900 | 102.4 | 950 |
| 2016 | May | SH154 | Sealcoat | Car | 70 | | Center Line | Rumble Bars | 80.2 | 900 | 106.6 | 1013 |
| 2016 | May | SH154 | Sealcoat | Car | 70 | | Edge Line | Rumble Bars | 79.3 | 800 | 111.3 | 800 |
| 2016 | May | SH154 | Sealcoat | Car | 70 | | Wheel Path | Control | 72.5 | 1000 | 105.6 | 1013 |
| 2016 | May | SH154 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 71.8 | 800 | 104.4 | 950 |
| 2016 | May | SH154 | Sealcoat | Truck | 55 | | Edge Line | Rumble Bars | 70.9 | 758 | 109.8 | 758 |
| 2016 | May | SH154 | Sealcoat | Truck | 55 | | Wheel Path | Control | 64.8 | 1000 | 102.6 | 1000 |
| 2016 | May | SH154 | Sealcoat | Truck | 70 | | Center Line | Rumble Bars | 74.3 | 667 | 107.0 | 1000 |
| 2016 | May | SH154 | Sealcoat | Truck | 70 | | Edge Line | Rumble Bars | 73.2 | 800 | 114.2 | 800 |
| 2016 | May | SH154 | Sealcoat | Truck | 70 | | Wheel Path | Control | 69.2 | 850 | 105.7 | 950 |
| 2016 | May | SH155a | Sealcoat | Car | 55 | | Center Line | Bars w/ Seal Coat | 77.4 | 800 | 105.4 | 800 |
| 2016 | May | SH155a | Sealcoat | Car | 55 | | Shoulder | Bars w/ Seal Coat | 76.0 | 800 | 106.1 | 800 |
| 2016 | May | SH155a | Sealcoat | Car | 55 | | Wheel Path | Control | 73.8 | 950 | 105.1 | 800 |
| 2016 | May | SH155a | Sealcoat | Truck | 55 | | Center Line | Bars w/ Seal Coat | 74.3 | 700 | 106.5 | 800 |
| 2016 | May | SH155a | Sealcoat | Truck | 55 | | Shoulder | Bars w/ Seal Coat | 70.6 | 600 | 107.0 | 800 |
| 2016 | May | SH155a | Sealcoat | Truck | 55 | | Wheel Path | Control | 69.6 | 800 | 105.9 | 800 |
| 2016 | May | SH155b | Asphalt | Car | 55 | | Center Line | Bars+Aud Marking | 77.4 | 800 | 100.2 | 1000 |
| 2016 | May | SH155b | Asphalt | Car | 55 | | Shoulder | Rumble Bars | 77.2 | 800 | 108.1 | 800 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2016 | May | SH155b | Asphalt | Car | 55 | | Wheel Path | Control | 68.0 | 800 | 99.4 | 1000 |
| 2016 | May | SH155b | Asphalt | Truck | 55 | | Center Line | Bars+Aud Marking | 74.3 | 800 | 100.4 | 950 |
| 2016 | May | SH155b | Asphalt | Truck | 55 | | Shoulder | Rumble Bars | 71.1 | 758 | 111.5 | 800 |
| 2016 | May | SH155b | Asphalt | Truck | 55 | | Wheel Path | Control | 65.0 | 573 | 99.9 | 950 |
| 2016 | May | SH300 | Asphalt | Car | 55 | | Center Line | Milled Rumble | 75.7 | 700 | 98.1 | 950 |
| 2016 | May | SH300 | Asphalt | Car | 55 | | Edge Line | Milled Rumble | 77.6 | 800 | 107.0 | 800 |
| 2016 | May | SH300 | Asphalt | Car | 55 | | Wheel Path | Control | 68.2 | 800 | 98.7 | 1000 |
| 2016 | May | SH300 | Asphalt | Car | 70 | | Center Line | Milled Rumble | 80.2 | 800 | 101.2 | 913 |
| 2016 | May | SH300 | Asphalt | Car | 70 | | Edge Line | Milled Rumble | 80.6 | 673 | 113.9 | 800 |
| 2016 | May | SH300 | Asphalt | Car | 70 | | Wheel Path | Control | 72.1 | 1000 | 101.0 | 1250 |
| 2016 | May | SH300 | Asphalt | Truck | 55 | | Center Line | Milled Rumble | 73.5 | 400 | 98.4 | 1250 |
| 2016 | May | SH300 | Asphalt | Truck | 55 | | Edge Line | Milled Rumble | 72.5 | 800 | 111.1 | 800 |
| 2016 | May | SH300 | Asphalt | Truck | 55 | | Wheel Path | Control | 63.6 | 630 | 98.4 | 1250 |
| 2016 | May | SH300 | Asphalt | Truck | 70 | | Center Line | Milled Rumble | 76.9 | 750 | 101.4 | 950 |
| 2016 | May | SH300 | Asphalt | Truck | 70 | | Edge Line | Milled Rumble | 76.8 | 800 | 115.6 | 800 |
| 2016 | May | SH300 | Asphalt | Truck | 70 | | Wheel Path | Control | 68.3 | 600 | 100.4 | 1063 |
| 2016 | May | SH315 | Sealcoat | Car | 55 | | Center Line | Aud Marking w/ Seal Coat | 76.0 | 800 | 105.1 | 800 |
| 2016 | May | SH315 | Sealcoat | Car | 55 | | Wheel Path | Control | 74.6 | 920 | 105.0 | 840 |
| 2016 | May | SH315 | Sealcoat | Car | 70 | | Center Line | Aud Marking w/ Seal Coat | 78.8 | 900 | 109.3 | 800 |
| 2016 | May | SH315 | Sealcoat | Car | 70 | | Wheel Path | Control | 75.4 | 1000 | 108.9 | 800 |
| 2016 | May | SH315 | Sealcoat | Truck | 55 | | Center Line | Aud Marking w/ Seal Coat | 70.2 | 800 | 104.8 | 800 |
| 2016 | May | SH315 | Sealcoat | Truck | 55 | | Wheel Path | Control | 68.3 | 800 | 104.5 | 900 |
| 2016 | May | SH315 | Sealcoat | Truck | 70 | | Center Line | Aud Marking w/ Seal Coat | 73.5 | 800 | 108.6 | 800 |
| 2016 | May | SH315 | Sealcoat | Truck | 70 | | Wheel Path | Control | 70.9 | 900 | 107.9 | 900 |
| 2016 | May | SH43 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 79.0 | 800 | 104.7 | 800 |
| 2016 | May | SH43 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 78.6 | 800 | 107.8 | 800 |
| 2016 | May | SH43 | Sealcoat | Car | 55 | | Wheel Path | Control | 72.5 | 1000 | 103.6 | 800 |
| 2016 | May | SH43 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 73.6 | 400 | 105.5 | 800 |
| 2016 | May | SH43 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 72.7 | 515 | 108.8 | 800 |
| 2016 | May | SH43 | Sealcoat | Truck | 55 | | Wheel Path | Control | 68.9 | 850 | 104.5 | 850 |
| 2016 | May | US79 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 80.1 | 800 | 105.4 | 1000 |
| 2016 | May | US79 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 77.8 | 775 | 110.2 | 900 |
| 2016 | May | US79 | Sealcoat | Car | 55 | | Shoulder | Milled Rumble w/ Bars | 89.8 | 630 | 113.6 | 800 |
| 2016 | May | US79 | Sealcoat | Car | 55 | | Wheel Path | Control | 71.6 | 900 | 105.1 | 1000 |
| 2016 | May | US79 | Sealcoat | Car | 70 | | Center Line | Rumble Bars | 85.2 | 1000 | 108.9 | 1125 |
| 2016 | May | US79 | Sealcoat | Car | 70 | | Edge Line | Aud Marking | 81.3 | 765 | 116.5 | 950 |
| 2016 | May | US79 | Sealcoat | Car | 70 | | Shoulder | Milled Rumble w/ Bars | 83.8 | 615 | 117.0 | 800 |
| 2016 | May | US79 | Sealcoat | Car | 70 | | Wheel Path | Control | 73.8 | 1000 | 108.3 | 1125 |
| 2016 | May | US79 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 77.2 | 800 | 105.6 | 1000 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2016 | May | US79 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 71.4 | 900 | 110.7 | 850 |
| 2016 | May | US79 | Sealcoat | Truck | 55 | | Shoulder | Milled Rumble w/ Bars | 76.4 | 700 | 112.0 | 800 |
| 2016 | May | US79 | Sealcoat | Truck | 55 | | Wheel Path | Control | 65.2 | 1000 | 104.7 | 1000 |
| 2016 | May | US79 | Sealcoat | Truck | 70 | | Center Line | Rumble Bars | 79.0 | 933 | 108.6 | 1000 |
| 2016 | May | US79 | Sealcoat | Truck | 70 | | Edge Line | Aud Marking | 74.6 | 758 | 117.5 | 850 |
| 2016 | May | US79 | Sealcoat | Truck | 70 | | Shoulder | Milled Rumble w/ Bars | 83.2 | 800 | 116.8 | 800 |
| 2016 | May | US79 | Sealcoat | Truck | 70 | | Wheel Path | Control | 69.1 | 1000 | 107.7 | 1000 |
| 2016 | May | US80 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 79.0 | 900 | 103.6 | 850 |
| 2016 | May | US80 | Sealcoat | Car | 55 | | Shoulder | Rumble Bars | 77.2 | 850 | 108.0 | 800 |
| 2016 | May | US80 | Sealcoat | Car | 55 | | Wheel Path | Control | 73.6 | 1000 | 103.6 | 850 |
| 2016 | May | US80 | Sealcoat | Car | 70 | | Center Line | Rumble Bars | 81.5 | 950 | 107.9 | 900 |
| 2016 | May | US80 | Sealcoat | Car | 70 | | Shoulder | Rumble Bars | 80.1 | 900 | 112.5 | 800 |
| 2016 | May | US80 | Sealcoat | Car | 70 | | Wheel Path | Control | 75.6 | 1000 | 107.5 | 950 |
| 2016 | May | US80 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 74.3 | 700 | 104.7 | 850 |
| 2016 | May | US80 | Sealcoat | Truck | 55 | | Shoulder | Rumble Bars | 72.4 | 800 | 109.7 | 715 |
| 2016 | May | US80 | Sealcoat | Truck | 55 | | Wheel Path | Control | 70.4 | 950 | 104.6 | 1000 |
| 2016 | May | US80 | Sealcoat | Truck | 70 | | Center Line | Rumble Bars | 74.6 | 850 | 108.6 | 950 |
| 2016 | May | US80 | Sealcoat | Truck | 70 | | Shoulder | Rumble Bars | 74.8 | 800 | 114.1 | 758 |
| 2016 | May | US80 | Sealcoat | Truck | 70 | | Wheel Path | Control | 71.8 | 1000 | 108.3 | 1000 |
| 2016 | Dec | FM1519 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 74.9 | 800 | 105.8 | 800 |
| 2016 | Dec | FM1519 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 75.6 | 800 | 109.5 | 800 |
| 2016 | Dec | FM1519 | Sealcoat | Car | 55 | | Wheel Path | Control | 68.9 | 800 | 103.6 | 920 |
| 2016 | Dec | FM1519 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 73.3 | 800 | 107.5 | 1000 |
| 2016 | Dec | FM1519 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 72.3 | 800 | 111.0 | 900 |
| 2016 | Dec | FM1519 | Sealcoat | Truck | 55 | | Wheel Path | Control | 68.1 | 800 | 105.2 | 1000 |
| 2016 | Dec | FM2088 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 75.3 | 800 | 106.8 | 800 |
| 2016 | Dec | FM2088 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 75.6 | 800 | 108.2 | 800 |
| 2016 | Dec | FM2088 | Sealcoat | Car | 55 | | Wheel Path | Control | 71.2 | 800 | 105.9 | 800 |
| 2016 | Dec | FM2088 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 73.0 | 800 | 108.6 | 800 |
| 2016 | Dec | FM2088 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 73.3 | 850 | 110.1 | 800 |
| 2016 | Dec | FM2088 | Sealcoat | Truck | 55 | | Wheel Path | Control | 69.8 | 1000 | 106.7 | 1000 |
| 2016 | Dec | FM2791 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 74.1 | 800 | 107.1 | 800 |
| 2016 | Dec | FM2791 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 75.0 | 800 | 109.3 | 800 |
| 2016 | Dec | FM2791 | Sealcoat | Car | 55 | | Wheel Path | Control | 70.8 | 900 | 105.9 | 800 |
| 2016 | Dec | FM2791 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 71.2 | 800 | 107.7 | 1000 |
| 2016 | Dec | FM2791 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 72.3 | 800 | 110.3 | 800 |
| 2016 | Dec | FM2791 | Sealcoat | Truck | 55 | | Wheel Path | Control | 68.3 | 900 | 106.0 | 1000 |
| 2016 | Dec | IH369 | Asphalt | Car | 55 | | Center Line | Aud Marking | 78.4 | 800 | 102.7 | 920 |
| 2016 | Dec | IH369 | Asphalt | Car | 55 | | Edge Line | Aud Marking | 78.6 | 433 | 113.6 | 800 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2016 | Dec | IH369 | Asphalt | Car | 55 | | Wheel Path | Control | 66.5 | 800 | 98.7 | 1000 |
| 2016 | Dec | IH369 | Asphalt | Car | 70 | | Center Line | Aud Marking | 77.8 | 950 | 103.1 | 1188 |
| 2016 | Dec | IH369 | Asphalt | Car | 70 | | Edge Line | Aud Marking | 80.3 | 672 | 113.6 | 1160 |
| 2016 | Dec | IH369 | Asphalt | Car | 70 | | Wheel Path | Control | 70.8 | 1000 | 99.9 | 1250 |
| 2016 | Dec | IH369 | Asphalt | Truck | 55 | | Center Line | Aud Marking | 75.1 | 1000 | 100.1 | 1050 |
| 2016 | Dec | IH369 | Asphalt | Truck | 55 | | Edge Line | Aud Marking | 75.0 | 800 | 115.0 | 840 |
| 2016 | Dec | IH369 | Asphalt | Truck | 55 | | Wheel Path | Control | 67.1 | 800 | 98.0 | 1600 |
| 2016 | Dec | IH369 | Asphalt | Truck | 70 | | Center Line | Aud Marking | 75.9 | 920 | 101.3 | 1640 |
| 2016 | Dec | IH369 | Asphalt | Truck | 70 | | Edge Line | Aud Marking | 76.8 | 800 | 118.2 | 758 |
| 2016 | Dec | IH369 | Asphalt | Truck | 70 | | Wheel Path | Control | 69.6 | 560 | 99.7 | 1600 |
| 2016 | Dec | SH11 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 77.8 | 800 | 107.2 | 800 |
| 2016 | Dec | SH11 | Sealcoat | Car | 55 | | Edge Line | Rumble Bars | 78.2 | 800 | 109.6 | 800 |
| 2016 | Dec | SH11 | Sealcoat | Car | 55 | | Wheel Path | Control | 72.5 | 800 | 107.3 | 800 |
| 2016 | Dec | SH11 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 74.3 | 800 | 108.9 | 850 |
| 2016 | Dec | SH11 | Sealcoat | Truck | 55 | | Edge Line | Rumble Bars | 73.9 | 800 | 112.2 | 758 |
| 2016 | Dec | SH11 | Sealcoat | Truck | 55 | | Wheel Path | Control | 69.9 | 900 | 108.9 | 1000 |
| 2016 | Dec | SH154 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 76.3 | 800 | 104.9 | 880 |
| 2016 | Dec | SH154 | Sealcoat | Car | 55 | | Edge Line | Rumble Bars | 75.7 | 800 | 109.1 | 800 |
| 2016 | Dec | SH154 | Sealcoat | Car | 55 | | Wheel Path | Control | 69.5 | 850 | 104.5 | 950 |
| 2016 | Dec | SH154 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 73.8 | 800 | 106.5 | 1000 |
| 2016 | Dec | SH154 | Sealcoat | Truck | 55 | | Edge Line | Rumble Bars | 72.3 | 800 | 111.7 | 800 |
| 2016 | Dec | SH154 | Sealcoat | Truck | 55 | | Wheel Path | Control | 67.5 | 1000 | 105.1 | 1000 |
| 2016 | Dec | SH300 | Asphalt | Car | 55 | | Center Line | Milled Rumble | 79.1 | 800 | 100.9 | 1000 |
| 2016 | Dec | SH300 | Asphalt | Car | 55 | | Edge Line | Milled Rumble | 75.6 | 800 | 108.7 | 800 |
| 2016 | Dec | SH300 | Asphalt | Car | 55 | | Wheel Path | Control | 67.3 | 800 | 101.2 | 867 |
| 2016 | Dec | SH300 | Asphalt | Truck | 55 | | Center Line | Milled Rumble | 74.7 | 800 | 100.3 | 1300 |
| 2016 | Dec | SH300 | Asphalt | Truck | 55 | | Edge Line | Milled Rumble | 74.8 | 658 | 109.3 | 800 |
| 2016 | Dec | SH300 | Asphalt | Truck | 55 | | Wheel Path | Control | 65.6 | 800 | 101.2 | 1000 |
| 2016 | Dec | SH8 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 74.9 | 800 | 105.8 | 800 |
| 2016 | Dec | SH8 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 75.9 | 800 | 111.5 | 933 |
| 2016 | Dec | SH8 | Sealcoat | Car | 55 | | | Rumble Bars | 76.4 | 800 | 109.7 | 800 |
| 2016 | Dec | SH8 | Sealcoat | Car | 55 | | Wheel Path | Control | 69.9 | 800 | 106.3 | 800 |
| 2016 | Dec | SH8 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 73.0 | 800 | 106.6 | 1000 |
| 2016 | Dec | SH8 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 71.4 | 900 | 112.7 | 950 |
| 2016 | Dec | SH8 | Sealcoat | Truck | 55 | | | Rumble Bars | 70.6 | 850 | 108.8 | 850 |
| 2016 | Dec | SH8 | Sealcoat | Truck | 55 | | Wheel Path | Control | 67.8 | 850 | 106.2 | 1000 |
| 2016 | Dec | US259 | Asphalt | Car | 55 | | Center Line | Aud Marking | 72.1 | 800 | 98.9 | 920 |
| 2016 | Dec | US259 | Asphalt | Car | 55 | | | Rumble Bars | 77.9 | 400 | 99.2 | 950 |
| 2016 | Dec | US259 | Asphalt | Car | 55 | | Edge Line | Aud Marking | 73.1 | 575 | 107.4 | 900 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2016 | Dec | US259 | Asphalt | Car | 55 | | | Milled Rumble | 83.3 | 973 | 110.4 | 800 |
| 2016 | Dec | US259 | Asphalt | Car | 55 | | Wheel Path | Control | 67.7 | 800 | 99.3 | 1000 |
| 2016 | Dec | US259 | Asphalt | Truck | 55 | | Center Line | Aud Marking | 71.5 | 700 | 100.2 | 1008 |
| 2016 | Dec | US259 | Asphalt | Truck | 55 | | | Rumble Bars | 75.7 | 725 | 100.3 | 1450 |
| 2016 | Dec | US259 | Asphalt | Truck | 55 | | Edge Line | Aud Marking | 70.8 | 1000 | 110.6 | 1000 |
| 2016 | Dec | US259 | Asphalt | Truck | 55 | | | Milled Rumble | 78.0 | 700 | 113.0 | 715 |
| 2016 | Dec | US259 | Asphalt | Truck | 55 | | Wheel Path | Control | 65.9 | 800 | 101.1 | 1000 |
| 2016 | Dec | US67 | Sealcoat | Car | 55 | | Center Line | Rumble Bars | 78.7 | 800 | 107.4 | 800 |
| 2016 | Dec | US67 | Sealcoat | Car | 55 | | Edge Line | Aud Marking | 76.6 | 800 | 109.5 | 800 |
| 2016 | Dec | US67 | Sealcoat | Car | 55 | | Wheel Path | Control | 72.6 | 900 | 106.4 | 1000 |
| 2016 | Dec | US67 | Sealcoat | Car | 70 | | Center Line | Rumble Bars | 82.6 | 800 | 110.8 | 800 |
| 2016 | Dec | US67 | Sealcoat | Car | 70 | | Wheel Path | Control | 75.9 | 850 | 109.2 | 900 |
| 2016 | Dec | US67 | Sealcoat | Truck | 55 | | Center Line | Rumble Bars | 74.7 | 800 | 109.3 | 933 |
| 2016 | Dec | US67 | Sealcoat | Truck | 55 | | Edge Line | Aud Marking | 73.1 | 800 | 111.3 | 800 |
| 2016 | Dec | US67 | Sealcoat | Truck | 55 | | Wheel Path | Control | 69.6 | 1000 | 107.5 | 1000 |
| 2016 | Dec | US67 | Sealcoat | Truck | 70 | | Center Line | Rumble Bars | 77.8 | 800 | 112.0 | 1000 |
| 2016 | Dec | US67 | Sealcoat | Truck | 70 | | Wheel Path | Control | 72.8 | 1000 | 110.6 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB1 | Edge Line | Aud Marking | 81.1 | 700 | 113.3 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB1 | Wheel Path | Control | 71.6 | 1000 | 105.8 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB2 | Edge Line | Aud Marking | 78.4 | 800 | 109.5 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB2 | Wheel Path | Control | 70.9 | 800 | 105.4 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB3 | Edge Line | Aud Marking | 73.8 | 800 | 106.8 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB3 | Wheel Path | Control | 71.5 | 900 | 105.4 | 900 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB4 | Edge Line | Aud Marking | 79.5 | 766 | 110.7 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB4 | Wheel Path | Control | 71.9 | 900 | 105.7 | 900 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB5 | Edge Line | Aud Marking | 80.5 | 740 | 111.3 | 766 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB5 | Wheel Path | Control | 71.3 | 900 | 105.6 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB6 | Edge Line | Aud Marking | 80.4 | 800 | 112.8 | 664 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | EB6 | Wheel Path | Control | 73.7 | 900 | 105.7 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB1 | Edge Line | Aud Marking | 79.8 | 643 | 112.6 | 867 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB1 | Wheel Path | Control | 72.6 | 1000 | 105.2 | 900 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB2 | Edge Line | Aud Marking | 77.4 | 800 | 111.0 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB2 | Wheel Path | Control | 72.0 | 1000 | 105.3 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB3 | Edge Line | Aud Marking | 79.5 | 800 | 110.9 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB3 | Wheel Path | Control | 71.5 | 1000 | 105.2 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB4 | Edge Line | Aud Marking | 79.2 | 800 | 110.7 | 900 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB4 | Wheel Path | Control | 72.0 | 900 | 105.1 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB5 | Edge Line | Aud Marking | 80.1 | 800 | 112.0 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB5 | Wheel Path | Control | 72.1 | 1000 | 105.7 | 800 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB6 | Edge Line | Aud Marking | 80.4 | 743 | 110.4 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Car | 55 | WB6 | Wheel Path | Control | 71.4 | 900 | 105.6 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB1 | Edge Line | Aud Marking | 76.3 | 725 | 110.8 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB1 | Wheel Path | Control | 67.7 | 1000 | 105.0 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB2 | Edge Line | Aud Marking | 73.7 | 800 | 109.6 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB2 | Wheel Path | Control | 68.1 | 1000 | 104.8 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB3 | Edge Line | Aud Marking | 68.3 | 1000 | 106.3 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB3 | Wheel Path | Control | 67.1 | 1000 | 104.7 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB4 | Edge Line | Aud Marking | 75.3 | 800 | 111.6 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB4 | Wheel Path | Control | 67.2 | 1000 | 105.0 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB5 | Edge Line | Aud Marking | 75.0 | 740 | 112.2 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB5 | Wheel Path | Control | 68.7 | 1000 | 104.9 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB6 | Edge Line | Aud Marking | 74.3 | 800 | 113.2 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | EB6 | Wheel Path | Control | 67.6 | 1000 | 104.9 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB1 | Edge Line | Aud Marking | 76.7 | 800 | 112.6 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB1 | Wheel Path | Control | 68.0 | 1000 | 104.7 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB2 | Edge Line | Aud Marking | 73.8 | 800 | 112.6 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB2 | Wheel Path | Control | 68.5 | 1000 | 105.2 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB3 | Edge Line | Aud Marking | 74.9 | 800 | 111.1 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB3 | Wheel Path | Control | 67.8 | 1000 | 104.2 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB4 | Edge Line | Aud Marking | 73.9 | 740 | 112.7 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB4 | Wheel Path | Control | 68.7 | 1000 | 105.1 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB5 | Edge Line | Aud Marking | 74.4 | 800 | 111.5 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB5 | Wheel Path | Control | 70.3 | 1000 | 105.3 | 1000 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB6 | Edge Line | Aud Marking | 76.9 | 700 | 111.7 | 800 |
| 2017 | Feb | FM389 | Sealcoat | Truck | 55 | WB6 | Wheel Path | Control | 69.0 | 1000 | 105.4 | 1000 |
| 2017 | Feb | Idle | NA | Car | 0 | | NA | NA | 52.7 | 800 | 60.2 | 1250 |
| 2017 | Feb | Idle | NA | Truck | 0 | | NA | NA | 46.6 | 477 | 60.9 | 893 |
| 2017 | Feb | SH21 | Asphalt | Car | 55 | | Center Line | Aud Marking | 83.1 | 800 | 111.9 | 1100 |
| 2017 | Feb | SH21 | Asphalt | Car | 55 | | Edge Line | Aud Marking | 78.1 | 840 | 100.5 | 1000 |
| 2017 | Feb | SH21 | Asphalt | Car | 55 | | Wheel Path | Control | 68.8 | 800 | 102.0 | 1000 |
| 2017 | Feb | SH21 | Asphalt | Truck | 55 | | Center Line | Aud Marking | 74.2 | 733 | 99.6 | 1167 |
| 2017 | Feb | SH21 | Asphalt | Truck | 55 | | Edge Line | Aud Marking | 73.5 | 880 | 107.6 | 880 |
| 2017 | Feb | SH21 | Asphalt | Truck | 55 | | Wheel Path | Control | 66.4 | 1000 | 101.0 | 1000 |
| 2017 | Feb | SH21b | Asphalt | Car | 55 | | Edge Line | Aud Marking | 79.7 | 715 | 112.5 | 800 |
| 2017 | Feb | SH21b | Asphalt | Car | 55 | | Wheel Path | Control | 67.9 | 800 | 98.3 | 800 |
| 2017 | Feb | SH21b | Asphalt | Car | 70 | | Edge Line | Aud Marking | 84.0 | 743 | 117.4 | 800 |
| 2017 | Feb | SH21b | Asphalt | Car | 70 | | Wheel Path | Control | 72.5 | 950 | 100.2 | 800 |
| 2017 | Feb | SH21b | Asphalt | Truck | 55 | | Edge Line | Aud Marking | 74.8 | 800 | 110.6 | 800 |

| Year | Month | Route | Surface | Vehicle | Speed | Section | Location | Treatment | Interior Noise | | OBSI Noise | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg (dBA) | Peak Freq. | Avg (dBA) | Peak Freq. |
| 2017 | Feb | SH21b | Asphalt | Truck | 55 | | Wheel Path | Control | 67.6 | 525 | 98.1 | 758 |
| 2017 | Feb | SH21b | Asphalt | Truck | 70 | | Edge Line | Aud Marking | 77.2 | 700 | 114.5 | 800 |
| 2017 | Feb | SH21b | Asphalt | Truck | 70 | | Wheel Path | Control | 72.0 | 400 | 100.3 | 800 |
| 2017 | Feb | SH21c | Sealcoat | Car | 55 | | Center Line | Rumble Strip w/ Seal Coat | 86.3 | 800 | 105.0 | 900 |
| 2017 | Feb | SH21c | Sealcoat | Car | 55 | | Edge Line | Rumble Strip w/ Seal Coat | 83.1 | 673 | 109.8 | 800 |
| 2017 | Feb | SH21c | Sealcoat | Car | 55 | | Wheel Path | Control | 70.6 | 800 | 102.2 | 1000 |
| 2017 | Feb | SH21c | Sealcoat | Car | 70 | | Center Line | Rumble Strip w/ Seal Coat | 88.0 | 800 | 111.0 | 800 |
| 2017 | Feb | SH21c | Sealcoat | Car | 70 | | Edge Line | Rumble Strip w/ Seal Coat | 84.0 | 800 | 117.7 | 800 |
| 2017 | Feb | SH21c | Sealcoat | Car | 70 | | Wheel Path | Control | 73.6 | 1000 | 105.5 | 1250 |
| 2017 | Feb | SH21c | Sealcoat | Truck | 55 | | Center Line | Rumble Strip w/ Seal Coat | 82.7 | 600 | 105.3 | 1125 |
| 2017 | Feb | SH21c | Sealcoat | Truck | 55 | | Edge Line | Rumble Strip w/ Seal Coat | 79.1 | 800 | 112.5 | 800 |
| 2017 | Feb | SH21c | Sealcoat | Truck | 55 | | Wheel Path | Control | 70.2 | 1000 | 101.4 | 1250 |
| 2017 | Feb | SH21c | Sealcoat | Truck | 70 | | Center Line | Rumble Strip w/ Seal Coat | 83.4 | 800 | 109.1 | 1063 |
| 2017 | Feb | SH21c | Sealcoat | Truck | 70 | | Edge Line | Milled Rumble | 81.2 | 800 | 118.1 | 800 |
| 2017 | Feb | SH21c | Sealcoat | Truck | 70 | | Wheel Path | Control | 73.1 | 900 | 105.3 | 1563 |

| Dependent Variable | Independent Variables | Analysis Method | Data Set | Sample Size |
|---|---|---|---|---|
| - Interior Noise Level<br>- Change in Interior Noise | - Vehicle Type<br>- Route-Treatment | MANOVA | All data | 749 |
| - Interior Noise Level<br>- Change in Interior Noise Level | - Vehicle Speed<br>- Date-Route-Vehicle-Treatment | MANOVA | Routes tested both at 55 and 70 mph<br>(IH 369, US 67, SH 21b, SH21c, SH 154, SH 300, SH 315, US 79, US 80) | 212 |
| - Change in Interior Noise Level<br>- Change in Peak Frequency | - Vehicle Type<br>- Section | MANOVA | Brenham data, 2nd trip | 94 |
| - Change in Interior Noise Level<br>- Change in Peak Frequency | - Treatment Type | Whisker-box plot comparison | All data except for Brenham test deck. | 218 (car)<br><br>216 (truck) |
| - Interior Noise Level | - Exterior (OBSI) Noise Level<br>- Vehicle Type | Linear Regression | All Data | 829 |
| - Wayside Noise Level | - Exterior (OBSI) Noise Level | Linear Regression | Subset of Brenham data (WB1, WB2, WB5, WB6) | 83 |

## *Linear Models*

### *The GLM Procedure*

| Class Level Information | | |
|---|---|---|
| **Class** | **Levels** | ***Values*** |
| Speed | 2 | 55 70 |
| FullDescrip_NoSpeed | 32 | 1IH369_AsphaltCarCenter Line_Aud Marking<br>1IH369_AsphaltCarEdge Line_Aud Marking<br>1IH369_AsphaltTruckCenter Line_Aud Marking<br>1IH369_AsphaltTruckEdge Line_Aud Marking<br>Etc. |

| | |
|---|---|
| Number of Observations Read | 253 |
| Number of Observations Used | 253 |

*Generated by the SAS System ('Local', W32_7PRO) on May 16, 2017 at 3:08:00 PM*

## Linear Models

### The GLM Procedure

**Dependent Variable: iLeq**

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 32 | 3981.682123 | 124.427566 | 53.84 | <.0001 |
| Error | 220 | 508.443010 | 2.311105 | | |
| Corrected Total | 252 | 4490.125133 | | | |

| R-Square | Coeff Var | Root MSE | iLeq Mean |
|---|---|---|---|
| 0.886764 | 1.942997 | 1.520232 | 78.24158 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Speed | 1 | 346.688841 | 346.688841 | 150.01 | <.0001 |
| FullDescrip_NoSpeed | 31 | 3610.319096 | 116.461906 | 50.39 | <.0001 |

| Parameter | Estimate | | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 74.76201798 | B | 0.54598548 | 136.93 | <.0001 |
| Speed 55 | -2.35108770 | B | 0.19195910 | -12.25 | <.0001 |
| Speed 70 | 0.00000000 | B | . | . | . |
| FullDescrip_NoSpeed 1IH369_AsphaltCarCenter Line_Aud Marking | 4.68809797 | B | 0.73877683 | 6.35 | <.0001 |
| FullDescrip_NoSpeed 1IH369_AsphaltCarEdge Line_Aud Marking | 5.77111666 | B | 0.76049451 | 7.59 | <.0001 |
| FullDescrip_NoSpeed 1IH369_AsphaltTruckCenter Line_Aud Marking | 1.89648837 | B | 0.72110924 | 2.63 | 0.0091 |
| FullDescrip_NoSpeed 1IH369_AsphaltTruckEdge Line_Aud Marking | 2.33908497 | B | 0.73877683 | 3.17 | 0.0018 |
| | Etc. | | | | |

## Linear Models

### The GLM Procedure

| Class Level Information | | |
|---|---|---|
| **Class** | **Levels** | **Values** |
| Vehicle | 2 | Car Truck |
| FullDescrip_NoVeh | 96 | 1FM1519_Sealcoat55Center Line_Bars<br>1FM1519_Sealcoat55Edge Line_Aud Marking<br>1FM1971_Sealcoat55Center Line_Bars+Aud<br>1FM1971_Sealcoat55Edge Line_Aud Marking<br>Etc. |

| | |
|---|---|
| Number of Observations Read | 749 |
| Number of Observations Used | 749 |

Generated by the SAS System ('Local', W32_7PRO) on May 16, 2017 at 3:20:56 PM

## Linear Models

### The GLM Procedure

**Dependent Variable: iLeq**

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 96 | 9585.04740 | 99.84424 | 55.33 | <.0001 |
| Error | 652 | 1176.52326 | 1.80448 | | |
| Corrected Total | 748 | 10761.57066 | | | |

| R-Square | Coeff Var | Root MSE | iLeq Mean |
|---|---|---|---|
| 0.890674 | 1.747654 | 1.343311 | 76.86363 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Vehicle | 1 | 3214.962667 | 3214.962667 | 1781.65 | <.0001 |
| FullDescrip_NoVeh | 95 | 5743.054704 | 60.453207 | 33.50 | <.0001 |

| Parameter | Estimate | | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 72.93987133 | B | 0.47790666 | 152.62 | <.0001 |
| Vehicle Car | 4.49434885 | B | 0.10647687 | 42.21 | <.0001 |
| Vehicle Truck | 0.00000000 | B | . | . | . |
| FullDescrip_NoVeh 1FM1519_Sealcoat55Center Line_Bars | -1.12302263 | B | 0.67165533 | -1.67 | 0.0950 |
| FullDescrip_NoVeh 1FM1519_Sealcoat55Edge Line_Aud Marking | -1.14833012 | B | 0.69527091 | -1.65 | 0.0991 |
| FullDescrip_NoVeh 1FM1971_Sealcoat55Center Line_Bars+Aud | 0.93191187 | B | 0.67165533 | 1.39 | 0.1658 |
| FullDescrip_NoVeh 1FM1971_Sealcoat55Edge Line_Aud Marking | 2.04145225 | B | 0.67165533 | 3.04 | 0.0025 |
| Etc. | | | | | |

## Linear Models

### The GLM Procedure

| Class Level Information | | |
|---|---|---|
| Class | Levels | Values |
| Section | 12 | EB1 EB2 EB3 EB4 EB5 EB6 WB1 WB2 WB3 WB4 WB5 WB6 |
| Vehicle | 2 | Car Truck |

| | |
|---|---|
| Number of Observations Read | 94 |
| Number of Observations Used | 94 |

Generated by the SAS System ('Local', W32_7PRO) on May 16, 2017 at 3:37:04 PM

## Linear Models

### The GLM Procedure

**Dependent Variable: iLeq**

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 12 | 826.2622229 | 68.8551852 | 101.31 | <.0001 |
| Error | 81 | 55.0499682 | 0.6796292 | | |
| Corrected Total | 93 | 881.3121911 | | | |

| R-Square | Coeff Var | Root MSE | iLeq Mean |
|---|---|---|---|
| 0.937536 | 1.073262 | 0.824396 | 76.81221 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Section | 11 | 349.3445829 | 31.7585984 | 46.73 | <.0001 |
| Vehicle | 1 | 535.2292187 | 535.2292187 | 787.53 | <.0001 |

| Parameter | Estimate | | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 76.32817076 | B | 0.32011573 | 238.44 | <.0001 |
| Section EB1 | -0.04193757 | B | 0.44065835 | -0.10 | 0.9244 |
| Section EB2 | -2.66254187 | B | 0.42684084 | -6.24 | <.0001 |
| Section EB3 | -7.59794828 | B | 0.42798902 | -17.75 | <.0001 |
| Section EB4 | -1.35521666 | B | 0.41602516 | -3.26 | 0.0016 |
| Section EB5 | -0.98346137 | B | 0.40645095 | -2.42 | 0.0178 |
| Section EB6 | -1.29963611 | B | 0.41602516 | -3.12 | 0.0025 |
| Section WB1 | -0.50206921 | B | 0.45881477 | -1.09 | 0.2771 |
| Section WB2 | -3.10062637 | B | 0.45881477 | -6.76 | <.0001 |
| Section WB3 | -1.52269975 | B | 0.42684084 | -3.57 | 0.0006 |
| Section WB4 | -2.20023164 | B | 0.41546557 | -5.30 | <.0001 |
| Section WB5 | -1.51689000 | B | 0.44065835 | -3.44 | 0.0009 |
| Section WB6 | 0.00000000 | B | . | . | . |
| Vehicle Car | 4.80475024 | B | 0.17121308 | 28.06 | <.0001 |
| Vehicle Truck | 0.00000000 | B | . | . | . |

## Linear Models

### The GLM Procedure

| Class Level Information | | |
|---|---|---|
| Class | Levels | Values |
| Section | 12 | EB1 EB2 EB3 EB4 EB5 EB6 WB1 WB2 WB3 WB4 WB5 WB6 |
| Vehicle | 2 | Car Truck |

| | |
|---|---|
| Number of Observations Read | 94 |
| Number of Observations Used | 94 |

Generated by the SAS System ('Local', W32_7PRO) on May 16, 2017 at 3:37:08 PM

## Linear Models

### The GLM Procedure

**Dependent Variable: iLeqDiff**

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 12 | 326.7497550 | 27.2291463 | 27.58 | <.0001 |
| Error | 81 | 79.9696633 | 0.9872798 | | |
| Corrected Total | 93 | 406.7194183 | | | |

| R-Square | Coeff Var | Root MSE | iLeqDiff Mean |
|---|---|---|---|
| 0.803379 | 14.75707 | 0.993620 | 6.733174 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Section | 11 | 307.9936712 | 27.9994247 | 28.36 | <.0001 |
| Vehicle | 1 | 30.2438423 | 30.2438423 | 30.63 | <.0001 |

| Parameter | Estimate | | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 7.881575371 | B | 0.38582566 | 20.43 | <.0001 |
| Section EB1 | 0.592755643 | B | 0.53111199 | 1.12 | 0.2677 |
| Section EB2 | -1.913080938 | B | 0.51445817 | -3.72 | 0.0004 |
| Section EB3 | -6.700589455 | B | 0.51584203 | -12.99 | <.0001 |
| Section EB4 | -0.683784279 | B | 0.50142236 | -1.36 | 0.1764 |
| Section EB5 | -0.715100938 | B | 0.48988286 | -1.46 | 0.1482 |
| Section EB6 | -1.838277946 | B | 0.50142236 | -3.67 | 0.0004 |
| Section WB1 | -0.533774271 | B | 0.55299536 | -0.97 | 0.3373 |
| Section WB2 | -3.074641938 | B | 0.55299536 | -5.56 | <.0001 |
| Section WB3 | -0.882388313 | B | 0.51445817 | -1.72 | 0.0901 |
| Section WB4 | -2.270262431 | B | 0.50074790 | -4.53 | <.0001 |
| Section WB5 | -2.554097571 | B | 0.53111199 | -4.81 | <.0001 |
| Section WB6 | 0.000000000 | B | . | . | . |
| Vehicle Car | 1.142140134 | B | 0.20635787 | 5.53 | <.0001 |
| Vehicle Truck | 0.000000000 | B | . | . | . |

## Linear Models

### The GLM Procedure

| Class Level Information | | |
|---|---|---|
| **Class** | **Levels** | **Values** |
| Section | 12 | EB1 EB2 EB3 EB4 EB5 EB6 WB1 WB2 WB3 WB4 WB5 WB6 |
| Vehicle | 2 | Car Truck |

| | |
|---|---|
| Number of Observations Read | 94 |
| Number of Observations Used | 94 |

Generated by the SAS System ('Local', W32_7PRO) on May 16, 2017 at 3:37:12 PM

## Linear Models

### The GLM Procedure

**Dependent Variable: iPeakDiff**

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 12 | 204.2307924 | 17.0192327 | 10.56 | <.0001 |
| Error | 81 | 130.6039666 | 1.6123946 | | |
| Corrected Total | 93 | 334.8347591 | | | |

| R-Square | Coeff Var | Root MSE | iPeakDiff Mean |
|---|---|---|---|
| 0.609945 | 28.79035 | 1.269801 | 4.410509 |

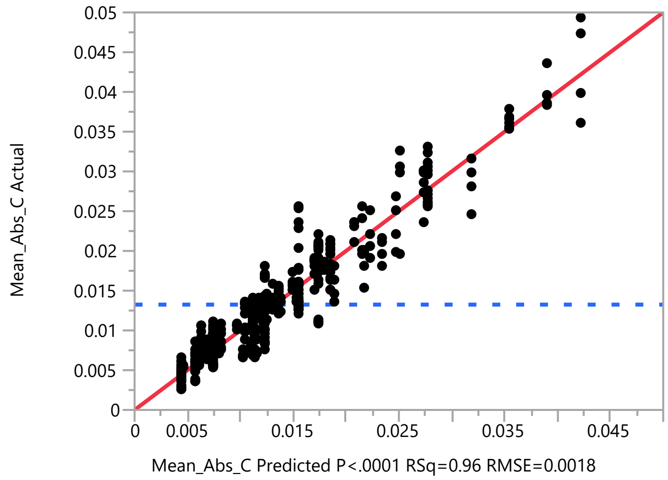
| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Section | 11 | 154.0055460 | 14.0005042 | 8.68 | <.0001 |
| Vehicle | 1 | 38.2003463 | 38.2003463 | 23.69 | <.0001 |

| Parameter | Estimate | | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 5.416656369 | B | 0.49306782 | 10.99 | <.0001 |
| Section EB1 | 1.115462594 | B | 0.67873720 | 1.64 | 0.1042 |
| Section EB2 | -1.705696133 | B | 0.65745437 | -2.59 | 0.0112 |
| Section EB3 | -3.419259102 | B | 0.65922288 | -5.19 | <.0001 |
| Section EB4 | -0.543671252 | B | 0.64079520 | -0.85 | 0.3987 |
| Section EB5 | 0.715176798 | B | 0.62604823 | 1.14 | 0.2567 |
| Section EB6 | -0.446197046 | B | 0.64079520 | -0.70 | 0.4882 |
| Section WB1 | 1.988630885 | B | 0.70670316 | 2.81 | 0.0061 |
| Section WB2 | -1.087689515 | B | 0.70670316 | -1.54 | 0.1277 |
| Section WB3 | -0.017270111 | B | 0.65745437 | -0.03 | 0.9791 |
| Section WB4 | -0.313248183 | B | 0.63993326 | -0.49 | 0.6258 |
| Section WB5 | -0.249681183 | B | 0.67873720 | -0.37 | 0.7139 |
| Section WB6 | 0.000000000 | B | . | . | . |
| Vehicle Car | -1.283614340 | B | 0.26371606 | -4.87 | <.0001 |
| Vehicle Truck | 0.000000000 | B | . | . | . |

# APPENDIX C:
# VIBRATION RESULTS

## Results of Fitting Mixed Effect ANOVA to Atlanta District Trip 1 Vibration Data

### Response Mean_Abs_C
### Actual by Predicted Plot




### Summary of Fit

| | |
|---|---|
| RSquare | 0.95708 |
| RSquare Adj | 0.951988 |
| Root Mean Square Error | 0.001776 |
| Mean of Response | 0.013247 |
| Observations (or Sum Wgts) | 463 |

### Fixed Effect Tests

| Source | Nparm | DF | DFDen | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Vehicle Type | 1 | 1 | 401 | 3551.865 | <.0001* |
| Treatment | 24 | 24 | 408 | 107.8052 | <.0001* |
| Vehicle Type*Treatment | 24 | 24 | 401 | 52.1914 | <.0001* |

### Effect Details
### Vehicle Type
### Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car | 0.02249630 | 0.00049882 |
| Truck | 0.00944073 | 0.00049986 |

## Treatment

## Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| CAM | 0.01571815 | 0.00087572 |
| CAM wSC | 0.00889529 | 0.00093168 |
| CAM wSC 70mph | 0.01415779 | 0.00093168 |
| CLB | 0.01469862 | 0.00099300 |
| CLRS | 0.01466978 | 0.00089574 |
| CLRS 70mph | 0.02185728 | 0.00089574 |
| CRB | 0.01553614 | 0.00056336 |
| CRB 70mph | 0.01916814 | 0.00067249 |
| CRB wSC | 0.01489816 | 0.00076158 |
| CRB+CAM | 0.02009915 | 0.00090678 |
| CRB+CRS | 0.01977276 | 0.00078036 |
| CRB+CRS 70mph | 0.02862276 | 0.00082137 |
| EAM | 0.01153609 | 0.00054474 |
| EAM 70mph | 0.01802776 | 0.00079702 |
| ERB | 0.01076473 | 0.00084455 |
| ERB 70mph | 0.01521473 | 0.00084455 |
| Inlane | 0.00787854 | 0.00049643 |
| Inlane 70mph | 0.01168492 | 0.00056835 |
| SRB | 0.01034194 | 0.00064260 |
| SRB 70mph | 0.01418456 | 0.00084132 |
| SRB wSC | 0.00933801 | 0.00075206 |
| SRB+SRS | 0.02550193 | 0.00080113 |
| SRB+SRS 70mph | 0.02265610 | 0.00082137 |
| SRS | 0.01664478 | 0.00089574 |
| SRS 70mph | 0.01734478 | 0.00089574 |

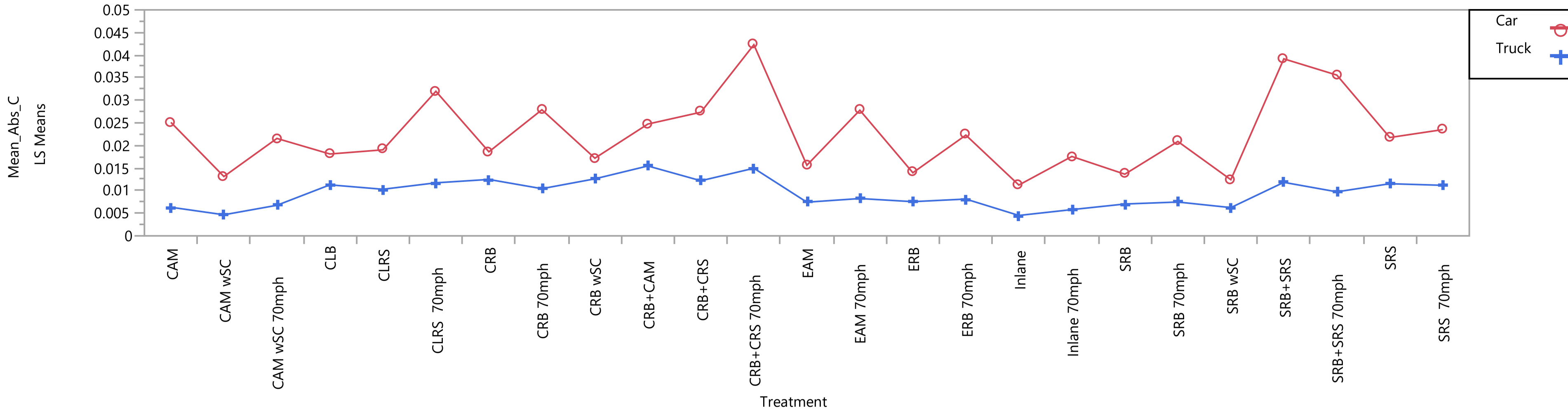
## Vehicle Type*Treatment

## Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car,CAM | 0.02510565 | 0.00109563 |
| Car,CAM wSC | 0.01312862 | 0.00109382 |
| Car,CAM wSC 70mph | 0.02155362 | 0.00109382 |
| Car,CLB | 0.01811112 | 0.00108770 |
| Car,CLRS | 0.01903228 | 0.00109382 |
| Car,CLRS 70mph | 0.03198228 | 0.00109382 |
| Car,CRB | 0.01859241 | 0.00063707 |
| Car,CRB 70mph | 0.02789964 | 0.00081783 |
| Car,CRB wSC | 0.01718331 | 0.00090569 |
| Car,CRB+CAM | 0.02473665 | 0.00110288 |
| Car,CRB+CRS | 0.02735610 | 0.00093365 |
| Car,CRB+CRS 70mph | 0.04228943 | 0.00106510 |
| Car,EAM | 0.01562299 | 0.00059029 |
| Car,EAM 70mph | 0.02779943 | 0.00098833 |
| Car,ERB | 0.01396473 | 0.00105231 |
| Car,ERB 70mph | 0.02228973 | 0.00105231 |
| Car,Inlane | 0.01124231 | 0.00052694 |
| Car,Inlane 70mph | 0.01756492 | 0.00063391 |
| Car,SRB | 0.01364040 | 0.00072715 |
| Car,SRB 70mph | 0.02088456 | 0.00104973 |

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car,SRB wSC | 0.01242551 | 0.00087330 |
| Car,SRB+SRS | 0.03916443 | 0.00106510 |
| Car,SRB+SRS 70mph | 0.03557276 | 0.00093365 |
| Car,SRS | 0.02175728 | 0.00109382 |
| Car,SRS 70mph | 0.02350728 | 0.00109382 |
| Truck,CAM | 0.00633065 | 0.00102116 |
| Truck,CAM wSC | 0.00466196 | 0.00120796 |
| Truck,CAM wSC 70mph | 0.00676196 | 0.00120796 |
| Truck,CLB | 0.01128612 | 0.00140403 |
| Truck,CLRS | 0.01030728 | 0.00109382 |
| Truck,CLRS 70mph | 0.01173228 | 0.00109382 |
| Truck,CRB | 0.01247986 | 0.00061951 |
| Truck,CRB 70mph | 0.01043663 | 0.00076886 |
| Truck,CRB wSC | 0.01261301 | 0.00087330 |
| Truck,CRB+CAM | 0.01546165 | 0.00110288 |
| Truck,CRB+CRS | 0.01218943 | 0.00093365 |
| Truck,CRB+CRS 70mph | 0.01495610 | 0.00093365 |
| Truck,EAM | 0.00744919 | 0.00060105 |
| Truck,EAM 70mph | 0.00825610 | 0.00093365 |
| Truck,ERB | 0.00756473 | 0.00105231 |
| Truck,ERB 70mph | 0.00813973 | 0.00105231 |
| Truck,Inlane | 0.00451478 | 0.00052349 |
| Truck,Inlane 70mph | 0.00580492 | 0.00063391 |
| Truck,SRB | 0.00704348 | 0.00076672 |
| Truck,SRB 70mph | 0.00748456 | 0.00104973 |
| Truck,SRB wSC | 0.00625051 | 0.00087330 |
| Truck,SRB+SRS | 0.01183943 | 0.00086043 |
| Truck,SRB+SRS 70mph | 0.00973943 | 0.00106510 |
| Truck,SRS | 0.01153228 | 0.00109382 |
| Truck,SRS 70mph | 0.01118228 | 0.00109382 |

## LS Means Plot




## LSMeans Differences Tukey HSD

α=0.050

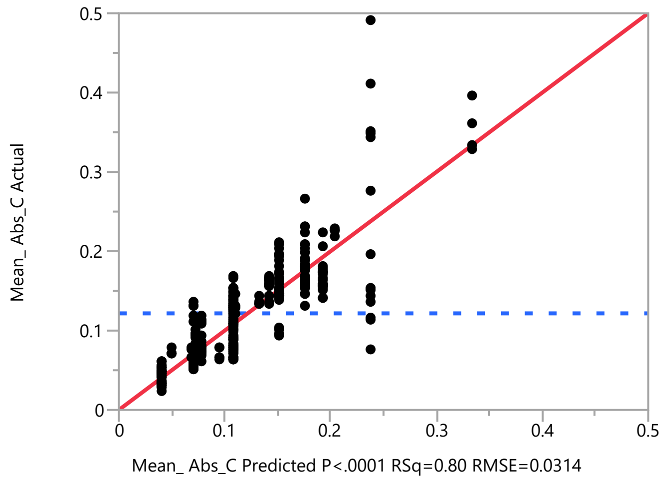
| Level | | | | | | | | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Car,CRB+CRS 70mph | A | | | | | | | | | | | | | 0.04228943 |
| Car,SRB+SRS | A | B | | | | | | | | | | | | 0.03916443 |
| Car,SRB+SRS 70mph | | B | C | | | | | | | | | | | 0.03557276 |
| Car,CLRS 70mph | | | C | D | | | | | | | | | | 0.03198228 |
| Car,CRB 70mph | | | | D | E | | | | | | | | | 0.02789964 |
| Car,EAM 70mph | | | | D | E | | | | | | | | | 0.02779943 |
| Car,CRB+CRS | | | | D | E | | | | | | | | | 0.02735610 |
| Car,CAM | | | | | E | F | | | | | | | | 0.02510565 |
| Car,CRB+CAM | | | | | E | F | G | | | | | | | 0.02473665 |
| Car,SRS 70mph | | | | | E | F | G | H | | | | | | 0.02350728 |
| Car,ERB 70mph | | | | | | F | G | H | I | | | | | 0.02228973 |
| Car,SRS | | | | | | F | G | H | I | J | | | | 0.02175728 |
| Car,CAM wSC 70mph | | | | | | F | G | H | I | J | | | | 0.02155362 |
| Car,SRB 70mph | | | | | | F | G | H | I | J | K | | | 0.02088456 |
| Car,CLRS | | | | | | | G | H | I | J | K | L | M | 0.01903228 |

| Level | | | | | | | | | | | | | | | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Car,CRB | | I | J | K | | M | | | | | | | | | | | | | | | 0.01859241 |
| Car,CLB | H | I | J | K | L | M | N | | | | | | | | | | | | | | 0.01811112 |
| Car,Inlane 70mph | | | J | K | L | M | | | | | | | | | | | | | | | 0.01756492 |
| Car,CRB wSC | | | J | K | L | M | N | O | | | | | | | | | | | | | 0.01718331 |
| Car,EAM | | | | | L | | N | O | P | | | | | | | | | | | | 0.01562299 |
| Truck,CRB+CAM | | | | K | L | M | N | O | P | Q | | | | | | | | | | | 0.01546165 |
| Truck,CRB+CRS 70mph | | | | | L | M | N | O | P | Q | | | | | | | | | | | 0.01495610 |
| Car,ERB | | | | | L | | N | O | P | Q | R | | | | | | | | | | 0.01396473 |
| Car,SRB | | | | | | | N | O | P | Q | R | | | | | | | | | | 0.01364040 |
| Car,CAM wSC | | | | | | | N | O | P | Q | R | S | | | | | | | | | 0.01312862 |
| Truck,CRB wSC | | | | | | | | | P | Q | R | S | | | | | | | | | 0.01261301 |
| Truck,CRB | | | | | | | | | | Q | R | | | | | | | | | | 0.01247986 |
| Car,SRB wSC | | | | | | | | | P | Q | R | S | T | | | | | | | | 0.01242551 |
| Truck,CRB+CRS | | | | | | | | | P | Q | R | S | T | U | | | | | | | 0.01218943 |
| Truck,SRB+SRS | | | | | | | | | | Q | R | S | T | U | | | | | | | 0.01183943 |
| Truck,CLRS 70mph | | | | | | | | | P | Q | R | S | T | U | V | | X | | | | 0.01173228 |
| Truck,SRS | | | | | | | | | P | Q | R | S | T | U | V | | X | | | | 0.01153228 |
| Truck,CLB | | | | | | | | O | P | Q | R | S | T | U | V | W | X | Y | Z | | 0.01128612 |
| Car,Inlane | | | | | | | | | | | R | S | T | U | | | | | | | 0.01124231 |
| Truck,SRS 70mph | | | | | | | | | | Q | R | S | T | U | V | W | X | | | | 0.01118228 |
| Truck,CRB 70mph | | | | | | | | | | | R | S | T | U | | | X | | | | 0.01043663 |
| Truck,CLRS | | | | | | | | | | Q | R | S | T | U | V | W | X | Y | | | 0.01030728 |
| Truck,SRB+SRS 70mph | | | | | | | | | | | R | S | T | U | V | W | X | Y | Z | | 0.00973943 |
| Truck,EAM 70mph | | | | | | | | | | | | S | T | U | V | W | X | Y | Z | | 0.00825610 |
| Truck,ERB 70mph | | | | | | | | | | | | S | T | U | V | W | X | Y | Z | [ | 0.00813973 |
| Truck,ERB | | | | | | | | | | | | | T | U | V | W | X | Y | Z | [ | 0.00756473 |
| Truck,SRB 70mph | | | | | | | | | | | | | | U | V | W | X | Y | Z | [ | 0.00748456 |
| Truck,EAM | | | | | | | | | | | | | | | V | W | | Y | Z | | 0.00744919 |
| Truck,SRB | | | | | | | | | | | | | | | V | W | | Y | Z | [ | 0.00704348 |
| Truck,CAM wSC 70mph | | | | | | | | | | | | | | U | V | W | X | Y | Z | [ | 0.00676196 |
| Truck,CAM | | | | | | | | | | | | | | | V | W | X | Y | Z | [ | 0.00633065 |
| Truck,SRB wSC | | | | | | | | | | | | | | | | W | | Y | Z | [ | 0.00625051 |
| Truck,Inlane 70mph | | | | | | | | | | | | | | | | | | | Z | [ | 0.00580492 |
| Truck,CAM wSC | | | | | | | | | | | | | | | | | | Y | Z | [ | 0.00466196 |
| Truck,Inlane | | | | | | | | | | | | | | | | | | | | [ | 0.00451478 |

Levels not connected by same letter are significantly different.

## Results of Fitting Mixed Effect ANOVA to Atlanta District Trip 2 Vibration Data

### Response Mean_ Abs_C
### Actual by Predicted Plot




### Summary of Fit

| | |
|---|---|
| RSquare | 0.797319 |
| RSquare Adj | 0.784976 |
| Root Mean Square Error | 0.031385 |
| Mean of Response | 0.121689 |
| Observations (or Sum Wgts) | 332 |

### Fixed Effect Tests

| Source | Nparm | DF | DFDen | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Treatment | 9 | 9 | 309.4 | 39.4296 | <.0001* |
| Vehicle Type | 1 | 1 | 302.9 | 437.0284 | <.0001* |
| Treatment*Vehicle Type | 9 | 9 | 303.1 | 11.5064 | <.0001* |

### Effect Details
### Treatment
### Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| CAM | 0.15914161 | 0.00906783 |
| CLRS | 0.14436274 | 0.01437351 |
| CRB | 0.14338754 | 0.00705421 |
| CRB 70mph | 0.22228086 | 0.01377939 |
| EAM | 0.11132007 | 0.00723096 |
| ERB | 0.10788644 | 0.01024163 |
| Inlane | 0.07536414 | 0.00674335 |
| Inlane 70mph | 0.12756836 | 0.01377939 |
| SRB | 0.10083699 | 0.01389605 |
| SRS | 0.15185759 | 0.01007705 |

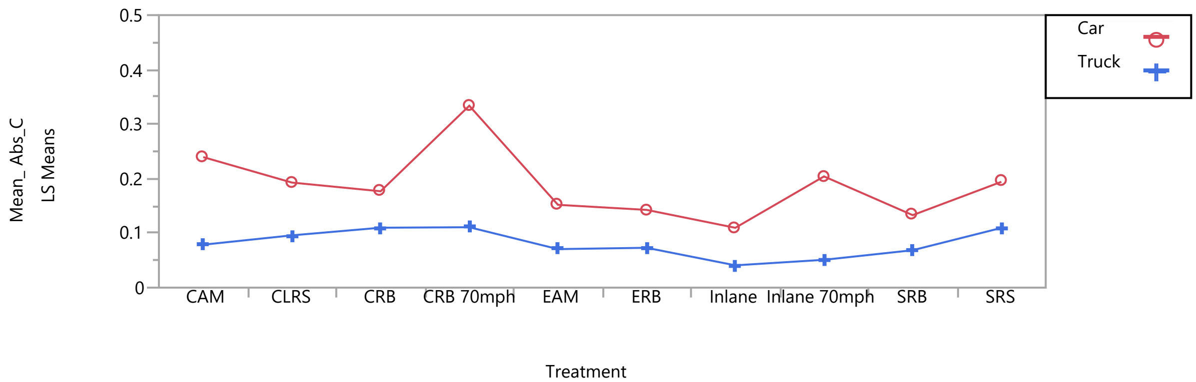
### Vehicle Type
### Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car | 0.18784859 | 0.00697569 |
| Truck | 0.08095269 | 0.00701855 |

### Vehicle Type*Treatment
### Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car,CAM | 0.23948417 | 0.01085785 |
| Car,CLRS | 0.19278774 | 0.01849424 |
| Car,CRB | 0.17682639 | 0.00785273 |
| Car,CRB 70mph | 0.33373086 | 0.01769175 |
| Car,EAM | 0.15193680 | 0.00814541 |
| Car,ERB | 0.14266387 | 0.01136703 |
| Car,Inlane | 0.10980575 | 0.00747943 |
| Car,Inlane 70mph | 0.20408086 | 0.01769175 |
| Car,SRB | 0.13302449 | 0.01778276 |
| Car,SRS | 0.19414492 | 0.01106181 |
| Truck,CAM | 0.07879906 | 0.01075969 |
| Truck,CLRS | 0.09593774 | 0.01711100 |
| Truck,CRB | 0.10994870 | 0.00814256 |
| Truck,CRB 70mph | 0.11083086 | 0.01769175 |
| Truck,EAM | 0.07070335 | 0.00825518 |
| Truck,ERB | 0.07310901 | 0.01337419 |
| Truck,Inlane | 0.04092252 | 0.00754450 |
| Truck,Inlane 70mph | 0.05105586 | 0.01769175 |
| Truck,SRB | 0.06864949 | 0.01778276 |
| Truck,SRS | 0.10957026 | 0.01339318 |

### LS Means Plot




### LSMeans Differences Tukey HSD

α=0.050

| Level | | | | Least Sq Mean |
|---|---|---|---|---|
| Car,CRB 70mph | A | | | 0.33373086 |
| Car,CAM | B | | | 0.23948417 |
| Car,Inlane 70mph | B | C | D | 0.20408086 |
| Car,SRS | | C | | 0.19414492 |

| Level | | | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|---|---|
| Car,CLRS | B | C | D | E | | | | | 0.19278774 |
| Car,CRB | | C | D | | | | | | 0.17682639 |
| Car,EAM | | | D | E | | | | | 0.15193680 |
| Car,ERB | | | D | E | F | | | | 0.14266387 |
| Car,SRB | | C | D | E | F | G | H | | 0.13302449 |
| Truck,CRB 70mph | | | | E | F | G | H | | 0.11083086 |
| Truck,CRB | | | | | F | G | | | 0.10994870 |
| Car,Inlane | | | | | F | G | | | 0.10980575 |
| Truck,SRS | | | | | F | G | H | | 0.10957026 |
| Truck,CLRS | | | | | F | G | H | I | 0.09593774 |
| Truck,CAM | | | | | | G | H | | 0.07879906 |
| Truck,ERB | | | | | | G | H | I | 0.07310901 |
| Truck,EAM | | | | | | | H | | 0.07070335 |
| Truck,SRB | | | | | | G | H | I | 0.06864949 |
| Truck,Inlane 70mph | | | | | | G | H | I | 0.05105586 |
| Truck,Inlane | | | | | | | | I | 0.04092252 |

Levels not connected by same letter are significantly different.

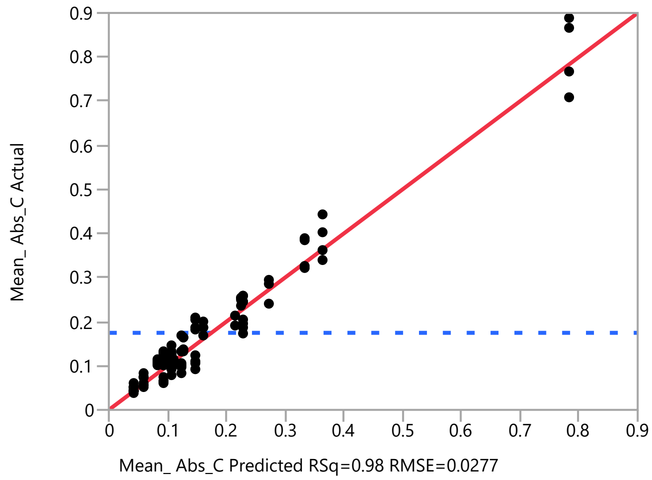
## Roadway

## Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| FM 2088 | 0.13433089 | 0.00683378 |
| FM 2791 | 0.12507496 | 0.00683378 |
| FM519 | 0.12760766 | 0.00705074 |
| IH 369 | 0.15300294 | 0.00552717 |
| SH 11 | 0.15396962 | 0.00690228 |
| SH 154 | 0.14316363 | 0.00680156 |
| SH 300 | 0.10806290 | 0.00757902 |
| SH 8 | 0.13660114 | 0.00627444 |
| US 259 | 0.10777285 | 0.00531579 |
| US 67 | 0.15441978 | 0.00546206 |

**Results of Fitting Mixed Effect ANOVA to Bastrop, Lincoln, Bryan Vibration Data**

## Response Mean_ Abs_C
## Actual by Predicted Plot




## Summary of Fit

| | |
|---|---|
| RSquare | 0.975808 |
| RSquare Adj | 0.970731 |
| Root Mean Square Error | 0.027698 |
| Mean of Response | 0.174668 |
| Observations (or Sum Wgts) | 99 |

## Fixed Effect Tests

| Source | Nparm | DF | DFDen | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Vehicle Type | 1 | 1 | 79.03 | 955.2655 | <.0001* |
| Treatment | 8 | 8 | 79.75 | 154.9485 | <.0001* |
| Vehicle Type*Treatment | 8 | 8 | 79.03 | 90.9585 | <.0001* |

## Effect Details
## Vehicle Type
## Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car | 0.29678908 | 0.01275692 |
| Truck | 0.10414329 | 0.01267543 |

## Treatment
## Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| CAM | 0.19341052 | 0.01714176 |
| CLRS | 0.23072447 | 0.01663606 |
| CLRS 70mph | 0.47334947 | 0.01663606 |
| EAM | 0.17781709 | 0.01412684 |
| EAM 70mph | 0.16230667 | 0.01806673 |

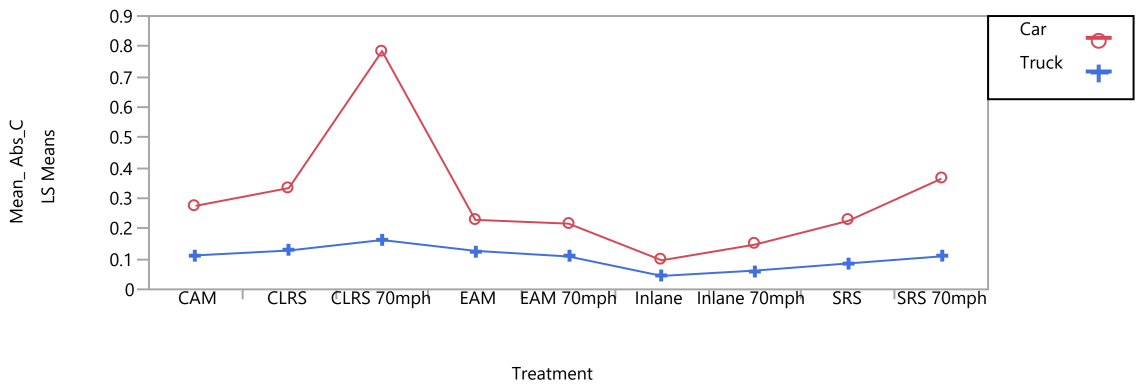
| Level | Least Sq Mean | Std Error |
|---|---|---|
| Inlane | 0.06999583 | 0.01303184 |
| Inlane 70mph | 0.10460516 | 0.01402982 |
| SRS | 0.15544947 | 0.01663606 |
| SRS 70mph | 0.23653697 | 0.01663606 |

## Vehicle Type*Treatment

## Least Squares Means Table

| Level | Least Sq Mean | Std Error |
|---|---|---|
| Car,CAM | 0.27499385 | 0.02092096 |
| Car,CLRS | 0.33357447 | 0.01930430 |
| Car,CLRS 70mph | 0.78424947 | 0.01930430 |
| Car,EAM | 0.22883776 | 0.01563681 |
| Car,EAM 70mph | 0.21637334 | 0.02345566 |
| Car,Inlane | 0.09572500 | 0.01420544 |
| Car,Inlane 70mph | 0.14739891 | 0.01564560 |
| Car,SRS | 0.22557447 | 0.01930430 |
| Car,SRS 70mph | 0.36437447 | 0.01930430 |
| Truck,CAM | 0.11182719 | 0.01933274 |
| Truck,CLRS | 0.12787447 | 0.01930430 |
| Truck,CLRS 70mph | 0.16244947 | 0.01930430 |
| Truck,EAM | 0.12679642 | 0.01605100 |
| Truck,EAM 70mph | 0.10824001 | 0.02055005 |
| Truck,Inlane | 0.04426667 | 0.01420544 |
| Truck,Inlane 70mph | 0.06181141 | 0.01564560 |
| Truck,SRS | 0.08532447 | 0.01930430 |
| Truck,SRS 70mph | 0.10869947 | 0.01930430 |

## LS Means Plot




## LSMeans Differences Tukey HSD

α=0.050

| Level | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|
| Car,CLRS 70mph | A | | | | | | 0.78424947 |
| Car,SRS 70mph | | B | | | | | 0.36437447 |
| Car,CLRS | | B | C | | | | 0.33357447 |
| Car,CAM | | | C | D | | | 0.27499385 |
| Car,EAM | | | | D | E | | 0.22883776 |
| Car,SRS | | | | D | E | | 0.22557447 |
| Car,EAM 70mph | | | | D | E | F | 0.21637334 |

| Level | | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|---|
| Truck,CLRS 70mph | E | F | G | | | | | 0.16244947 |
| Car,Inlane 70mph | | F | G | H | | | | 0.14739891 |
| Truck,CLRS | | F | G | H | I | | | 0.12787447 |
| Truck,EAM | | | G | H | I | | | 0.12679642 |
| Truck,CAM | | | G | H | I | J | | 0.11182719 |
| Truck,SRS 70mph | | | G | H | I | J | | 0.10869947 |
| Truck,EAM 70mph | | | G | H | I | J | K | 0.10824001 |
| Car,Inlane | | | | | I | J | | 0.09572500 |
| Truck,SRS | | | | H | I | J | K | 0.08532447 |
| Truck,Inlane 70mph | | | | | | J | K | 0.06181141 |
| Truck,Inlane | | | | | | | K | 0.04426667 |

Levels not connected by same letter are significantly different.