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Quantification of the Effectiveness and External Noise of Rumble Strip Designs

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16. Abstract
Rumble strips are roadway safety countermeasures that alert inattentive drivers by generating in-vehicle noise to minimize roadway departure crashes and prompt speed reduction for vehicles approaching stop-controlled intersections. Despite these safety benefits, they often generate external noise and complaints from nearby residents. This report presents the findings of a research project funded by the Illinois Department of Transportation to identify longitudinal and transverse rumble strip designs that reduce external noise while maintaining sufficient internal noise to ensure their effectiveness in reducing related crashes. The research tasks of this project focused on (1) performing a case study of existing transverse rumble strips on US-41 to collect external noise levels; (2) conducting a literature review to gather and analyze the latest research studies on rumble strips; (3) performing a national survey of state departments of transportation to collect their feedback on utilizing rumble strips; (4) collecting noise measurements of US-41 rumble strips after their 2022 reconstruction for comparison with their baseline external noise levels collected in task 1; (5) conducting initial field evaluations of existing and new rumble strip designs to identify top-performing designs; (6) performing a second round of field evaluations of top-performing rumble strip designs using a representative sample of test vehicles; (7) developing a decision support tool for ranking the most effective rumble strip designs based on their noise performance, roadway traffic, and sensitivity of nearby areas to rumble strip external noise; and (8) creating a model for ranking and optimizing the selection of competing rumble strip construction projects based on their safety benefits.

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Longitudinal Rumble Strips, Transverse Rumble Strips, Sinusoidal Rumble Strips, Rumble Strips Effectiveness, Internal Noise, External Noise, Traffic Noise, Roadway Safety, Design Optimization

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EXECUTIVE SUMMARY

Rumble strips are a proven safety countermeasure intended to alert drivers when they are about to leave the roadway and/or approach stop-controlled intersections through the generation of in-vehicle noise. Despite these safety benefits, they generate external noise that may cause complaints from nearby residents. The main goal of this research project is to identify rumble strip designs that reduce external noise while maintaining sufficient internal noise to ensure their effectiveness in reducing related crashes. Key findings of this report are listed as follows:

- The National Cooperative Highway Research Program report (NCHRP 641) recommends an increase of 3 to 15 dBA in internal noise levels for rumble strips to be effective in alerting inattentive drivers.

- Survey respondents reported that shoulder line, edge line, centerline, and transverse rumble strip designs were used by 92.3%, 76.9%, 100.0%, and 84.6% of the responding state departments of transportation (DOTs), respectively.

- Survey respondents reported that milled, rolled, formed, raised, and sinusoidal rumble strip types were used by 92.3%, 23.1%, 23.1%, 30.8%, and 61.5% of the responding state DOTs, respectively.

- Percentages of surveyed state DOTs that reported a reduction in crashes as a result of utilizing traditional longitudinal, transverse, and sinusoidal rumble strips were 100.0%, 66.7%, and 66.7%, respectively.

- Percentages of surveyed state DOT respondents that reported receiving complaints because of noise generated by traditional longitudinal, transverse, and sinusoidal rumble strips were 100.0%, 88.8%, and 33.3%, respectively.

- Of surveyed state DOTs, 66.7% reported sinusoidal rumble strips as a design modification to address noise complaints from nearby residents.

- Percentages of surveyed state DOT respondents reporting that they conducted studies on the effectiveness and external noise of traditional longitudinal, transverse, and sinusoidal rumble strips were 53.8%, 15.4%, and 50.0%, respectively.

- Twenty promising longitudinal and five transverse rumble strip designs were constructed on a roadway segment on US-45 from County Line Road to Joliet Road and tested in the initial and second rounds of field evaluations to analyze their effectiveness in alerting inattentive drivers and reducing external noise levels.

- An initial round of field evaluations collected and analyzed internal and external noise levels generated by the 25 rumble strips using three test vehicles (sedan, SUV, and medium truck) to identify top-performing rumble strip designs.

- Top-performing 10 longitudinal and 5 transverse rumble strip designs were selected for further testing in the second round of field evaluations.
- A second round of field evaluations focused on testing the identified top-performing 10 longitudinal and 5 transverse rumble strip designs using 10 additional test vehicles that provided a representative sample of vehicles on Illinois roads with adequate variations in type, size, weight, and model.
- Fourteen longitudinal rumble strip designs fully satisfied and one additional design closely satisfied the NCHRP 641 recommended internal noise increase of 3 to 15 dBA for all 10 test vehicles in the second round of field evaluations.
- One transverse rumble strip design fully satisfied and two additional designs closely satisfied the NCHRP 641 recommended internal noise increase of 3 to 15 dBA for all 10 test vehicles in the second round of field evaluations.
- Overall performance of the identified top-performing rumble strip designs was analyzed based on their generated internal and external noise levels by 13 test vehicles in the initial and second rounds of field evaluations.
- Four tested shoulder rumble strip designs fully or closely complied with NCHRP 641 internal noise recommended range and reduced external noise at 50 feet compared to IDOT's 8-inch shoulder design by an average ranging from 14% to 93%.
- One tested centerline rumble strip design was able to comply closely with the NCHRP 641 internal noise recommended range and reduce external noise at 50 feet compared to IDOT's 12-inch centerline design by an average of 19%.
- Three tested transverse rumble strip designs were able to fully or closely satisfy the NCHRP 641 internal noise recommended range and reduce external noise at 50 feet compared to IDOT's 25-strip transverse design by an average ranging from 22% to 77%.
- A decision support tool (DST) was developed to help IDOT rank top-performing rumble strip designs for each roadway project based on (a) collected internal and external noise levels generated by each rumble strip design; (b) roadway traffic distribution in terms of the percentage of passenger cars, single-unit trucks, and multiple-unit trucks; (c) type of roadway and whether it is a freeway; and (d) type of activities in the surrounding area of the roadway and its sensitivity to external noise generated by rumble strips.
- A prioritization model was developed to support IDOT in (1) ranking competing rumble strip construction projects based on the annual number of different types of crashes on a roadway segment due to lack of rumble strips; and (2) optimizing the selection of competing rumble strip projects to maximize total roadway safety benefits while considering available budget for all rumble strip projects.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Rumble strips are effective roadway safety measures that generate in-vehicle noise to alert inattentive drivers who are about to depart their traveling lanes and/or approach stop-controlled intersections (NCHRP Synthesis 490, 2016). Despite these safety benefits, they generate external noise that may cause complaints from nearby residents (El-Rayes, et al., 2023; FHWA, 2015a). The main goal of this research project is to identify longitudinal and transverse rumble strip designs that reduce external noise while maintaining sufficient internal noise to ensure their effectiveness in reducing related crashes. To accomplish this goal, this research project focused on eight tasks. First, the researchers performed a case study of existing transverse rumble strips on US-41 to collect external noise levels. Second, they conducted a literature review to gather and analyze the latest research studies on rumble strips. Third, they performed a national survey of state departments of transportation (DOTs) to collect feedback on utilizing rumble strips. Fourth, the researchers collected noise measurements of US-41 rumble strips after reconstruction in 2022 for comparison with the baseline external noise levels collected in task 1. Fifth, they conducted initial field evaluations of existing and new rumble strip designs to identify top-performing designs and, sixth, performed a second round of field evaluations of top-performing rumble strip designs using a representative sample of test vehicles. Seventh, they developed a decision support tool for ranking the most effective rumble strip designs based on noise performance, roadway traffic, and sensitivity of nearby areas to rumble strip external noise. Eighth, they created a model for ranking and optimizing the selection of competing rumble strip construction projects based on safety benefits. The findings of the remaining research tasks are described in more detail in Chapter 2 to Chapter 6 (Chehab, 2022; El-Rayes, et al., 2023), as shown in Figure 1.

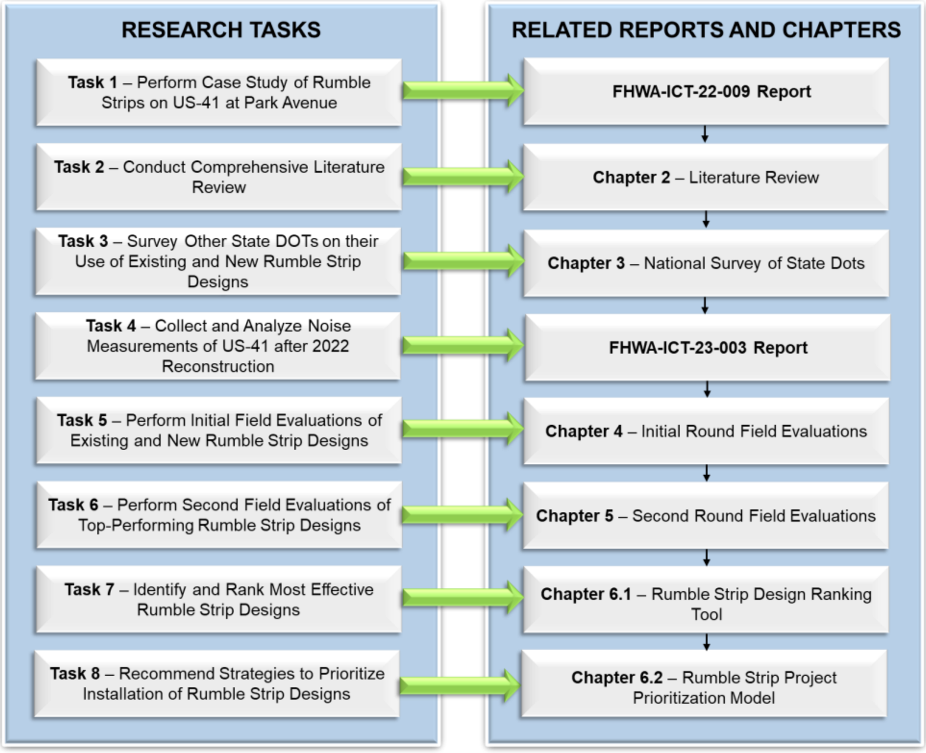


Figure 1. Diagram. Research tasks and related reports and chapters.

CHAPTER 2: LITERATURE REVIEW

This chapter presents the findings of a comprehensive literature review that was conducted to gather and analyze current practices as well as the latest research studies on rumble strip designs that reduce external noise while maintaining sufficient internal noise, to ensure effectiveness in reducing the potential for crashes. This literature review focused on rumble strip (1) designs, types, and requirements; (2) effectiveness; (3) external noise performance; (4) noise testing procedures; and (5) challenges and maintenance, which are described in more detail in Appendix A. Key findings of this literature review are listed as follows:

- Rumble strips are low-cost safety measures that can be used to alert inattentive drivers by generating in-vehicle noise and vibration when they leave the roadway and/or approach stop-controlled intersections.

- Rumble strips are classified into four main designs based on their roadway placement—edge line, shoulder line, centerline, and transverse—and five main types based on their construction method: milled-in, rolled-in, formed, raised, or sinusoidal.

- To ensure the effectiveness of rumble strips, FHWA recommends an increase of 3 to 15 dBA in internal noise levels for rumble strips to be effective in alerting inattentive drivers.

- Multiple state DOTs utilized alternative rumble strip designs and types to improve effectiveness, minimize noise complaints from nearby residents, and/or accommodate bicyclists. These alternative rumble strip designs and types include football-shaped, audible markings, angled transverse, wheel path, gapped, variable spacing, and sinusoidal.

- Shoulder rumble strips were reported to reduce run-off-road crashes by 20% to 72%, providing a benefit-cost ratio that ranges from 5:1 to 20:1. Transverse rumble strips were reported to reduce crashes by 20% to 40% at stop-controlled intersections, with an expected benefit-cost ratio of 13:1 when installed on all primary roadways.

- Sinusoidal rumble strips were reported to generate less external noise than traditional rumble strips by multiple state DOTs including California and Oregon, who reported reductions up to 8 and 15 dBA, respectively.

- External noise measurements of rumble strips are conducted using AASHTO T 389 and T 390 standards, while internal noise levels are measured using the SAE J1447 standard.

- FHWA reported several rumble strip challenges, including noise to nearby environments, winter road maintenance, and bicyclist accommodations.

CHAPTER 3: NATIONAL SURVEY OF STATE DOTs

This chapter presents the findings of a national survey of state DOTs, which is described in more detail in Appendix B. The survey gathered and analyzed state DOTs' feedback on rumble strip designs and types, benefits of rumble strips, external noise generated by rumble strips, conducted studies on rumble strip designs, challenges of rumble strips, and additional feedback. Key findings of the national survey are listed as follows:

- A total of 15 survey respondents from 13 state DOTs provided feedback on their experience in utilizing different designs and types of rumble strips.

- Survey respondents reported that shoulder line, edge line, centerline, and transverse rumble strip designs were used by 92.3%, 76.9%, 100.0%, and 84.6% of the responding state DOTs, respectively.

- Survey respondents reported that milled, rolled, formed, raised, and sinusoidal rumble strip types were used by 92.3%, 23.1%, 23.1%, 30.8%, and 61.5% of the responding state DOTs, respectively.

- Percentages of responding state DOTs that reported a reduction in crashes as a result of utilizing traditional longitudinal, transverse, and sinusoidal rumble strips are 100.0%, 66.7%, and 66.7%, respectively.

- Percentages of state DOT respondents that reported receiving complaints because of noise generated by traditional longitudinal, transverse, and sinusoidal rumble strips are 100.0%, 88.8%, and 33.3%, respectively.

- Of responding state DOTs, 66.7% reported sinusoidal rumble strips as a design modification to address noise complaints from nearby residents.

- Percentages of state DOT respondents reporting that they conducted studies on the effectiveness and external noise of traditional longitudinal, transverse, and sinusoidal rumble strips are 53.8%, 15.4%, and 50.0%, respectively.

CHAPTER 4: INITIAL ROUND OF FIELD EVALUATIONS

This chapter presents a concise description of the initial round of field evaluations that were conducted to collect and analyze external and internal noise data generated by 25 constructed rumble strips on US-45. This chapter is organized into five sections: (a) identifying 25 promising longitudinal and transverse rumble strip designs that have the potential to provide sufficient internal noise to alert inattentive drivers while minimizing external noise and related complaints from nearby residents; (b) developing a detailed design for these 25 promising longitudinal and transverse rumble strip designs; (c) constructing the 25 rumble strips on US-45; (d) internal and external noise data collection equipment and methods; and (e) conducting an initial round of field evaluations to collect and analyze external and internal noise data generated by the 25 constructed rumble strips on US-45.

IDENTIFICATION OF PROMISING RUMBLE STRIPS

In this task, a total of 25 longitudinal and transverse rumble strip designs were identified to enable the construction and the evaluation of promising designs, patterns, and dimensions. These identified rumble strip designs include 20 longitudinal shoulder and centerline rumble strip designs and 5 transverse rumble strip designs, as shown in Tables 1 and 2. The 20 longitudinal and 5 transverse rumble strip designs were identified in consultation with the Technical Review Panel based on findings of a national survey of state DOTs officials summarized in Appendix B, a comprehensive literature review summarized in Appendix A, and a preliminary field evaluation of sinusoidal rumble strip designs that were constructed in 2021 in McHenry County, Illinois, and tested in 2022.

The identified 20 promising longitudinal shoulder and centerline rumble strips can be organized in five main design groups: (a) three traditional shoulder IDOT designs (designs 1 through 3); (b) three traditional centerline IDOT designs (designs 4 through 6); (c) two top-performing sinusoidal designs (designs 7 and 8) from the preliminary field evaluations in McHenry County, Illinois; (d) six top-performing state DOT sinusoidal designs (designs 9 through 14) that were identified through a comprehensive literature review and national survey; and (e) six novel sinusoidal designs (designs 15 through 20) that were developed to investigate the impact of new variations in design parameters including shallower depths and tapered profile shapes that were reported in the literature to reduce external noise while generating effective internal noise levels, as shown in Table 1.

Similarly, the identified five promising transverse rumble strips designs can be categorized into two design groups: (a) one IDOT traditional transverse design (design 1) that can be used as a baseline for comparison with alternative designs and (b) four novel transverse designs (designs 2 through 5) that were developed to study the impact of promising variations in design parameters including staggered traditional grooves (design 2), sinusoidal profile shape (design 3), angled traditional grooves (design 4), and shorter panel length of rumble strips (design 5), as shown in Table 2. These novel transverse designs were identified based on the findings of a literature review to reduce their external noise while generating effective internal noise levels.

Table 1. Identified Longitudinal Rumble Strip Designs

Design Group	Design No.	Rumble Strip Design	Design Dimensions				
			Depth	Width	Length	Spacing	Wavelength
(a) Traditional and Modified IDOT Shoulder Design	1	IDOT Shoulder (8″)	7/16″	6–7″	8″	12″	N/A
	2	IDOT Interstate Shoulder (16″)	7/16 ± 1/16	6–7″	16″	12″	N/A
	3	IDOT Shoulder (modified)	3/8″	7″	7″	12″	N/A
(b) Traditional and Modified IDOT Centerline Design	4	IDOT Centerline	7/16″	7″	12″	12″ w/ 24″ paired gap	N/A
	5	IDOT Centerline with paired gap	3/8″	7″	12″	12″ w/ 24″ paired gap	N/A
	6	IDOT Centerline (modified)	3/8″	7″	16″	4″ center gap	N/A
(c) Sinusoidal Designs from Preliminary Field Evaluation	7	IDOT McHenry 1	1/8″ to 3/8″	N/A	8″	N/A	16″
	8	IDOT McHenry 2	1/8″ to 3/8″	N/A	8″	N/A	12″
(d) Top-Performing State DOT Sinusoidal Designs from Literature Review and Survey	9	Caltrans	0″ to 5/16″	N/A	8″	N/A	14″
	10	Indiana DOT	1/8″ to 1/2″	N/A	16″	N/A	12″
	11	Minnesota DOT	1/16″ to 1/2″	N/A	14″	N/A	14″
	12	Montana DOT	1/8″ to 1/2″	N/A	14″ tapered	N/A	24″
	13	Washington DOT	0″ to 1/2″	N/A	12″ tapered	N/A	16″
	14	Oregon DOT	1/16″ to 3/8″	N/A	14″	N/A	16″
(e) Novel Sinusoidal Designs	15	Straight edge 12″ SRS*	1/16″ to 1/2″	N/A	12″	N/A	14″
	16	Reduced profile straight 12″ SRS*	1/8″ to 1/2″	N/A	12″	N/A	14″
	17	Tapered edge 12″ SRS*	1/8″ to 1/2″	N/A	12″ tapered	N/A	14″
	18	Reduced profile tapered 16″ SRS*	0″ to 5/16″	N/A	16″ tapered	N/A	12″
	19	Reduced profile straight 16″ SRS*	0″ to 5/16″	N/A	16″	N/A	14″
	20	Extended wavelength 12″ SRS*	1/16″ to 3/8″	N/A	12″	N/A	20″

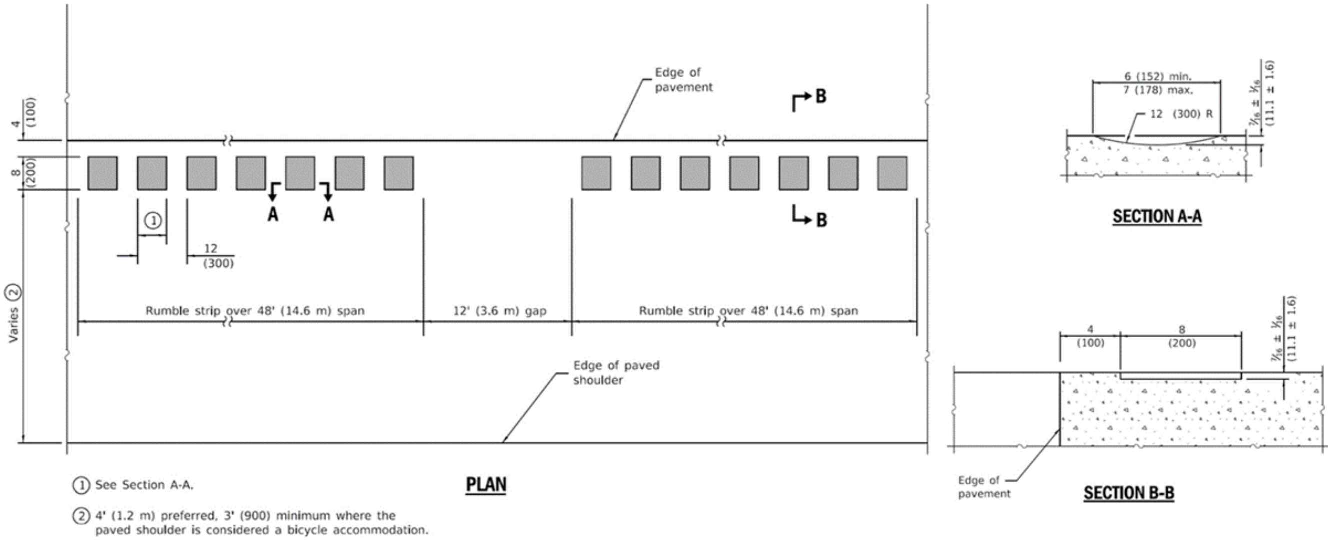
SRS*: Sinusoidal Rumble Strips

Table 2. Identified Transverse Rumble Strip Designs

Design Group	Design No.	Rumble Strip Design	Design Dimensions						
			Depth	Width	Length	Spacing	Panel Length	Offset	Wavelength
(a) IDOT Traditional Transverse Design	1	IDOT Traditional Design	3/16″	4″	Lane width	12″	25 strips	N/A	N/A
(b) Novel Transverse Designs	2	IDOT Traditional with Alternate Placement	3/16″	4″	4′ each	2′ within the same set 1′ with the alternating set	25 strips	Lane edge: 6″ min, 1′ desired from centerline & edge line Lane center: 6″ min, 2′ desired between sets	N/A
	3	OKDOT Sinusoidal Design	0″-7/16″	16″	5 cycles over 8′	N/A	11′ 8″	2′	14″
	4	Angled Transverse	3/16″	4″	Lane width	12″	25 strips at 10 degrees	N/A	N/A
	5	IDOT Traditional Shorter Design	3/16″	4″	Lane width	12″	15 strips	N/A	N/A

DESIGN OF PROMISING RUMBLE STRIPS

A detailed design was developed for the identified 25 rumble strips by a licensed professional engineer with related experience on IDOT roadway projects to ensure compliance with IDOT standards and construction work permit requirements. The developed detailed design included plans, profiles, and sections for the 25 rumble strips as shown in the example designs in Figures 2, 3, 4, and 5. A complete set of all detailed designs is included in Appendix C.



① See Section A-A.

② 4' (1.2 m) preferred, 3' (900) minimum where the paved shoulder is considered a bicycle accommodation.

Figure 2. Illustration. Longitudinal traditional design 1: IDOT shoulder (8”).

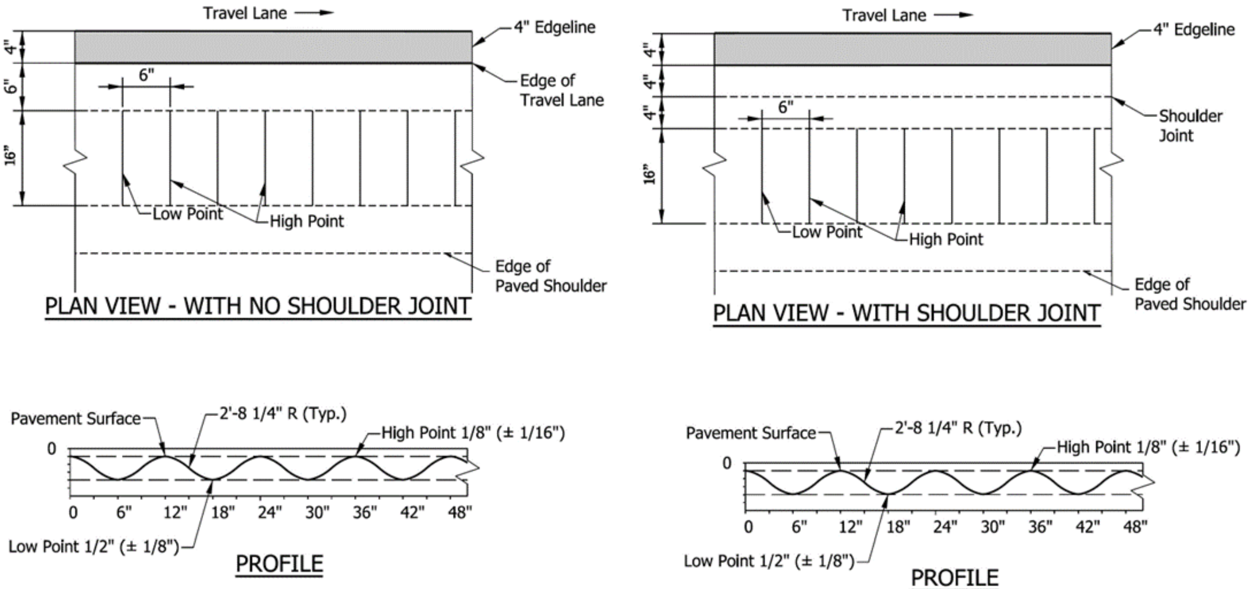


Figure 3. Illustration. Longitudinal sinusoidal design 10: Indiana DOT.

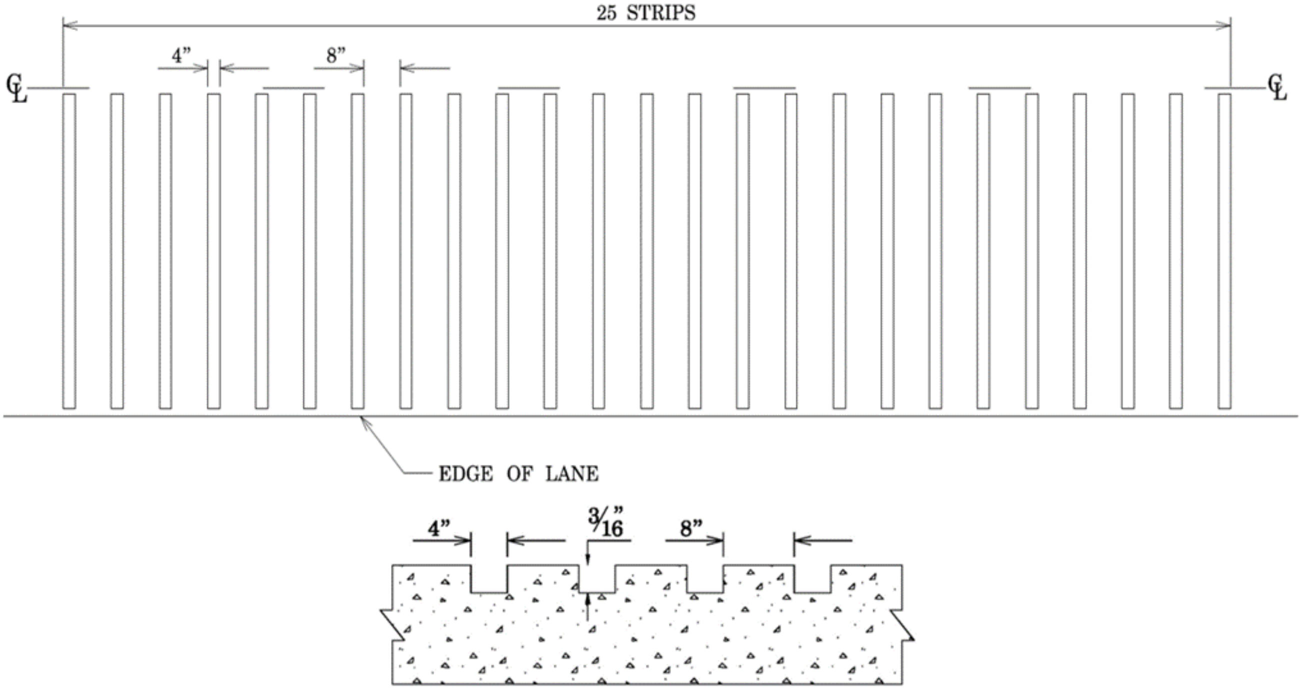


Figure 4. Illustration. Transverse design 1: IDOT traditional design.

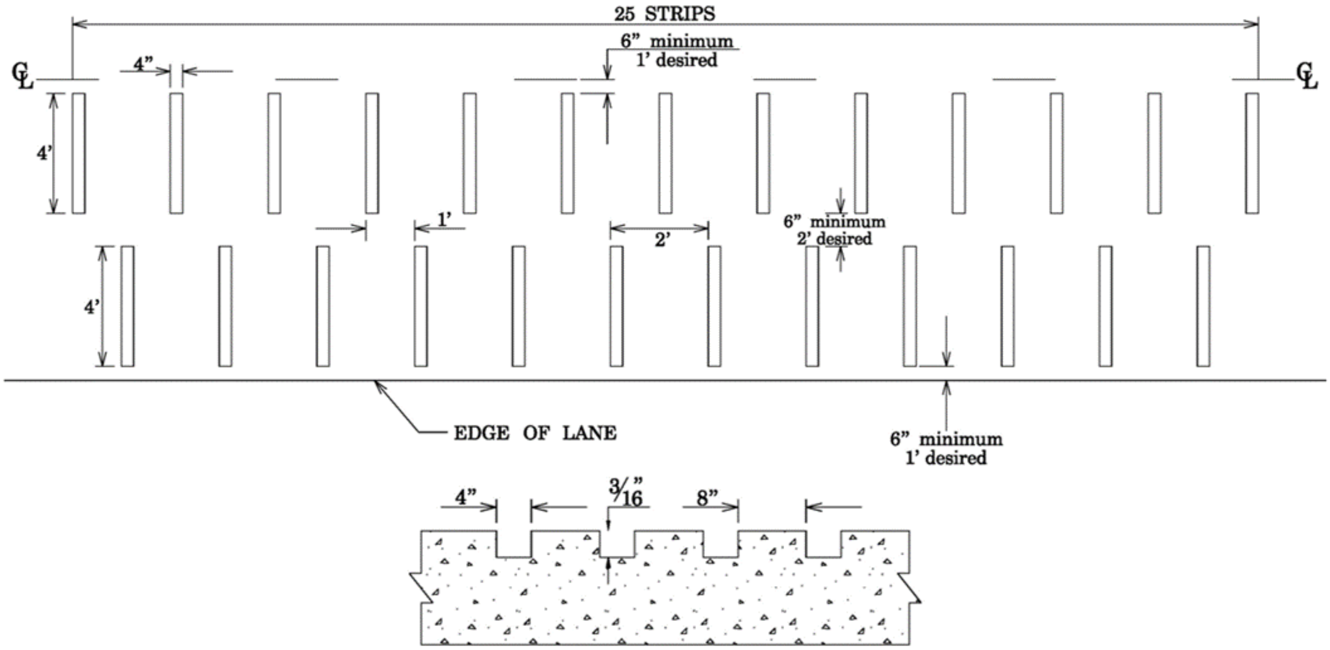


Figure 5. Illustration. Transverse design 2: IDOT traditional with alternate placement.

CONSTRUCTION OF RUMBLE STRIPS

This section provides an overview of the location of the 25 constructed rumble strips on US-45 and their construction equipment and methods.

Location of Rumble Strips

The construction location of the 25 rumble strips was identified in consultation with the Technical Review Panel to ensure that the selected roadway location complies with the AASHTO T-389 (2020) requirements for site selection. Based on these requirements, the roadway test site should be (a) straight and leveled with a homogenous pavement surface to ensure consistency of all collected noise measurements, (b) free of extraneous material such as gravel and located away from buildings, signboards, and safety barriers to avoid interference with noise measurements, (c) located away from intrusive noise sources such as airports to avoid noise contamination, and (d) long enough and located away from intersections to enable the testing vehicles to safely accelerate and decelerate during all field test passes. To comply with these AASHTO T-389 requirements, the Technical Review Panel and research team identified US-45 at the segment from County Line Road to Joliet Road as the location for constructing the 25 rumble strips, as shown in Figure 6.

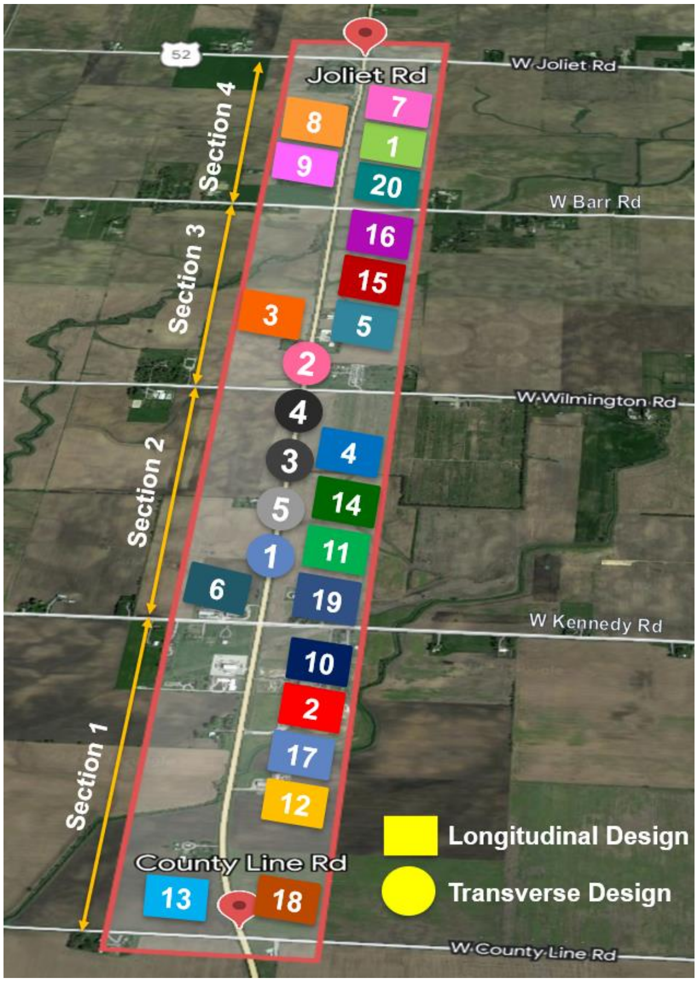


Figure 6. Illustration. Location of rumble strips.

The research team then conducted a site visit to inspect visually the selected roadway segment to identify and mark the specific location for constructing the identified 25 rumble strips, as shown in Figure 6. The construction locations of the 25 rumble strip designs were organized in four sections based on their geometric dimensions to facilitate their construction process, as shown in Figure 6. Each longitudinal rumble strip design was constructed with a continuous length of 500 feet and separated by at least 200 feet each, as shown in Figure 7. This length was determined to generate at least a five-second measurement by a traveling vehicle at a speed of 50 miles per hour, as recommended by the American Association of State Highway and Transportation Officials (AASHTO T 389-20, 2020).

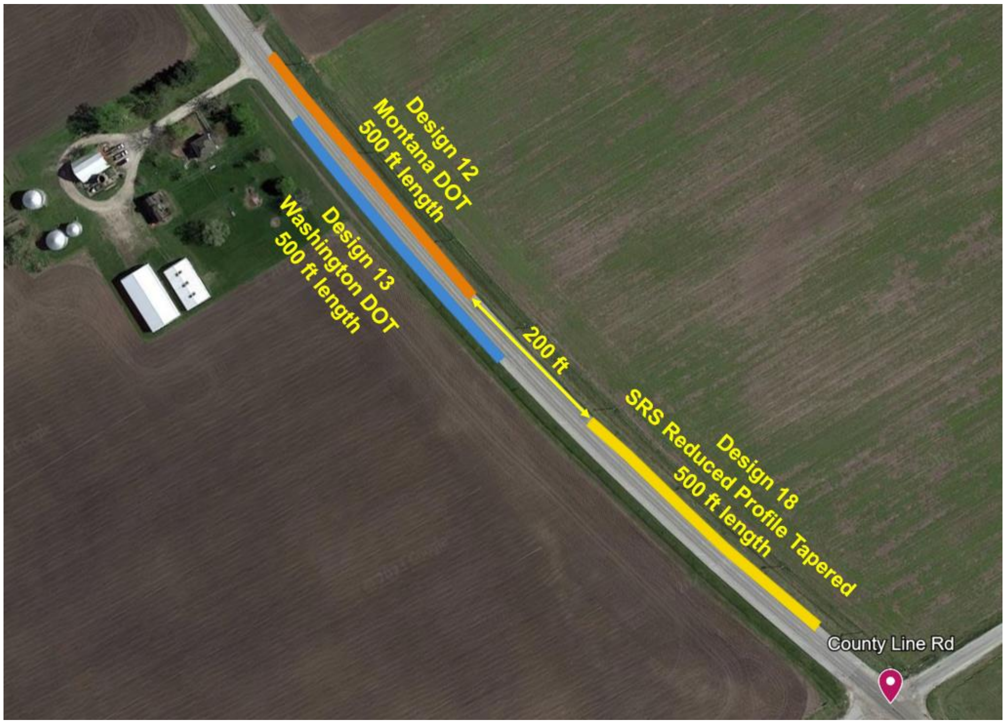


Figure 7. Illustration. Example arrangement of rumble strips in section 1.

Construction of Rumble Strips on US-45

To ensure compliance with IDOT roadway construction permit requirements, the research team worked with a professional engineer and a licensed roadway contractor to prepare and submit all related work permit documents, including detailed design drawings, highway bond, and traffic control plan. Upon receipt of the approved IDOT work permit, the research team coordinated with the roadway contractor to proceed with the construction of the 25 rumble strip designs, which was completed over three days: June 26, 27, and July 24, 2023, as shown in Table 3. Note that the construction operations during the first two days (June 26 and 27) utilized a versatile milling machine that can switch between traditional and sinusoidal rumble strip cuts (see Figure 8) to construct all 20 longitudinal traditional and sinusoidal rumble strips as well as one sinusoidal transverse rumble strip, as shown in Table 3. The construction of the four remaining transverse rumble strips utilized a bobcat loader with asphalt planer that was deployed on the construction site on July 24, 2023, as shown in Figure 16.

(a) Milling traditional rumble strips (b) Milling sinusoidal rumble strips

Figure 8. Photo. Milling machine for traditional and sinusoidal rumble strips.

Table 3. Construction Progress of the 25 Rumble Strip Designs

US-45 Section No.	Construction Progress		
	1st Day June 26, 2023	**2nd Day June 27, 2023**	**3rd Day July 24, 2023**
Section 1 From County Line Rd to Kennedy Rd	Longitudinal designs no. 18, 12, 13, 17, 2, and 10	N/A	N/A
Section 2 From Kennedy Rd to Wilmington Rd	Longitudinal designs no. 19, 11, 14 and Transverse design no. 3	Longitudinal designs no. 4 and 6	Transverse designs no. 1, 5, and 4
Section 3 From Wilmington Rd to Barr Rd	N/A	Longitudinal designs no. 5, 15, 16, and 3	Transverse design no. 2
Section 4 From Barr Rd to Joliet Rd	N/A	Longitudinal designs no. 20, 1, 7, 8, and 9	N/A

Construction Method and Equipment

The construction method of the 25 rumble strips was performed in four sequential steps. First, the research team used a marking spray to mark the specific location of each rumble strip design on the ground according to the planned arrangement (see Figure 10). Second, the foreman adjusted the milling drum and the diamond heads according to the design dimensions, while the traffic control team closed the road lane before starting the milling operation (see Figure 11 and Figure 12). Third, the foreman milled the pavement using a milling machine while two quality control crew members followed the milling machine to verify the accuracy of the milled rumble strip dimensions (depth, length, width, and spacing/wavelength) and informed the foreman of any deviation using a walkie-talkie (see Figure 13). Fourth, resulting debris were swept off the roadway after the milling operation (see Figure 14).

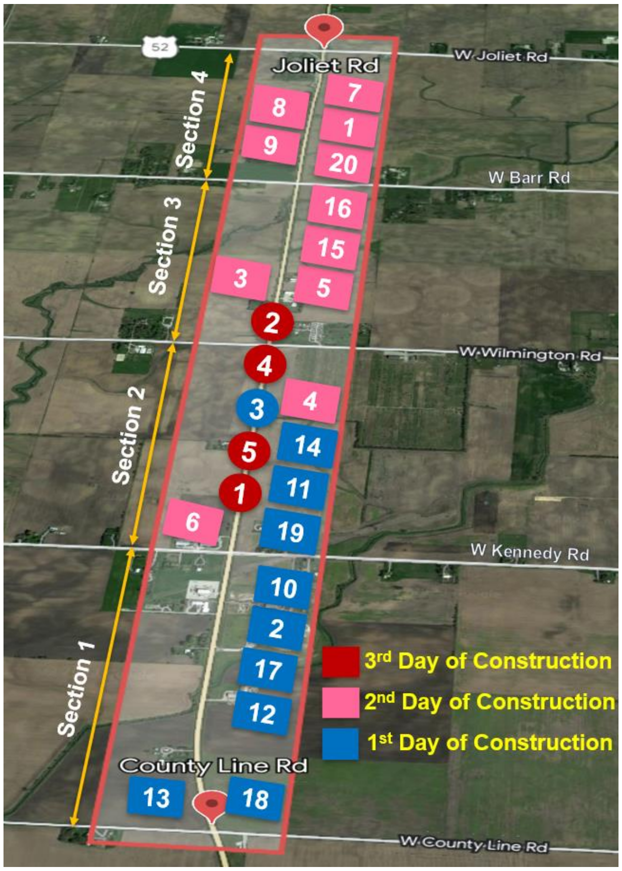
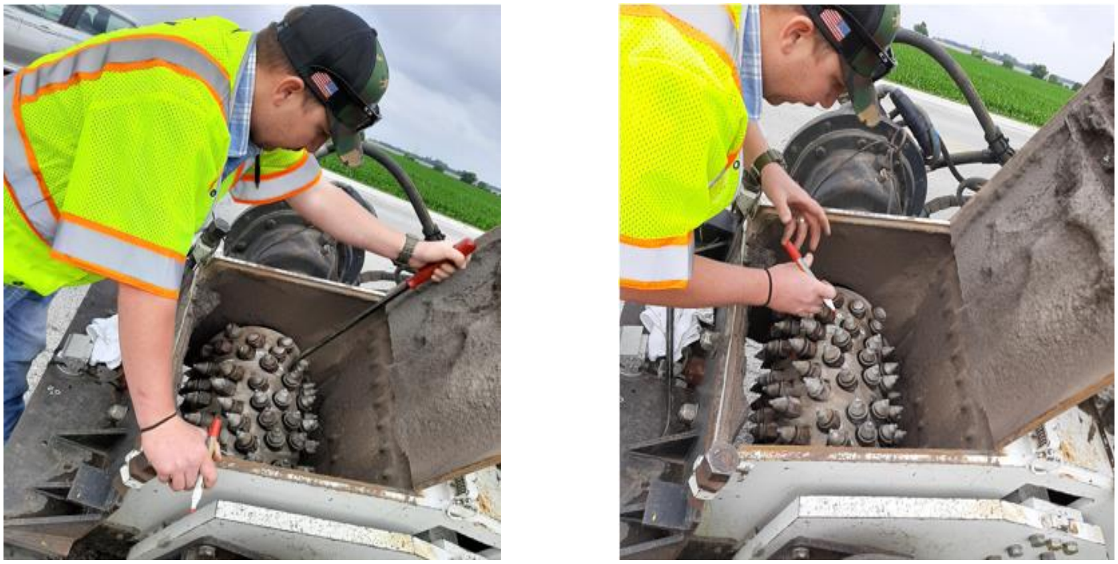


Figure 9. Illustration. Construction schedule of rumble strips.

The construction equipment utilized for milling the 25 rumble strips on US-45 included (1) a versatile milling machine that can switch between traditional and sinusoidal cuts (see Figure 15) to complete the milling of all 20 longitudinal rumble strips and one sinusoidal transverse rumble strip; (2) a bobcat loader with asphalt planer to perform the milling of the remaining four transverse rumble strips (see Figure 15); (3) a sweeping vehicle to clean the debris off the roadway (see Figure 16); (4) a ruler with depth gauge to verify the accuracy of the milled rumble strips (see Figure 17); and (5) a walkie-talkie to enable communication between the equipment operator and the construction quality control team (see Figure 18).

Figure 10. Photo. Marking locations of rumble strips.



(a) Milling drum for traditional rumble strip (b) Milling drum for sinusoidal rumble strip

Figure 11. Photo. Milling drum adjustment to grind traditional and sinusoidal rumble strips.

Figure 12. Photo. Lane closure and traffic control.

Figure 13. Photo. Rumble strip milling and quality control procedures.

Figure 14. Photo. Roadway sweeping.

(a) Milling machine for traditional and sinusoidal rumble strips

(b) Bobcat loader with asphalt planer

Figure 15. Photo. Milling machines for longitudinal and transverse rumble strips.

Figure 16. Photo. Sweeping vehicle.

Figure 17. Photo. Ruler with depth gauge.

Figure 18. Photo. Walkie-Talkie.

Quality Control of Constructed Rumble Strips

To ensure the quality control of all 25 constructed rumble strips, their actual as-built dimensions (depth, width, length, spacing/wavelength, and panel length) were measured on-site after their construction, as shown in Tables 4 and 5. These as-built dimensions were then compared to the original design dimensions to ensure quality control of the milling procedure and verify the accuracy of the construction operations. The findings of this comparison confirm that the as-built width, length, spacing/wavelength, and panel length of all 25 constructed rumble strips were identical to their design dimensions. The only difference between the as-built and design dimensions was that the depth of the as-built rumble strips slightly varied by approximately ±1/8″ which are often caused by the imperfections and inconsistent levels of the pavement surface.

Table 4. As-Built Dimensions of Longitudinal Rumble Strips

Design No.	Rumble Strip Design	As-Built Dimensions				
		Depth	Width	Length	Spacing	Wavelength
1	IDOT Shoulder (8″)	9/16″	7″	8″	12″	N/A
2	IDOT Interstate Shoulder (16″)	9/16″	7″	16″	12″	N/A
3	IDOT Shoulder (modified)	4/8″	7″	7″	12″	N/A
4	IDOT Centerline	9/16″	7″	12″	12″ w/ 24″ paired gap	N/A
5	IDOT Centerline with paired gap	2/8″	7″	12″	12″ w/ 24″ paired gap	N/A
6	IDOT Centerline (modified)	4/8″	7″	16″	4″ center gap	N/A
7	IDOT McHenry 1	1/8″ to 4/8″	N/A	8″	N/A	16″
8	IDOT McHenry 2	1/8″ to 4/8″	N/A	8″	N/A	12″
9	Caltrans	1/8″ to 7/16″	N/A	8″	N/A	14″
10	Indiana DOT	1/8″ to 1/2″	N/A	16″	N/A	12″
11	Minnesota DOT	1/8″ to 1/2″	N/A	14″	N/A	14″
12	Montana DOT	1/8″ to 1/2″	N/A	14″ tapered	N/A	24″
13	Washington DOT	1/8″ to 1/2″	N/A	12″ tapered	N/A	16″
14	Oregon DOT	1/8″ to 4/8″	N/A	14″	N/A	16″
15	Straight edge 12″ SRS*	0″ to 1/2″	N/A	12″	N/A	14″
16	Reduced profile straight 12″ SRS*	1/8″ to 1/2″	N/A	12″	N/A	14″
17	Tapered edge 12″ SRS*	1/8″ to 1/2″	N/A	12″ tapered	N/A	14″
18	Reduced profile tapered 16″ SRS*	0″ to 7/16″	N/A	16″ tapered	N/A	12″
19	Reduced profile straight 16″ SRS*	1/8″ to 5/16″	N/A	16″	N/A	14″
20	Extended wavelength 12″ SRS*	1/16″ to 3/8″	N/A	12″	N/A	20″

SRS*: Sinusoidal Rumble Strips

Table 5. As-Built Dimensions of Transverse Rumble Strips

Design No.	Rumble Strip Design	As-Built Dimensions						
		Depth	Width	Length	Spacing	Panel Length	Offset	Wavelength
1	IDOT Traditional Design	5/16″	4″	10′	12″	24′ 7″	N/A	N/A
2	IDOT Traditional with Alternate Placement	5/16″	4″	4′ each	2′ within same set 1′ with alternating set	24′ 3″	edge line & lane centerline: 6″ between sets: 10″	N/A
3	OKDOT Sinusoidal Design	1/8″–7/16″	16″	10 cycles	N/A	23″	2′	14″
4	Angled Transverse	5/16″	4″	10′	12″	25′ 10″	N/A	N/A
5	IDOT Traditional Shorter Design	5/16″	4″	10′	12″	15′ 5″	N/A	N/A

NOISE DATA COLLECTION EQUIPMENT AND METHODS

This section focuses on the data collection equipment and methods that were used in both the initial and second round of field evaluations to collect external and internal noise measurement data that were generated by the constructed rumble strips on US-45. The noise data-collection equipment and methods were selected to ensure compliance with the AASHTO Statistical Isolated Pass-by (SIP) Method for external noise data collection (AASHTO T 389-20, 2020) and SAE Standard for Measurement of Interior Sound Levels for internal noise data collection (SAE J1477, 2000).

Noise Measurement Equipment

The external and internal noise levels generated by the 25 rumble strip designs on US-45 were collected using (a) two class I PCE-430 sound meters to collect external noise data at 25 and 50 feet following the recommendations of AASHTO T 389-20, (b) a CEM DT-8852 sound meter to collect internal noise data inside all test vehicles following the recommendations of SAE J1477, (c) a sound calibrator to calibrate the utilized sound meters, (d) tripods to set up the height of sound meter microphones based on the recommendations of AASHTO T 389-20 and SAE J1477, (e) a weather station to verify the atmospheric conditions and wind speeds on site comply with AASHTO T 389-20 requirements, and (f) a laser speed gun to verify the speed of the test vehicles, as shown in Figure 19.

(a) Class I PCE-430 Sound Meter (b) CEM DT-8852 Sound Meter (c) Sound Calibrator

(d) Tripods (e) Weather Station (f) Laser Speed Gun

Figure 19. Photo. Noise measurement equipment.

Method for Collecting External Noise Measurements

The external noise measurement data generated by the 25 rumble strip designs on US-45 were collected following the AASHTO SIP Method (AASHTO T 389-20, 2020). Accordingly, two sound meters were placed on the right-of-way of US-45 to collect the external noise generated while the test vehicle was traveling over the rumble strips. The first sound meter was placed 25 feet from the center of the rumble strips and mounted on a tripod 5 feet above the US-45 pavement level. The second microphone was located 50 feet from the center of the rumble strips and mounted on a tripod 12 feet above pavement level, as shown in Figure 20. All measurements were verified using a measuring tape. Weather data were also collected on-site using a weather station, especially wind speed, to make sure that it did not exceed the AASHTO recommended threshold of 11 miles per hour. In addition, the test vehicle speed was also collected using a laser speed gun to ensure that it was traveling on the rumble strips at the designated speed of 50 mph.

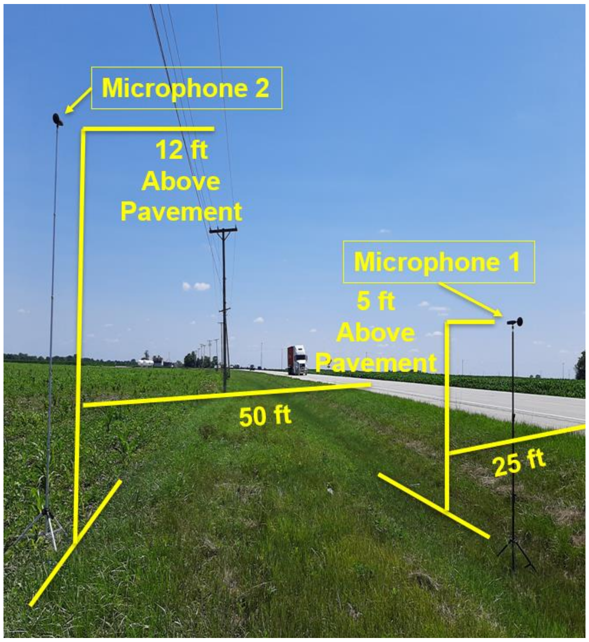


Figure 20. Illustration. Equipment setup for external noise measurement.

Method for Collecting Internal Noise Measurements

Internal noise measurement data were collected following the Society of Automotive Engineers Standard for Measurement of Interior Sound Levels (SAE J1477, 2000). A single sound meter was placed securely on a tripod approximately 28 inches above the front passenger seat of the test vehicle, facing forward in the direction of travel, as shown in Figure 21. Its purpose was to collect both the baseline sound level of the pavement and the noise levels generated when the test vehicle strikes the rumble strips. During these measurements, all potential sources of internal noise such as car windows, air conditioning, heating, radio, signal flashers, windshield wipers, and any other source of noise were deactivated.

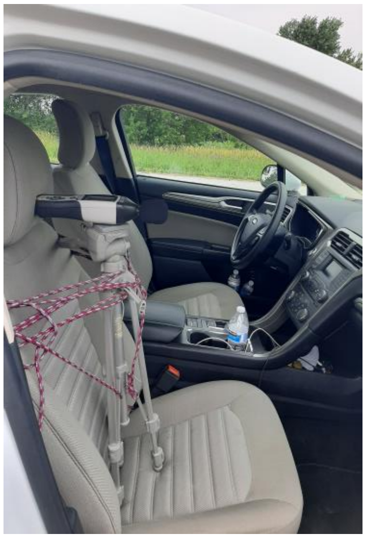


Figure 21. Photo. Equipment setup for internal noise measurement.

FIELD EVALUATIONS

This section presents a concise description of the initial round of field evaluations that were conducted to collect and analyze external and internal noise data generated by the 25 constructed rumble strips on US-45. Accordingly, this section is organized into four subsections: (a) listing the three test vehicles used in this field evaluations, (b) collecting and analyzing external noise data generated by the three test vehicles, (c) collecting and analyzing internal noise data, and (d) identifying the top-performing rumble strip designs that will be selected for further testing in a second round of evaluations using additional test vehicles.

Test Vehicles

The 25 rumble strips on US-45 were tested using three different types of vehicles, including a sedan, a SUV, and a medium truck, as shown in Figure 22. The test vehicles were used to drive over all 25 rumble strip designs at 50 mph in cruise control mode for at least five seconds for all longitudinal rumble strips and over each entire transverse rumble strip panel during the collection of external and internal noise data.

(a) Sedan (b) Sport Utility Vehicle (c) Medium Truck

Figure 22. Photo. Test vehicles used in initial round of field evaluations.

Collection and Analysis of External Noise Data

External noise data generated by the 25 constructed rumble strips were collected following the AASHTO T 389-20 test method. The field measurements were conducted over 23 workdays from June 30 to August 22, 2023, excluding days with unfavorable weather conditions caused by high winds and precipitation. For each rumble strip design, the sedan and SUV were used to conduct at least 30 valid passes over each rumble strip design while the medium truck was used to conduct four valid passes over each rumble strip design at the same speed due to the safety challenges of operating and maneuvering the medium truck. A vehicle pass was classified as nonvalid and excluded from the collected dataset if noise data collection was contaminated by non-test vehicle noise such as other passing vehicles or if wind gusts exceeded 11 mph.

For each rumble strip design, the following external noise data were collected every 0.5 seconds using a Class I sound level meter at 25 and 50 feet: (1) baseline external noise data generated by each test vehicle driving over the immediately adjacent roadway pavement without striking the rumble strips and (2) rumble strip external noise data generated by each test vehicle driving over the rumble strips at 50 mph for at least five seconds for all longitudinal rumble strips and over each entire transverse rumble strip panel. These collected baseline and rumble strip external noise data were then averaged for each combination of rumble strip design, test vehicle, and measurement distance, as shown in Figures 23, 24, 25, 26, 27, and 28. These calculated average baseline and rumble strip external noise levels were used to calculate the average increase (Δ) in external noise levels generated by the test vehicle striking the rumble strips, as shown in Figures 29, 30, 31, 32, 33, and 34. The baseline and rumble strip external noise data, including sample size, average, and standard deviation for all combinations of rumble strips, test vehicles, and measurement distances, are included in Appendix D.

Collection and Analysis of Internal Noise Data

The internal noise data generated by the 25 rumble strip designs were collected following the Society of Automotive Engineers Standard for Measurement of Interior Sound Levels (SAE J1477, 2000). To minimize the risk of noise contamination, all potential sources of internal noise such as air conditioning, radio, and signal flashers were deactivated during the data collection.

For each of the tested 25 rumble strip designs, the internal noise generated by the aforementioned three test vehicles (sedan, SUV, and medium truck) was measured every 0.5 seconds using a CEM DT-8852 sound meter. The collected internal noise measurement data included: (1) baseline internal noise data generated by each test vehicle while passing over the roadway pavement immediately before striking the rumble strips, and (2) internal noise data generated by each test vehicle driving over the rumble strips at 50 mph for at least five seconds for all longitudinal rumble strips and over each entire transverse rumble strips panel. The collected internal noise measurement data were then analyzed to calculate: (a) average internal pavement baseline noise level and average internal rumble strip noise level for each combination of rumble strip design and test vehicle, as shown in example Figures 35 and 36; and (b) average internal noise level increase above ambient (Δ) generated by each test vehicle striking the rumble strip, as shown in Figures 37, 38, 39, 40, 41, and 42. The internal pavement baseline and rumble strip noise levels, including sample size, average, and standard deviation for all combinations of rumble strips and test vehicles, are included in Appendix D.

The objective of the analysis is to identify the rumble strip designs that produce an internal noise level increase that satisfies the NCHRP recommended range of 3 to 15 dBA (NCHRP 641, 2009). These identified rumble strip designs will be selected for further testing in a second round of evaluations using additional test vehicles.

The internal noise data generated by the 20 longitudinal and 5 transverse rumble strip designs were analyzed to identify the top-performing rumble strip designs. For the longitudinal rumble strips, five designs (1, 3, 4, 6, and 10) fully satisfied the NCHRP recommendations of a 3–15 dBA internal noise level increase for all three test vehicles, as shown in Table 6. Additionally, three designs (5, 12, and 18) fully satisfied the NCHRP recommended range for two test vehicles; however, they were slightly insufficient to meet the minimum threshold of 3 dBA for the tested medium truck, as shown in Table 6. Similarly, longitudinal design 2 fully satisfied the NCHRP recommended range for the tested medium truck; however, it did not satisfy the NCHRP recommended range of 3 to 15 dBA for the sedan and SUV. Design 2 generated internal noise level increases of 15.4 and 16.4 dBA in the tested sedan and SUV, respectively, which slightly exceeded the 15-dBA NCHRP maximum limit for the sedan but not for the SUV, as shown in Table 6. Eleven longitudinal rumble strip designs (7, 8, 9, 11, 13, 14, 15, 16, 17, 19, and 20) fully satisfied the NCHRP recommendations of a 3–15 dBA internal noise level increase for the tested sedan and SUV. However, they did not satisfy the 3-dBA NCHRP minimum limit for the tested medium truck, as shown in Table 6.

For the transverse rumble strips, four designs (1, 2, 4, and 5) fully satisfied the NCHRP recommendations of a 3–15 dBA internal noise level increase for all three test vehicles, as shown in Table 7. Additionally, transverse design 3 fully satisfied the NCHRP recommendations of a 3–15 dBA internal noise level increase for the tested sedan and SUV. However, it was slightly insufficient to meet the 3-dBA NCHRP minimum limit for the tested medium truck, as shown in Table 7.

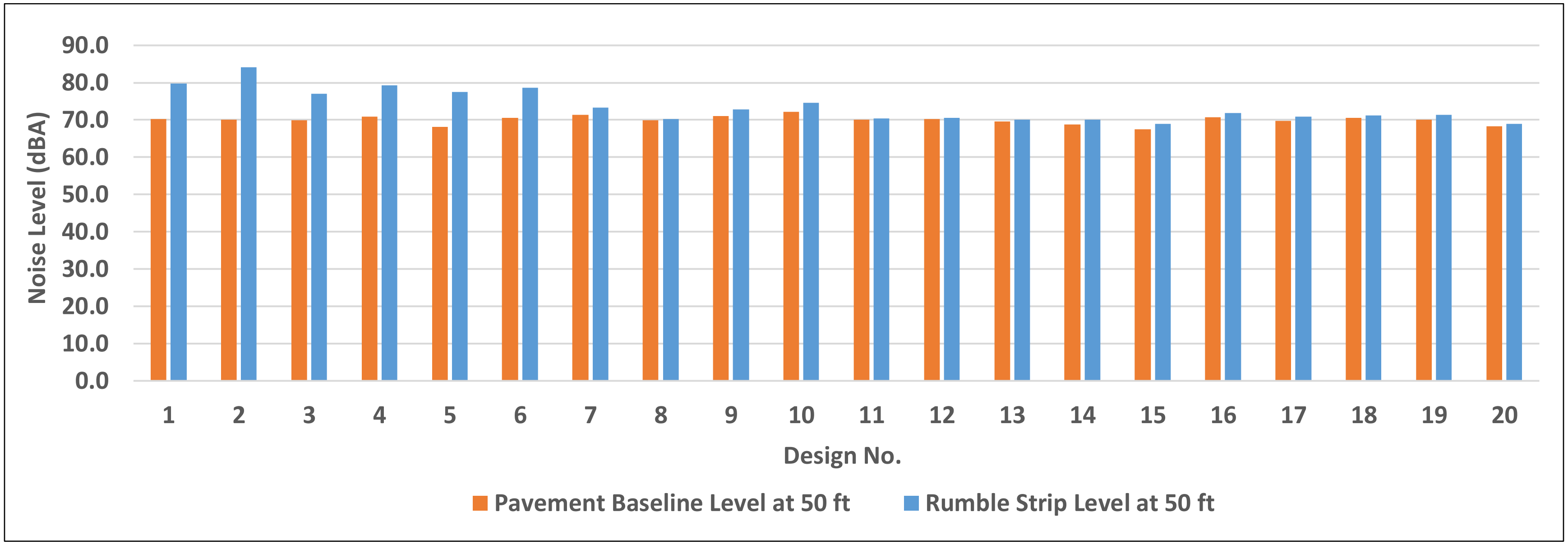


Figure 23. Graph. External noise of sedan and longitudinal rumble strips at 50 ft.

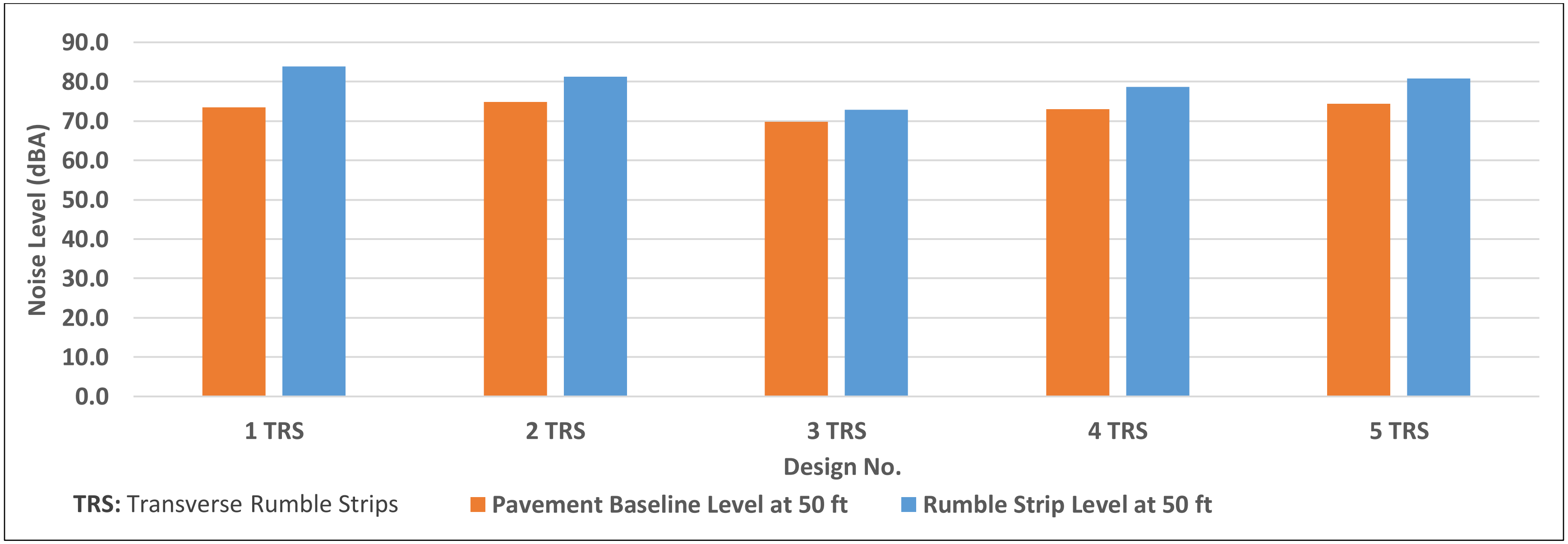


Figure 24. Graph. External noise of sedan and transverse rumble strips at 50 ft.

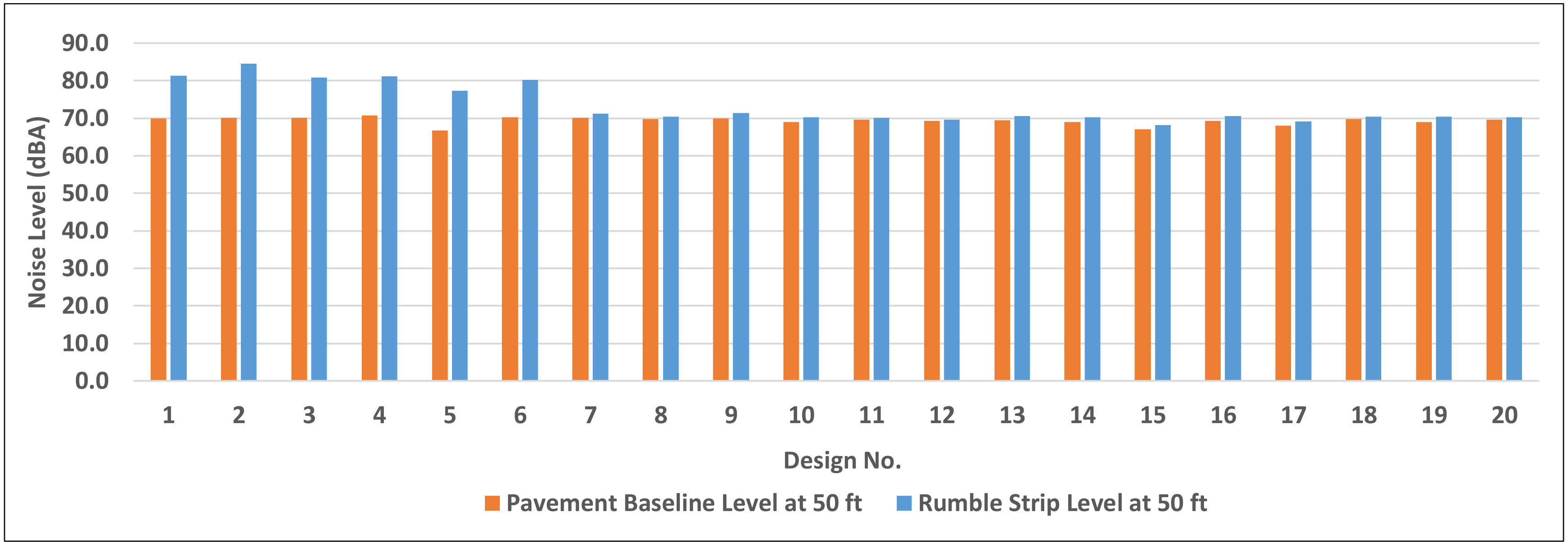


Figure 25. Graph. External noise of SUV and longitudinal rumble strips at 50 ft.

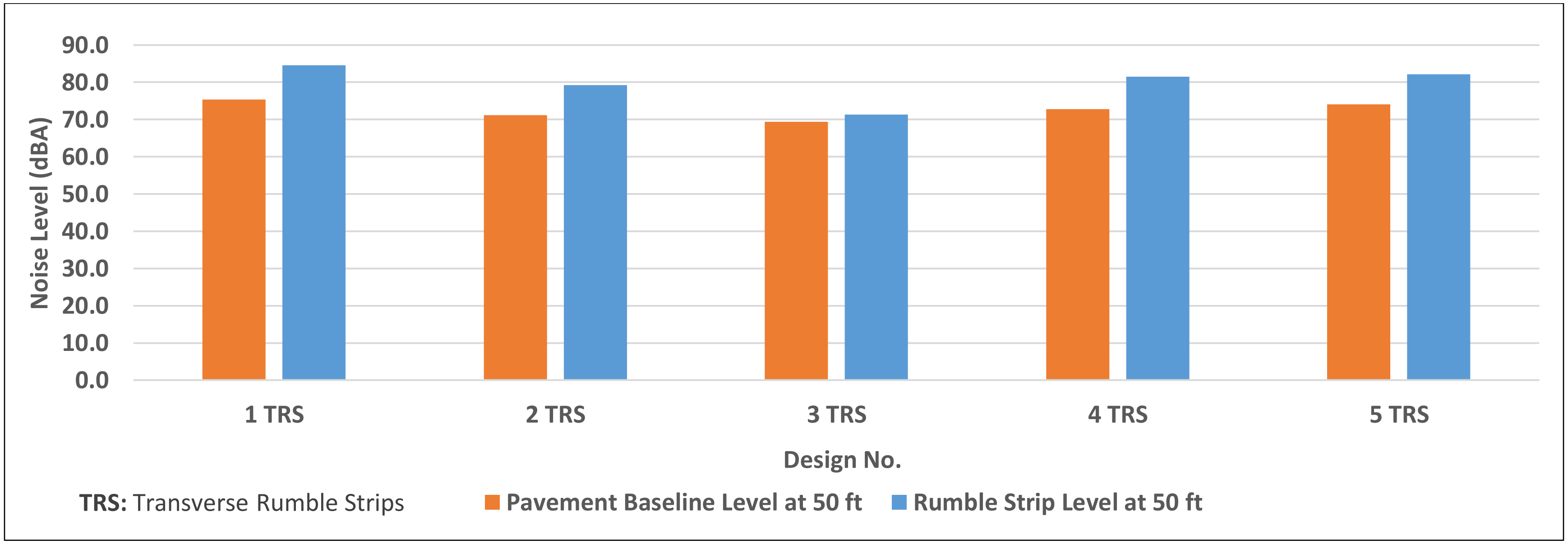


Figure 26. Graph. External noise of SUV and transverse rumble strips at 50 ft.

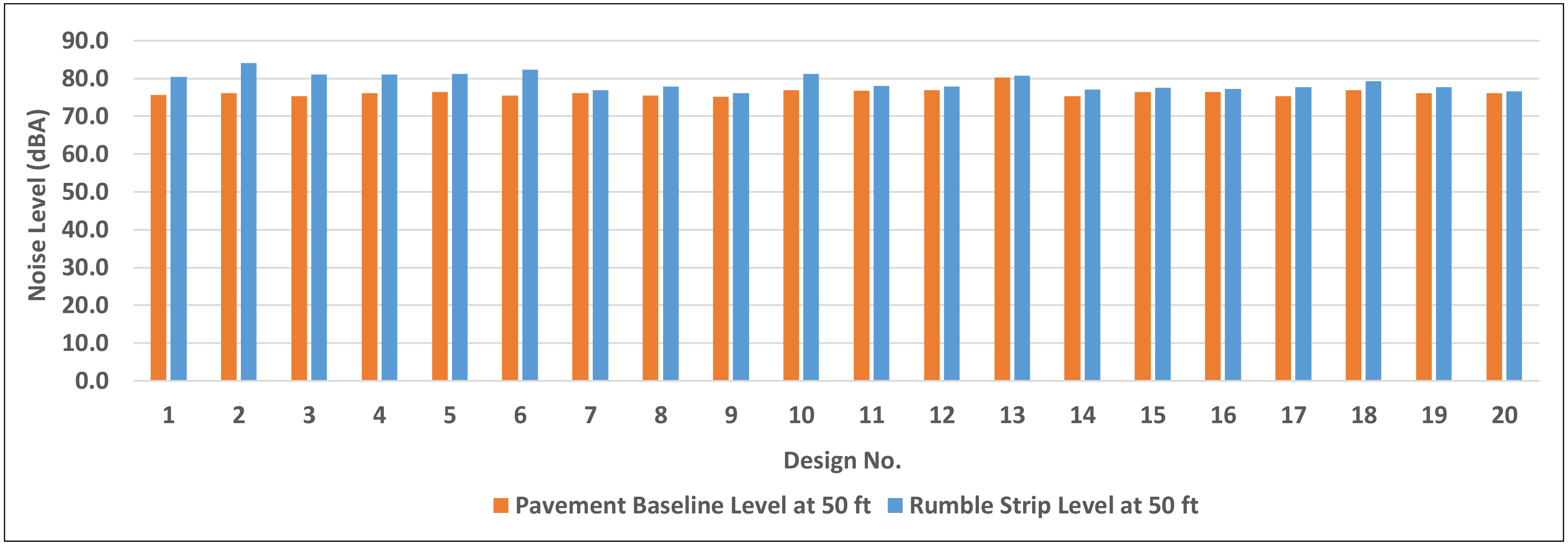


Figure 27. Graph. External noise of medium truck and longitudinal rumble strips at 50 ft.

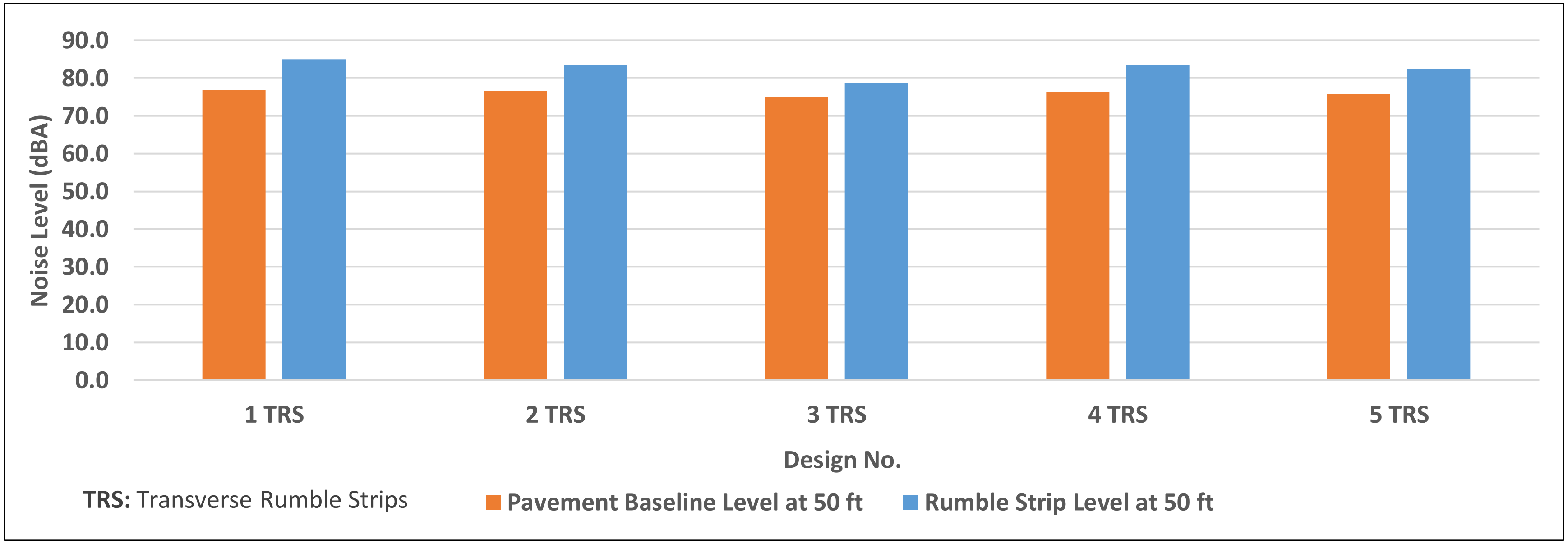


Figure 28. Graph. External noise of medium truck and transverse rumble strips at 50 ft.

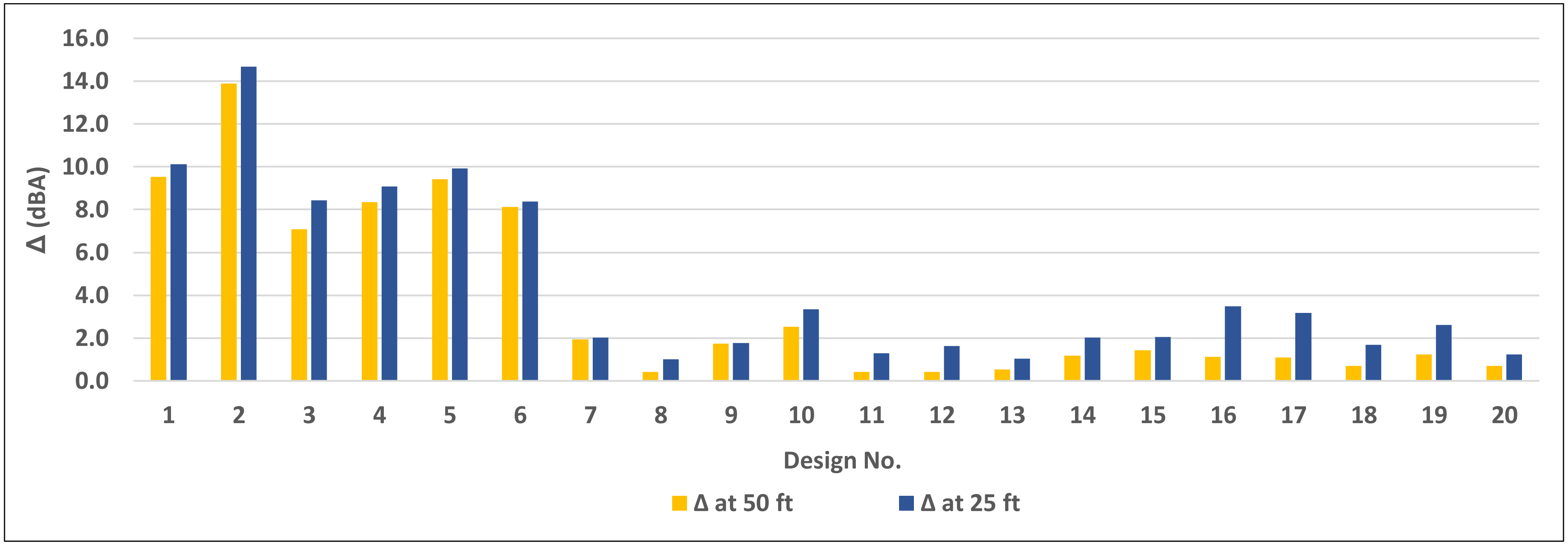


Figure 29. Graph. External noise increase (Δ) of sedan and longitudinal rumble strips.

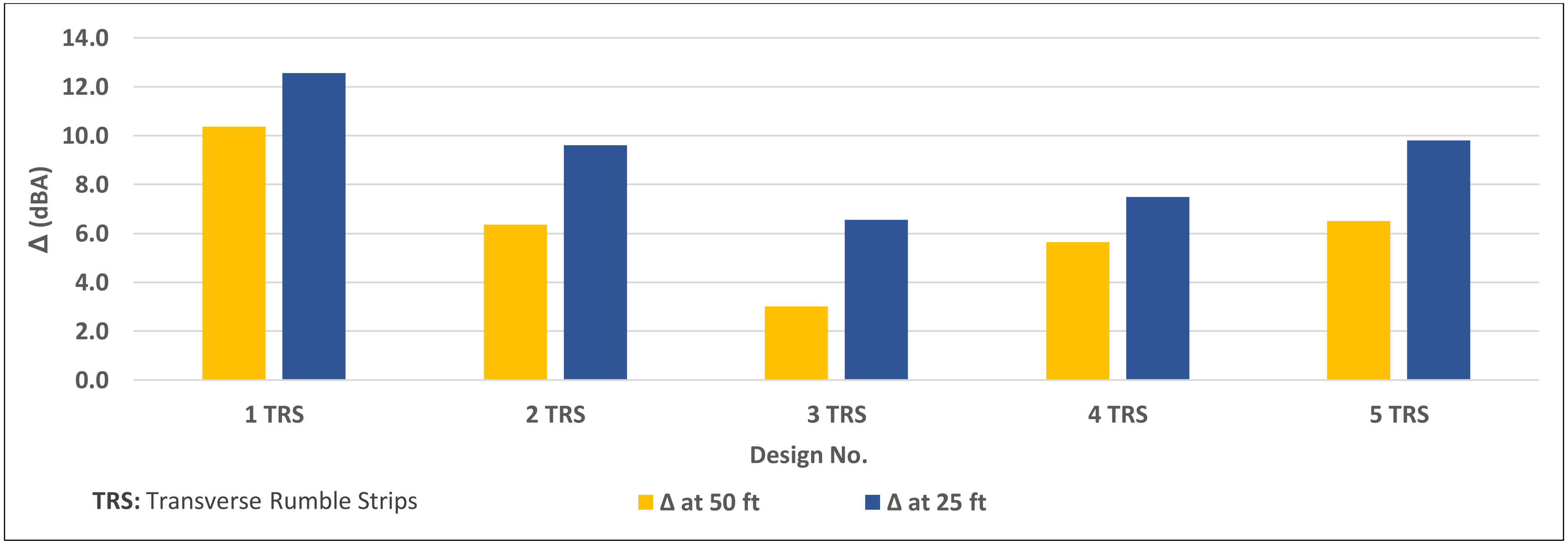


Figure 30. Graph. External noise increase (Δ) of sedan and transverse rumble strips.

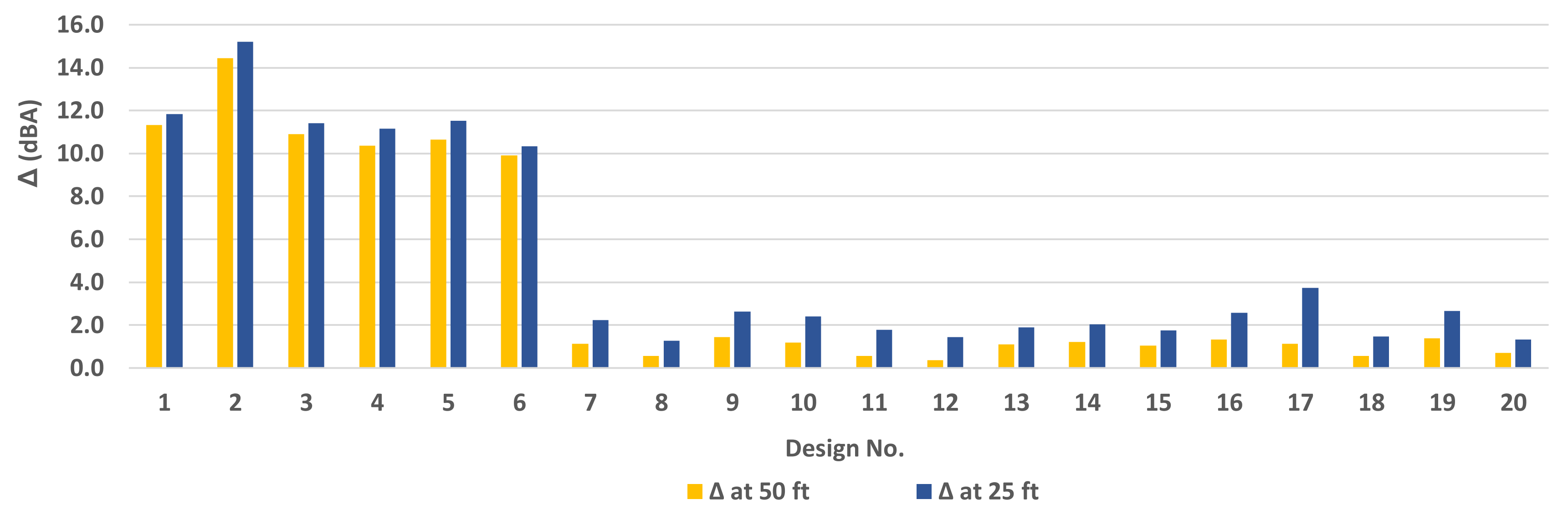


Figure 31. Graph. External noise increase (Δ) of SUV and longitudinal rumble strips.

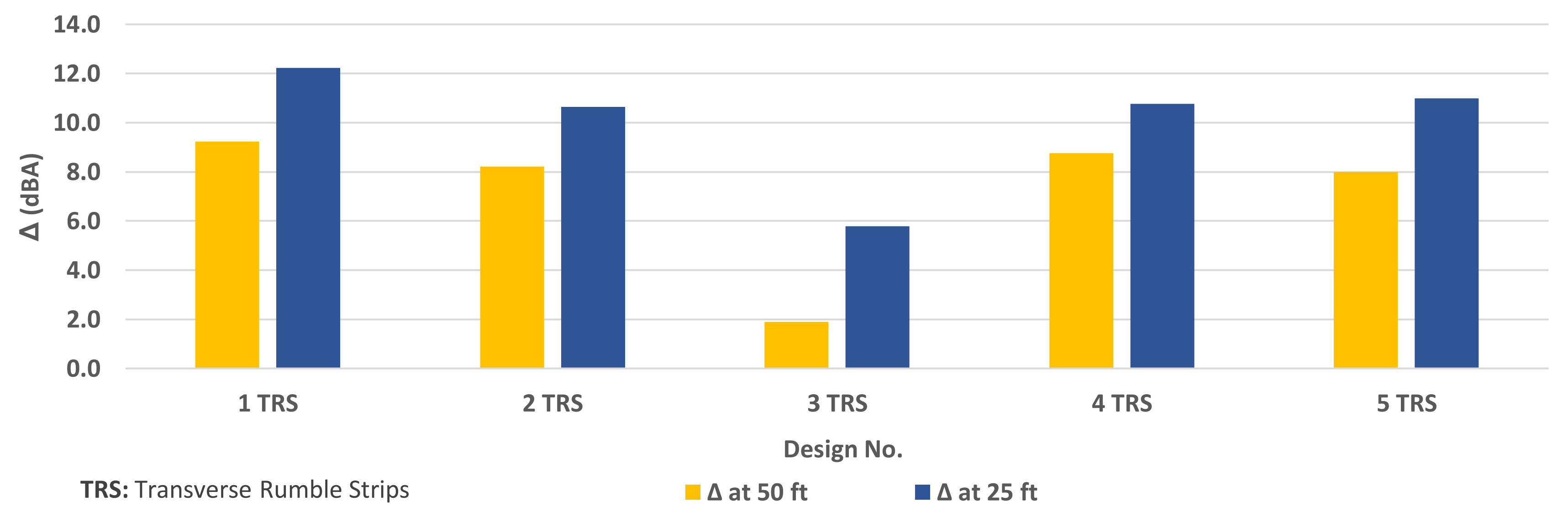


Figure 32. Graph. External noise increase (Δ) of SUV and transverse rumble strips.

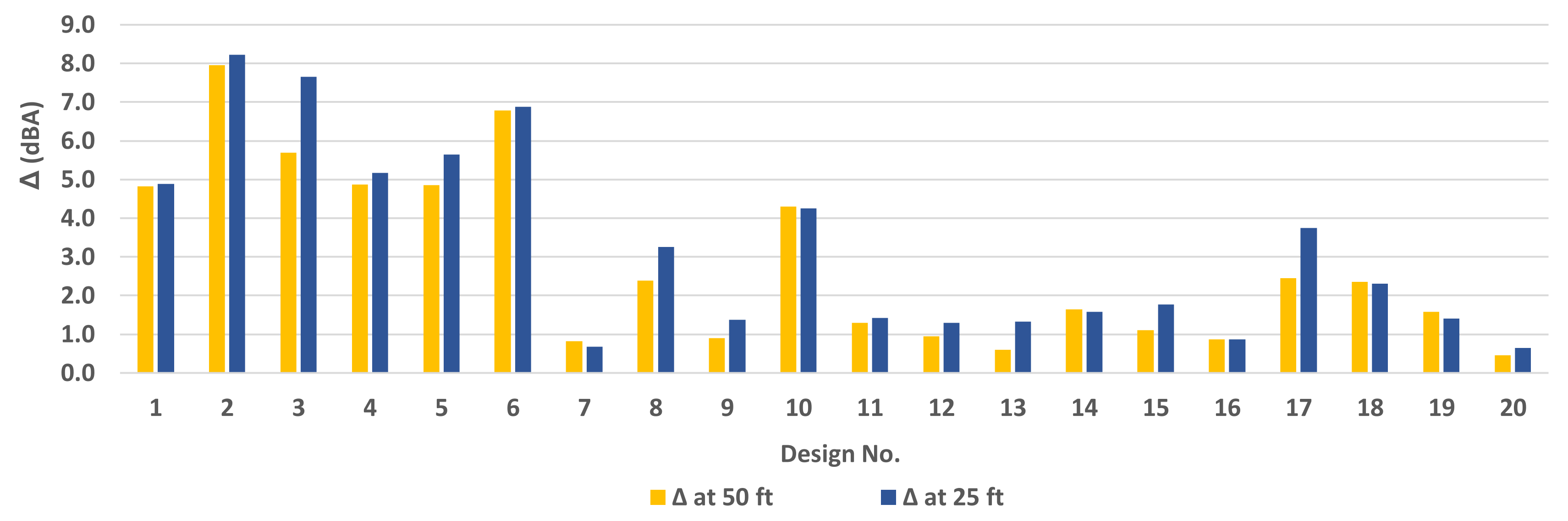


Figure 33. Graph. External noise increase (Δ) of medium truck and longitudinal rumble strips.

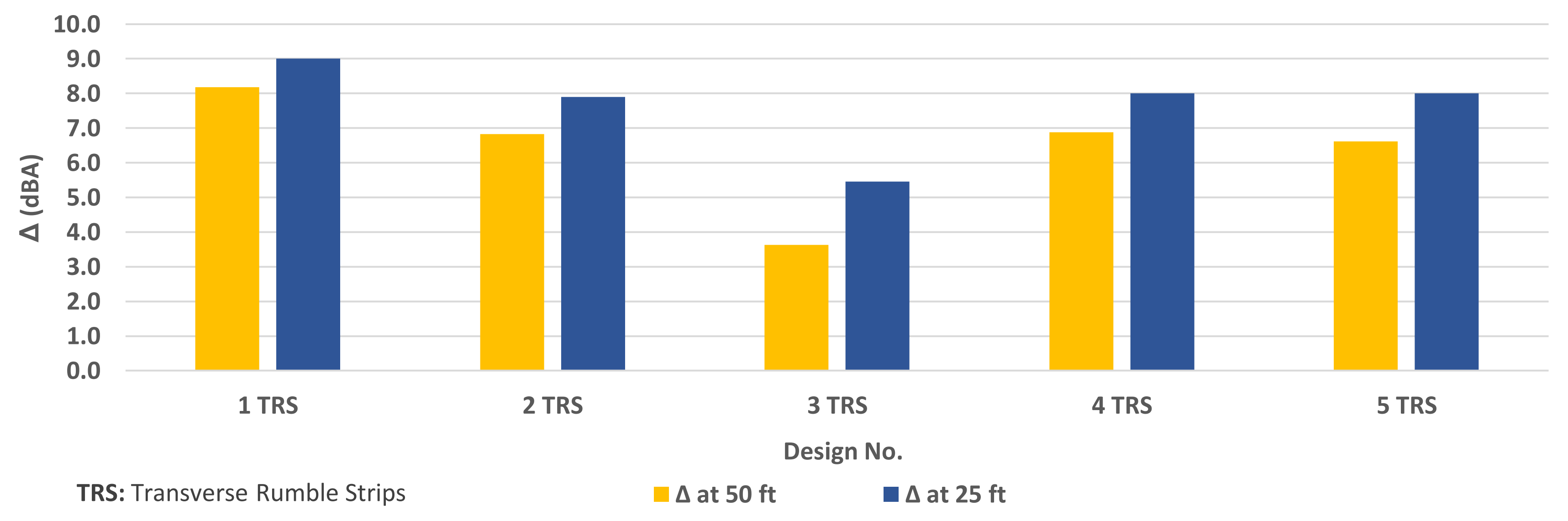


Figure 34. Graph. External noise increase (Δ) of medium truck and transverse rumble strips.

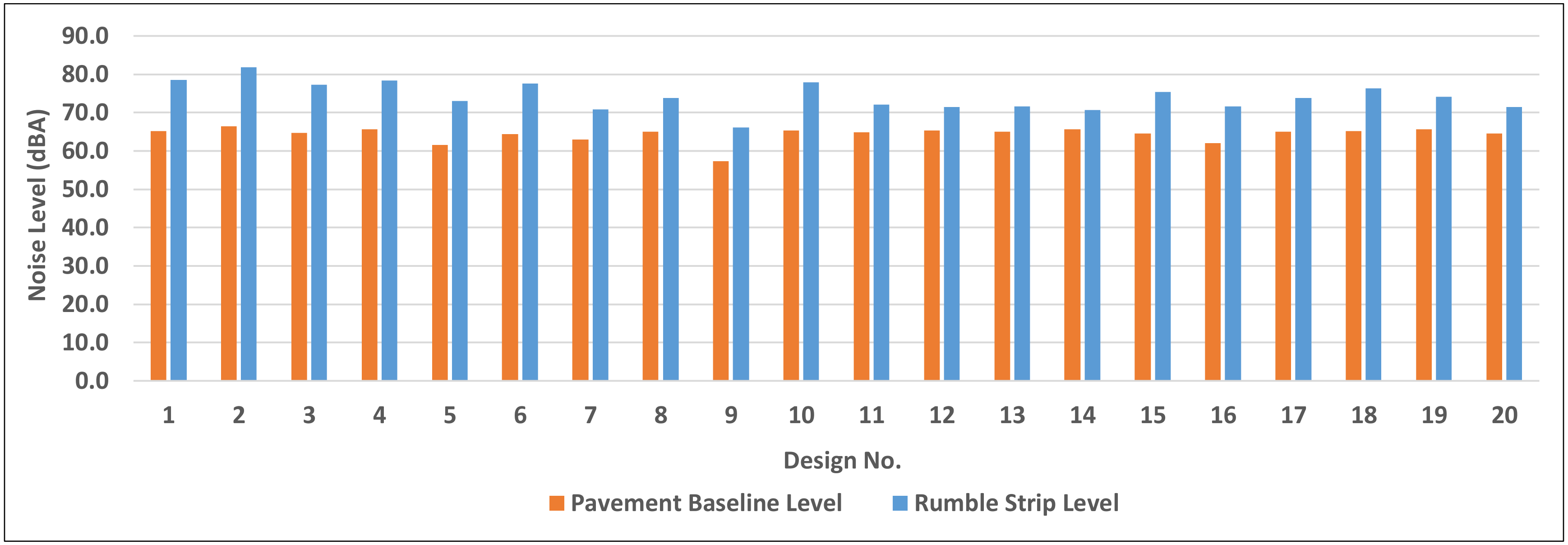


Figure 35. Graph. Internal noise of sedan and longitudinal rumble strips.

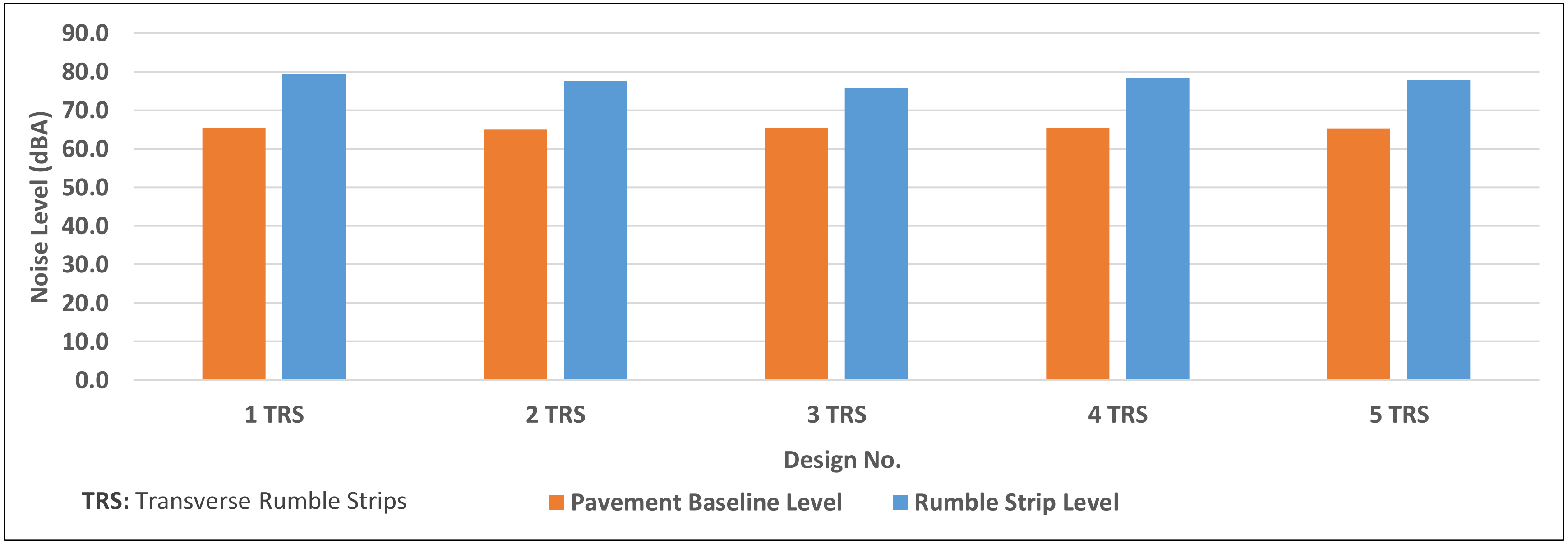


Figure 36. Graph. Internal noise of sedan and transverse rumble strips.

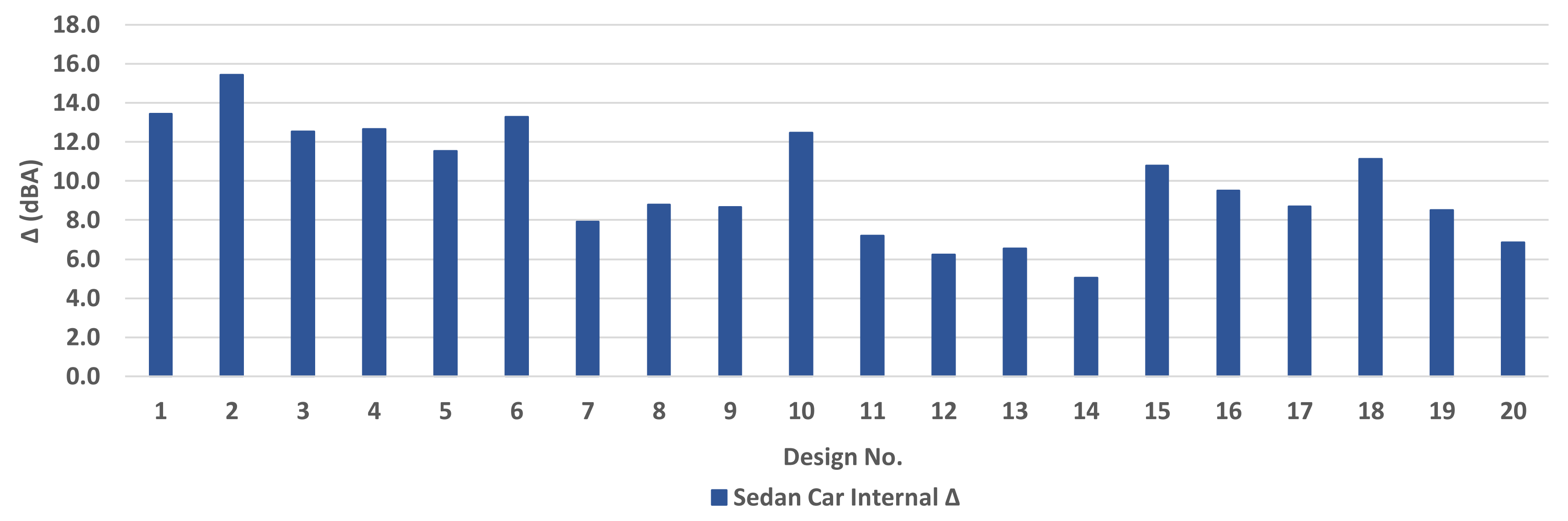


Figure 37. Graph. Internal noise increase (Δ) of sedan and longitudinal rumble strips.

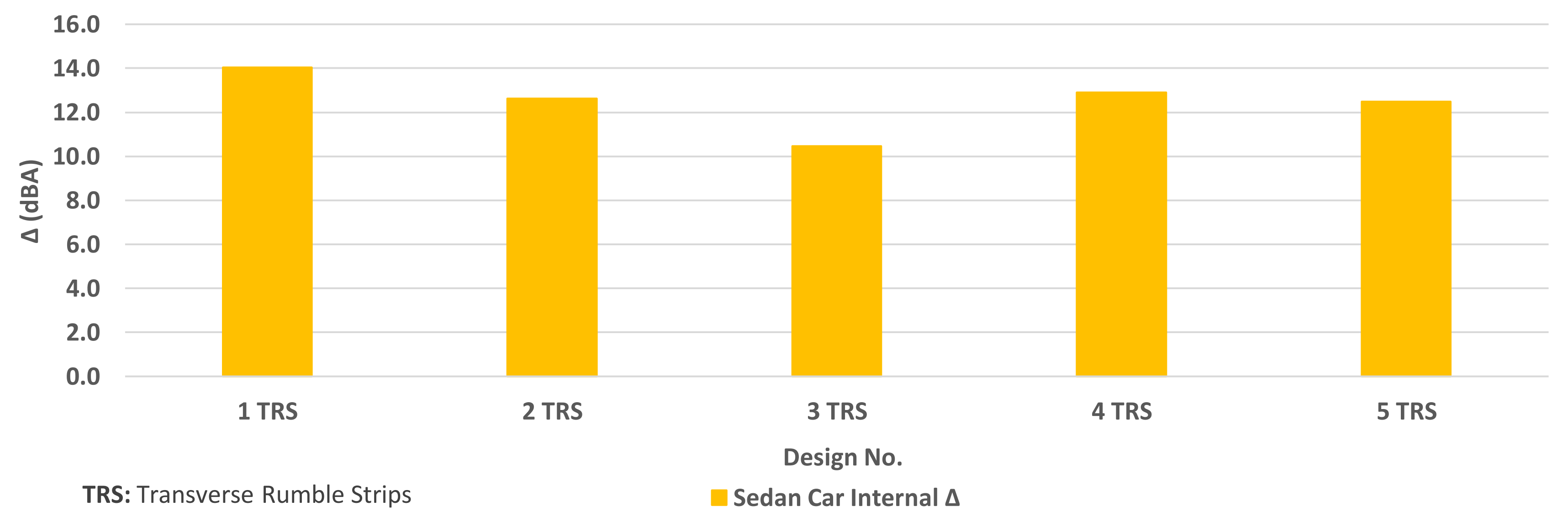


Figure 38. Graph. Internal noise increase (Δ) of sedan and transverse rumble strips.

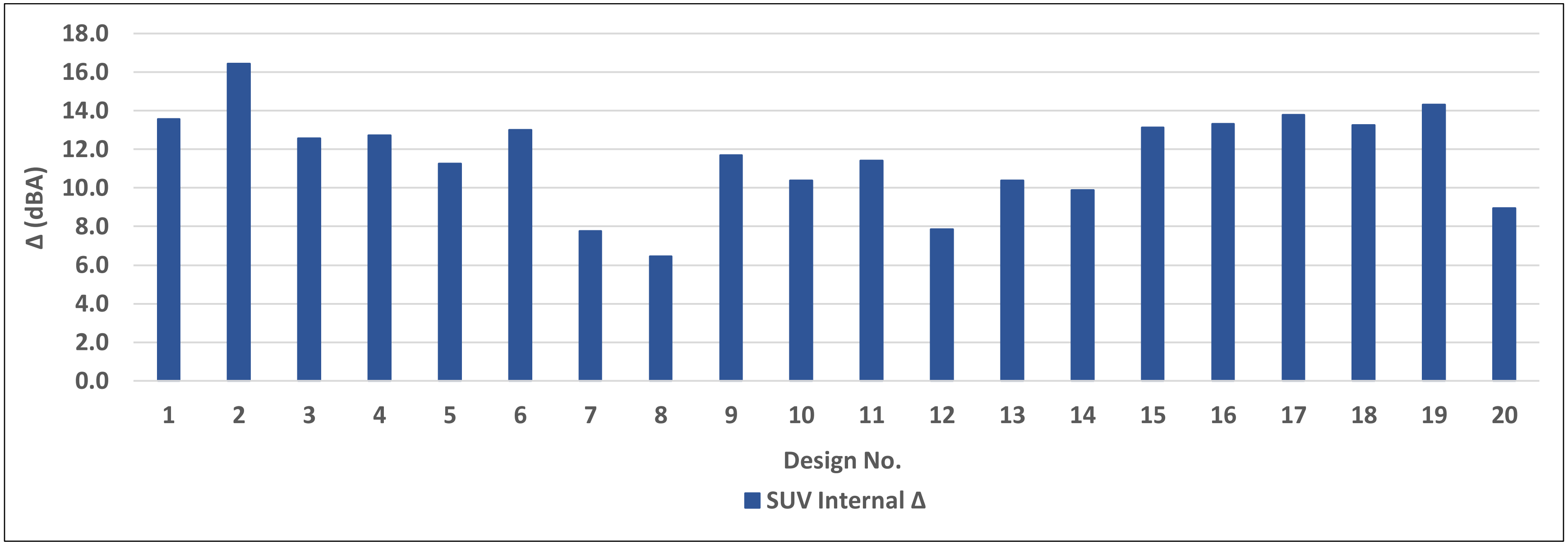


Figure 39. Graph. Internal noise increase (Δ) of SUV and longitudinal rumble strips.

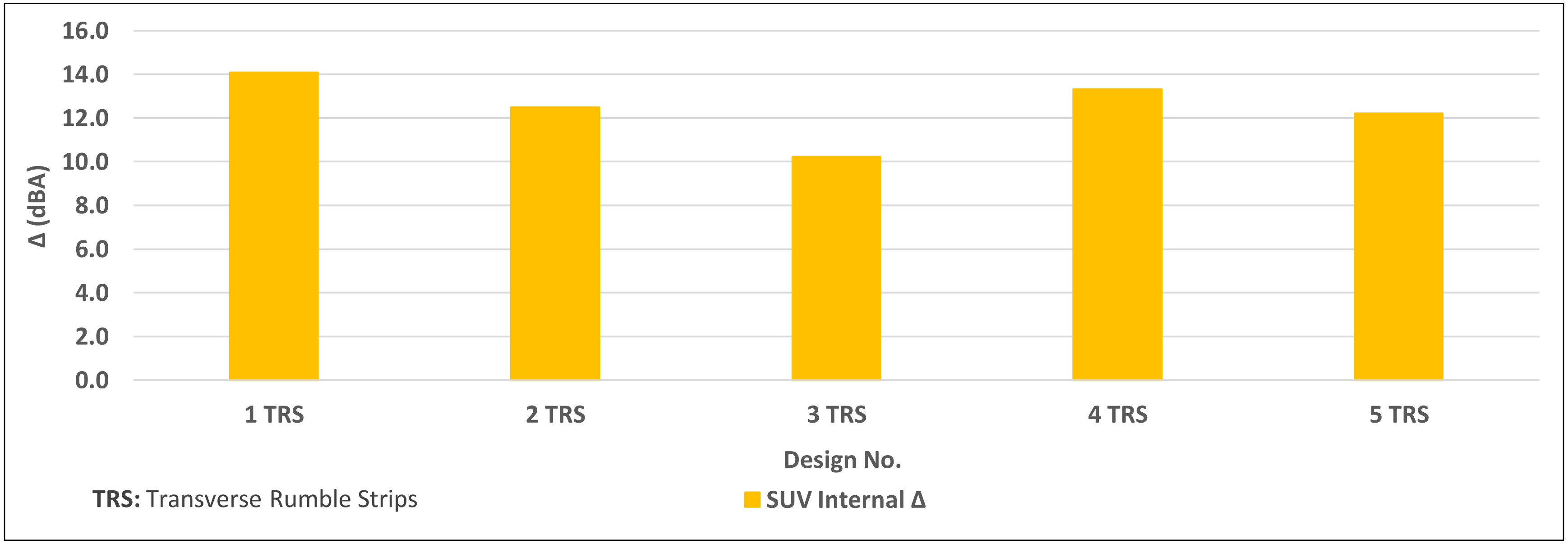


Figure 40. Graph. Internal noise increase (Δ) of SUV and transverse rumble strips.

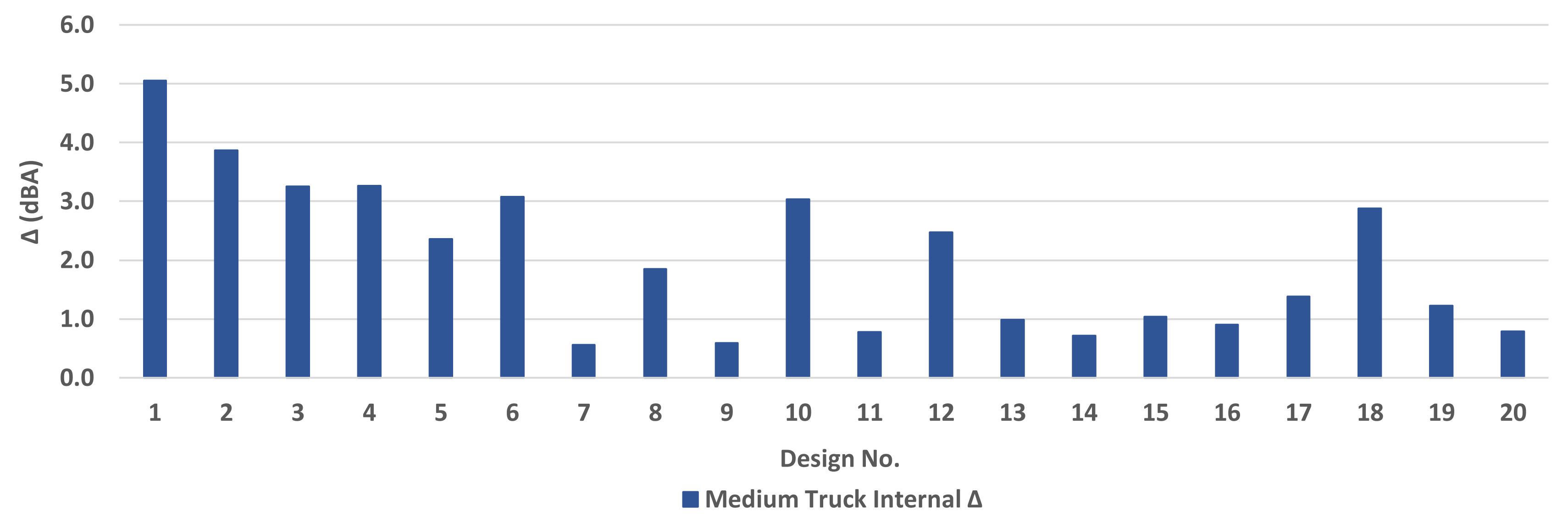


Figure 41. Graph. Internal noise increase (Δ) of medium truck and longitudinal rumble strips.

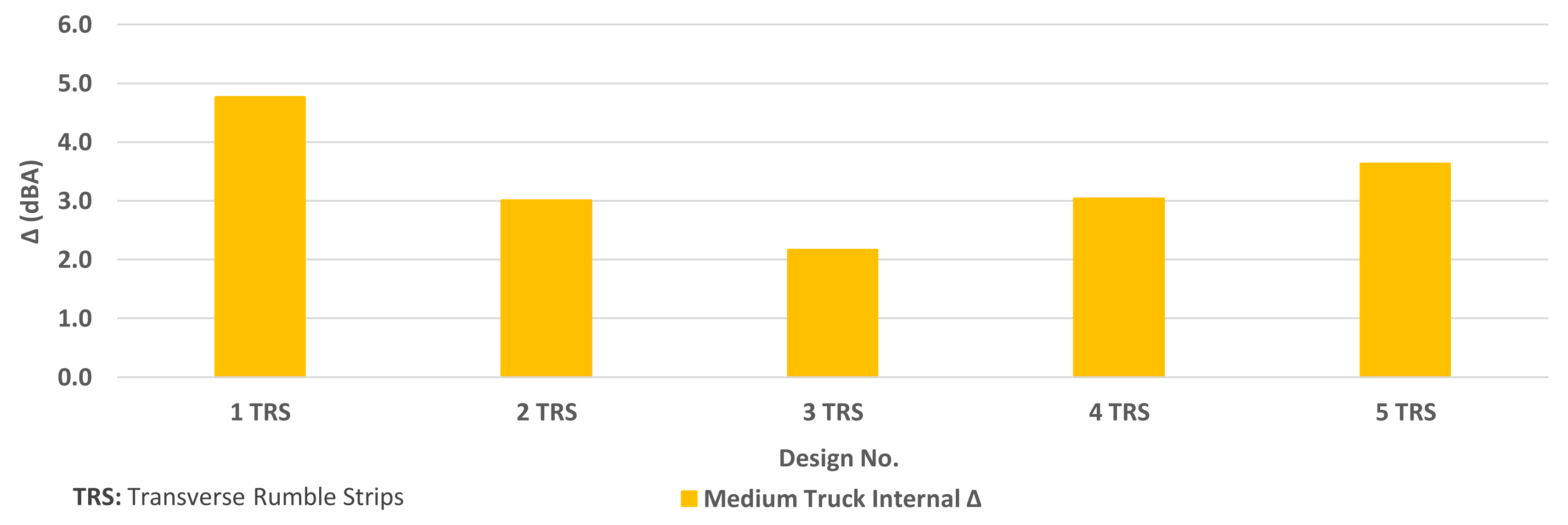


Figure 42. Graph. Internal noise increase (Δ) of medium truck and transverse rumble strips.

Top-Performing Rumble Strip Designs

This section focuses on identifying the top-performing rumble strip designs that will be further tested in the second round of field evaluations. The top-performing rumble strip designs are identified based on their overall performance with respect to generated internal and external noise levels. The first evaluation criterion is whether the rumble strip design generates an adequate internal noise level increase that satisfies the NCHRP recommended range of 3 to 15 dBA, and the second evaluation criterion is generating the minimum external noise level increase. Based on these two criteria, six longitudinal rumble strip designs (1, 2, 3, 4, 6, and 10) and four transverse rumble strip designs (1, 2, 4, and 5) satisfy the NCHRP recommendations for the internal noise level increase for the three test vehicles (sedan, SUV, and truck), as shown in Figures 43 and 44. In addition to these six longitudinal and four transverse rumble strips, three longitudinal designs (5, 12, and 18) and one transverse design (3) meet the NCHRP recommended range of 3 to 15 dBA for the sedan and the SUV; however, they slightly fall short in satisfying the minimum requirement of 3 dBA for the tested truck, as shown in Tables 6 and 7. Accordingly, the top-performing rumble strip designs that were identified in consultation with the Technical Review Panel for further testing in the second round of field evaluations using 10 additional test vehicles are (1) longitudinal rumble strip designs 1, 2, 3, 4, 5, 6, 8, 10, 12, and 18 and (2) transverse rumble strip designs 1, 2, 3, 4, and 5, as shown in Figures 43 and 44.

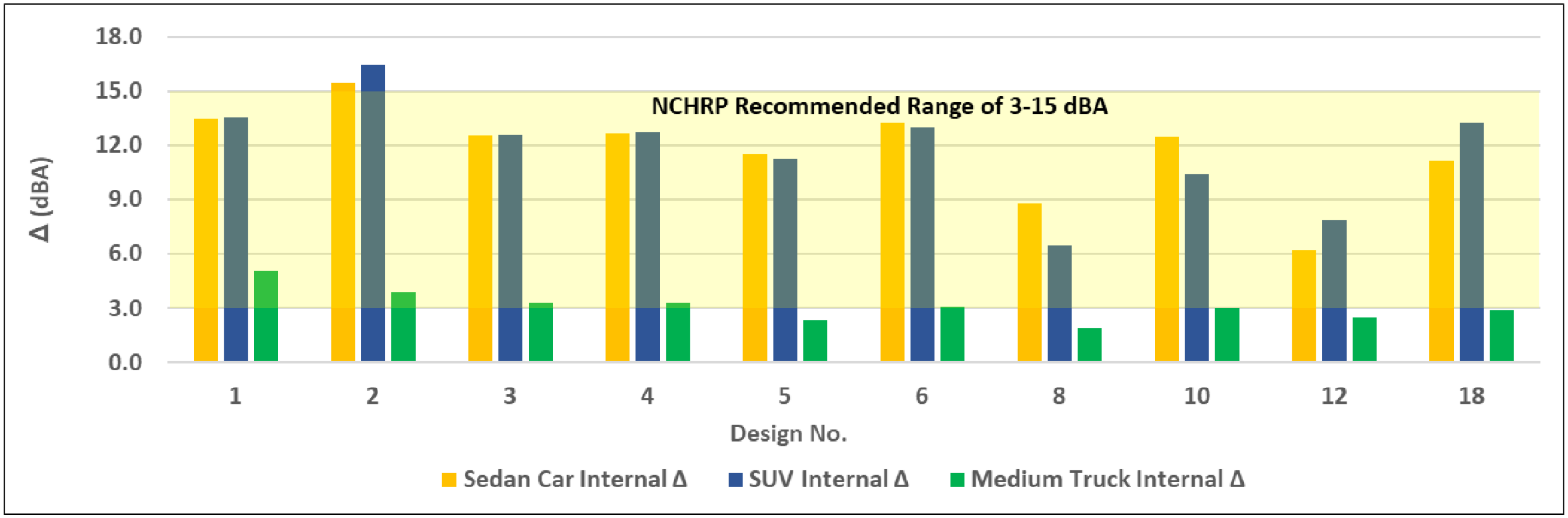


Figure 43. Graph. Selected longitudinal rumble strip designs for second round of evaluations.

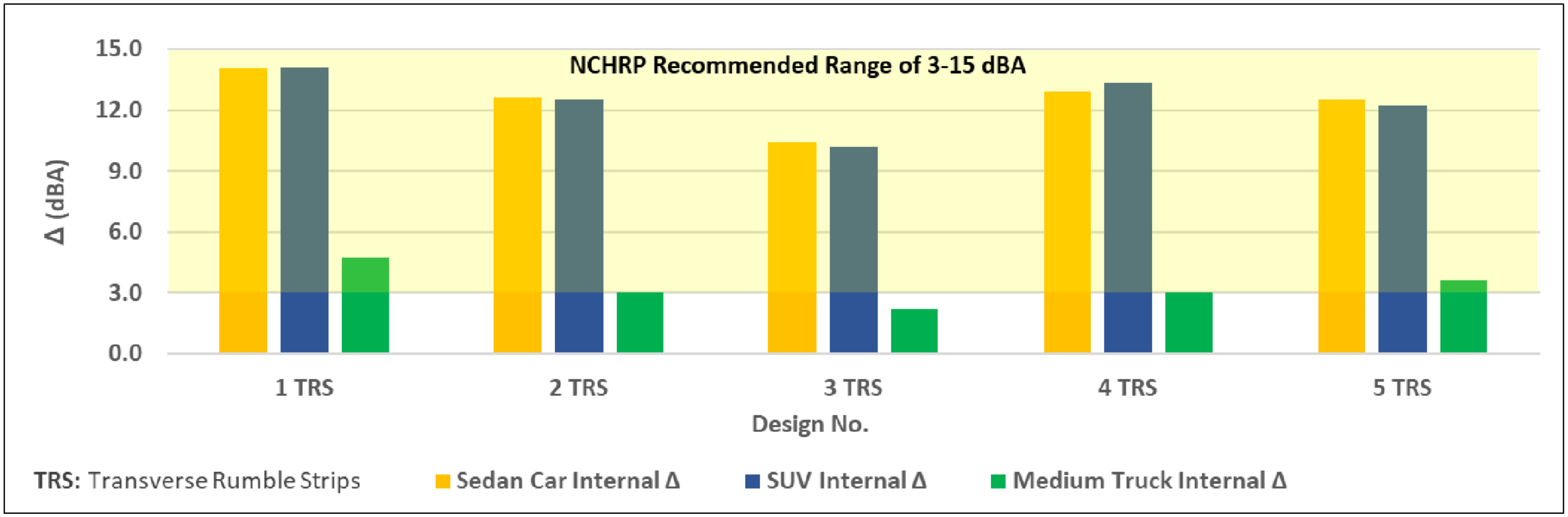


Figure 44. Graph. Selected transverse rumble strip designs for second round of evaluations.

Table 6. External and Internal Noise Increases (Δ) of Longitudinal Rumble Strips

Longitudinal Rumble Strips																					
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
External Δ at 50 ft (dBA)	**Sedan**	9.5	13.9	7.1	8.3	9.4	8.1	1.9	0.4	1.7	2.5	0.4	0.4	0.5	1.2	1.4	1.1	1.1	0.7	1.2	0.7
	SUV	11.3	14.4	10.9	10.4	10.6	9.9	1.1	0.6	1.4	1.2	0.6	0.4	1.1	1.2	1.0	1.3	1.1	0.6	1.4	0.7
	Truck	4.8	8.0	5.7	4.9	4.8	6.8	0.8	2.4	0.9	4.3	1.3	1.0	0.6	1.6	1.1	0.9	2.4	2.3	1.6	0.5
External Δ at 25 ft (dBA)	**Sedan**	10.1	14.7	8.4	9.1	9.9	8.4	2.0	1.0	1.8	3.3	1.3	1.6	1.0	2.0	2.1	3.5	3.2	1.7	2.6	1.2
	SUV	11.8	15.2	11.4	11.2	11.5	10.3	2.2	1.3	2.6	2.4	1.8	1.4	1.9	2.0	1.8	2.6	3.7	1.5	2.7	1.3
	Truck	4.9	8.2	7.7	5.2	5.7	6.9	0.7	3.3	1.4	4.3	1.4	1.3	1.3	1.6	1.8	0.9	3.7	2.3	1.4	0.7
Internal Δ (dBA)	**Sedan**	13.4	15.4**	12.5	12.7	11.6	13.3	7.9	8.8	8.7	12.5	7.2	6.2	6.5	5.0	10.8	9.5	8.7	11.1	8.5	6.8
	SUV	13.6	16.4*	12.6	12.7	11.3	13.0	7.8	6.5	11.7	10.4	11.4	7.8	10.4	9.9	13.1	13.3	13.8	13.3	14.3	8.9
	Truck	5.1	3.9	3.3	3.3	2.4**	3.1	0.6*	1.9*	0.6*	3.0	0.8*	2.5**	1.0*	0.7*	1.0*	0.9*	1.4*	2.9**	1.2*	0.8*

***** Internal noise increases that do not satisfy NCHRP recommended range of 3 to 15 dBA noise increase.

** Internal noise increases that are slightly out of NCHRP recommended range of 3 to 15 dBA noise increase.

Table 7. External and Internal Noise Increases (Δ) of Transverse Rumble Strips

Transverse Rumble Strips						
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
External Δ at 50 ft (dBA)	**Sedan**	10.4	6.4	3.0	5.6	6.5
	SUV	9.2	8.2	1.9	8.8	8.0
	Truck	8.2	6.8	3.6	6.9	6.6
External Δ at 25 ft (dBA)	**Sedan**	12.6	9.6	6.6	7.5	9.8
	SUV	12.2	10.7	5.8	10.8	11.0
	Truck	9.0	7.9	5.5	8.0	8.0
Internal Δ (dBA)	**Sedan**	14.1	12.6	10.5	12.9	12.5
	SUV	14.1	12.5	10.2	13.3	12.2
	Truck	4.8	3.0	2.2**	3.0	3.6

** Internal noise increase that is slightly out of NCHRP recommended range of 3 to 15 dBA noise increase.

CHAPTER 5: SECOND ROUND OF FIELD EVALUATIONS

This chapter presents the findings of the second round of field evaluations that were designed to collect and analyze (a) external noise data generated by the 15 top-performing rumble strip designs identified in the initial round of field evaluations and (b) internal noise data generated by the entire set of 25 rumble strip designs. The following sections focus on the test vehicles used in the field evaluations, collection and analysis of external noise data, and collection and analysis of internal noise data.

TEST VEHICLES

A total of 10 test vehicles were used to collect external and internal noise data generated by the constructed rumble strip designs on US-45. These 10 test vehicles were selected in consultation with the Technical Review Panel to provide a representative sample of vehicles on Illinois roads with adequate variations in type, size, weight, and model, as shown in Table 8 and Figure 45. The 10 test vehicles were all used to drive over each rumble strip design at 50 mph in cruise control mode for at least five seconds for all longitudinal rumble strips and over each entire transverse rumble strip panel during the collection of external and internal noise data.

Table 8. Test Vehicles Used in the Second Round of Field Evaluations

#	Vehicle Make	Vehicle Type	Size	Weight	Model
a	Nissan Versa	Sedan	Compact	2,505 pounds	2018
b	Dodge Challenger	Sedan	Full-size	4,415 pounds	2023
c	Genesis G80	Electric Sedan	Full-size	4,453 pounds	2023
d	Ford Escape	SUV	Compact	3,668 pounds	2020
e	Chevrolet Suburban	SUV	Full-size	5,896 pounds	2015
f	Dodge Grand Caravan	Minivan	Minivan	4,510 pounds	2018
g	Toyota Tacoma	Pick-up Truck	Standard	4,550 pounds	2022
h	Chevrolet Silverado 1500	Pick-up Truck	1/2 Ton	5,620 pounds	2022
i	Box Truck GMC G-3500	Box Truck	10 ft	8,600 pounds	2012
j	Freightliner SD	Truck	Semi-Trailer	80,500 pounds	2018

(a) Compact sedan (b) Full-size sedan (c) Full-size electric sedan

(d) Compact SUV (e) Full-size SUV (f) Minivan

(g) Standard pick-up truck (h) 1/2 Ton pick-up truck (i) Box truck

(j) Semi-trailer truck

Figure 45. Photo. Test vehicles used in second round of field evaluations.

COLLECTION AND ANALYSIS OF EXTERNAL NOISE DATA

The external noise data produced by all 15 rumble strip designs were collected using the same measurement equipment and procedure used in the initial round of field evaluations in accordance with the AASHTO T 389-20 test method. The total duration of this round of field evaluations was 23 workdays, starting on October 23 and ending on December 5, 2023. This duration excludes days with adverse weather conditions caused by high winds and precipitation.

For each rumble strip design, external noise data were collected using (a) 12 valid passes by the sedans, SUVs, minivan, and standard pick-up truck traveling at 50 mph and (b) at least three valid passes by the 1/2 ton pick-up truck, box truck, and semi-trailer truck due to the challenges of operating and driving these trucks over each rumble strip design at 50 mph. External noise data were collected every 0.5 seconds for each rumble strip design at 25 and 50 feet. The collected noise data were analyzed to identify pavement baseline external noise levels and rumble strip external noise levels generated by each test vehicle driving over the rumble strips at 50 mph. For each combination of rumble strip design and test vehicle at both 25- and 50-foot distances, the collected noise data were analyzed to calculate the average baseline and rumble strip external noise levels, as shown in Figures 46, 47, 48, 49, 50, and 51, and the average increase (Δ) in external noise levels caused by each rumble strip design, as shown in Figures 52, 53, 54, 55, 56, 57, 58, and 59. The external noise data analysis and results including sample size, average, and standard deviation for all combinations of rumble strip designs, test vehicles, and measurement distances, are included in Appendix E.

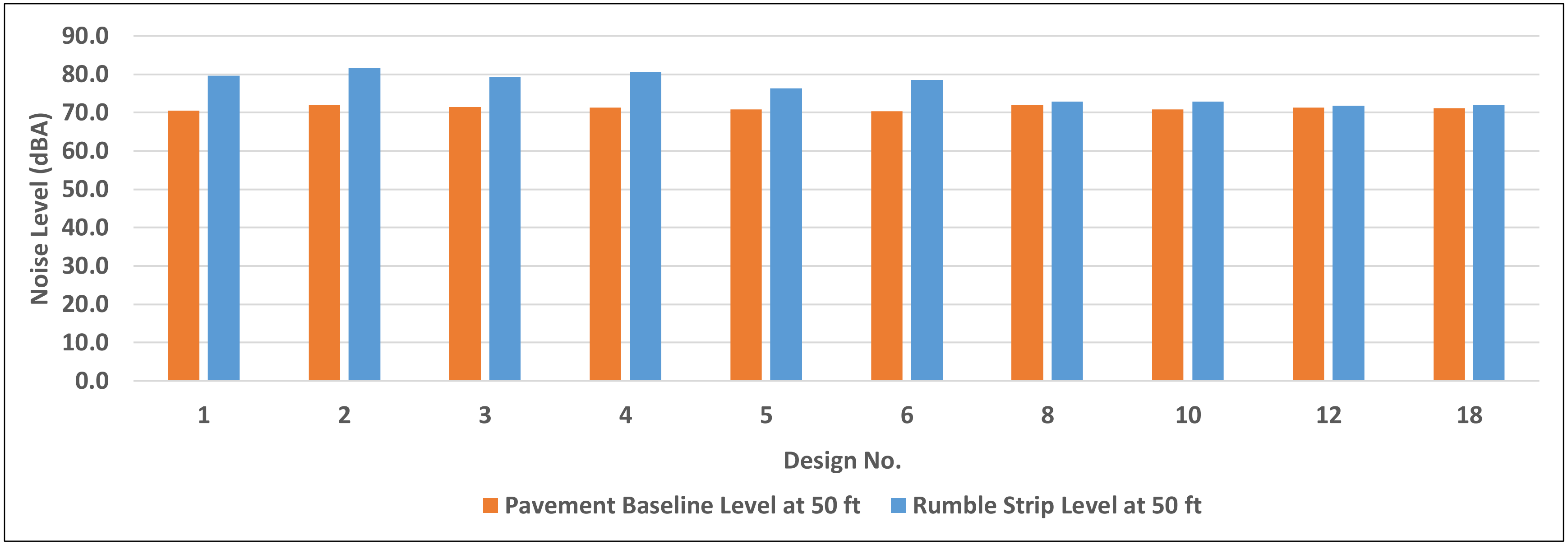


Figure 46. Graph. External noise of compact sedan and longitudinal rumble strips at 50 ft.

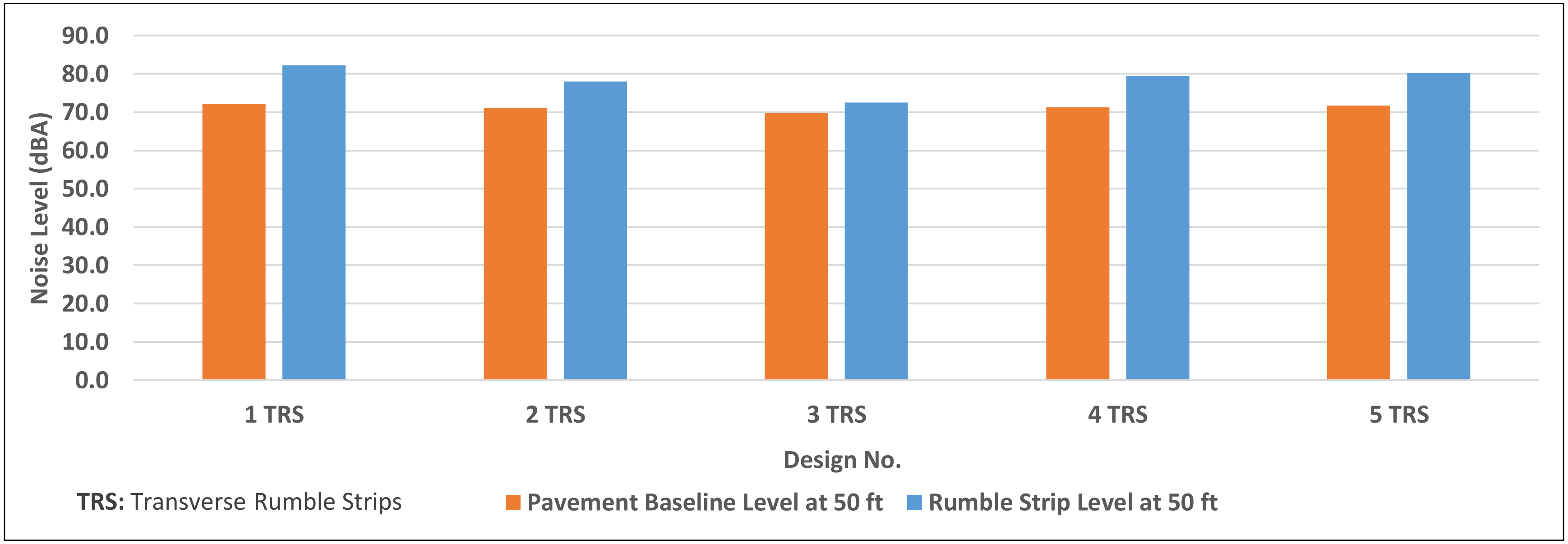


Figure 47. Graph. External noise of compact sedan and transverse rumble strips at 50 ft.

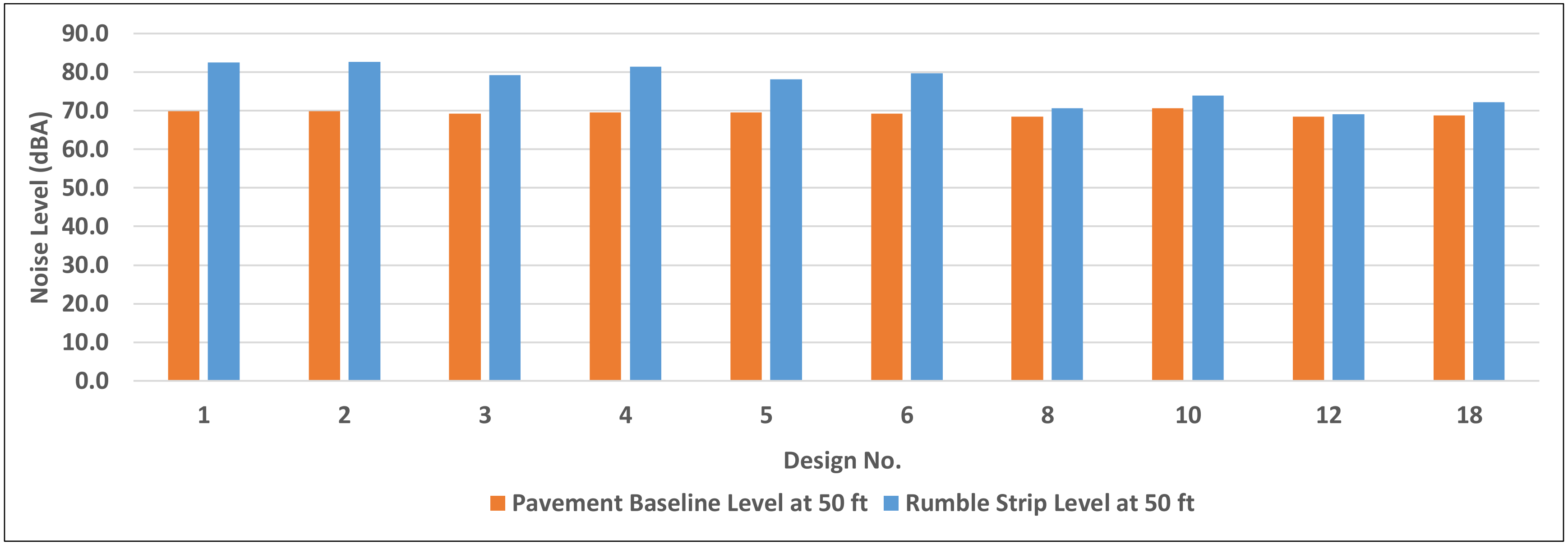


Figure 48. Graph. External noise of compact SUV and longitudinal rumble strips at 50 ft.

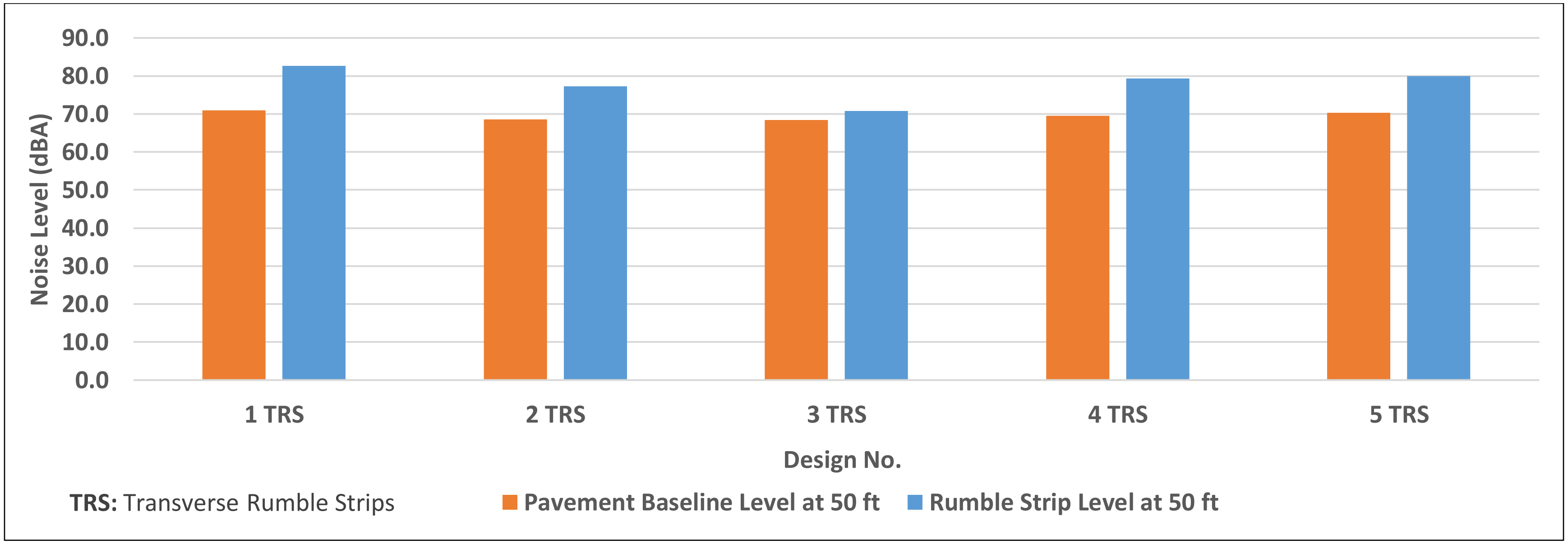


Figure 49. Graph. External noise of compact SUV and transverse rumble strips at 50 ft.

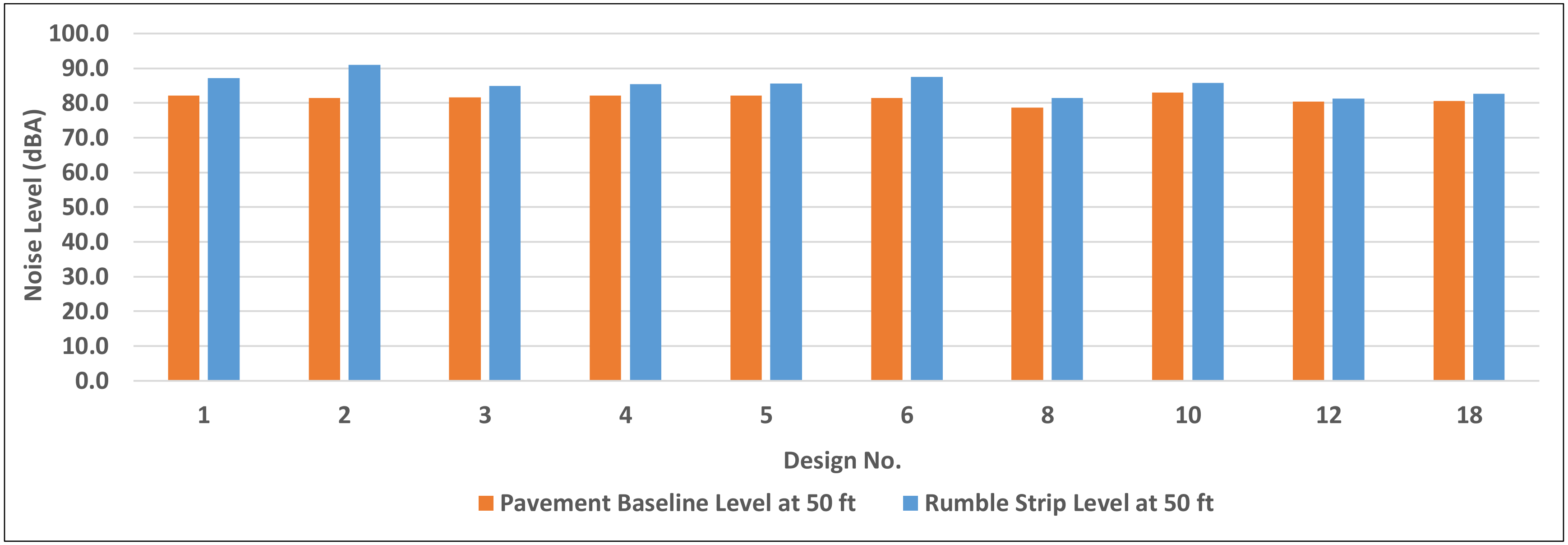


Figure 50. Graph. External noise of semi-trailer truck and longitudinal rumble strips at 50 ft.

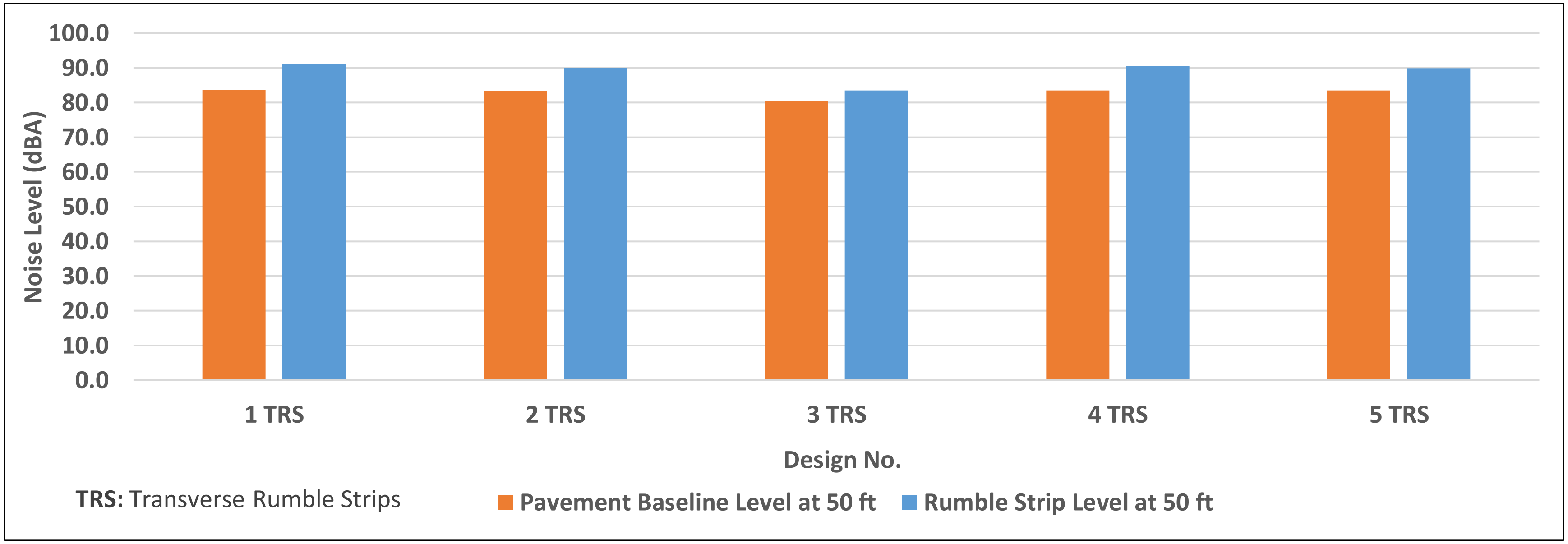


Figure 51. Graph. External noise of semi-trailer truck and transverse rumble strips at 50 ft.

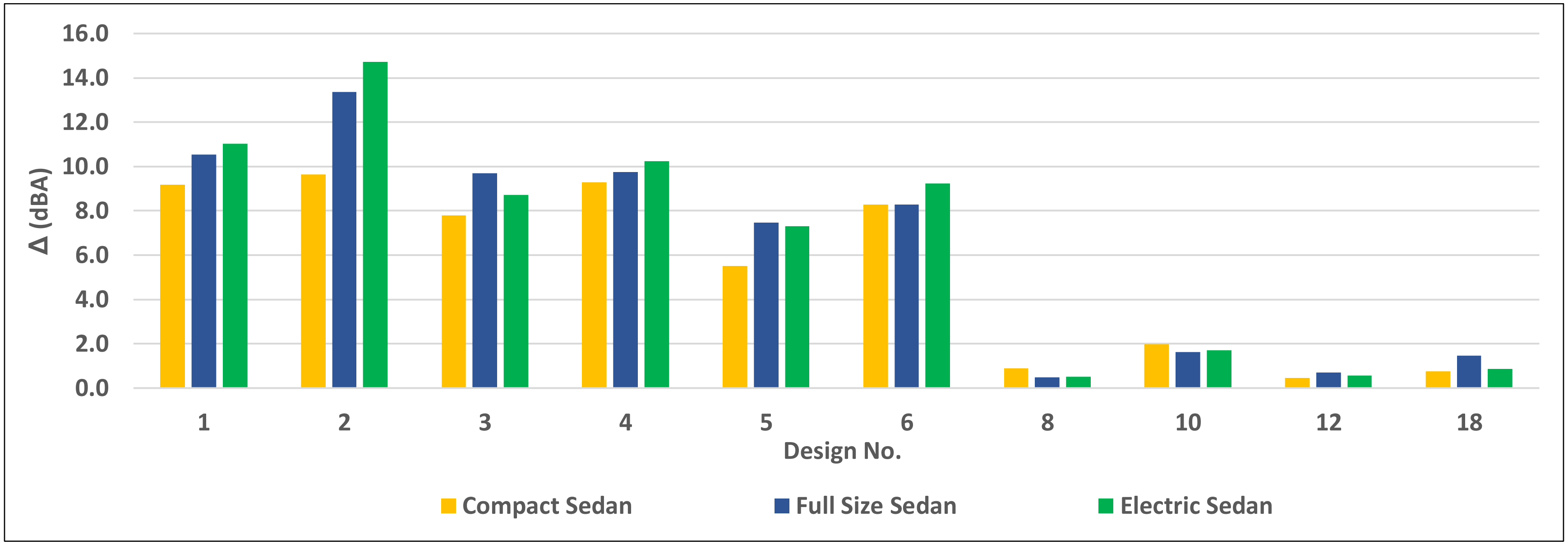


Figure 52. Graph. External noise increase (Δ) at 50 ft of sedans and longitudinal rumble strips.

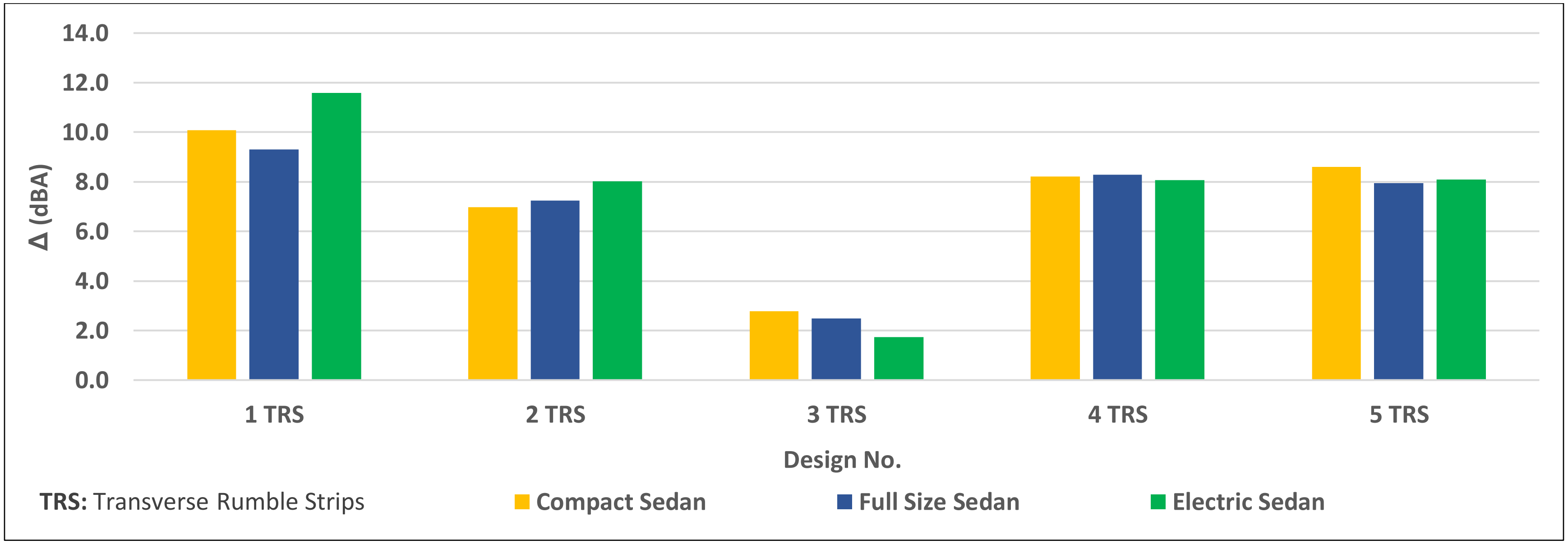


Figure 53. Graph. External noise increase (Δ) at 50 ft of sedans and transverse rumble strips.

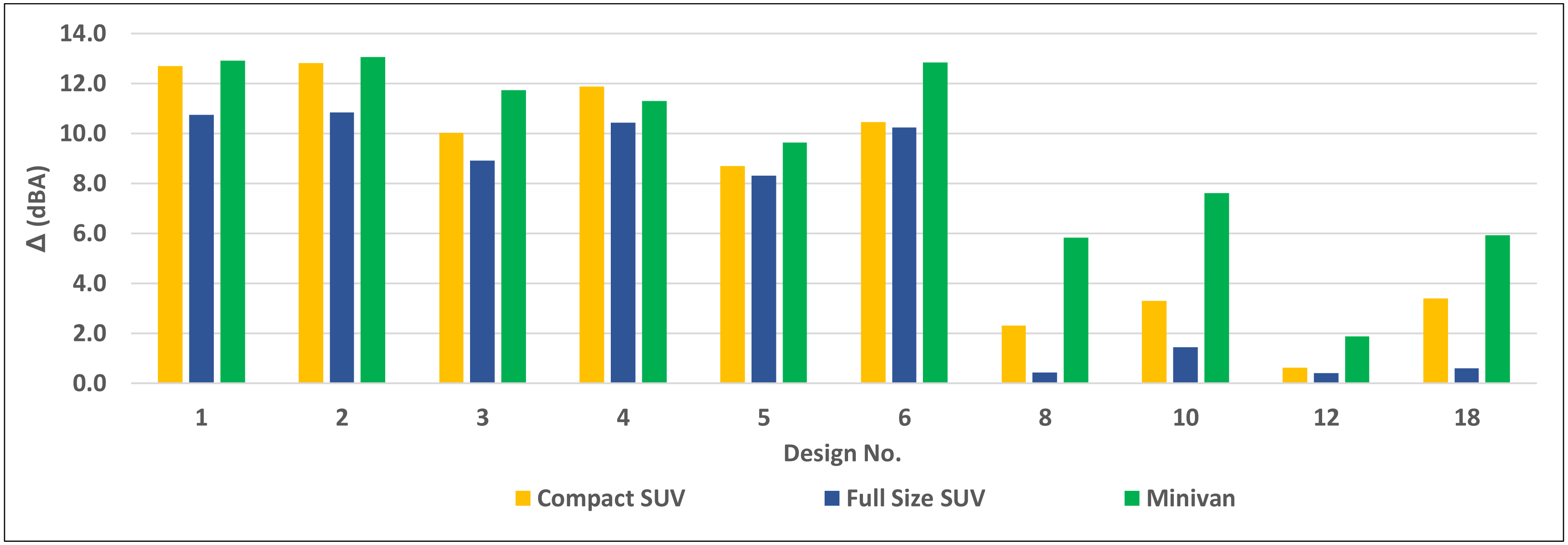


Figure 54. Graph. External noise increase (Δ) at 50 ft of SUVs, minivan, and longitudinal rumble strips.

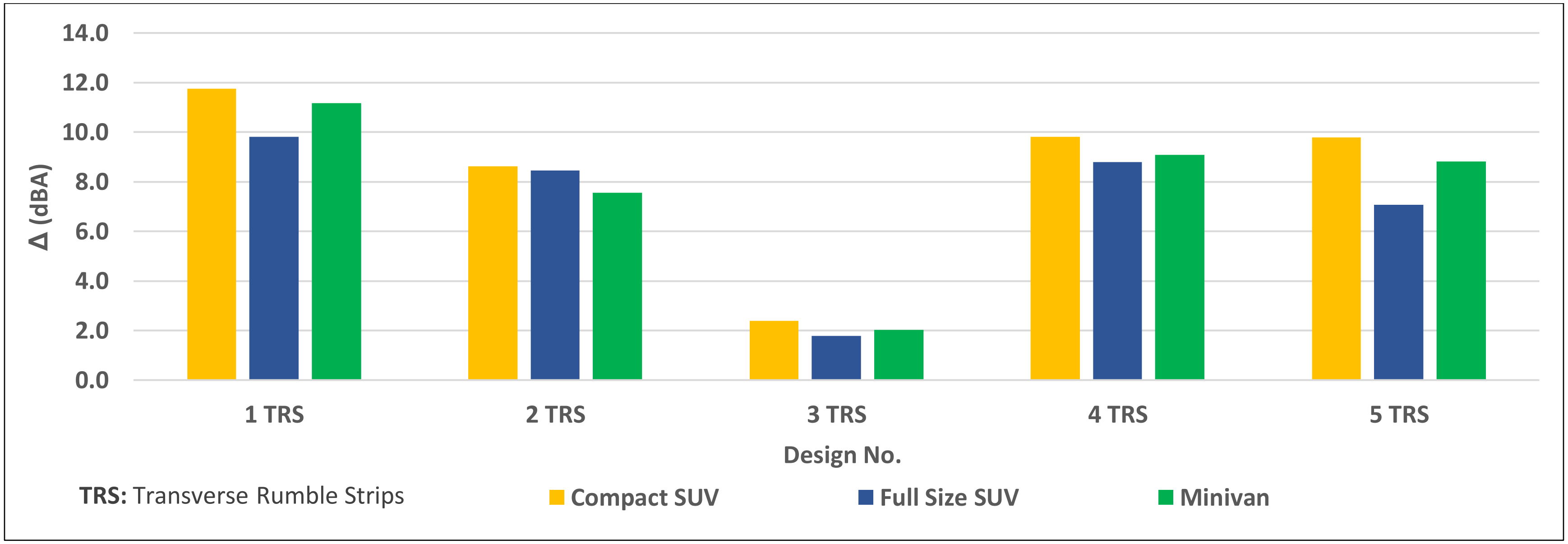


Figure 55. Graph. External noise increase (Δ) at 50 ft of SUVs, minivan, and transverse rumble strips.

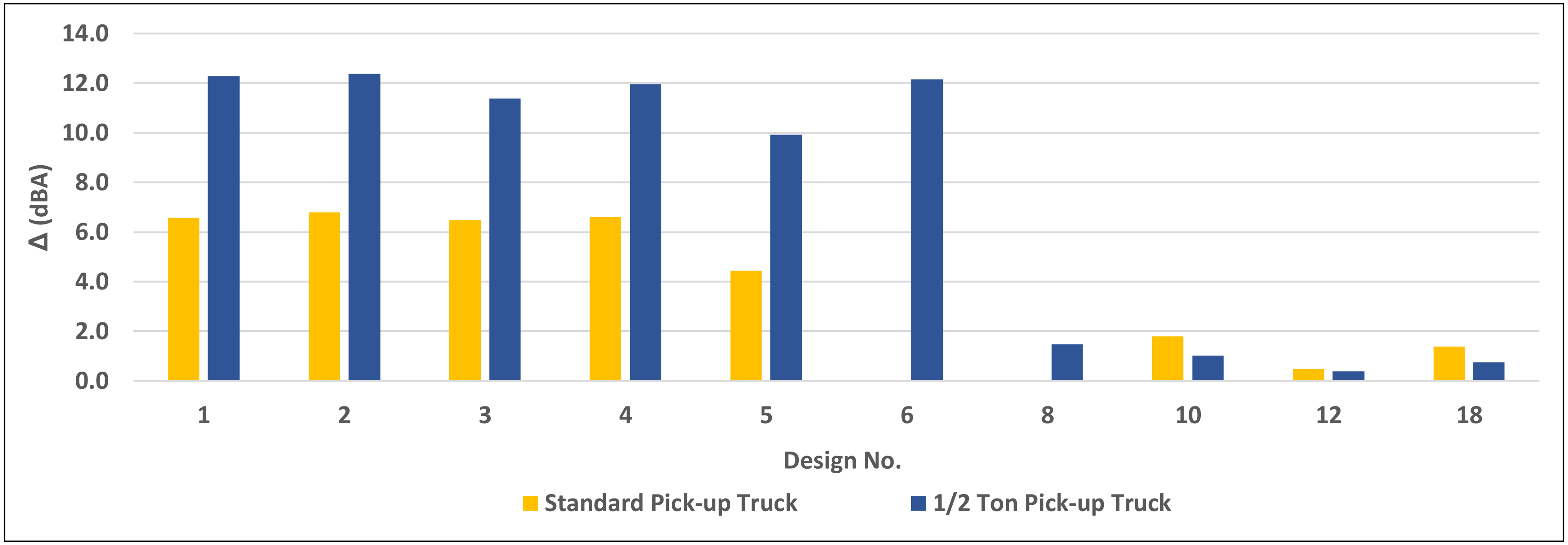


Figure 56. Graph. External noise increase (Δ) at 50 ft of pick-up trucks and longitudinal rumble strips.

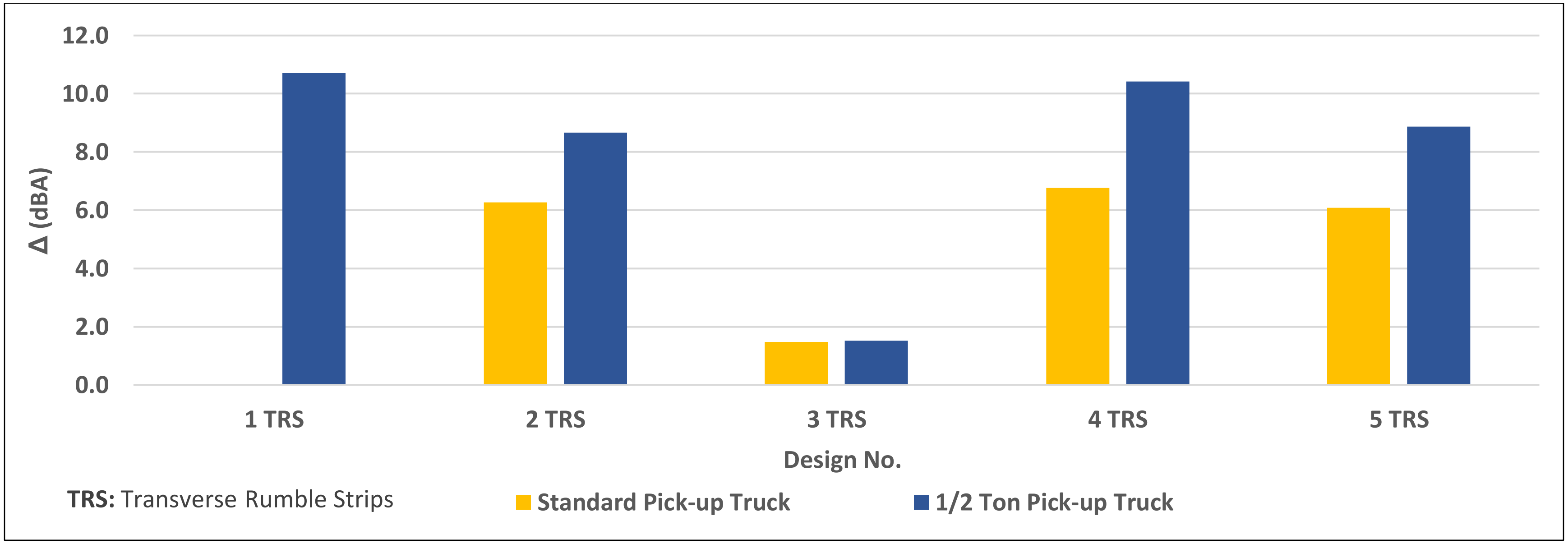


Figure 57. Graph. External noise increase (Δ) at 50 ft of pick-up trucks and transverse rumble strips.

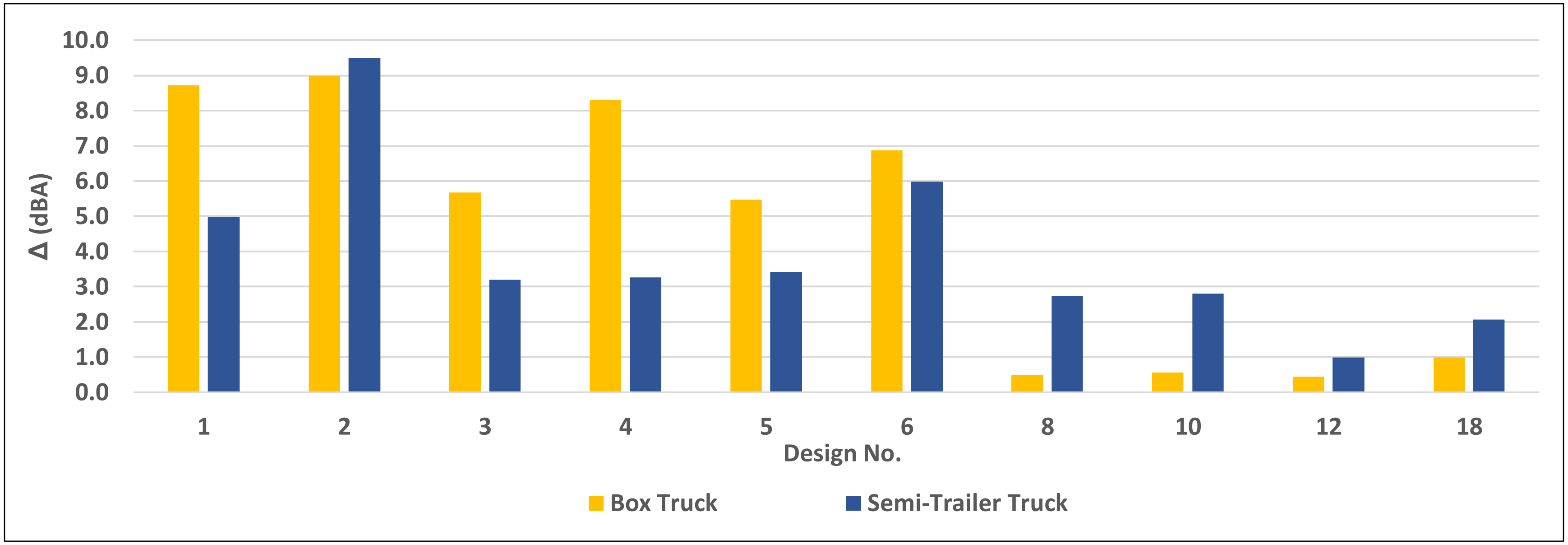


Figure 58. Graph. External noise increase (Δ) at 50 ft of trucks and longitudinal rumble strips.

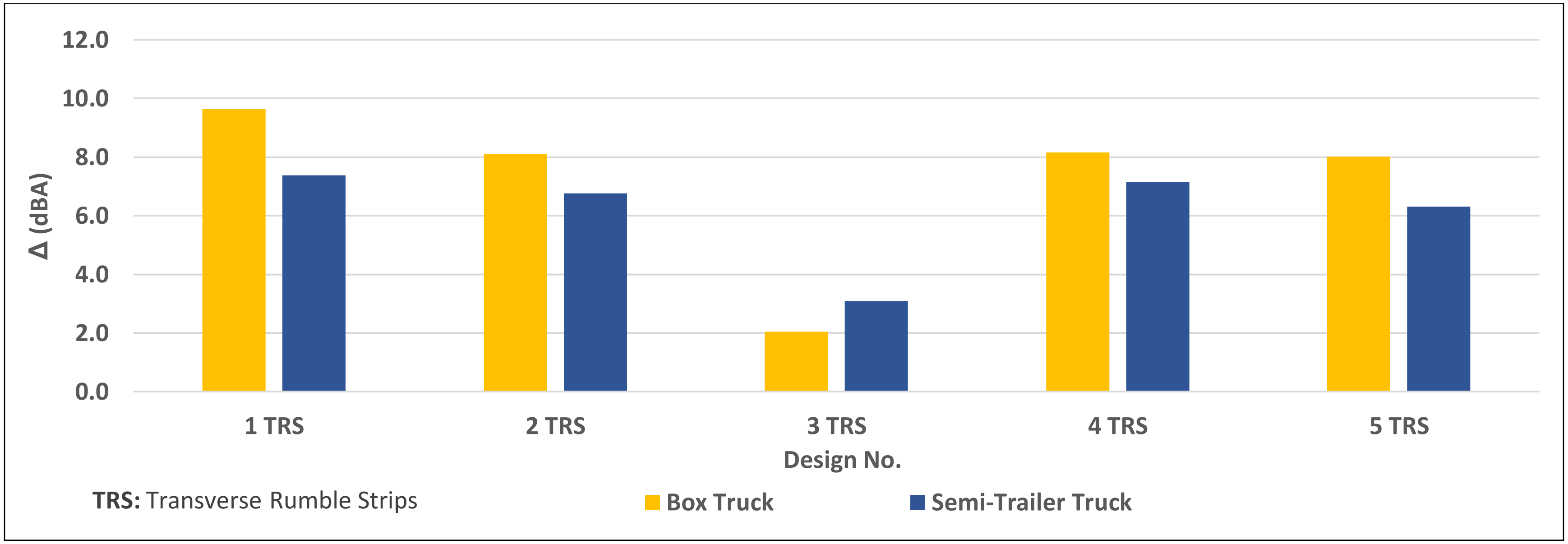


Figure 59. Graph. External noise increase (Δ) at 50 ft of trucks and transverse rumble strips.

COLLECTION AND ANALYSIS OF INTERNAL NOISE DATA

The internal noise measurement data of the 25 rumble strip designs were collected during the same period of the external noise measurement collection from October 23 to December 5, 2023. Internal noise data collection used the same equipment and procedures used in the initial round of field evaluations in accordance with SAE J1477 (2000).

Internal noise data generated by the 10 test vehicles were collected at intervals of 0.5 seconds for all 25 rumble strip designs. For each rumble strip design, the internal noise data were collected using (a) six valid passes by the sedans, SUVs, minivan, pick-up trucks, and box truck traveling at 50 mph and (b) four valid passes by the semi-trailer truck at 50 mph. The collected data were analyzed to identify pavement baseline internal noise levels and rumble strip internal noise levels generated by each test vehicle driving over the rumble strips at 50 mph. For each combination of rumble strip design and test vehicle, the collected noise data were analyzed to calculate the average baseline and rumble strip internal noise levels, as shown in Figures 60, 61, 62, 63, 64, and 65, and the average increase (Δ) in internal noise levels caused by each rumble strip design, as shown in Figures 66, 67, 68, 69, 70, 71, 72, and 73. The internal noise data analysis and results, including sample size, average, and standard deviation for all combinations of rumble strip designs and test vehicles, are included in Appendix E. The results of this internal noise data can be used to analyze the effectiveness of all 25 rumble strip designs in alerting inattentive drivers based on NCHRP recommendations that require rumble strips to generate an internal noise level increase of 3 to 15 dBA to ensure their effectiveness (NCHRP 641, 2009).

The effectiveness of the 20 longitudinal and 5 transverse rumble strip designs in alerting inattentive drivers was analyzed based on their generated internal noise level increases in all 10 test vehicles. Based on NCHRP recommendations, rumble strips need to generate an internal noise level increase of 3 to 15 dBA to ensure their effectiveness (NCHRP 641, 2009). For the longitudinal rumble strips, 14 designs (1, 3, 4, 5, 6, 8, 10, 12, 13, 15, 16, 17, 18, and 19) were capable of fully satisfying the NCHRP recommendations of a 3–15 dBA internal noise level increase for all 10 test vehicles, as shown in Table 9. Additionally, one longitudinal rumble strip design (9) fully satisfied the NCHRP recommended range for nine test vehicles; however, it was slightly insufficient to meet the minimum threshold of 3 dBA for the tested semi-trailer truck, as shown in Table 9. Similarly, five longitudinal rumble strip designs (2, 7, 11, 14, and 20) fully satisfied the NCHRP recommended range for nine test vehicles; however, they did not satisfy the recommended NCHRP minimum limit of 3 dBA. Design 2 generated an internal noise level increase of 16.8 dBA for the tested compact sedan, which exceeds the 15-dBA NCHRP limit, as shown in Table 9. Designs 7, 11, 14, and 20 generated an internal noise level increase of 1.6, 2, 1.9, and 1.7 dBA for the tested semi-trailer truck, respectively, which were insufficient to meet the NCHRP minimum threshold of 3 dBA, as shown in Table 9.

For the transverse rumble strips, only design 2 was capable of fully satisfying the NCHRP recommendations of a 3–15 dBA internal noise level increase for all 10 test vehicles, as shown in Table 9. Two additional transverse rumble strip designs (3 and 5) fully satisfied the NCHRP recommended range for nine test vehicles; however, they were slightly out of the NCHRP recommended range of a 3–15 dBA internal noise level increase. Transverse design 3 generated an internal noise level increase of 2.7 dBA in the tested semi-trailer truck, which is slightly less than the 3-dBA NCHRP limit, as shown in Table 10. Likewise, transverse design 5 generated an internal noise level increase of 15.2 dBA in the compact sedan, which slightly exceeds the 15-dBA NCHRP limit, as shown in Table 10. Similarly, transverse design 1 fully satisfied the NCHRP recommended range for nine test vehicles; however, it generated an internal noise level increase of 18.4 dBA in the compact sedan, which exceeds the NCHRP maximum threshold of 15 dBA, as shown in Table 10. Additionally, transverse design 4 fully satisfied the NCHRP recommended range for nine test vehicles, but it generated internal noise level increases of 18.2 and 16.5 dBA in the tested compact sedan and electric vehicle, respectively, which exceeded the NCHRP maximum threshold of 15 dBA, as shown in Table 10.

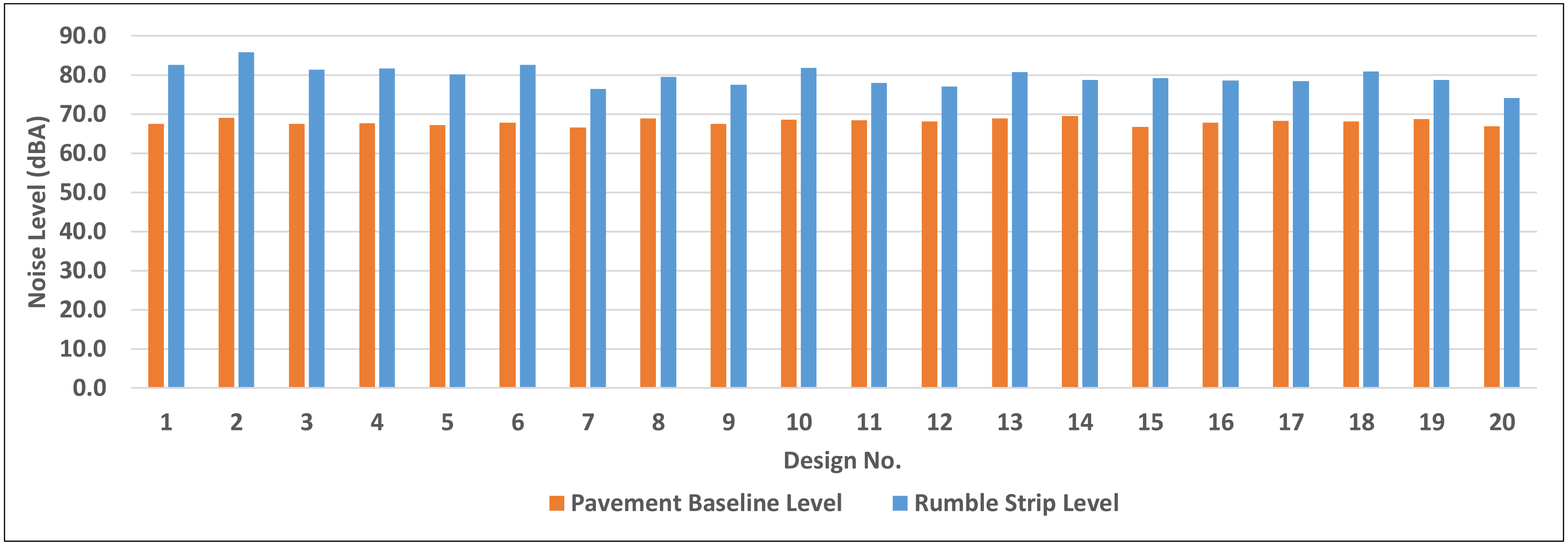


Figure 60. Graph. Internal noise of compact sedan and longitudinal rumble strips.

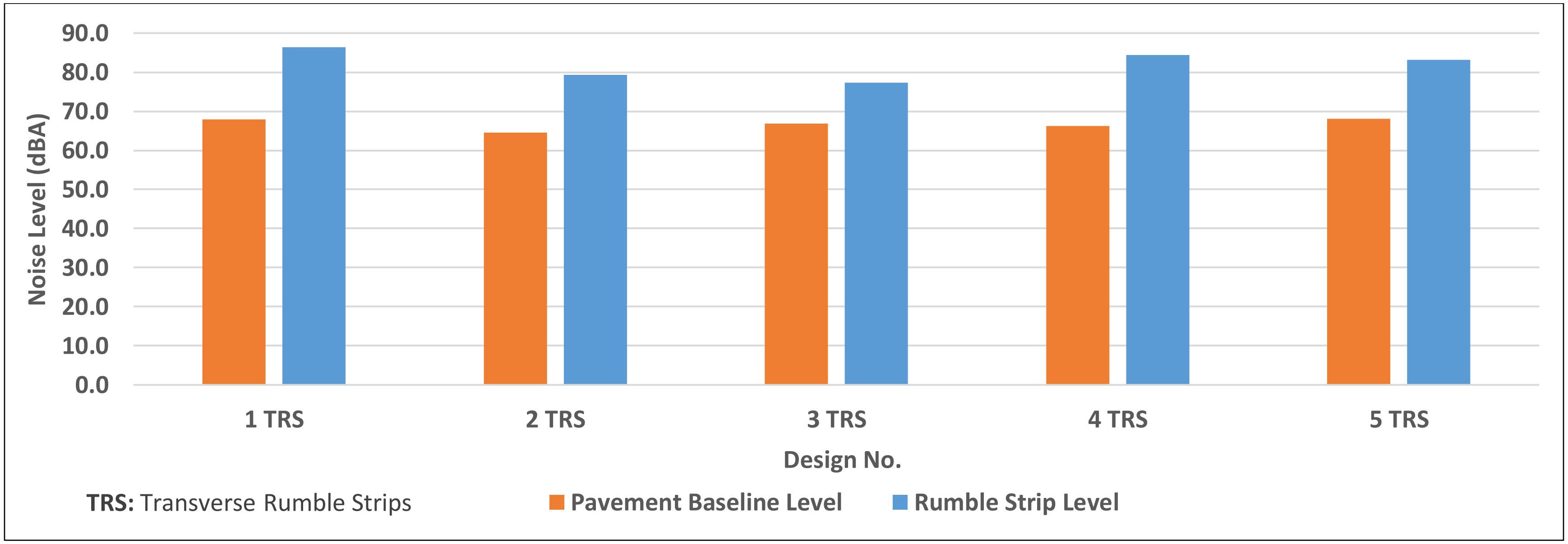


Figure 61. Graph. Internal noise of compact sedan and transverse rumble strips.

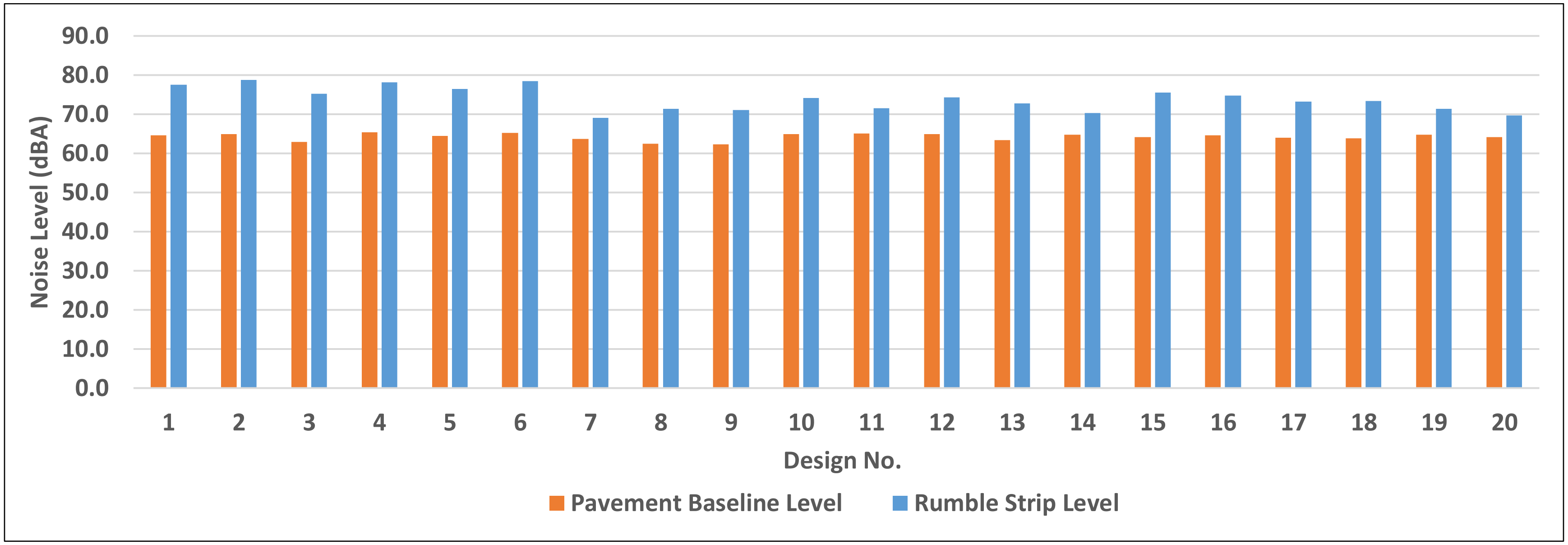


Figure 62. Graph. Internal noise of compact SUV and longitudinal rumble strips.

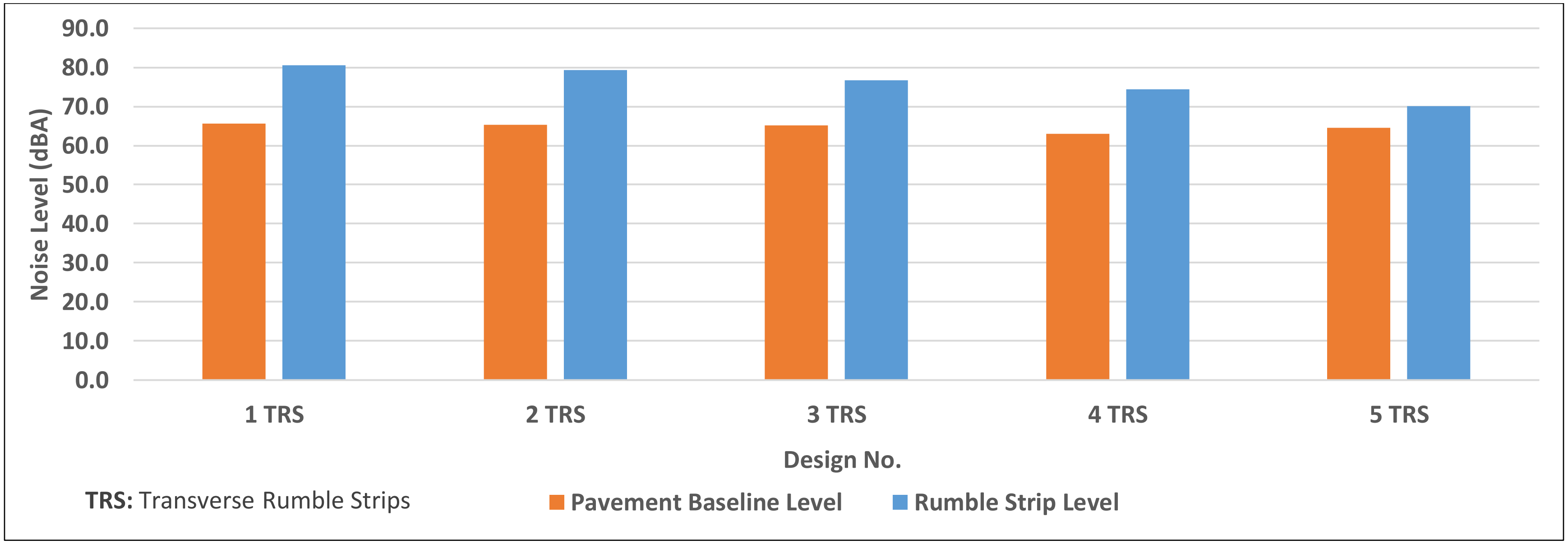


Figure 63. Graph. Internal noise of compact SUV and transverse rumble strips.

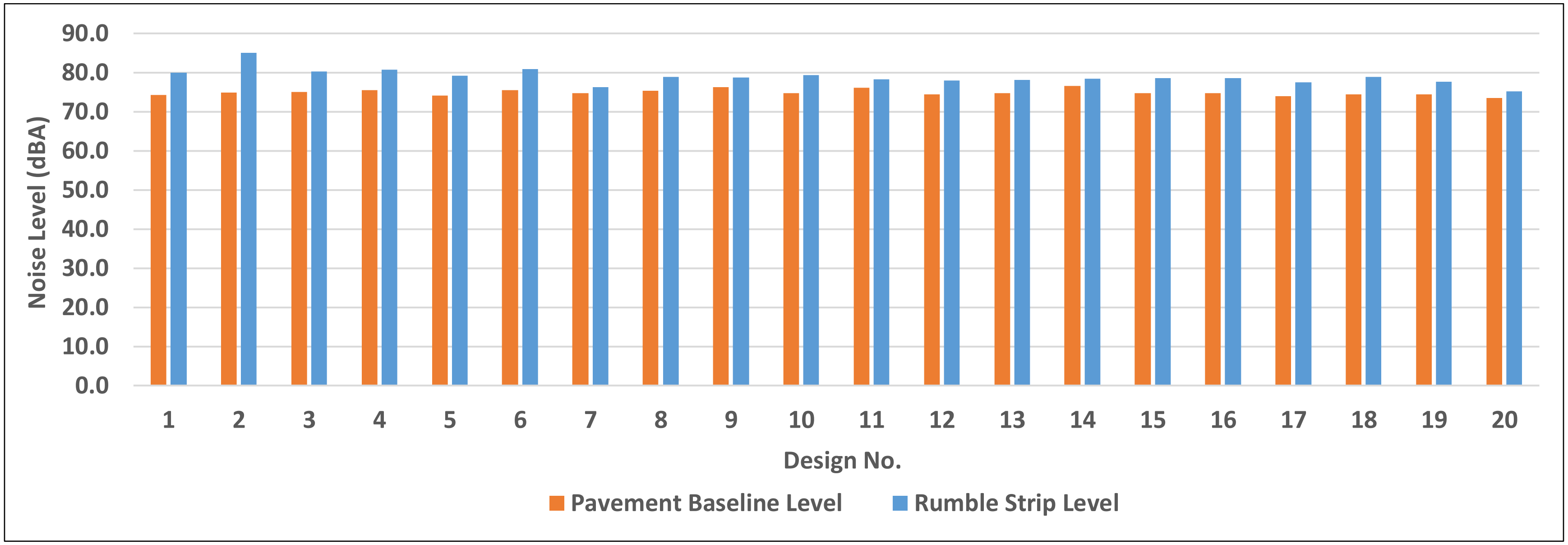


Figure 64. Graph. Internal noise of semi-trailer truck and longitudinal rumble strips.

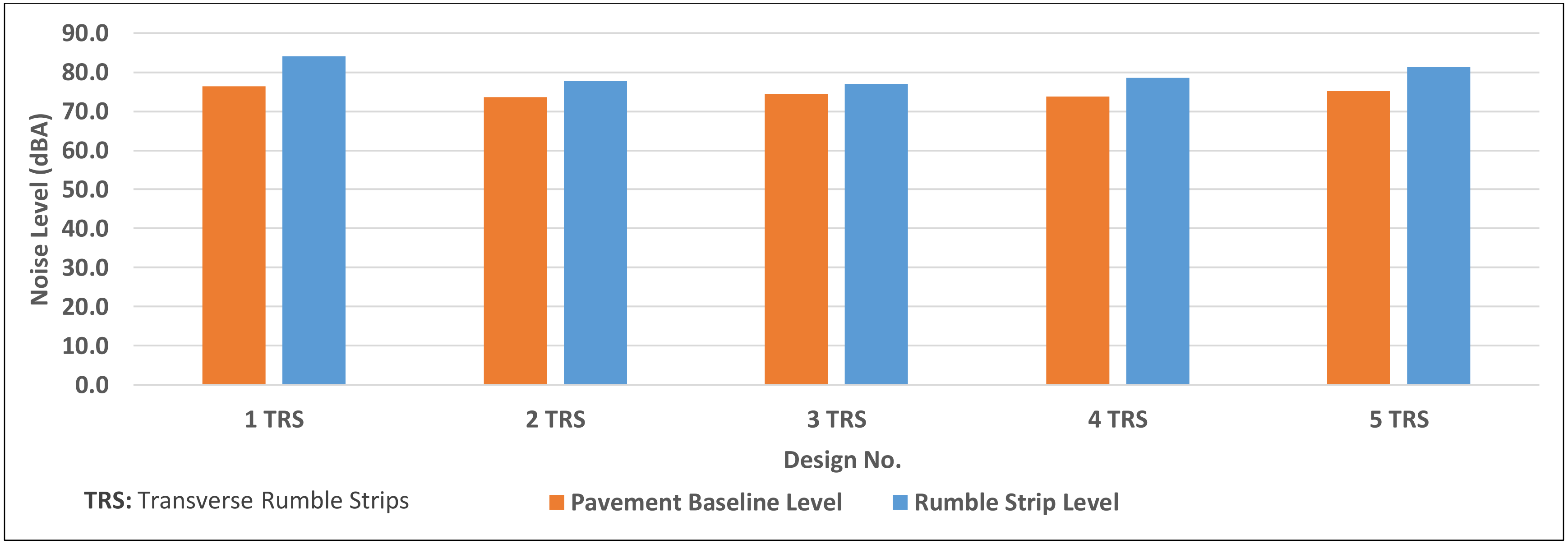


Figure 65. Graph. Internal noise of semi-trailer truck and transverse rumble strips.

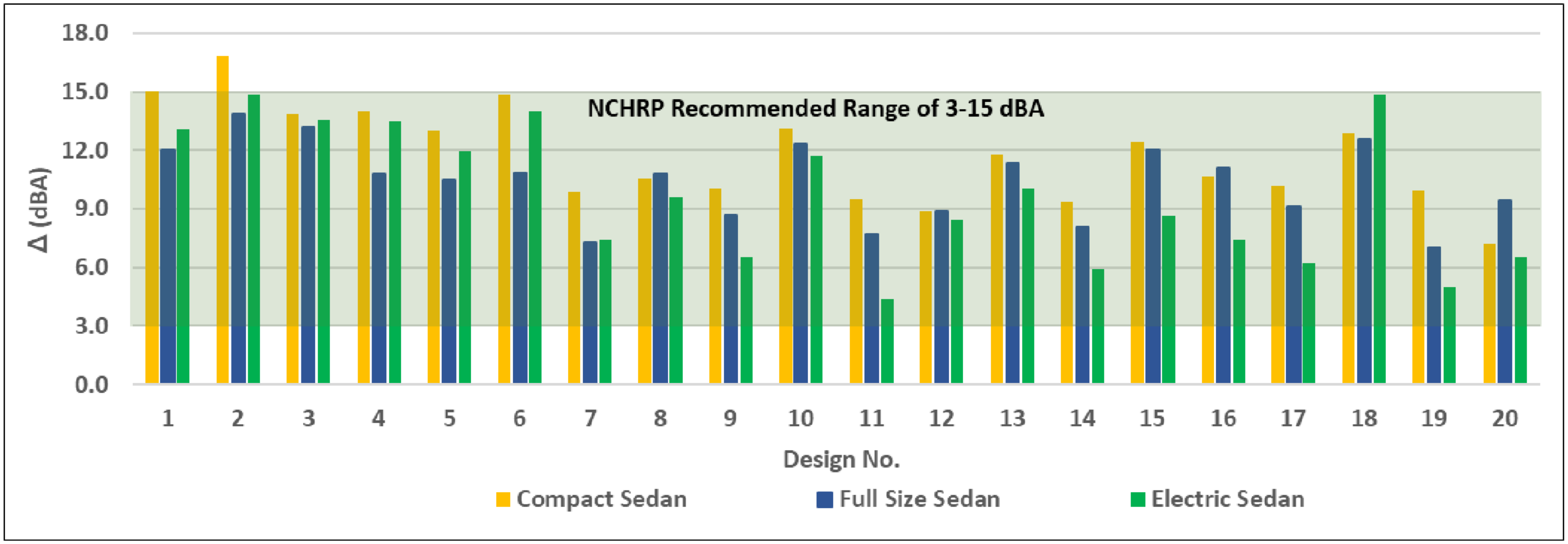


Figure 66. Graph. Internal noise increase (Δ) of sedans and longitudinal rumble strips.

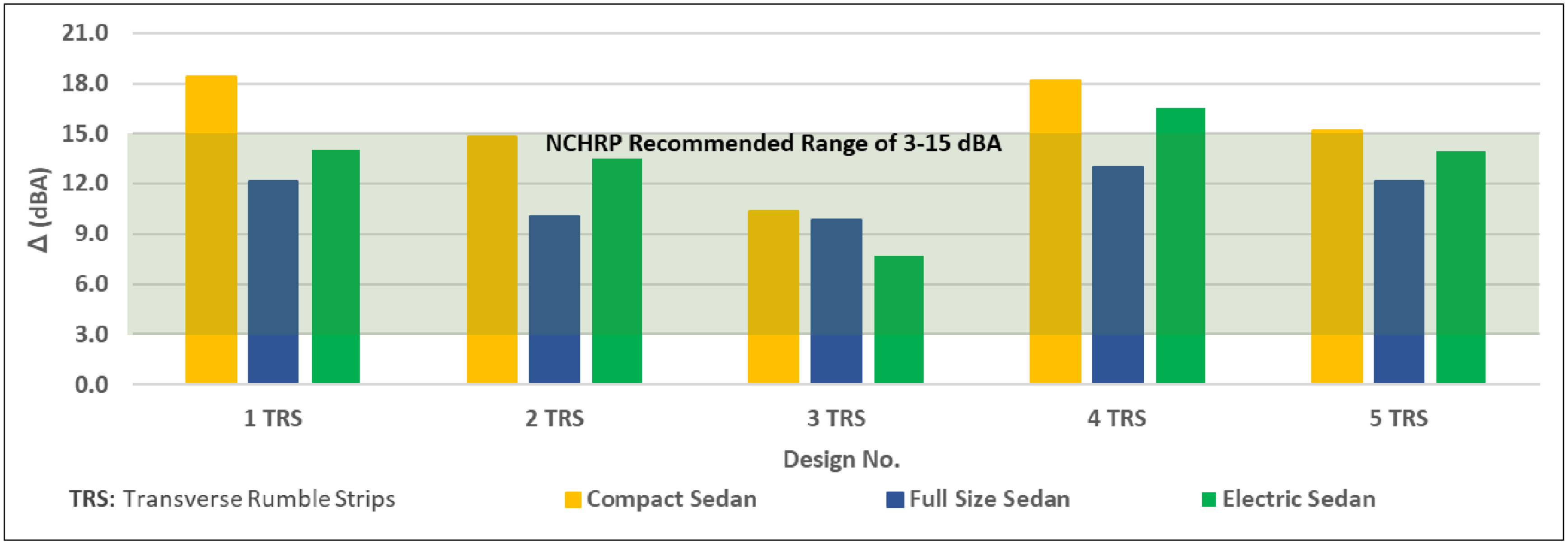


Figure 67. Graph. Internal noise increase (Δ) of sedans and transverse rumble strips.

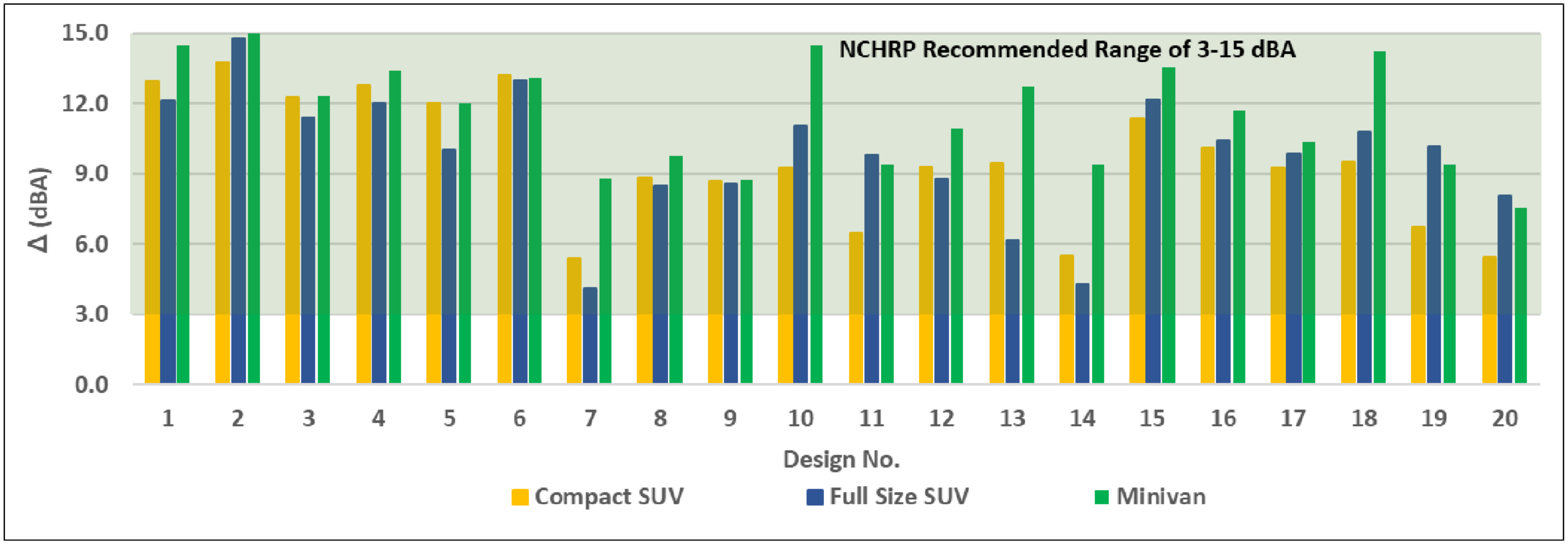


Figure 68. Graph. Internal noise increase (Δ) of SUVs, minivan, and longitudinal rumble strips.

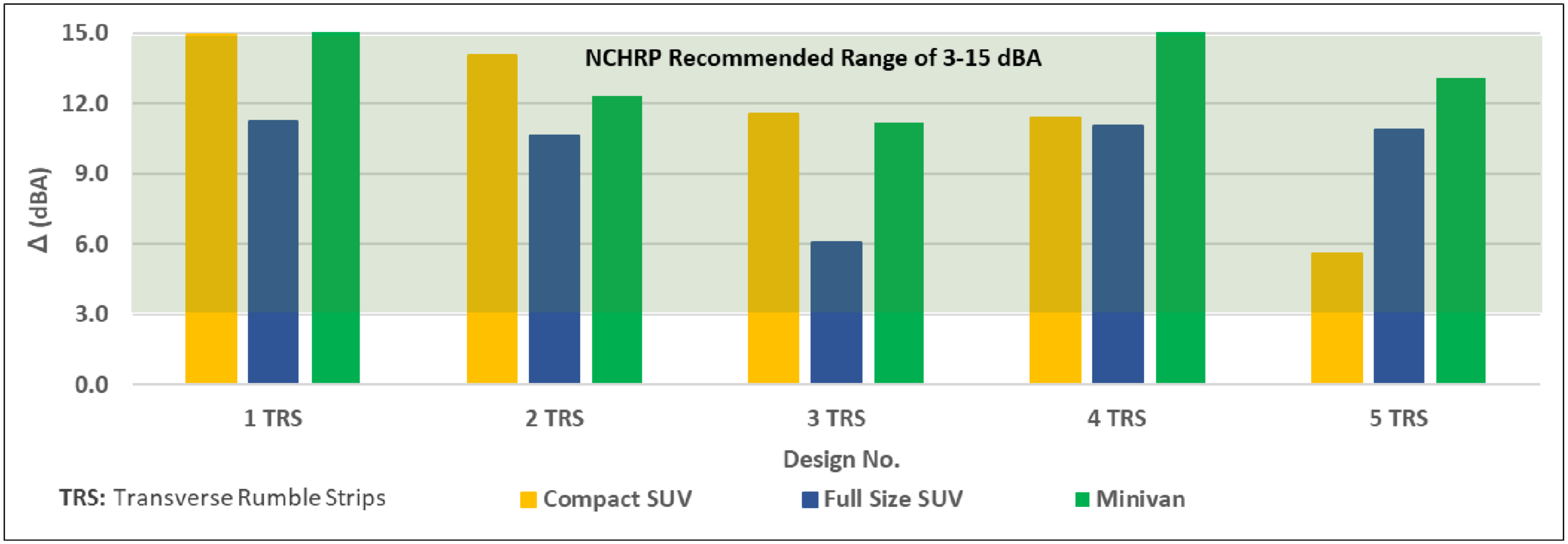


Figure 69. Graph. Internal noise increase (Δ) of SUVs, minivan, and transverse rumble strips.

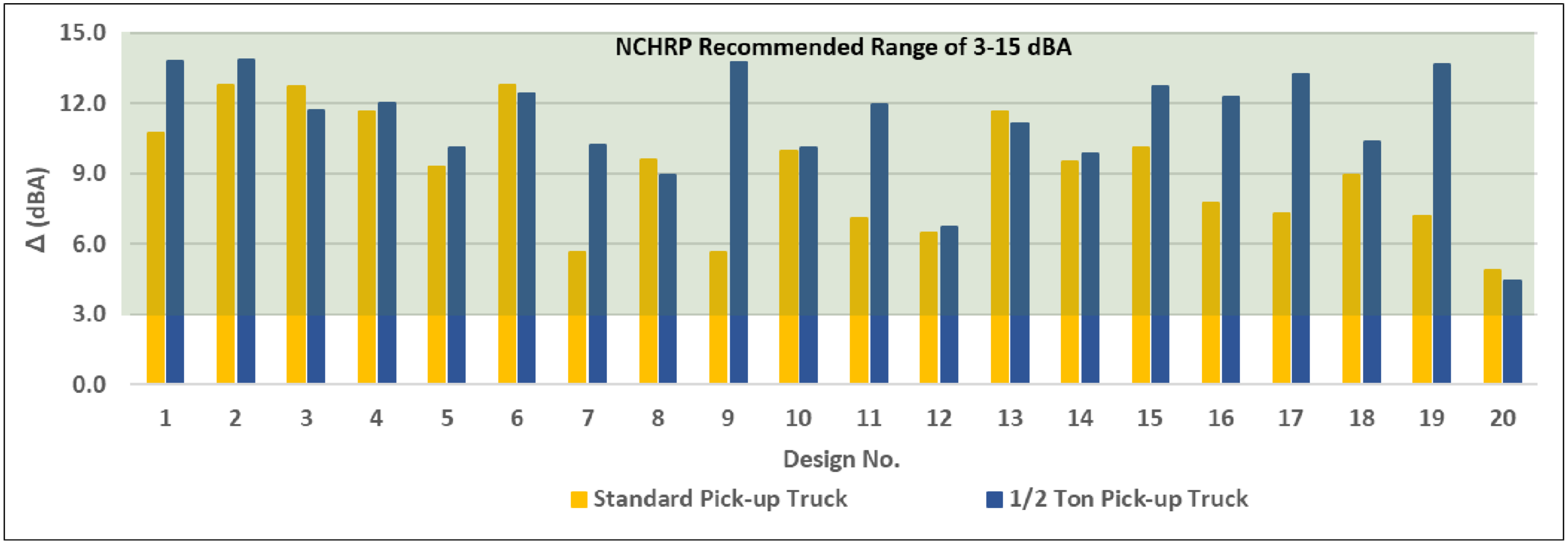


Figure 70. Graph. Internal noise increase (Δ) of pick-up trucks and longitudinal rumble strips.

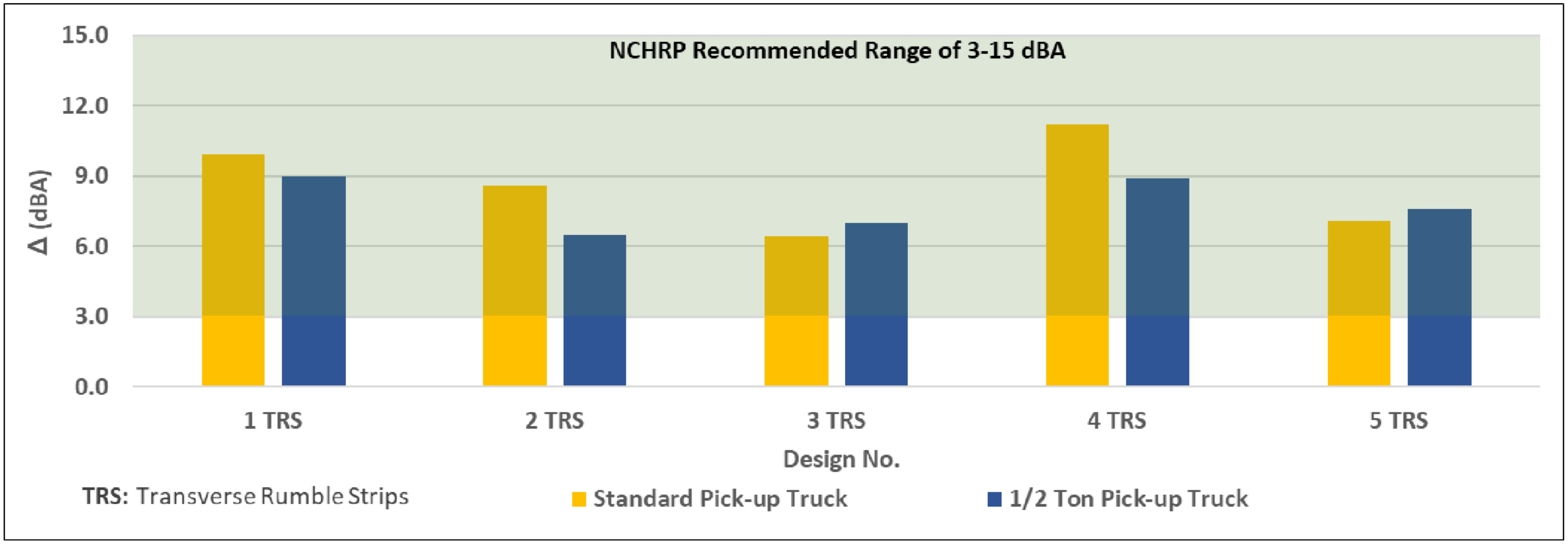


Figure 71. Graph. Internal noise increase (Δ) of pick-up trucks and transverse rumble strips.

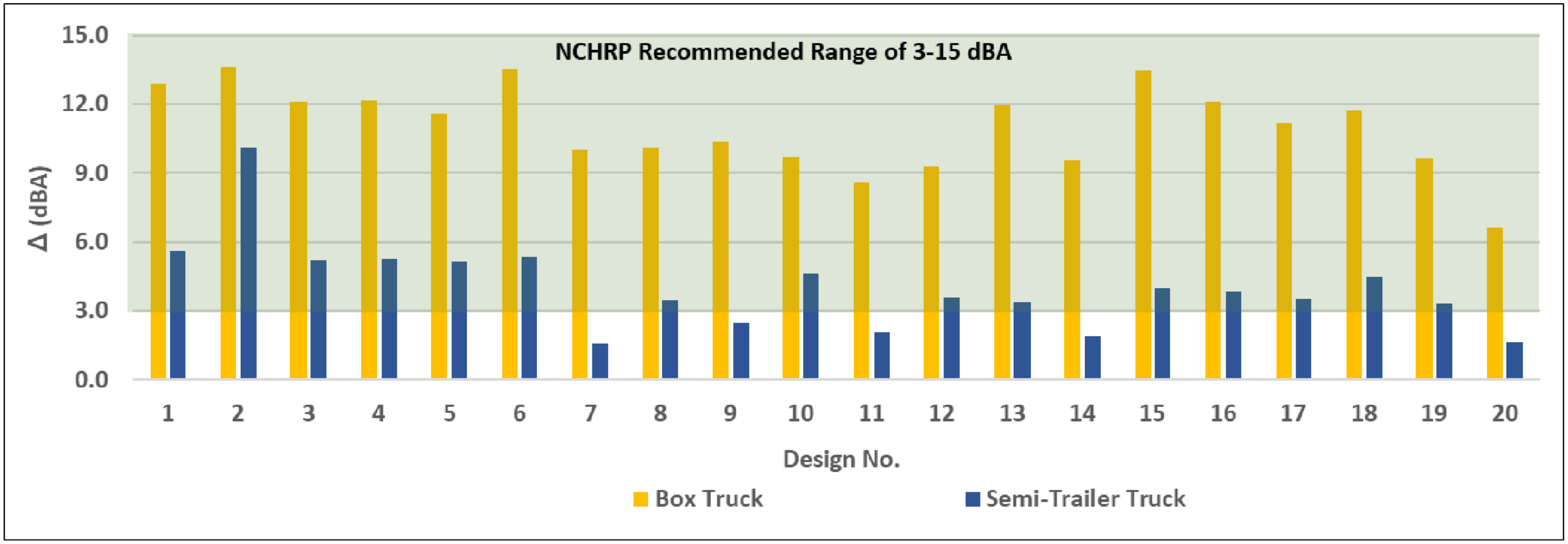


Figure 72. Graph. Internal noise increase (Δ) of trucks and longitudinal rumble strips.

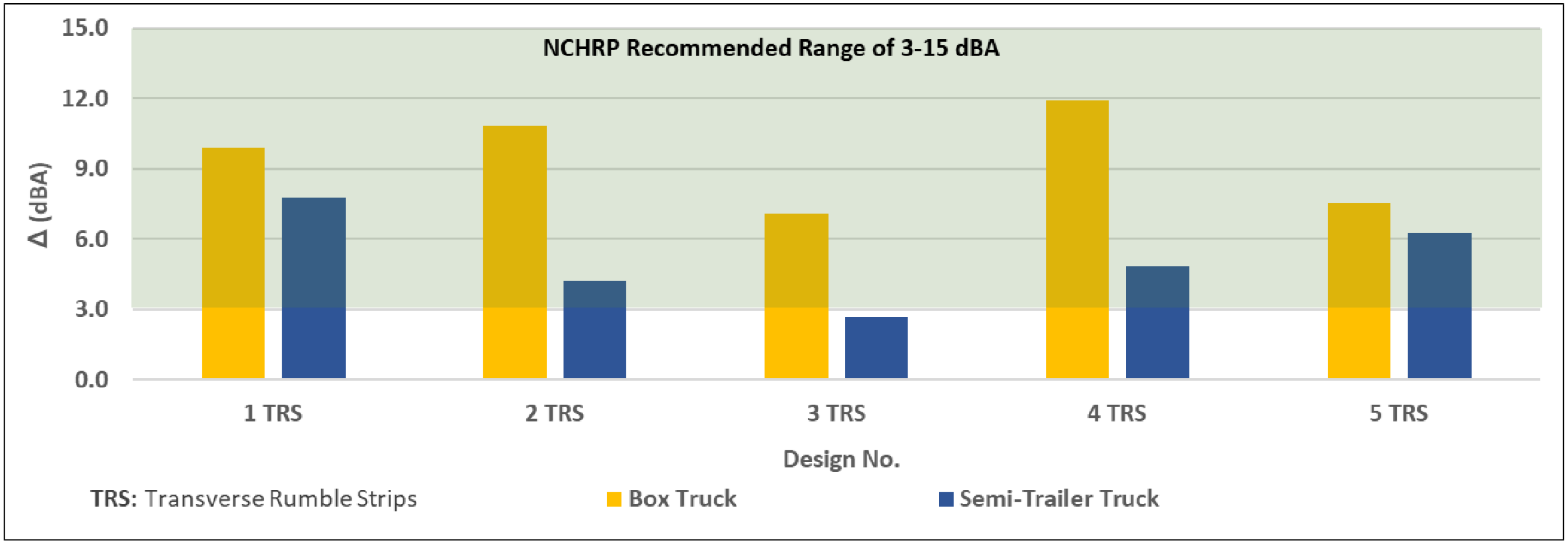


Figure 73. Graph. Internal noise increase (Δ) of trucks and transverse rumble strips.

Table 9. Internal Noise Increases (Δ) of Longitudinal Rumble Strips in Second-Round Evaluation

Internal Noise Increase Δ (dBA)																				
Design No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Semi-Trailer Truck	5.6	10.1	5.2	5.3	5.1	5.3	1.6*	3.5	2.5**	4.6	2.0*	3.6	3.4	1.9*	4.0	3.8	3.5	4.5	3.3	1.7*
Compact Sedan	15.0	16.8*	13.9	14.0	13.0	14.9	9.8	10.6	10.0	13.1	9.5	8.8	11.8	9.4	12.5	10.7	10.2	12.9	9.9	7.2
1/2 Ton Pick-up Truck	13.8	13.9	11.7	12.0	10.1	12.4	10.2	9.0	13.7	10.1	11.9	6.7	11.1	9.9	12.7	12.3	13.3	10.4	13.7	4.4
Full Size SUV	12.1	14.8	11.4	12.0	10.0	13.0	4.1	8.5	8.6	11.0	9.8	8.8	6.1	4.3	12.2	10.4	9.9	10.8	10.2	8.1
Box Truck	12.9	13.6	12.1	12.2	11.6	13.5	10.0	10.1	10.4	9.7	8.6	9.3	11.9	9.5	13.4	12.1	11.1	11.8	9.6	6.6
Standard Pick-up Truck	10.7	12.8	12.7	11.6	9.3	12.8	5.6	9.6	5.6	10.0	7.1	6.5	11.7	9.5	10.1	7.8	7.3	8.9	7.2	4.9
Minivan	14.5	15.0	12.3	13.4	12.0	13.1	8.8	9.8	8.7	14.5	9.4	10.9	12.7	9.4	13.5	11.7	10.4	14.2	9.4	7.6
Compact SUV	12.9	13.8	12.3	12.8	12.0	13.2	5.4	8.8	8.7	9.2	6.5	9.3	9.4	5.5	11.4	10.1	9.3	9.5	6.7	5.4
Electric Vehicle	13.0	14.9	13.5	13.5	12.0	14.0	7.4	9.6	6.6	11.7	4.4	8.4	10.1	5.9	8.6	7.4	6.3	14.8	5.0	6.6
Full Size Sedan	12.0	13.9	13.2	10.8	10.5	10.8	7.3	10.8	8.7	12.3	7.7	8.9	11.3	8.1	12.0	11.1	9.1	12.6	7.0	9.4

***** Internal noise increases that do not satisfy NCHRP recommended range of 3 to 15 dBA noise increase.

** Internal noise increases that are slightly out of NCHRP recommended range of 3 to 15 dBA noise increase.

Table 10. Internal Noise Increases (Δ) of Transverse Rumble Strips in Second-Round Evaluation

Internal Noise Increase Δ (dBA)					
Design No.	**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Semi-Trailer Truck	7.7	4.2	2.7**	4.8	6.3
Compact Sedan	18.4*	14.8	10.4	18.2*	15.2**
1/2 Ton Pick-up Truck	9.0	6.5	7.0	8.9	7.6
Full Size SUV	11.2	10.6	6.0	11.0	10.9
Box Truck	9.9	10.8	7.1	11.9	7.5
Standard Pick-up Truck	9.9	8.6	6.4	11.2	7.1
Minivan	15.0	12.3	11.2	15.0	13.1
Compact SUV	14.9	14.1	11.6	11.4	5.6
Electric Vehicle	14.0	13.5	7.7	16.5*	13.9
Full Size Sedan	12.2	10.1	9.9	13.0	12.1

* Internal noise increases that do not satisfy NCHRP recommended range of 3 to 15 dBA noise increase.

** Internal noise increases that are slightly out of NCHRP recommended range of 3 to 15 dBA noise increase.

INTERNAL AND EXTERNAL NOISE PERFORMANCE OF TESTED RUMBLE STRIPS

This section analyzes the overall performance of the identified top-performing rumble strip designs in both the initial and second rounds of field evaluations. The generated internal and external noise levels by the 13 test vehicles driving over the identified longitudinal and transverse rumble strip designs are summarized in Tables 11 and 12, respectively. The outcome of this analysis identifies longitudinal and transverse rumble strip designs that (a) fully or closely satisfy the NCHRP recommended range of 3 to 15 dBA internal noise level increase; and (b) comply with this NCHRP recommended range and reduce external noise level increases, as shown in Tables 11 and 12.

For the longitudinal rumble strips, five designs (1, 3, 4, 6, and 10) fully satisfied the NCHRP recommended range of 3 to 15 dBA internal noise increase, and three additional designs (5, 12, and 18) closely satisfied this NCHRP recommended range for all 13 test vehicles in the initial and second rounds of field evaluation, as shown in Table 11. Furthermore, the analysis identified five longitudinal rumble strip designs that fully or closely comply with this NCHRP recommended range and reduce external noise level increases, compared to their related IDOT baseline designs, as shown in Table 11. For example, shoulder rumble strip designs 3, 10, 12, and 18 that fully or closely complied with the NCHRP recommended internal noise range were able to reduce external noise at 50 feet by an average of 1.4 dBA (14%), 7.2 dBA (75%), 9 dBA (93%), and 7.9 dBA (83%), respectively, compared to the currently utilized IDOT design 1, as shown in Table 11. Similarly, centerline rumble strip design 5 closely complied with the NCHRP recommended internal noise increase range and reduced the external noise at 50 feet by an average of 1.7 dBA (19%) compared to IDOT baseline design 4, as shown in Table 11.

For the transverse rumble strips, design 2 fully satisfied the NCHRP recommended range of 3 to 15 dBA internal noise increase, and two additional designs (3 and 5) closely satisfied this NCHRP recommended range for all 13 test vehicles in the initial and second rounds of field evaluation, as shown in Table 12. Moreover, the analysis identified three transverse rumble strip designs that fully or closely comply with this NCHRP recommended range and reduce external noise level compared to IDOT baseline transverse design 1, as shown in Table 12. These fully or closely complied rumble designs (2, 3, and 5) were able to reduce external noise at 50 feet by an average of 2.4 dBA (24%), 7.6 dBA (77%), and 2.2 dBA (22%), respectively, compared to the currently utilized IDOT transverse design 1, as shown in Table 12.

Table 11. Internal and External Noise Increases of Top-Performing Longitudinal Rumble Strips

	Longitudinal Rumble Strips										
Longitudinal Design No.		1[a]	2	3[b]	4[a]	5[b]	6[a]	8	10[b]	12[b]	18[b]
Internal Noise Increase Δ (dBA)	**Initial Round of Field Evaluations**										
	Sedan[1]	13.4	15.4**	12.5	12.7	11.6	13.3	8.8	12.5	6.2	11.1
	SUV[1]	13.6	16.4*	12.6	12.7	11.3	13.0	6.5	10.4	7.8	13.3
	Medium Truck[2]	5.1	3.9	3.3	3.3	2.4**	3.1	1.9*	3.0	2.5**	2.9**
	Second Round of Field Evaluations										
	Semi-Trailer Truck[3]	5.6	10.1	5.2	5.3	5.1	5.3	3.5	4.6	3.6	4.5
	Compact Sedan[1]	15.0	16.8*	13.9	14.0	13.0	14.9	10.6	13.1	8.8	12.9
	1/2 Ton Pick-up Truck[2]	13.8	13.9	11.7	12.0	10.1	12.4	9.0	10.1	6.7	10.4
	Full Size SUV[1]	12.1	14.8	11.4	12.0	10.0	13.0	8.5	11.0	8.8	10.8
	Box Truck[2]	12.9	13.6	12.1	12.2	11.6	13.5	10.1	9.7	9.3	11.8
	Standard Pick-up Truck[2]	10.7	12.8	12.7	11.6	9.3	12.8	9.6	10.0	6.5	8.9
	Minivan[1]	14.5	15.0	12.3	13.4	12.0	13.1	9.8	14.5	10.9	14.2
	Compact SUV[1]	12.9	13.8	12.3	12.8	12.0	13.2	8.8	9.2	9.3	9.5
	Electric Vehicle[1]	13.0	14.9	13.5	13.5	12.0	14.0	9.6	11.7	8.4	14.8
	Full Size Sedan[1]	12.0	13.9	13.2	10.8	10.5	10.8	10.8	12.3	8.9	12.6
External Noise Increase Δ at 50 ft (dBA)	**Initial Round of Field Evaluations**										
	Sedan[1]	9.5	13.9	7.1	8.3	9.4	8.1	0.4	2.5	0.4	0.7
	SUV[1]	11.3	14.4	10.9	10.4	10.6	9.9	0.6	1.2	0.4	0.6
	Medium Truck[2]	4.8	8.0	5.7	4.9	4.8	6.8	2.4	4.3	1.0	2.3
	Second Round of Field Evaluations										
	Semi-Trailer Truck[3]	5.0	9.5	3.2	3.3	3.4	6.0	2.7	2.8	1.0	2.1
	Compact Sedan[1]	9.2	9.6	7.8	9.3	5.5	8.3	0.9	2.0	0.5	0.8
	1/2 Ton Pick-up Truck[2]	12.3	12.4	11.4	12.0	9.9	12.2	1.5	1.0	0.4	0.7
	Full Size SUV[1]	10.7	10.8	8.9	10.4	8.3	10.2	0.4	1.5	0.4	0.6
	Box Truck[2]	8.7	9.0	5.7	8.3	5.5	6.9	0.5	0.6	0.4	1.0
	Standard Pick-up Truck[2]	6.6	6.8	6.5	6.6	4.4			1.8	0.5	1.4
	Minivan[1]	12.9	13.1	11.7	11.3	9.6	12.8	5.8	7.6	1.9	5.9
	Compact SUV[1]	12.7	12.8	10.0	11.9	8.7	10.5	2.3	3.3	0.6	3.4
	Electric Vehicle[1]	11.0	14.7	8.7	10.2	7.3	9.2	0.5	1.7	0.6	0.9
	Full Size Sedan[1]	10.5	13.4	9.7	9.8	7.5	8.3	0.5	1.6	0.7	1.5
	Average	9.6	11.4	8.3	9.0	7.3	9.1	1.5	2.5	0.7	1.7
	Average Reduction	Base	Base	-1.4	Base	-1.7	0.1	Failed	-7.2	-9.0	-7.9

* Internal noise increases that do not satisfy NCHRP recommended range of 3 to 15 dBA noise increase.

** Internal noise increases that are slightly out of NCHRP recommended range of 3 to 15 dBA noise increase.

[a] Rumble strip designs that fully or closely satisfy NCHRP recommended range of 3 to 15 dBA noise increase.

[b] Rumble strip designs that fully or closely satisfy NCHRP recommended range of 3 to 15 dBA noise increase and reduce external noise levels.

[1] Test vehicles classified as passenger cars.

[2] Test vehicles classified as single-unit trucks.

[3] Test vehicles classified as multiple-unit trucks.

Table 12. Internal and External Noise Increases of Tested Transverse Rumble Strip Designs

Transverse Rumble Strips						
Transverse Design No.		**1 TRS**	**2 TRS [b]**	**3 TRS [b]**	**4 TRS**	**5 TRS [b]**
Internal Noise Increase Δ (dBA)	**Initial Round of Field Evaluations**					
	Sedan [1]	14.1	12.6	10.5	12.9	12.5
	SUV [1]	14.1	12.5	10.2	13.3	12.2
	Medium Truck [2]	4.8	3.0	2.2**	3.0	3.6
	Second Round of Field Evaluations					
	Semi-Trailer Truck [3]	7.7	4.2	2.7**	4.8	6.3
	Compact Sedan [1]	18.4*	14.8	10.4	18.2*	15.2**
	1/2 Ton Pick-up Truck [2]	9.0	6.5	7.0	8.9	7.6
	Full Size SUV [1]	11.2	10.6	6.0	11.0	10.9
	Box Truck [2]	9.9	10.8	7.1	11.9	7.5
	Standard Pick-up Truck [2]	9.9	8.6	6.4	11.2	7.1
	Minivan [1]	15.0	12.3	11.2	15.0	13.1
	Compact SUV [1]	14.9	14.1	11.6	11.4	5.6
	Electric Vehicle [1]	14.0	13.5	7.7	16.5*	13.9
	Full Size Sedan [1]	12.2	10.1	9.9	13.0	12.1
External Noise Increase Δ at 50 ft (dBA)	**Initial Round of Field Evaluations**					
	Sedan [1]	10.4	6.4	3.0	5.6	6.5
	SUV [1]	9.2	8.2	1.9	8.8	8.0
	Medium Truck [2]	8.2	6.8	3.6	6.9	6.6
	Second Round of Field Evaluations					
	Semi-Trailer Truck [3]	7.4	6.8	3.1	7.1	6.3
	Compact Sedan [1]	10.1	7.0	2.8	8.2	8.6
	1/2 Ton Pick-up Truck [2]	10.7	8.7	1.5	10.4	8.9
	Full Size SUV [1]	9.8	8.4	1.8	8.8	7.1
	Box Truck [2]	9.6	8.1	2.1	8.2	8.0
	Standard Pick-up Truck [2]		6.3	1.5	6.8	6.1
	Minivan [1]	11.2	7.6	2.0	9.1	8.8
	Compact SUV [1]	11.8	8.6	2.4	9.8	9.8
	Electric Vehicle [1]	11.6	8.0	1.7	8.1	8.1
	Full Size Sedan [1]	9.3	7.2	2.5	8.3	8.0
	Average	9.9	7.5	2.3	8.2	7.8
	Average Reduction	Base	-2.4	-7.6	Failed	-2.2

* Internal noise increases that do not satisfy NCHRP recommended range of 3 to 15 dBA noise increase.

** Internal noise increases that are slightly out of NCHRP recommended range of 3 to 15 dBA noise increase.

[b] Rumble strip designs that fully or closely satisfy NCHRP recommended range of 3 to 15 dBA noise increase and reduce external noise levels.

[1] Test vehicles classified as passenger cars.

[2] Test vehicles classified as single-unit trucks.

[3] Test vehicles classified as multiple-unit trucks.

COMPARISON TO RECENT STUDIES

This section compares the results of the initial and second field evaluations to those provided by two recently published studies: NCHRP 1107 (2024) and FHWA-ICT-23-003 (El-Rayes, et al., 2023). First, the NCHRP research project 1107 analyzed the internal and external noise performance of 25 sinusoidal and 1 traditional rumble strip designs in Indiana, Michigan, Washington, and California (NCHRP 1107, 2024). The NCHRP 1107 study conducted comprehensive internal and external noise measurements of 20 longitudinal designs, and their results are summarized in Table 26 and Table 27. These results were compared to those generated in this study for two similar design dimensions, and the results of this comparison confirm that the generated internal and external noise levels by these identical designs are very close, as shown in Table 13.

Table 13. Noise Performance Comparison of Sinusoidal Rumble Strip Designs

Research Study	Design No.	Rumble Strip Design	Test Speed (mph)	Dimensions				Noise Increase (Δ)	
				Wavelength (in.)	Recess (in.)	Depth (in.)	Length (in.)	Internal (dBA)	External at 25 ft (dBA)
This Study	8	IDOT McHenry 2	50	12	1/8	3/8	8	8.3	1.8
NCHRP 1107	–	Indiana 12-inch wavelength	45	12	1/8	3/8	N/A	7.9	1.5
This Study	16	SRS reduced profile straight	50	14	1/8	1/2	12	9.3	2.3
NCHRP 1107	–	Washington WB9	45	14	1/8	1/2	12	8.9	2.1

Second, the FHWA-ICT-23-003 study compared the external and internal noise levels generated by the transverse rumble strips that were constructed in 2019 at US-41 near the intersection with Park Avenue in Highland Park, Illinois, with those generated by their modified shorter and shallower design that was reconstructed in October 2022 (El-Rayes, et al., 2023). The internal noise level results of the FHWA-ICT-23-003 study were compared to those generated in the initial and second field evaluations for transverse design 1 (IDOT traditional design) and design 5 (IDOT traditional shorter design). This comparison confirms that the internal noise levels of the similar transverse rumble strip designs in both studies were very close, as shown in Table 14. While external noise measurements in this study utilized the AASHTO T 389-20 Isolated Pass-By method (2020), the external noise measurements in the FHWA-ICT-23-003 study were collected using the AASHTO T 390-20 Continuous-Flow Traffic method (2020) due to the inability to close traffic on this roadway during measurements. Accordingly, the external noise measurements of both studies cannot be compared directly; however, their results show that the shorter transverse designs in both studies caused a reduction in the generated external noise levels, as shown in Table 14.

Table 14. Noise Performance Comparison of Transverse Rumble Strip Designs

Research Study	Design No.	Rumble Strip Design	Test Speed (mph)	Dimensions				Noise Increase (Δ)		L_{eq} at 50 ft (dBA)
				Spacing (in.)	Depth (in.)	Length (in.)	Width (in.)	Internal (dBA)	External at 50 ft (dBA)	
This Study	1 TRS	IDOT Traditional Design (25 strips)	50	12	3/16	Lane width	4	13.8	9.9	N/A
FHWA-ICT-23-003	–	2019 US-41 Traditional Design (25 strips)	45	12	1/4	Lane width	4	12.0	N/A	83
This Study	5 TRS	IDOT Traditional Shorter Design (15 strips)	50	12	3/16	Lane width	4	13.4	7.8	N/A
FHWA-ICT-23-003	–	2022 US-41 Traditional Design (16 strips)	45	12	3/16	Lane width	4	14.8	N/A	76.5

CONCLUSION

This section presents the research findings of initial and second rounds of field evaluations for existing and new rumble strip designs, patterns, and dimensions. The goal of the initial round of field evaluations was to identify top-performing rumble strip designs for further testing in the second round of field evaluations.

The initial round of field evaluations comprised of four subtasks that focused on (1) identifying and developing detailed designs of 20 longitudinal and 5 transverse rumble strip designs; (2) obtaining a work permit and constructing the identified 25 rumble strip designs on US-45; (3) measuring internal and external noise generated by each tested rumble strip design using three types of vehicles: passenger sedan, SUV, and medium truck; and (4) analyzing the collected noise data of all tested rumble strip designs. Top-performing rumble strip designs were identified in consultation with the Technical Review Panel for further testing in the second round of field evaluations using 10 additional test vehicles. Based on their overall performance in generating adequate internal noise level increases that satisfy the NCHRP recommended range of 3 to 15 dBA and minimum external noise level, the identified 15 rumble strip designs were 10 longitudinal rumble strip designs (1, 2, 3, 4, 5, 6, 8, 10, 12, and 18) and 5 transverse rumble strip designs (1, 2, 3, 4, and 5).

The second round of field evaluations focused on testing the identified top-performing 10 longitudinal and 5 transverse rumble strip designs using 10 additional test vehicles that provided a representative sample of vehicles on Illinois roads with adequate variations in type, size, weight, and model. These 10 vehicles included compact sedan, full-size sedan, full-size electric sedan, compact SUV, full-size SUV, minivan, standard pick-up truck, 1/2-ton pick-up truck, box truck, and semi-trailer truck. The second round of field evaluations was implemented in two subtasks that focused on (a) collecting and analyzing the external noise data generated by the 15 top-performing rumble strip designs identified in the initial round of field evaluations and (b) collecting and analyzing the internal noise data generated by all 25 rumble strip designs. For the tested longitudinal rumble strip designs, the main findings of this analysis are (a) 14 designs (1, 3, 4, 5, 6, 8, 10, 12, 13, 15, 16, 17, 18, and 19) fully satisfied the NCHRP internal noise recommended range for all 10 test vehicles; (b) one longitudinal rumble strip design (9) fully satisfied the NCHRP internal noise recommended range for nine test vehicles and was slightly less than the minimum threshold of 3 dBA for the tested semi-trailer truck; (c) five longitudinal rumble strip designs (2, 7, 11, 14, and 20) fully satisfied the NCHRP recommended range for nine test vehicles but were unable to satisfy the recommended NCHRP minimum limit of 3 dBA; (d) design 2 generated an internal noise level increase of 16.8 dBA for the tested compact sedan which exceeds the 15-dBA NCHRP limit; (e) designs 7, 11, 14, and 20 generated internal noise level increases that were well below the NCHRP minimum threshold of 3 dBA for the tested semi-trailer truck. For the transverse rumble strip designs, the main findings of this analysis are (1) only design 2 fully satisfied the NCHRP internal noise recommended range for all 10 test vehicles; (2) designs 3 and 5 generated internal noise increases that fully satisfied the NCHRP recommended range for nine test vehicles, but were slightly lower and higher than the NCHRP minimum and maximum thresholds of 3 dBA and 15 dBA for the semi-trailer truck and compact sedan, respectively; (3) design 1 fully satisfied the NCHRP recommended range for nine test vehicles, but generated an internal noise level increase of 18.4 dBA in the compact sedan which exceeds the NCHRP maximum threshold of 15 dBA; and (4) design 4 fully satisfied the NCHRP recommended range for nine test vehicles, but it generated internal noise level increases of 18.2 and 16.5 dBA in the tested compact sedan and electric vehicle, respectively, which exceeded the NCHRP maximum threshold of 15 dBA.

The overall performance of the identified top-performing rumble strip designs was analyzed based on their generated internal and external noise levels by the 13 test vehicles in the initial and second rounds of field evaluations. The main outcomes of this analysis are (1) shoulder rumble designs 3, 10, 12, and 18 were able to fully or closely comply with NCHRP internal noise recommended range and reduce external noise compared to IDOT baseline design 1 at 50 feet by an average of 1.4 dBA (14%), 7.2 dBA (75%), 9 dBA (93%), and 7.9 dBA (83%), respectively; (2) centerline rumble strip design 5 was able to closely comply with the NCHRP internal noise recommended range and reduce external noise compared to IDOT baseline design 4 at 50 feet by an average of 1.7 dBA (19%); and (3) transverse rumble strip designs (2, 3, and 5) were able to fully or closely satisfy the NCHRP internal noise recommended range and reduce external noise compared to IDOT baseline transverse design 1 at 50 feet by an average of 2.4 dBA (24%), 7.6 dBA (77%), and 2.2 dBA (22%), respectively.

CHAPTER 6: RECOMMENDATIONS

This chapter presents the development of (1) recommendations for the use of effective rumble strip designs based on their internal and external noise performance in the initial and second rounds of field evaluations; (2) scoresheets that can be integrated into the BDE manual and used by IDOT to select the most effective rumble strip design for each project based on its specific requirements such as roadway traffic and potential noise complaints from nearby residential areas; (3) a decision support tool (DST) for ranking the most effective rumble strip designs based on their noise performance, roadway traffic, and sensitivity of nearby areas to rumble strip external noise; and (4) a model for ranking and optimizing the selection of competing rumble strip construction projects based on their safety benefits.

RECOMMENDATION FOR USING RUMBLE STRIP DESIGNS

This section provides recommendations for the use of shoulder, centerline, and transverse rumble designs based on the collected and analyzed internal and external noise measurements in the initial and second rounds of field evaluations and do not consider other related factors such as constructability and cost.

Shoulder Rumble Strips

A total of seven top-performing shoulder rumble strip designs were identified based on their internal and external noise performances in the initial and second rounds of field evaluations. These seven shoulder rumble strips include three traditional designs (1, 2, and 3) and four sinusoidal designs (8, 10, 12, and 18). The internal and external noise performance of these seven designs varied, as shown in Table 11. Accordingly, this section provides recommendations for their use for various types of roadway projects based on their internal and external noise performance, roadway traffic including volumes of heavy trucks, and proximity to areas that require serenity and low noise levels such as residential areas, as shown in Table 15. For example, designs 1 and 2 are recommended to be used on freeways and non-freeways that are far from residential areas because they satisfy the NCHRP recommendations for the internal noise increase of 3 to 15 dBA and they generate relatively higher levels of external noise, as shown in Table 18. Furthermore, design 2 is more preferred than design 1 for roads with a high traffic volume of multiple-unit trucks because it generates more noticeable internal noise increase for these vehicles, as shown in Table 18. Additionally, designs 3, 10, and 18 are recommended for freeways and non-freeways that are located near residential areas and experience a high traffic volume of multiple-unit trucks because they reduce the generated external noise levels while maintaining adequate internal noise for this type of truck, as shown in Table 18. On the other hand, designs 8 and 12 are recommended for non-freeways that are near residential areas and have low traffic volumes of single- and multiple-unit trucks because they reduce external noise levels and generate internal noise increases (3.5 dBA and 3.6 dBA) for multiple-unit trucks that are on the low end of the NCHRP recommended range of 3 to 15 dBA, as shown in Table 18.

Table 15. Recommendations for Using Shoulder Rumble Strip Designs on Roadway Projects

	Freeways near residential areas	Freeways far from residential areas	Non-freeways near residential areas	Non-freeways far from residential areas
Roadway with high volume of trucks	Designs 3, 10, and 18	Design 2	Designs 3, 10, and 18	Design 2
Roadway with low volume of trucks	Designs 3, 10, and 18	Design 1, 2	Designs 3, 8, 10, 12, and 18	Design 1, 2

Centerline Rumble Strips

Seven top-performing centerline rumble strip designs were identified based on their internal and external noise performance, roadway traffic including volumes of trucks, and proximity to residential areas. These recommended seven centerline rumble strip designs include three traditional designs (4, 5, and 6) and four sinusoidal designs (8, 10, 12, and 18), as shown in Table 16. For example, designs 4 and 6 are recommended for freeways and non-freeways that are far from residential areas because they generate relatively higher external noise levels and fully satisfy the NCHRP internal noise recommendations for all types of vehicles, as shown in Table 19. Moreover, designs 5, 10, and 18 are recommended for both freeways and non-freeways that are nearby residential neighborhoods and experience high traffic volumes of single- and multiple-unit trucks because they generate relatively lower external noise levels and adequate internal noise increases for trucks, as shown in Table 19. On the other hand, designs 8 and 12 are recommended for non-freeways that are near residential areas and have low traffic volumes of single- and multiple-unit trucks because they reduce external noise levels and generate internal noise increases (3.5 dBA and 3.6 dBA) for multiple-unit trucks that are on the low end of the NCHRP recommended range of 3 to 15 dBA, as shown in Table 16. It should be noted that rumble strip designs 8, 10, 12, and 18 can be used for both shoulder and centerline rumble strip applications.

Table 16. Recommendations for Using Centerline Rumble Strip Designs on Roadway Projects

	Freeways near residential areas	Freeways far from residential areas	Non-freeways near residential areas	Non-freeways far from residential areas
Roadway with high volume of trucks	Designs 5, 10, and 18	Designs 4 and 6	Designs 5, 10, and 18	Designs 4 and 6
Roadway with low volume of trucks	Designs 5, 10, and 18	Designs 4 and 6	Designs 5, 8, 10, 12, and 18	Designs 4 and 6

Transverse Rumble Strips

Five transverse rumble strip designs were identified based on their internal and external noise performance, roadway traffic including volumes of trucks, and proximity to residential areas. These identified transverse rumble strip designs include two traditional designs (1 and 5), one staggered design (2), one sinusoidal design (3), and one angled design (4), as shown in Table 17. For example, design 1 is recommended for freeways and non-freeways with high traffic volumes of trucks that are far from residential areas because it generates relatively higher external noise levels and satisfies the NCHRP recommended internal noise increases of 3 to 15 dBA for all vehicles, as shown in Table 20. On the other hand, designs 2, 4, and 5 are recommended for freeways and non-freeways that are near residential areas because they generate lower external noise levels than design 1 and fully satisfy the NCHRP recommended internal noise increases for all vehicles, as shown in Table 20. Furthermore, design 3 is recommended only for non-freeways that are near residential areas and have low traffic volumes of trucks because it generates the lowest external noise levels; however, its internal noise increase (2.7 dBA) for multiple-unit trucks is slightly lower than the NCHRP minimum threshold of 3 dBA, as shown in Table 20.

Table 17. Recommendations for Using Transverse Rumble Strip Designs on Roadway Projects

	Freeways near residential areas	Freeways far from residential areas	Non-freeways near residential areas	Non-freeways far from residential areas
Roadway with high volume of trucks	Designs 4 and 5	Design 1	Design 4 and 5	Design 1
Roadway with low volume of trucks	Designs 2, 4, and 5	Design 1	Designs 2, 3, 4, and 5	Design 1

SCORESHEETS FOR SELECTING RUMBLE STRIP DESIGNS

This section presents the development of three practical scoresheets that can be integrated into the BDE manual and used by IDOT to select the most effective shoulder, centerline, and transverse rumble strip designs for each project, as shown in Tables 18, 19, and 20, respectively. These scoresheets were designed to allow IDOT to evaluate the rumble strip designs based on (1) their generated average internal and external noise level increases by each type of vehicles including passenger cars, single-unit trucks, and multiple-unit trucks; and (2) roadway traffic distribution in terms of percentage of passenger cars, single-unit trucks, and multiple-unit trucks. These average noise level increases were calculated for the three types of vehicles (passenger car, single-unit truck, and multiple-unit truck) by averaging the internal level increase and external noise level increase at 50 ft that were collected during the field evaluations (see Tables 11 and 12). Note that the blank cells in Tables 18, 19, and 20 are input data that need to be provided by users and output data that can be calculated using the equations in Figure 75, as shown in the completed scoresheet example in Figure 74.

Table 18. Scoresheet for Shoulder Rumble Strip Designs

Design no. (d)		1		2		3		8		10		12		18	
Vehicle Type (v)	Percentage on Roadway (T_v)	Δ	Score	Δ (dBA)	Score	Δ	Score	Δ	Score	Δ	Score	Δ	Score	Δ	Score
		Internal Noise Performance													
Passenger Car (v = 1)		13.3		15.1		12.7		9.2		11.8		8.7		12.4	
Single-Unit Truck (v = 2)		10.6		11.0		10.0		7.6		8.2		6.2		8.5	
Multiple-Unit Truck (v = 3)		5.6		10.1		5.2		3.5		4.6		3.6		4.5	
Weighted Internal Noise Score (A_d)															
Internal Noise Relative Weight (B)															
Internal Noise Overall Score ($C_d = A_d \times B$)															
		External Noise Performance													
Passenger Car		11.0		12.8		9.4		1.4		2.7		0.7		1.8	
Single-Unit Truck		8.1		9.0		7.3		1.5		1.9		0.6		1.4	
Multiple-Unit Truck		5.0		9.5		3.2		2.7		2.8		1.0		2.1	
Weighted External Noise Score (F_d)															
External Noise Relative Weight (G)															
External Noise Overall Score ($H_d = F_d \times G$)															
Overall Performance Score ($P_d = C_d + H_d$)															

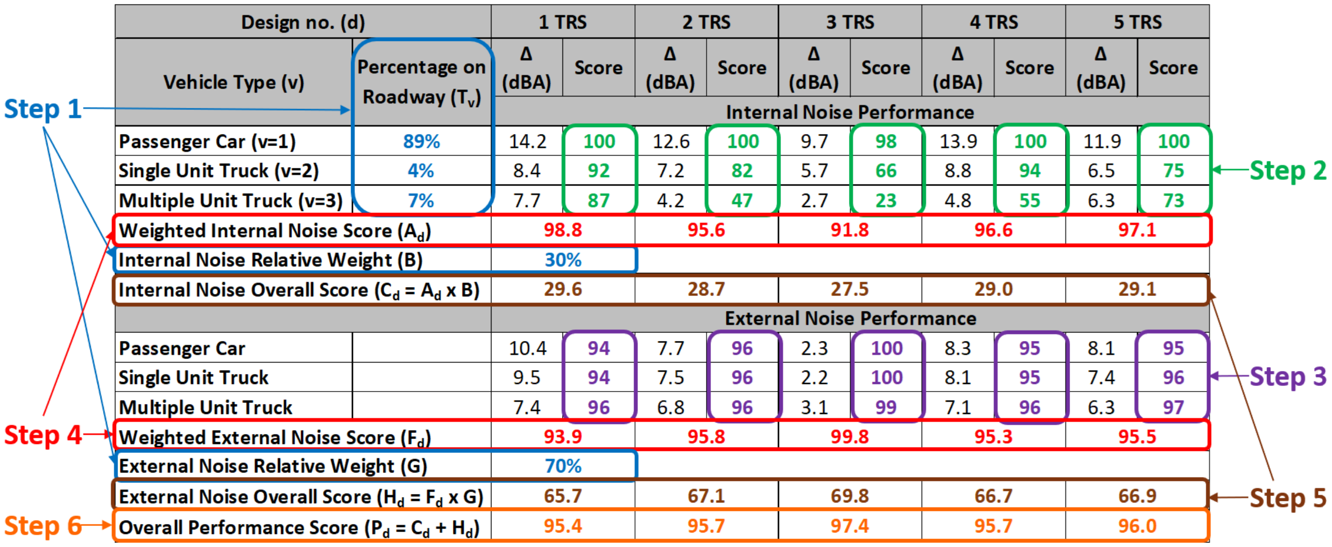
Table 19. Scoresheet for Centerline Rumble Strip Designs

Design no. (d)		4		5		6		8		10		12		18	
Vehicle Type (v)	Percentage on Roadway (T_v)	Δ	Score	Δ (dBA)	Score	Δ	Score	Δ	Score	Δ	Score	Δ	Score	Δ	Score
		Internal Noise Performance													
Passenger Car (v = 1)		12.7		11.5		13.2		9.2		11.8		8.7		12.4	
Single Unit Truck (v = 2)		9.8		8.3		10.5		7.6		8.2		6.2		8.5	
Multiple Unit Truck (v = 3)		5.3		5.1		5.3		3.5		4.6		3.6		4.5	
Weighted Internal Noise Score (A_d)															
Internal Noise Relative Weight (B)															
Internal Noise Overall Score ($C_d = A_d \times B$)															
		External Noise Performance													
Passenger Car		10.2		8.4		9.7		1.4		2.7		0.7		1.8	
Single-Unit Truck		7.9		6.2		8.6		1.5		1.9		0.6		1.4	
Multiple-Unit Truck		3.3		3.4		6.0		2.7		2.8		1.0		2.1	
Weighted External Noise Score (F_d)															
External Noise Relative Weight (G)															
External Noise Overall Score ($H_d = F_d \times G$)															
Overall Performance Score ($P_d = C_d + H_d$)															

Table 20. Scoresheet for Transverse Rumble Strip Designs

Design no. (d)		1 TRS		2 TRS		3 TRS		4 TRS		5 TRS	
Vehicle Type (v)	Percentage on Roadway (T_v)	Δ (dBA)	Score	Δ (dBA)	Score	Δ (dBA)	Score	Δ (dBA)	Score	Δ (dBA)	Score
		Internal Noise Performance									
Passenger Car (v = 1)		14.2		12.6		9.7		13.9		11.9	
Single-Unit Truck (v = 2)		8.4		7.2		5.7		8.8		6.5	
Multiple-Unit Truck (v = 3)		7.7		4.2		2.7		4.8		6.3	
Weighted Internal Noise Score (A_d)											
Internal Noise Relative Weight (B)											
Internal Noise Overall Score ($C_d = A_d \times B$)											
		External Noise Performance									
Passenger Car		10.4		7.7		2.3		8.3		8.1	
Single-Unit Truck		9.5		7.5		2.2		8.1		7.4	
Multiple-Unit Truck		7.4		6.8		3.1		7.1		6.3	
Weighted External Noise Score (F_d)											
External Noise Relative Weight (G)											
External Noise Overall Score ($H_d = F_d \times G$)											
Overall Performance Score ($P_d = C_d + H_d$)											

IDOT can use these scoresheets to select the most effective rumble strip designs for each project in six main steps that are illustrated using the example of a transverse rumble strip scoresheet in Figure 74.



Design no. (d)		1 TRS		2 TRS		3 TRS		4 TRS		5 TRS	
Vehicle Type (v)	Percentage on Roadway (T_v)	Δ (dBA)	Score	Δ (dBA)	Score	Δ (dBA)	Score	Δ (dBA)	Score	Δ (dBA)	Score
		Internal Noise Performance									
Passenger Car (v=1)	89%	14.2	100	12.6	100	9.7	98	13.9	100	11.9	100
Single Unit Truck (v=2)	4%	8.4	92	7.2	82	5.7	66	8.8	94	6.5	75
Multiple Unit Truck (v=3)	7%	7.7	87	4.2	47	2.7	23	4.8	55	6.3	73
Weighted Internal Noise Score (A_d)		98.8		95.6		91.8		96.6		97.1	
Internal Noise Relative Weight (B)		30%									
Internal Noise Overall Score ($C_d = A_d \times B$)		29.6		28.7		27.5		29.0		29.1	
		External Noise Performance									
Passenger Car		10.4	94	7.7	96	2.3	100	8.3	95	8.1	95
Single Unit Truck		9.5	94	7.5	96	2.2	100	8.1	95	7.4	96
Multiple Unit Truck		7.4	96	6.8	96	3.1	99	7.1	96	6.3	97
Weighted External Noise Score (F_d)		93.9		95.8		99.8		95.3		95.5	
External Noise Relative Weight (G)		70%									
External Noise Overall Score ($H_d = F_d \times G$)		65.7		67.1		69.8		66.7		66.9	
Overall Performance Score ($P_d = C_d + H_d$)		95.4		95.7		97.4		95.7		96.0	

Figure 74. Illustration. Example calculation of scoresheet for transverse rumble strip designs.

Step 1: Provide input data on the roadway traffic distribution for the roadway project that are represented by the percentage (T_v) of each vehicle type (v) that includes passenger cars (v = 1), single-unit trucks (v = 2), and multiple-unit trucks (v = 3) on the roadway, as shown in Figure 74. For roadway projects where this data is not readily available, these roadway traffic data percentages can be distributed equally among the three vehicle types ($T_1 = T_2 = T_3 = 33.33\%$). Furthermore, provide input data on the relative importance of internal (B) and external (G) noise in the roadway project area.

Step 2: Provide internal noise score ($I_{d,v}$) for each combination of rumble strip design (d) and vehicle type (v) that ranges from 0 to 100, as shown in Figure 74. This internal noise score ($I_{d,v}$) can be identified by IDOT based on (1) the internal noise increase Δ (dBA) generated by each rumble strip design (d) and vehicle type (v) that are listed in the scoresheet, as shown in Figure 74; and (2) the suggested score ranges listed in Table 21. These internal noise suggested score ranges are based on the NCHRP recommended range of 3 to 15 dBA (NCHRP 641, 2009) and they provide top scores for internal noise increases ranging from 10 to 15 dBA and gradually declining scores for lower and higher ranges, as shown in Table 21.

Table 21. Suggested Scores for Internal Noise Increase Levels

Internal Noise Increase Δ (dBA)	Suggested Score Range
Δ < 1	0
1 ≤ Δ < 2	0–5
2 ≤ Δ < 3	5–31
3 ≤ Δ < 6	31–70
6 ≤ Δ < 8	70–90
8 ≤ Δ < 10	90–100
10 ≤ Δ < 15	100–100
15 ≤ Δ < 16	100–60
16 ≤ Δ ≤ 17	60–0
X > 17	0

Step 3: Provide the external noise score ($E_{d,v}$) for each combination of rumble strip design (d) and vehicle type (v) that ranges from 0 to 100, as shown in Figure 74. This external noise score ($E_{d,v}$) can be identified by IDOT based on the external noise increase Δ (dBA) generated by each rumble strip design (d) and vehicle type (v) that are listed in the scoresheet, as shown in Figure 74.

Step 4: Calculate the weighted internal (A_d) and external (F_d) noise scores of each rumble strip design (d) that represents the collective performance of all vehicle types on the roadway, as shown in Figure 74 and calculated using the equations in Figure 75. For example, the weighted internal noise score (A_1) of transverse rumble design 1 (d = 1) was calculated using equation (a) in Figure 75 as follows: $A_1 = (89\% \times 100\% + 4\% \times 92\% + 7\% \times 87\%)/100\%$, as shown in Figure 74. Similarly, the weighted external noise score (F_1) of transverse rumble design 1 (d = 1) was calculated using equation (b) in Figure 75 as follows: $F_1 = (89\% \times 94\% + 4\% \times 94\% + 7\% \times 96\%)/100\%$, as shown in Figure 74.

$$A_d = \frac{\sum_{v=1}^{3}(I_{d,v} \times T_v)}{100\%}$$

(a) Weighted internal noise score equation

$$F_d = \frac{\sum_{v=1}^{3}(E_{d,v} \times T_v)}{100\%}$$

(b) Weighted external noise score equation

Figure 75. Equation. Weighted internal and external noise score equations.

Where

v is vehicle type, where v = 1, 2, and 3 represent passenger car, single-unit truck, and multiple-unit truck, respectively
d is rumble strip design number
$I_{d,v}$ is internal noise score of vehicle type v and rumble strip design d
$E_{v,d}$ is external noise score of vehicle type v and rumble strip design d
T_v is the percentage of vehicle type v on the roadway

Step 5: Calculate the internal (C_d) and external (H_d) noise overall score of each rumble strip design (d) by multiplying the internal (B) and external (G) noise relative importance in the project location by the weighted internal (A_d) and external (F_d) noise scores of each rumble strip design (d) that were calculated in the previous step, as shown in Figure 74.

Step 6: Calculate the overall performance score (P_d) for each rumble strip design (d) by summing its internal (C_d) and external (H_d) noise overall scores that were calculated in the previous step, as shown in Figure 74.

DECISION SUPPORT TOOL FOR RANKING RUMBLE STRIP DESIGNS

A practical decision support tool (DST) was developed to enable IDOT to rank the most effective rumble strip designs for each roadway safety project based on their noise performance, roadway traffic, and sensitivity of nearby areas to rumble strip external noise. The development and the use of the decision support tool (DST) are described in more detail in Appendix F.

OPTIMIZATION MODEL FOR PRIORITIZING RUMBLE STRIP PROJECTS

An optimization model was developed to enable IDOT decision makers to rank and optimize the selection of competing rumble strip construction projects based on their safety benefits. The model is developed to rank and prioritize competing rumble strip construction projects to maximize total roadway safety benefits while considering available budget for all rumble strip projects. The development and the use of the optimization model are described in more detail in Appendix G.

CHAPTER 7: FUTURE RESEARCH

The research team identified two promising research areas that need further in-depth analysis and investigation. These future research areas can focus on (1) investigating the impact of winter conditions on the performance of sinusoidal rumble strips and (2) developing a data-driven model to quantify the impact of pavement aging and traffic volume on rumble strip noise performance and effectiveness.

IMPACT OF WINTER WEATHER ON SINUSOIDAL RUMBLE STRIP PERFORMANCE

Problem Statement

In this study, sinusoidal rumble strips outperformed traditional rumble strips in terms of generating significantly lower external noise levels while maintaining adequate internal noise levels to alert inattentive drivers. Despite the superior noise performance of sinusoidal rumble strips, several studies reported the potential of damage during snow plowing operations and creating slippery roadway conditions during winter events due to the formation of ice sheets in the rumble strip grooves (NCHRP Synthesis 339, 2005). Accordingly, there is a pressing need to investigate and compare the impact of winter weather conditions on the performance of sinusoidal and traditional rumble strips in order to analyze the feasibility of expanding the use of sinusoidal rumble strips on IDOT roadways.

Objective and Scope of Proposed Research

The objective of this research is to evaluate the impact of winter weather conditions on the performance of sinusoidal and traditional rumble strips by investigating potential damages caused by snow plowing operations and the potential formation of ice sheets in the grooves of rumble strips. To accomplish this objective, the proposed tasks for this study are as follows. First, identify a representative sample of sinusoidal, traditional, longitudinal, and transverse rumble strips that will be investigated in the proposed study, including the recently constructed designs on US-45. Second, conduct annual field assessments of potential damage caused by snow plowing operations using measurements of rumble strip depths, visual documentation of chipped edges, and/or scanners before and after each winter season. Third, perform annual field measurements to collect noise levels generated by the rumble strips to evaluate the impact of aging and traffic volumes on their effectiveness. Fourth, conduct field measurements after each winter event to collect data on roadway friction over the rumble strips using mobile road weather information sensors (RWIS) to investigate the potential formation of ice sheets and slippery roadway conditions within the grooves of the rumble strip. Fifth, compare the performance of sinusoidal and traditional rumble strips in terms of their resilience to snow plowing operation and roadway friction after winter events. Sixth, provide recommendations on expanding the use of sinusoidal rumble strips on IDOT roadways based on their analyzed field performance. The findings of this study are expected to provide much-needed data and insight on the safety and practicality of sinusoidal rumble strip designs—especially transverse designs because they are struck by all vehicles unlike longitudinal designs, which are occasionally struck by inattentive drivers.

Expected Outcome

The expected outcome of this research includes (1) assessment of damages and deterioration of various rumble strip designs due to snow plowing operations during winter weather conditions in Illinois; (2) impact of aging and traffic volumes on the effectiveness of rumble strip designs; (3) in-depth analysis of roadway friction over alternative rumble strip designs and their potential for forming ice sheets and slippery roadway conditions; (4) comparison of the performance of sinusoidal and traditional rumble strips in terms of their resilience to snow plowing damage and roadway friction during winter weather conditions; and (5) recommendations on expanding the use of sinusoidal rumble strips on IDOT roadways based on their analyzed field performance.

DATA-DRIVEN MODEL TO QUANTIFY THE IMPACT OF PAVEMENT AGING ON RUMBLE STRIP PERFORMANCE

Problem Statement

Rumble strips are a cost-effective roadway safety countermeasure that generate in-vehicle noise and vibration to alert inattentive drivers who are about to depart their traveling lanes and/or approach stop-controlled intersections. Despite these safety benefits, rumble strips' performance and effectiveness deteriorate over time due to pavement aging and traffic volumes. Accordingly, there is a pressing need to quantify the impact of pavement aging and traffic volumes on rumble strip performance to identify a cost-effective date for re-milling and/or reconstructing aging rumble strips to restore their effectiveness and their safety benefits. This is expected to provide much-needed support to IDOT decision-makers to optimize the timing of rumble strip construction projects to maximize their effectiveness and safety benefits while minimizing their construction cost.

Objective and Scope of Proposed Research

The goal of this research is to quantify the impact of pavement aging and traffic volumes on rumble strip performance to identify a cost-effective date for re-milling and/or re-constructing aging rumble strips. To achieve this objective, the research can be organized in five tasks. First, identify a representative sample of sinusoidal, traditional, longitudinal, and transverse rumble strips that will be evaluated in this study, including the recently constructed designs on US-45. Second, conduct semi-annual field measurements in all locations of the identified rumble strips to collect data on their pavement type, traffic volumes, age, condition, and generated internal noise levels using a representative sample of test vehicles. Third, develop deterioration models based on the collected data to predict rumble strip condition based on its pavement type, traffic volume, and age. Fourth, create a practical decision support tool that enables IDOT to identify an optimal date for rumble strip re-milling and/or reconstruction to maximize rumble strips' effectiveness and safety benefits while minimizing their construction cost. Fifth, provide recommendations that can be used by IDOT to update its related practices, policies, specifications, and/or standards.

Expected Outcome

The expected outcome of this research includes (1) a comprehensive dataset for a representative sample of rumble strips on Illinois roads that includes their pavement type, traffic volumes, age, condition, and generated internal noise levels; (2) reliable deterioration models for predicting rumble strip condition based on pavement type, traffic volume, and age; (3) a practical decision support tool for optimizing the planning of rumble strip re-milling and/or reconstruction; and (4) recommendations for IDOT to update its related practices, policies, specifications, and/or standards.

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APPENDIX A: LITERATURE REVIEW

APPENDIX A1: INTRODUCTION

The Federal Highway Agency (FHWA) reported that an average of 51% (19,158) of the motor vehicle fatalities recorded in the United States from 2016 to 2018 were caused by vehicles leaving their travel lanes (FHWA, 2022a). To address this hazard, rumble strips are low-cost safety measures that are often used to alert inattentive drivers by generating in-vehicle noise and vibration when they leave the roadway. This in-vehicle noise and vibration can minimize vehicles drifting outside their travel lane whether outside the roadway or onto opposing traffic (FHWA 2012). A report published by the National Cooperative Highway Research Program (NCHRP) stated that rumble strips should generate additional noise of 3 to 15 dBA above the ambient in-vehicle sound level to alert inattentive, distracted, drowsy, or fatigued drivers (NCHRP 2009). This range of acceptable additional noise defines the minimum, desirable, and maximum design values to be 3, 6, and 15 dBA, respectively (NCHRP 2009). This internal rumble strip noise was reported by NCHRP to be effective in reducing crashes on rural two-lane roads and urban two-lane roads by up to 45% and 64%, respectively (NCHRP 2016). Furthermore, another study reported that the use of shoulder line rumble strips and centerline rumble strips resulted in a 36% and 44% reduction in fatal and injury roadway crashes respectively (FHWA 2017c).

Despite the aforementioned safety benefits of rumble strips, a recent FHWA study noted that their external noise does little to alert drivers and often causes complaints from nearby residents (FHWA 2017b). To address this, several state DOTs such as Washington, Minnesota, and Indiana DOTs have recently conducted studies to test the effectiveness of various rumble strip designs including sinusoidal rumble strips (MnDOT 2016, Laughlin & Donahue 2018, and KTC 2020). Sinusoidal rumble strips, also known as "mumble strips," have recently been used to significantly reduce external noise while still providing enough internal noise and vibration to alert drivers by utilizing an oscillating sine wave pattern (FHWA 2017b).

The objective of this report is to present the findings of a comprehensive literature review that was conducted to gather and analyze current practices and the latest research studies on rumble strip designs that reduce external noise while maintaining sufficient internal noise, to ensure effectiveness in reducing the potential for crashes. This literature review focuses on rumble strip: (1) designs, types, and requirements, (2) effectiveness, (3) external noise, (4) noise and vibration testing procedures, and (5) challenges and maintenance.

APPENDIX A2: RUMBLE STRIP DESIGNS, TYPES, AND REQUIREMENTS

This chapter highlights the different rumble strip (1) designs, (2) types, (3) Federal requirements, and (4) alternative rumble strips.

Designs

Rumble strips can be classified into four main designs based on their roadway placement: edge line, shoulder line, centerline, and transverse, as shown in Figure 76 (FHWA 2017c). Edge line, shoulder line and centerline rumble strips are all longitudinal rumble strips that are installed parallel to the travel lane to alert drivers when they leave the roadway, while transverse rumble strips are installed in the wheel path perpendicular to the travel lane to alert drivers to slow down due to upcoming change in road conditions (CH2M Hill 2017). Edge and shoulder line rumble strips reduce run-off crashes by warning drivers that have unintentionally drifted outside the travel lane, as shown in Figure 77, respectively. Shoulder line rumble strips are installed at an offset distance from the edge line markings while the edge line rumble strips are installed on the edge line markings, as shown in Figure 78 (MnDOT 2014). Centerline Rumble Strips are designed to warn drivers when they cross the centerline to avoid head-on collisions, as shown in Figure 79. The design specifications of the aforementioned longitudinal rumble strips include offset (A), length (B), width (C), depth (D), spacing (E), and bicycle gap (F) if any, as shown in Figures 77 to 79 (FHWA 2018).

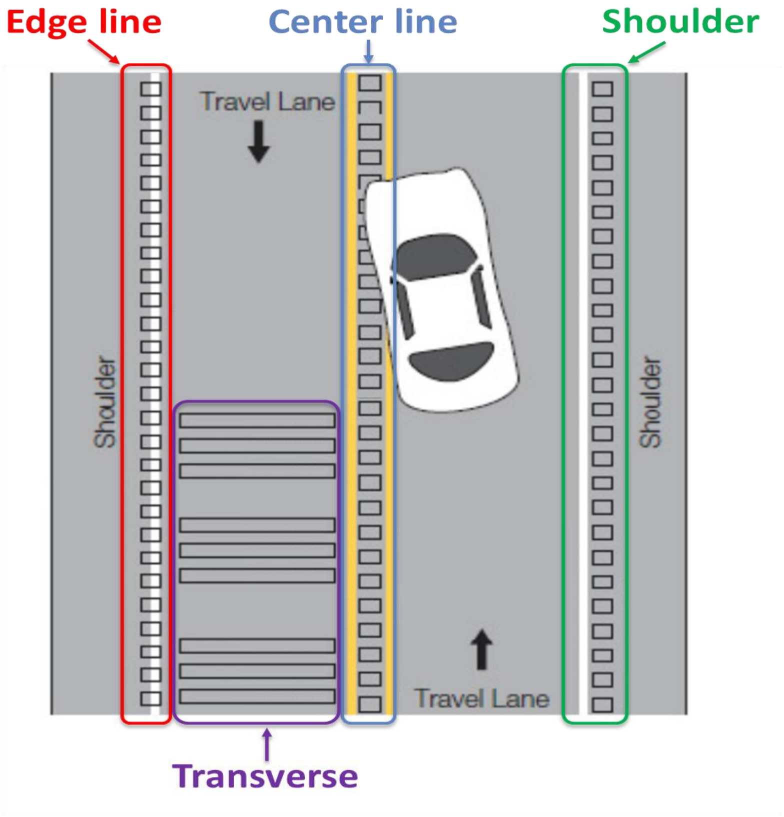


Figure 76. Photo. Rumble strip designs.

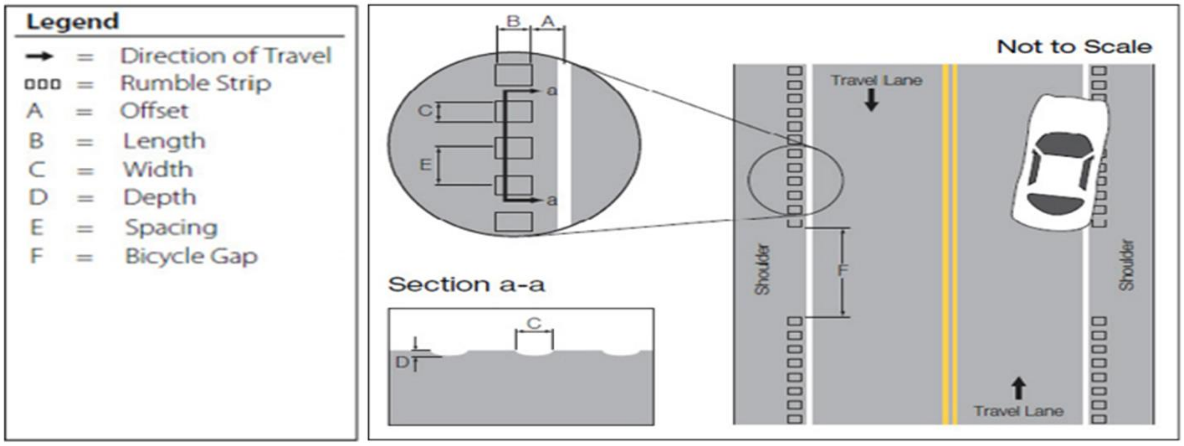


Figure 77. Photo. Shoulder line rumble strip specifications and position.

Source: FHWA, 2018

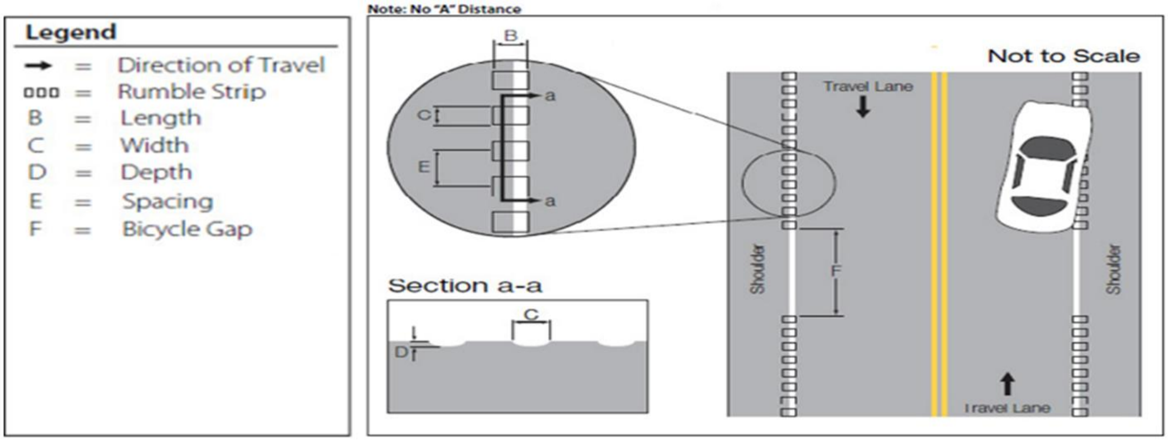


Figure 78. Photo. Edge line rumble strip specifications and position.

Source: FHWA, 2018

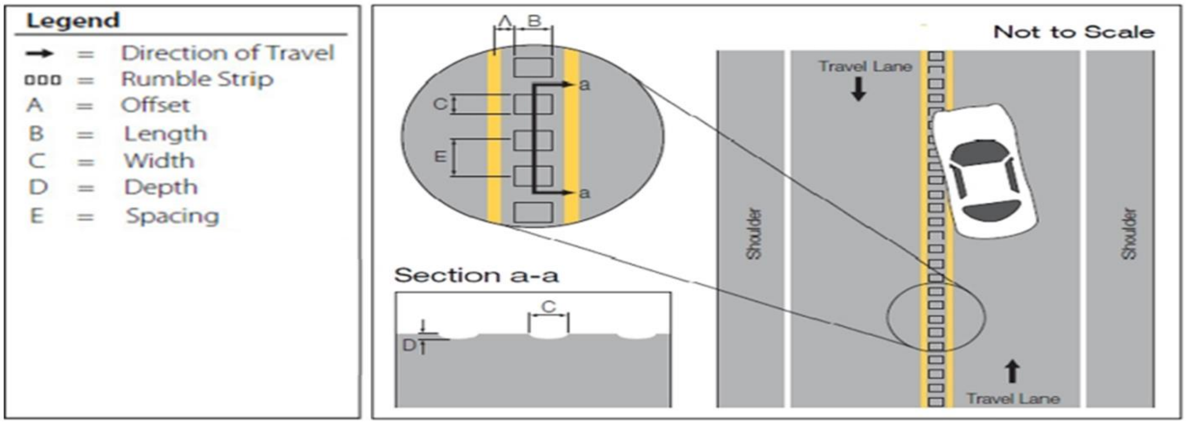


Figure 79. Photo. Centerline rumble strip specifications and position.

Source: FHWA 2018

Transverse rumble strips are placed in the travel lane perpendicular to the direction of travel and they are used to alert drivers of a need to slow down or stop, or to other upcoming changes that may not be anticipated by an inattentive driver. Typical locations for these rumble strips are on approaches to intersections, toll plazas, horizontal curves, and work zones (FHWA 2022b). Transverse rumble strips are typically designed to include two to five panels that are located prior to the required speed reduction zone to alert drivers, as shown in Figure 80. Minnesota DOT reported that their use of transverse rumble strips with three panels did not provide a significant difference in driver behavior compared to transverse rumble strips with two panels (MnDOT, 2001). The design specifications of the transverse rumble strips include offset (A), length (B), width (C), depth (D), spacing (E), panel size (F), and the number of panels (G), as shown in Figure 80 (FHWA 2018). The average panel size and average number of panels for grooved/milled transverse rumble strips, reported by state DOTs in Table 22, are 14.6 feet and 3.4 panels, respectively.

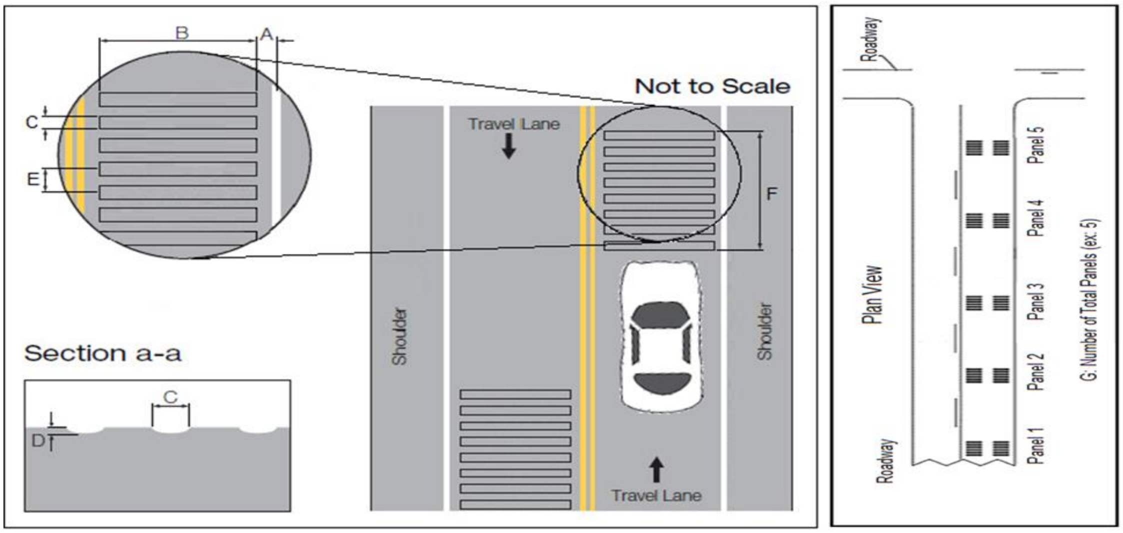


Figure 80. Photo. Transverse rumble strip specifications and position.

Table 22. State DOTs Transverse Rumble Strip Design Specifications

State	Type	Offset (A)	Length (B)	Width (C)	Depth (D)	Spacing (E)	Size of panel (F)	Total panels (G)
Alabama	Raised	N/A	Variable	8″	5/8″	18″	6.67′	N/A
Arizona	Grooved	N/A	Lane Width	4″	3/8″	12′	8′ (At 15 Angle)	3
Arkansas	Grooved	N/A	Lane Width	3.5″ - 5″	1.5″	24″	10.33′	N/A
Colorado	Grooved	N/A	Travel Lane	4″	1/2″	12″	11′ - 4″	4
	Grooved	N/A	Travel Lane	4″	1/2″	12″	11′ - 4″	3
	Raised	N/A	Travel Lane	4″	1/4″	12″	11′ - 4″	3
Florida (DOT)	Raised	1.5′ with paved shoulders	Travel Lane	2″	1/2″	12″	5′	4
Florida (Palm Beach)	Raised	N/A	Travel Lane	2″	1/2″	12″	5′	N/A
Georgia	Raised	4″ Both Sides of Lane Edge	Lane Width - Offset	4″	1″ Max	8″	20′	3
Hawaii	Raised	N/A	3′	N/A	N/A	36″	24′	N/A
Idaho	Grooved	N/A	N/A	6″	N/A	18″	11′	N/A
	Grooved	N/A	N/A	6″	N/A	18″	17′	N/A
Illinois	Grooved	N/A	Lane Width	4″	1/4″	10″	25′	3
Indiana	Raised	N/A	Lane Width	8″	Raised 1/4″	8″	7′ - 4″	2 Basic + 4 Additional
Iowa	Grooved	12″ (From Centerline) 24″ (From Edge Line)	12′ or Travel Line	4″	3/8″	12″	24′	2
Kansas	Grooved	6″ (From Center Line) 16″ (From Edge Line)	Lane Width - Offset	4″	3/8″	12″	24′ (At 10 Angle)	3
	Raised	1′	2 x 4′ (1′ gap in the middle)	12″	1″	12″	11′	3
Kentucky	Milled	1′	4′	4″	1/2″	12″	6′	4
Maryland	Raised	N/A	Lane Width	1st layer 10″ 2nd layer 5″	N/A	6′	54′	3 Mandatory 1 Optional
		N/A	Lane Width	1st layer 10″ 2nd layer 5″	N/A	4.5′	40.5′	
Michigan	Raised	12″	Lane Width - Offset + B:L	8″	Raised 3/8″	20″	24′ - 40′	3
Minnesota	Grooved	9″ (From Centerline) 20″ (From Edge Line)	2 x 3′4″ (3′ Gap in The Middle)	6″	1/2″	12″	5′	5
Mississippi	Raised	1′ Both Sides	Lane Width - Offset	4″ - 8″	1/2″ - 1″	12″	8.5′	N/A

State	Type	Offset (A)	Length (B)	Width (C)	Depth (D)	Spacing (E)	Size of panel (F)	Total panels (G)
Missouri	Grooved	12″ (From center line) 18″ (From Edge Line)	Lane Width - Offset + B:L	4″	3/8″	8″	24′ (At 10 Angle)	2
Nebraska	Grooved	1′	Lane Width - Offset	4″	3/4″	16″	24.33′	N/A
	Raised	N/A	2 x 3.5′	6″	3/4″	18″	24.5′	N/A
New Jersey	Grooved	N/A	Travel Lane	1st layer 6″ 2nd layer 4″	1/4″ divided into two layers	24″	11′	3
New Mexico	Grooved	1′ Both Sides	2 x 4′ (2′ gap in the middle)	6″	3/8″	12″	11′-4″	5
North Dakota	Grooved	12″ Both Sides	Lane Width - Offset	4″	1/2″ - 5/8″	8″	15′ or 25′-4″	6
Oklahoma	Raised	12″	2 x 4′ (2′ gap in the middle)	1st layer 6″ 2nd layer 4″	1/4″	12″	11″	3
	Milled Sinusoidal	2′	8′ Staggered	16″	1/16″ to 1/2″	N/A	11′ - 8″	3
Ohio	Grooved	6″ (From solid yellow) 18″ (From Edge Line)	Lane Width - Offset	4″	1/2″- 5/8″	12″	14′-4″	3
Oregon	Grooved	6″ (From solid yellow) 18″ (From Edge Line)	Lane Width - Offset	6″	1/2″	12″	5′	3 Mandatory + 2 Optional
Pennsylvania	Raised	N/A	Lane Width	4″	1/2″	12″	14.33′ - 19.33′	N/A
South Dakota	Grooved	N/A	2 x 3.5′	6″	1/2″	18″	11.33′	N/A
Texas	Raised	Minimum 1″ Desired 6″	2 x 4′ (2′ gap in the middle)	N/A	N/A	2′	8′	2
	Raised	Minimum 1″ Desired 6″	2 x 4′ (2′ gap in the middle)	N/A	N/A	1′ Alternating	9′	2
West Virginia	Grooved	N/A	Lane Width	4″	3/4″	12″	11.3′	N/A
Wisconsin	Grooved	12″ (From Centerline) 18″ (From Edge Line)	Lane Width - Offset	4″	1/2″ - 5/8″	12″	25′	3

Types

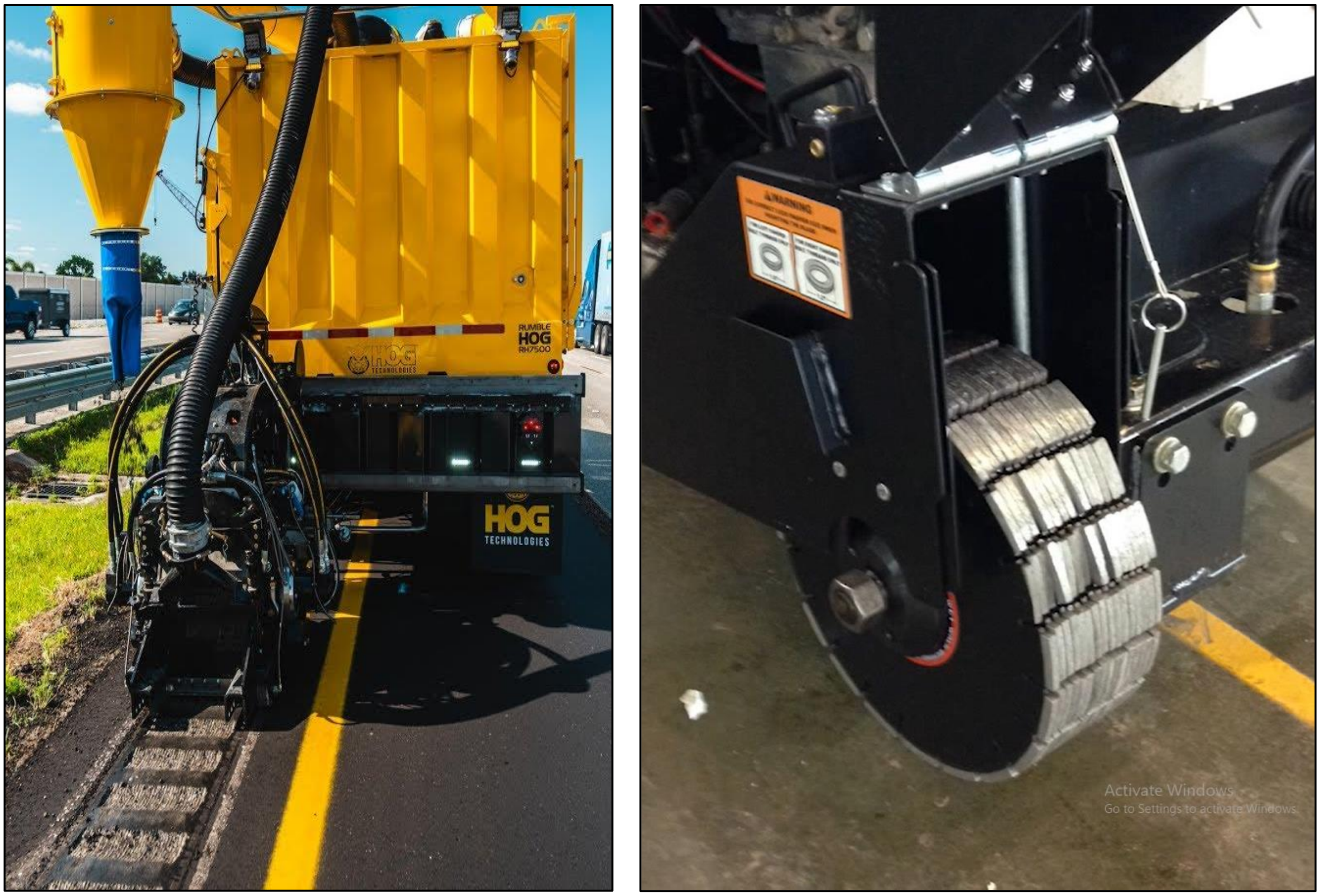
Rumble strips can be classified into five main types based on their construction method: (a) milled-in, (b) rolled-in, (c) formed, (d) raised, or (e) sinusoidal, as shown in Figure 81 (FHWA 2011a). Milled-in rumble strips are constructed by cutting a consistent size and shape of a rumble strip into the pavement using a machine with a rotary cutting head, as shown in Figure 82 (FHWA 2015b). Additionally, rumble strips can be installed as part of a construction project or resurfacing project in both concrete and asphalt pavements; however, they are significantly cheaper to mill in asphalt pavements since concrete wears the milling head 2-3 times quicker than asphalt (FHWA 2011b and FHWA 2015c).

(a) Milled-In (b) Rolled-In

(c) Formed (d) Raised

(e) Sinusoidal

Figure 81. Photo. Rumble strip types.



(a) Milling on shoulder (b) Rotary cutting head

Figure 82. Photo. Milled rumble strip installation process.

Rolled rumble strips have rounded or V-shaped grooves that require a time-sensitive installation process on the compacted surface during the paving or re-paving of the road. Rolled rumble strips are pressed into hot asphalt using a roller head attached to a steel pipe, which is welded onto a rotating drum, as seen in Figures 83 and 84 (Carlson & Miles 2003). However, rolled rumble strips tend to cause difficulties during construction due to insufficient compaction, inconsistent dimensions, and difficulties installing patterns such as bicycle gaps. They also tend to produce less vibration than milled rumble strips due to the inconsistencies during construction (FHWA 2011c).

Figure 83. Photo. Rolled rumble strip installation process (Back View).

Source: CoDOT 1996

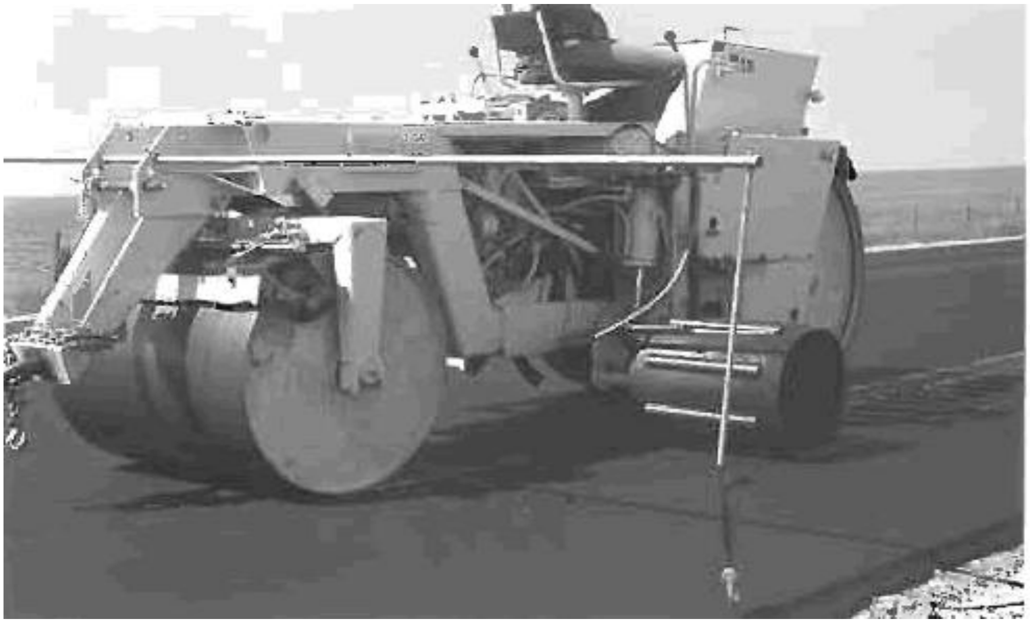


Figure 84. Photo. Rolled rumble strip installation process (Front View).

Source: CoDOT 1996

Formed rumble strips, similar to rolled rumble strips, are designed to have a V-shaped or Rounded finish. Formed rumble strips are constructed using prefabricated corrugated forms that are pressed into the concrete shoulder while the concrete is curing. Installation during road construction tends to create consistency and limitation concerns (Carlson & Miles 2003 and FHWA 2011d).

A number of studies have reported that asphalt pavements are quieter than concrete pavements by a range of 2-5 dBA (Kandhal 2004). Another study by the World Road Association reported that hot mix asphalt (HMA) and Portland cement concrete (PCC) pavements produce a noise level range of 72-79.5 dBA and 76-85 dBA, respectively (Kandhal 2004). Additionally, a NJDOT (2015) study compared the difference in noise levels generated by dense-grade asphalt, stone matrix asphalt, and PCC. The study reported that concrete pavements were on average louder than asphalt-based roadways by 4.1 dBA, however, diamond grinding the surface of concrete pavements proved to be comparable to the HMA pavements (Bennert et. al 2005).

Raised rumble strip types are divided into side-by-side raised pavement markers, rumble bars, or plastic inserts within thermoplastic pavement markings, as shown in Figure 85 (FHWA 2016a). These pavement markers are attached to the top of new or existing pavement using an adhesive, as shown in Figures 86-a and 86-b illustrates the adherence of the raised rumble strip to the pavement using a 48-pound tamper cart equipped with an added weight of 198 pounds (KDOT 2002). This type of rumble strip is usually more popular in warmer climates where snowplows are not often used. Additionally, they are often considered an adequate substitution in areas where milled rumble strips are not practical, such as bridge decks or on thin surface courses (FHWA 2016b).

(a) Side-by-side Markers

(b) Plastic Inserts

(c) Rumble Bars

Figure 85. Photo. Types of raised rumble strips.

(a) Adhesive application

(b) Tamper cart

Figure 86. Photo. Raised rumble strip installation process.

Transportation agencies often limit installing rumble strips in residential and noise-sensitive areas due to the unexpected and loud noise generated when a vehicle strikes a rumble strip, which can be disruptive to those in the surrounding area (FHWA 2017b). Sinusoidal rumble strips have been recently implemented for reduced external noise. The United Kingdom, Netherlands, and Sweden were some of the first to construct and test sinusoidal rumble strips (Hurwitz et al. 2019). Sinusoidal rumble strips are construction similar to milled rumble strips except the milling occurs over a continuous cut that varies in depth to create a wave like pattern or sinusoidal curve, as shown in Figures 87 and 88. State DOTs such as California DOT, Minnesota DOT, and Oregon DOT have conducted studies to evaluate the effectiveness of sinusoidal rumble strips using US practices and technology (Hurwitz et al. 2019).

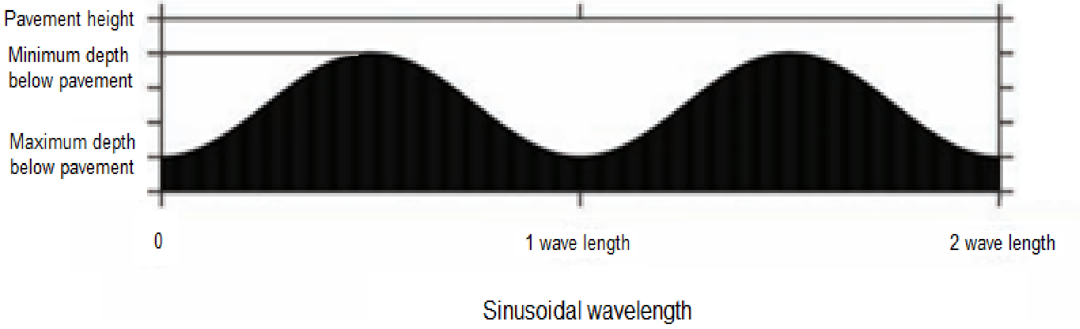


Figure 87. Photo. Sinusoidal rumble strip wave pattern specification.

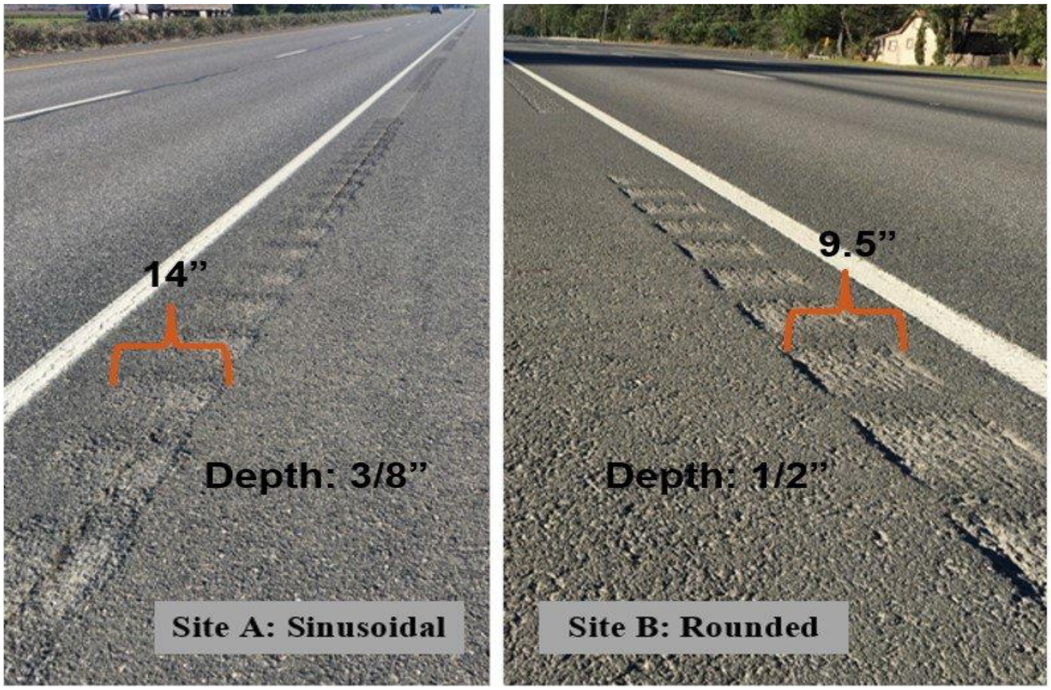


Figure 88. Photo. Sinusoidal rumble strip vs rounded rumble strip (milled).

Source: Hurwitz et al., 2019

Federal Requirements

Federal Highway Administration guidelines specify the need for rumble strips to generate an in-vehicle increase of 3 to 15 A-weighted decibels (dBA) with a desired range of 6 to 15 dBA to alert inattentive drivers to remain within travel lanes and/or slow down (NCHRP 2009). An A-weighted decibel (dBA) is the relative loudness of sounds as perceived by humans and can be measured by commercially available sound level meters (FHWA 2018). For shoulder line rumble strips, FHWA recommends their installation at locations with high incident roadway departure crash sites, when a minimum 11 ft lane can be maintained, at limited clear zone areas (steep slopes, trees, utilities, rock outcrops), on horizontal curves, on long tangent sections, and at approaches to a narrow bridge (FHWA 2015d). For centerline rumble strips, FHWA recommends their installation at locations with at high incident head-on and opposing-sideswipe crash sites, when a minimum of 22 feet of total pavement width can be maintained, along roadways with frequent horizontal curvature, through a continuous area, and in passing and no-passing zones (FHWA 2015d). On the other hand, FHWA recommends avoiding the installation of rumble strips at locations with bridge deck and approach slabs, right turn acceleration and deceleration lanes, pavement less than 2 inches (50 mm) in depth (applies to milled rumble strips only), after pavement markings have been placed, and when pavement exhibits alligator and fatigue cracking, or generally in poor condition (FHWA 2015f).

Alternative Rumble Strips

A number of alternative rumble strip designs and types have been studied by state DOTs to improve effectiveness, minimize noise complaints from nearby residents, and/or accommodate bicyclists (TxDOT 2005, Gardner et al. 2007, and Oneyear et al. 2021). These alternative rumble strip designs and types include (1) football-shaped, (2) audible markings, (3) angled transverse, (4) wheel path, (5) gapped, (6) variable spacing, and (7) sinusoidal in-lane. The following sections provide a concise description of these alternative rumble strip designs and types.

Football Shaped

Football-Shaped or Football Cutter were studied by the Kansas Department of Transportation (Gardner et al. 2007) as a replacement for traditional rumble strips to provide a better self-cleaning rumble strip and better accommodate bicyclists and motorcyclists (Gardner et al. 2007), as shown in Figure 89. In this study, the dimensions of a single football cutter rumble strip were specified to be depth of 0.5 inches, width of 9 inches, and length of 16 inches. KDOT investigated the performance of football cutter design using four criteria: water collection, debris collection, internal noise and vibration, and bicyclist survey. The water and debris tests reported no significant improvement of the football cutter design compared to traditional rumble strips. The internal noise and vibration testing were conducted using 1 passenger vehicle, 1 minivan, 1 SUV, 2 pickup trucks, and 1 dump truck. The reported results of the measured internal noise are summarized in Table 23. The bicycle survey found that 96% of respondents preferred the rideability over football-shaped rumble strip compared to traditional milled rumble strips.

Table 23. Internal Noise of Traditional and Football Cutter Rumble Strips (Gardner et al. 2007)

Vehicle	Baseline Pavement	Traditional Rumble Strip	Football Cutter
Passenger Vehicle	69.6 dBA	78.9 dBA	83.3 dBA
Minivan	67.3 dBA	79.6 dBA	83.5 dBA
Sports Utility Vehicle	67.4 dBA	83.6 dBA	83.3 dBA
Pickup Truck 1	78.5 dBA	86.2 dBA	86.2 dBA
Pickup Truck 2	70.4 dBA	78.2 dBA	78.9 dBA
Dump Truck	85.9 dBA	109.0 dBA	117.3 dBA

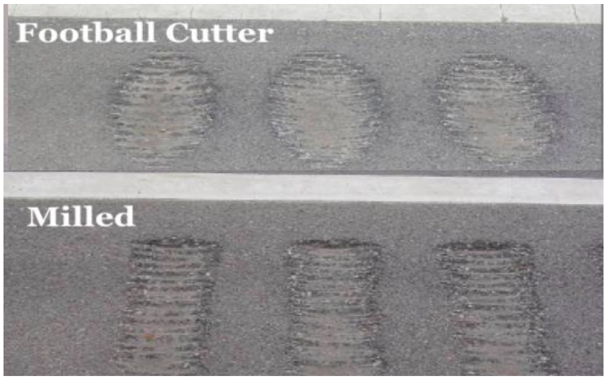


Figure 89. Photo. Football cutter rumble strip and rectangular rumble strip.

Source: KDOT, 2007

Audible Markings

Audible markings were studied by TxDOT as an alternative for rumble strips to be used in situations where rumble strip installation is not possible. Audible markings are “pavement markings designed with the intent to provide audible and tactile feedback that the driver is driving on the line” (Pike et al. 2019). In this study, TxDOT investigated the performance of four forms of audible markings: profiled pavement marking, inverted profile marking, checkered pattern marking, and dot marking, as shown in Figure 90. First, the profiled pavement form of audible markings was reported to generate internal noise levels of greater than 10 dBA on average for passenger cars which satisfies the FHWA desirable requirements of 6 dBA to 15 dBA. Second, the inverted profile form of audible markings was reported to generate internal noise levels of greater than 5 dBA on average for passenger cars which satisfies the FHWA minimum requirements of 3 dBA but does not provide the FHWA desired level of 6 dBA. The third and fourth forms of audible markings (dot and checkered) were both reported to generate internal noise levels of greater than 4 dBA on average for passenger cars which satisfies the FHWA minimum requirements of 3 dBA but does not provide the FHWA desired level of 6 dBA (NCHRP 2009 and Pike et al. 2019). Based on these results, the first and second best performing treatments were reported to be profiled pavement audible marking, and a combination of raised rumble bars and audible markings that generated an increase of more than 8 dBA on average for passenger cars, as shown in Figure 91 (Pike et al. 2019). It should be noted that all testing in this study was performed on roadways with seal coat or asphalt surfaces (Pike et al. 2019). It should also be noted that raised rumble bars can create challenges during roadway winter maintenance and snow removal operations (FHWA 2016b).

(a) Profiled Pavement Marking

(b) Inverted Profile Marking

(c) Checkered Marking

(d) Dot Marking

Figure 90. Photo. Audible pavement markings.

Source: TxDOT, 2019

(a) Combined with Inverted Profile (b) Combined with Checkered

Figure 91. Photo. Combining raised rumble bars with audible pavement markings.

Source: TxDOT, 2019

Angeled Transverse

Angled transverse rumble strips were reported to be used by Missouri DOT as an alternative to traditional full travel lane transverse rumble strips to improve effectiveness, as shown in Figure 92 (Sun et al. 2011). This configuration is designed based on the assumption that it creates an isolated effect for each wheel compared to traditional transverse rumble strips, where the driver is expected to feel four separate impacts rather than just 2 simultaneous impacts (Sun et al. 2011). This alternative rumble strip configuration was reported to be used at an angle of 15, 10, 12, and 10 degrees by Arizona, Illinois, Kansas, and Missouri DOTs, respectively (IDOT n.d., MoDOT 2011, AzDOT 2014, and Schrock et al. 2016). Another study by MoDOT reported that 23% of drivers braked when passing over angled transverse rumble strips compared to 21% in areas with perpendicular rumble strips (MoDOT 2022).

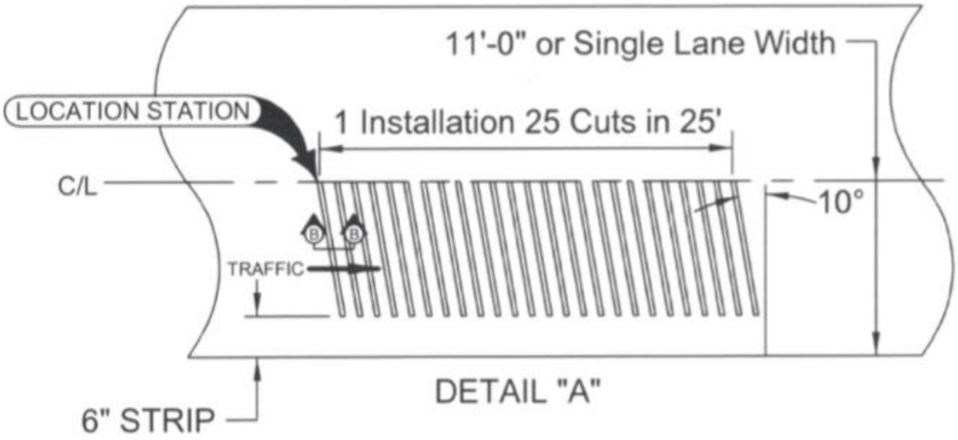


Figure 92. Photo. Angled transverse rumble strip.

Source: IDOT n.d.

Wheel Path

Wheel path transverse rumble strips were reported to be used by Minnesota, New Mexico, and Texas DOTs as an alternative to traditional full travel lane transverse rumble strips to better accommodate motorcyclists, as shown in Figure 93 (MnDOT 2001, NMDOT 2013, TxDOT 2006, and Oneyear et al. 2021). IowaDOT reported that wheel path rumble strips provided better accommodations for motorcyclists who are able to avoid striking the rumble strips by driving in the space between (Oneyear et al. 2021). This design can also be modified to produce a staggered wheel path transverse design which in theory provides an individual strike with each wheel rather than simultaneously, as shown in Figure 94 (TxDOT 2006). It should be noted that MnDOT reported that drivers who are familiar with the locations of wheel path transverse rumble strips will frequently straddle in between the pattern to avoid striking the rumble strips. The study also reported full in-lane transverse rumble strips are a more effective method for breaking patterns of in-alert drivers versus the wheel-path design (MnDOT, 2001).

Figure 93. Photo. Wheel path transverse rumble strip.

Source: Oneyear et al. 2021

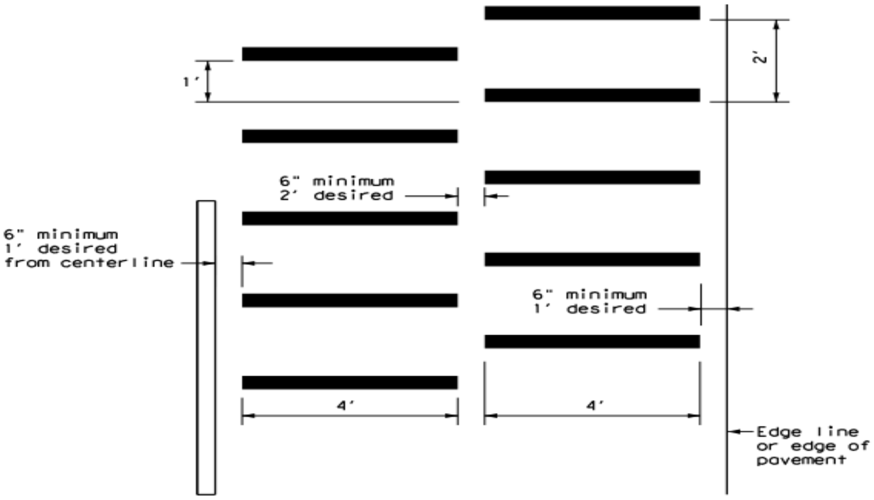


Figure 94. Photo. Staggered wheel-path transverse rumble strip.

Source: TxDOT, 2006

Gapped

Gapped rumble strips are utilized as an alternative to continuous rumble strips to better accommodate bicyclists moving into the travel lane and minimize pavement degradation by avoiding the milling through the centerline pavement joint, as shown in Figures 95 and 96 (Tufuor et al. 2017 and FHWA 2011a). The bicycle gap is utilized by many state DOTs that place gaps intermittently throughout the longitudinal rumble strips at intervals of 40-60 feet. The range of the bicycle gap length is 10-12 feet to allow for a smooth transition between the bicycle lane and the travel lane when needed without suffering severe vibrations generated by riding over the rumble strips, as shown in Figure 95 (FHWA, 2017). The centerline gap is a modified version of the traditional centerline rumble strip, which allows the installation of rumble strips without the need to mill the strip along the construction joint to minimize pavement degradation and provide longer-lasting centerline joint, as shown in Figure 96 (Tufuor et al. 2017 and FHWA 2011a).

Figure 95. Photo. Rumble strip design with bicycle gap.

Source: FHWA 2017b

Figure 96. Photo. Rumble strip design with centerline gap.

Source: Oneyear et al. 2021

Alternate Spacing

Rather than using a uniform spacing in traditional centerline rumble strips, a number of state DOTs utilize a pattern of alternating 12 inches and 24 inches spacing on milled centerline rumble strips, as shown in Figure 97 (NCHRP 2005, IDOT 2016, VTrans 2017, WisDOT 2018, IowaDOT 2019, MDOT

2020, and MDT 2021). Kansas DOT evaluated the performance of twelve centerline rumble strip patterns, four with 24 inch spacing, four with 12 inch spacing, and four with the 12 and 24 inch alternate spacing using seven different vehicles. Each spacing pattern had four different lengths (5 inches, 8 inches, 12 inches, and 16 inches) and the same depth (0.5 inches) and width (6.5 inches), hence the 4 designs per spacing pattern. Although the study reported inconsistencies in the results of the noise measurements, it was determined that the four rumble strip patterns with the 12-inch spacing produced higher internal noise levels than any of the others, followed by the 4 patterns for the alternate 12 and 24 inch spacing (Russell & Rys 2006). Additionally, the four patterns for the alternate 12 and 24 inch spacing produced the highest internal vibration in four of six vehicles tested for internal vibration and the second highest in the remaining two vehicles (Russell & Rys 2006). The same study conducted a driver impression survey after installing these two patterns, where 36%, 34%, and 9% of respondents felt that both patterns, the continuous pattern, and the alternate pattern alerted them adequately, respectively (Russell & Rys 2006).

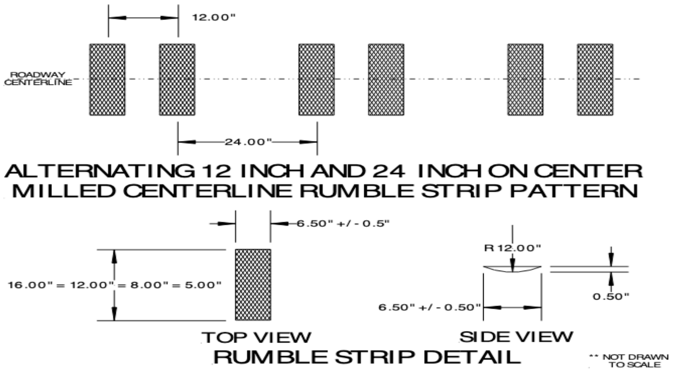


Figure 97. Photo. Kansas alternate spacing blueprint.

Source: KDOT, 2006

Transverse Sinusoidal

Oklahoma DOT includes in its specifications a design for transverse sinusoidal rumble strips that requires alternating strips of ten sinusoidal cycles with a width of 16 inches and length of 11 feet 8 inches, as shown in Figure 98 (OKDOT 2020).

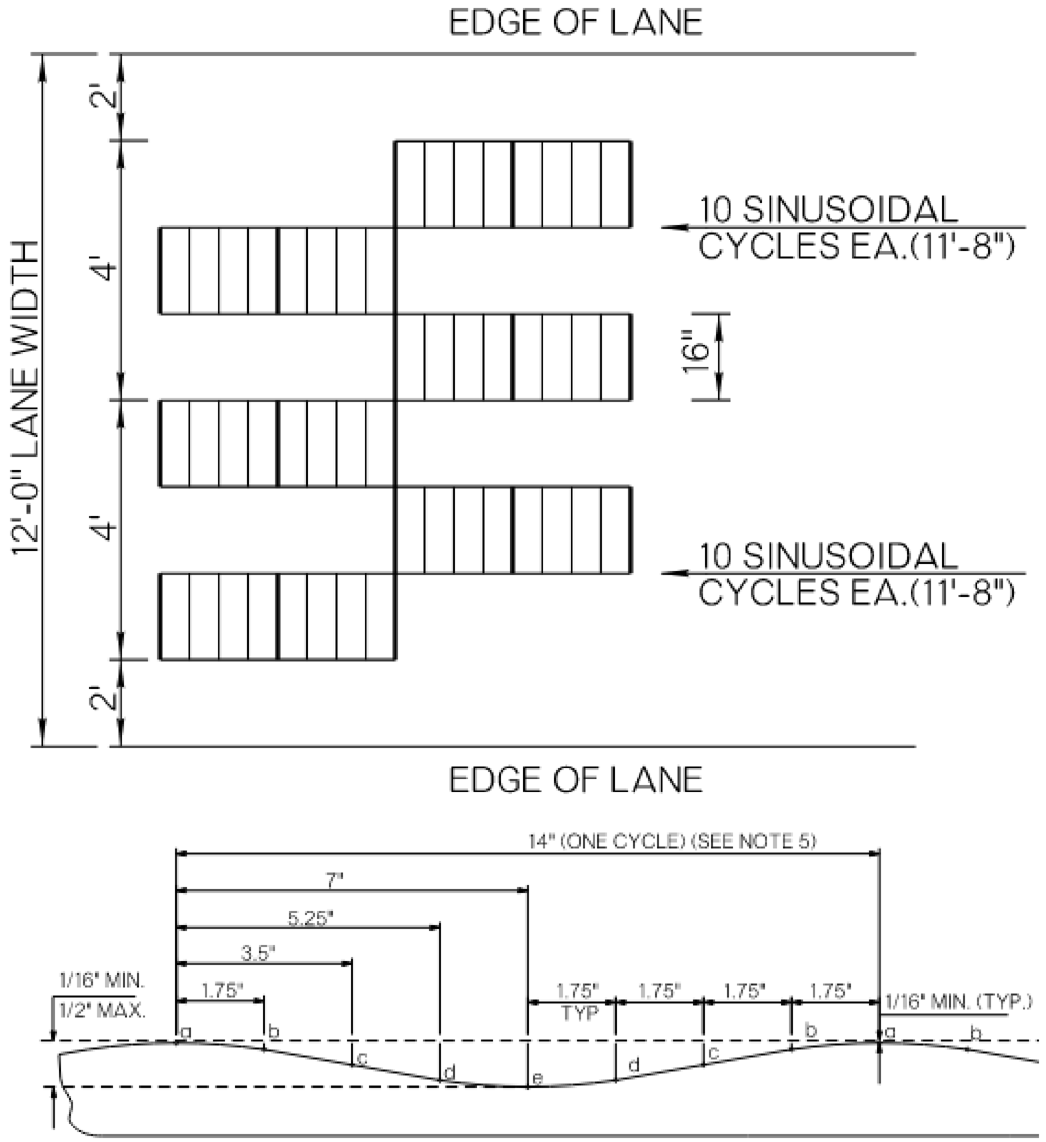


Figure 98. Photo. Transverse sinusoidal rumble strips.

Source: OKDOT, 2020

APPENDIX A3: RUMBLE STRIP EFFECTIVENESS

Rumble strips are an effective safety countermeasure to reduce roadway departure crashes in cases of distracted or fatigued drivers. Roadway departure crashes are defined as crashes that occur after a vehicle crosses an edge line, a centerline, or otherwise leaves the travel lane (FHWA, 2014). This chapter highlights the reported effectiveness of (1) shoulder line and edgeline rumble strips, (2) centerline rumble strips, and (3) transverse rumble strips.

Shoulder Line and Edgeline Rumble Strips

Shoulder line and edgeline rumble strips (see Figure 76) are used to warn drivers when their vehicle strays out of the traveling lane towards the shoulder or median. Shoulder line rumble strips have been reported to reduce run-off-road crashes by 20% to 72%, compared to similar roadway conditions without rumble strips. In addition, shoulder line rumble strips were reported to provide a benefit-cost ratio that ranges from 5:1 to 20:1 (MnDOT 2001). Shoulder line rumble strips have become a well-established safety countermeasure on high volume and speed roads such as the New York Thruway, where their addition has resulted in an 88% and 95% decrease in run-off-road crashes and fatalities, respectively. It should be noted that the safety benefits of shoulder line rumble strips may be less significant on low-volume roads (FHWA 2011c).

Edgeline rumble strips have been reported to decrease shoulder encroachments by approximately 50% after their implementation (FHWA 2017c). Further reported benefits of edgeline rumble strips include nighttime visibility improvement in low-lit and dim areas, where the back wall of the milled rumble strip acts as a reflector bouncing the light off the head beams of oncoming traffic even after rainy conditions, as shown in Figure 99 (FHWA 2015c). One study evaluated the wet-night visibility of rumble strips and flat thermoplastic lines under light, medium, and heavy rainfall rates using a closed rain tunnel. It was reported that there was a minor change in detection distance under light rain conditions and a 13 to 38% increase in detection distance under medium and heavy rainfall rates for rumble strip lines (FHWA 2017c).

Figure 99. Photo. Daytime and nighttime visibility of edgeline rumble strips.

Source: FHWA, 2015

Centerline Rumble Strips

Centerline rumble strips are considered to be an effective countermeasure for head-on and opposite direction sideswipe collisions, along with single vehicle run-off to the left, as shown in Figure 76 (FHWA 2011a). Centerline rumble strips were reported to reduce cross-over crashes by an average of 40 – 60% (FHWA 2015d). An NCHRP study reported that installing centerline rumble strips may reduce head-on crashes by 34 to 95 percent, an average of about 65% reduction overall (NCHRP 2009). FHWA reported that centerline rumble strips have resulted in reducing injury crashes in rural and urban areas by 37 to 91% and 38 to 50%, respectively (FHWA 2015d). Additionally, Washington

DOT reported a reduction of 37% in total crossover collisions and 57% in serious injury or fatal crossover collisions after installing centerline rumble strips (WSDOT & Sexton 2014). Centerline rumble strips also play an important role in supporting drivers' navigation during deteriorating weather conditions such as snow, fog, or blinding rain. The rumble strips act as an effective indicator of the center of the road separating the oncoming traffic lane due to the vibrations created by rumbles, which often support drivers in navigating their own lane (FHWA 2011a).

Transverse Rumble Strips

Transverse rumble strips are installed within the travel lane and perpendicular to the direction of travel to alert drivers of the need to slow down or possibly come to a full stop, as shown in Figure 76. Iowa DOT reported that the installation of transverse rumble strips at stop-controlled intersections reduced crashes by 20% to 40% (IowaDOT 2022). Minnesota DOT reported that the installation of transverse rumble strips produced significant increases in the distances between the intersection and (1) the point that the driver starts deceleration (980 to 1100 feet), and (2) the point that the driver applies the brake (480 to 590 feet), as shown in Figure 100 (MnDOT 2001).

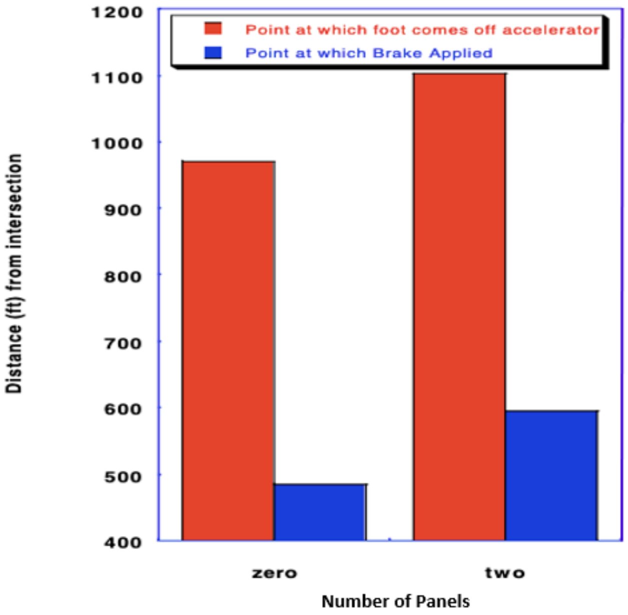


Figure 100. Graph. Braking and deceleration distance.

Source: MnDOT, 2001

Minnesota DOT and Contra Costa County evaluated the effectiveness of transverse rumble strips at stop-controlled approaches by investigating driver behavior at intersections with transverse rumble strips. The study reported that transverse rumble strips increased drivers' full stops by 26% and 30% for the Minnesota and Contra Costa County studies, respectively (NCHRP 1993). In addition, transverse rumble strips have been found to reduce the speed of drivers approaching an intersection by 2 to 5 mph when compared to intersections without rumble strips (IowaDOT 2014). Iowa DOT further reported that the installation of transverse rumble strips on primary roads may lead to a benefit-cost ratio of about 13 (Oneyear et al. 2021).

APPENDIX A4: RUMBLE STRIP EXTERNAL NOISE

Despite the benefits of rumble strips in alerting inattentive drivers, there have been many reports of noise complaints from nearby residents because of their generated external noise (Anund et al. 2017). This chapter presents the main findings of a comprehensive literature review on (1) external noise generated by rumble strips, and (2) noise mitigation techniques.

External Noise Generated by Rumble Strips

Washington DOT reported that have received an increasing number of noise complaints from nearby residents of rumble strips in suburban and rural areas mainly complaining about sleep disruption at night. The disruption in rural areas may be attributed to the lower nighttime noise in comparison to urban areas, making the relative change in noise levels higher (Laughlin & Donahue 2018). Similarly, many other state DOTs such as Minnesota, North Carolina, and Oregon have also reported receiving similar noise complaints from nearby residents (MnDOT 2016, ODOT 2019, and Findley et al. 2020). Accordingly, rumble strip external noise and their related complaints need to be mitigated while ensuring that rumble strips generate an adequate level of internal noise to alert drivers (FHWA 2015c).

Mitigation Techniques

A number of mitigation techniques have been studied by state DOTs to minimize noise for nearby residential areas and wildlife habitats (Caltrans 2018, WSDOT 2019, and ODOT 2019). These mitigation techniques include (1) sinusoidal rumble strips, (2) bituminous surface treatment overlay, (3) epoxy filled rumble strips, and (4) buffer zones. The following sections provide a concise description of these mitigation techniques.

Sinusoidal Rumble Strips

A number of states and NCHRP have studied sinusoidal rumble strips as an alternative to the traditional milled rumble strip to minimize external noise affecting nearby areas (MnDOT 2016, Caltrans 2018, Washington 2018, INDOT 2019, Big Sky Acoustics 2019, ODOT 2019, NCHRP 2024). Sinusoidal rumble strips produce a lower external noise level due to having a wave-like rumble shape that is continuous and lessens the external noise produced (MnDOT 2022). This section analyzes the reported findings of several sinusoidal noise studies that were conducted by (1) California DOT, (2) Indiana DOT, (3) Minnesota DOT, (4) Montana DOT, (5) Oregon DOT, (6) Washington DOT, and (7) NCHRP research project 1107.

California DOT

California DOT (Caltrans) reported that the external noise from sinusoidal rumble strips is 3 to 8 decibels quieter than traditional rumble strips based on their measured external noise generated by 3 passenger cars, 1 SUV, and 1 truck, as shown in Figure 101 (Caltrans 2018). In addition, the sinusoidal rumble strips generated internal noise level increases that ranged from 2.6 dBA to 20.0 dBA for all tested vehicles, as shown in Figure 102. The increase in internal noise generated by two of the passenger cars and the SUV satisfies the FHWA requirements of 3 to 15 dBA. On the other hand, the Chevy Malibu passenger car generated an increase in internal noise level of 20 dBA which exceeds the FHWA maximum limit of 15 dBA. Similarly, the 4-yard dump truck generated an increase in internal noise level of 2.6 dBA which is slightly less than the minimum FHWA recommendation of 3 dBA, as shown in Figure 102 (Caltrans 2018).

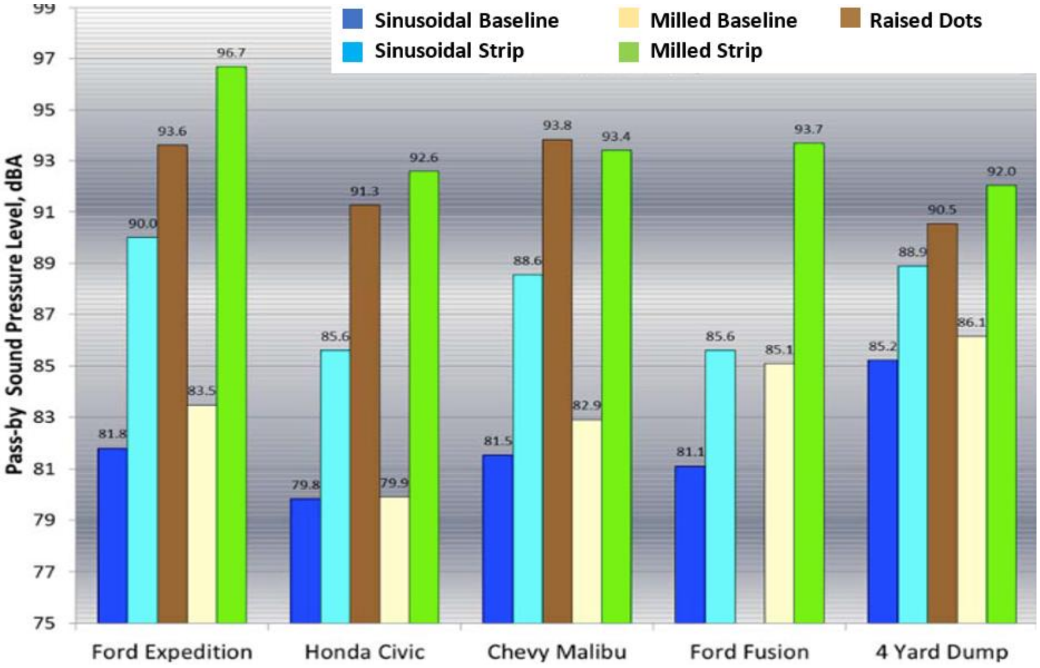


Figure 101. Graph. Generated external noise levels by sinusoidal and traditional rumble strips.

Source: Caltrans 2018

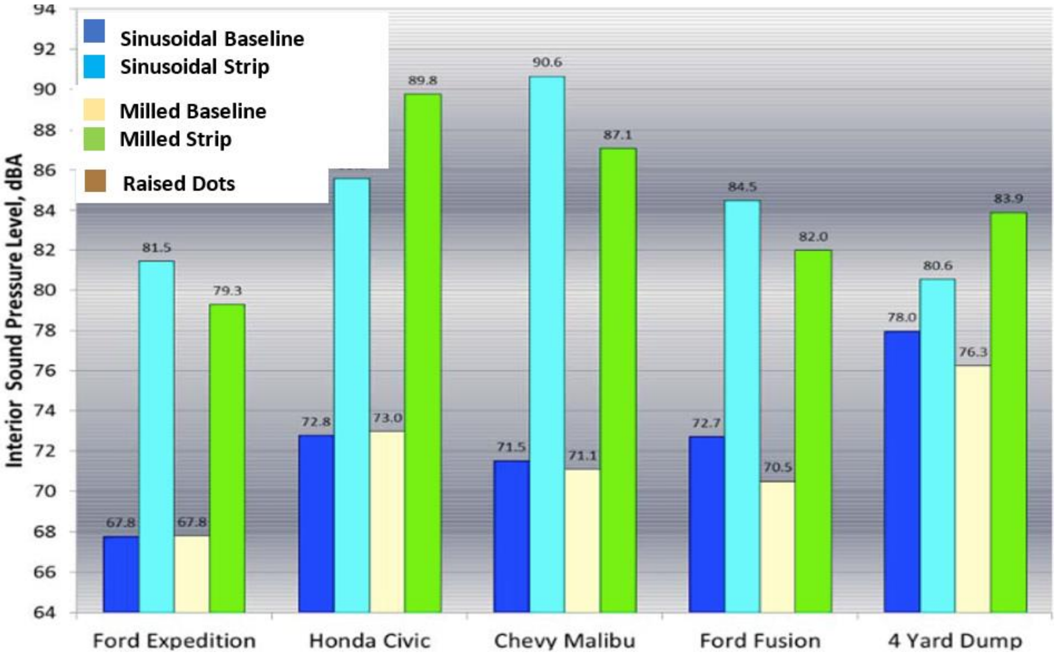
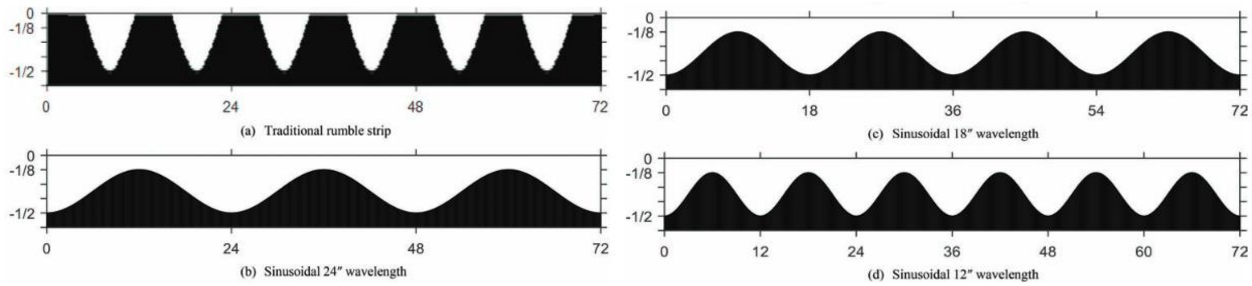


Figure 102. Graph. Generated internal noise levels by sinusoidal and traditional rumble strips.

Source: Caltrans 2018

Indiana DOT

Indiana DOT analyzed the performance of 3 sinusoidal and 1 traditional rumble strip designs based on their generated internal and external noise, as shown in Figure 103 (INDOT 2019). The outcome of this performance analysis shows that the increase in generated internal noise compared to no rumble strip by (1) traditional rumble strip design was 9 dBA, and (2) the 3 sinusoidal rumble strip designs ranged from 5 to 12.5 dBA, as shown in Table 24 (INDOT 2019). Similarly, the measured increase in external noise generated by (a) traditional rumble strip design was 5 dBA, and (2) the 3 sinusoidal rumble strip designs ranged from -0.5 to 3 dBA, as shown in Table 3 (INDOT 2019). Furthermore, the results of this study illustrate that the best performing rumble strip was sinusoidal with the 12-inch wavelength that produced an internal increase of 12.5 dBA and a 0.5 dBA decrease in external noise, as shown in Table 24. This design satisfies the FHWA requirements of 6 to 15 dBA in internal noise increase while producing almost no increase in external noise.



(a) Traditional rumble strip

(c) Sinusoidal 18″ wavelength

(b) Sinusoidal 24″ wavelength

(d) Sinusoidal 12″ wavelength

Figure 103. Photo. INDOT tested rumble strip designs.

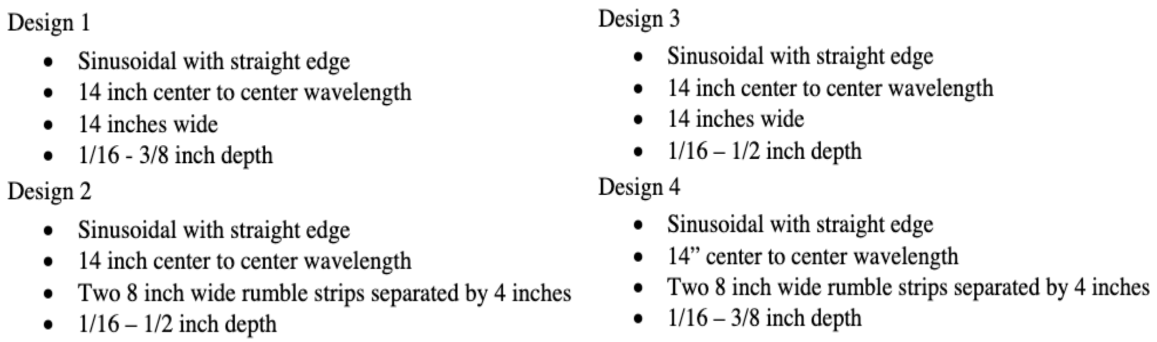
Source: INDOT 2019

Table 24. Internal and External Noise of Sinusoidal and Traditional Rumble Strips (INDOT 2019)

Car Type	Rumble Strip Design	Measured External Noise	Delta External from Baseline	Measured Internal Noise	Delta Internal from Baseline
Impala	Baseline	71.0 dBA	-	71.5 dBA	-
Impala	(a) Traditional	75.5 dBA	4.5 dBA	80.0 dBA	8.5 dBA
Impala	(b) 24” Sine Wave	71.5 dBA	0.5 dBA	76.5 dBA	5.0 dBA
Impala	(c) 18” Sine Wave	74.0 dBA	3.0 dBA	77.0 dBA	5.5 dBA
Impala	(d) 12” Sine Wave	70.5 dBA	-0.5 dBA	84.0 dBA	12.5 dBA
Van	Baseline	72.0 dBA	-	73.5 dBA	-
Van	(a) Traditional	78.5 dBA	6.5 dBA	79.0 dBA	5.5 dBA
Van	(b) 24” Sine Wave	71.5 dBA	-0.5 dBA	76.5 dBA	3.0 dBA
Van	(c) 18” Sine Wave	75.5 dBA	3.0 dBA	75.0 dBA	1.5 dBA
Van	(d) 12” Sine Wave	72.5 dBA	0.5 dBA	81.0 dBA	7.5 dBA
Tandem Axel	Baseline	82.0 dBA	-	81.0 dBA	-
Tandem Axel	(a) Traditional	N/A			
Tandem Axel	(b) 24” Sine Wave	81.0 dBA	-1.0 dBA	77.0 dBA	-4.0 dBA
Tandem Axel	(c) 18” Sine Wave	82.5 dBA	0.5 dBA	76.0 dBA	-5.0 dBA
Tandem Axel	(d) 12” Sine Wave	84.0 dBA	2.0 dBA	84.0 dBA	3.0 dBA

Minnesota DOT

Minnesota DOT analyzed the performance of four sinusoidal and one traditional rumble strip designs based on their generated internal and external noise using three vehicles including passenger car, pickup truck, and heavy truck, as shown in Figure 104 (MnDOT 2016). For the tested passenger car, the outcome of this performance analysis shows that the increase in internal noise generated by (1) traditional rumble strip design was 18 dBA, and (2) the four sinusoidal rumble strip designs ranged from 12 to 15 dBA, as shown in Figure 105 (MnDOT 2016). Similarly, the measured increase in external noise generated by (a) traditional rumble strip design was 16 dBA, and (b) the four sinusoidal rumble strip designs ranged from 0 to 8 dBA, as shown in Figure 105 (MnDOT 2016). Furthermore, the results of this study illustrate that the best performing rumble strip was sinusoidal design 4 for the passenger vehicle, producing an internal increase of 12 dBA and no external increase, as shown in Figure 105. This design satisfies the FHWA requirements of 6 to 15 dBA in internal noise increase while producing almost no increase in the external noise. The internal and external noise generated by the pickup and heavy trucks in these tests can be found in the published report of this study (MnDOT 2016).



Design 1

- Sinusoidal with straight edge
- 14 inch center to center wavelength
- 14 inches wide
- 1/16 - 3/8 inch depth

Design 2

- Sinusoidal with straight edge
- 14 inch center to center wavelength
- Two 8 inch wide rumble strips separated by 4 inches
- 1/16 – 1/2 inch depth

Design 3

- Sinusoidal with straight edge
- 14 inch center to center wavelength
- 14 inches wide
- 1/16 – 1/2 inch depth

Design 4

- Sinusoidal with straight edge
- 14” center to center wavelength
- Two 8 inch wide rumble strips separated by 4 inches
- 1/16 – 3/8 inch depth

Figure 104. Illustration. MnDOT sinusoidal rumble strip design specifications.

Source: MnDOT 2016

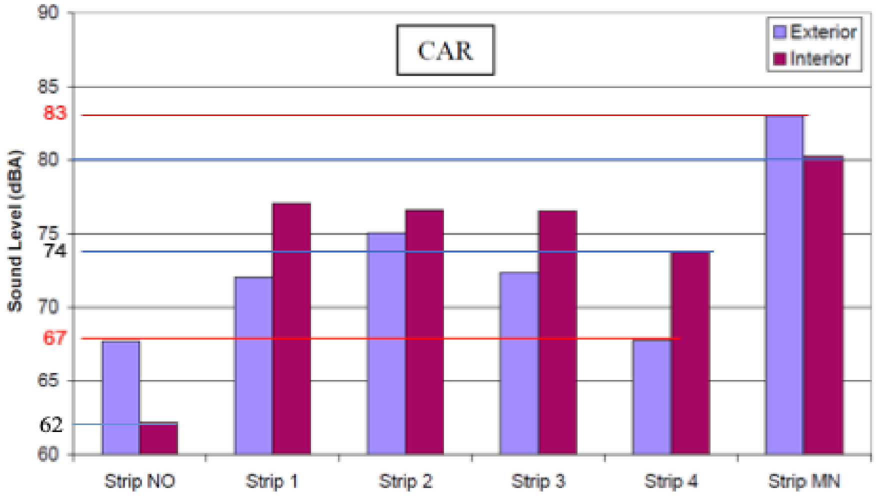
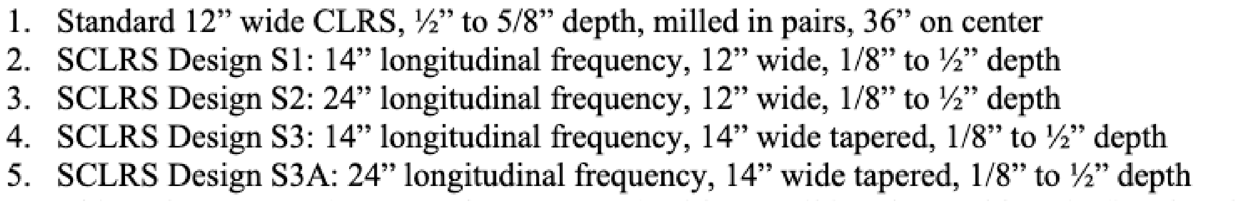


Figure 105. Graph. Internal and external noise levels for MnDOT sinusoidal and traditional rumble strip.

Source: MnDOT 2016

Montana DOT

Montana DOT analyzed the performance of four sinusoidal and one traditional rumble strip designs based on their generated external noise using three vehicles including passenger vehicle, medium truck, and heavy truck, as shown in Figure 106 (MDT 2019). For the tested passenger vehicle, the outcome of this performance analysis shows that the external noise generated at 50 mph by (a) traditional rumble strip design was 9.4 dBA, and (2) the four sinusoidal rumble strip designs ranged from 0 to 1.2 dBA, as shown in Figure 107 (MDT 2016). The study also tested the internal noise and vibration qualitatively, where two members of the research team drove over the three sinusoidal rumble strips. It was determined by the research team that sinusoidal design 3A provided the best internal performance overall for the passenger vehicle, medium truck, and heavy truck (MDT 2019). The internal and external noise generated by the medium and heavy trucks in these tests can be found in the published report of this study (MDT 2019).



1. Standard 12” wide CLRS, ½” to 5/8” depth, milled in pairs, 36” on center
2. SCLRS Design S1: 14” longitudinal frequency, 12” wide, 1/8” to ½” depth
3. SCLRS Design S2: 24” longitudinal frequency, 12” wide, 1/8” to ½” depth
4. SCLRS Design S3: 14” longitudinal frequency, 14” wide tapered, 1/8” to ½” depth
5. SCLRS Design S3A: 24” longitudinal frequency, 14” wide tapered, 1/8” to ½” depth

Figure 106. Illustration. MDT sinusoidal and traditional rumble strip design specifications.

Source: MDT 2019

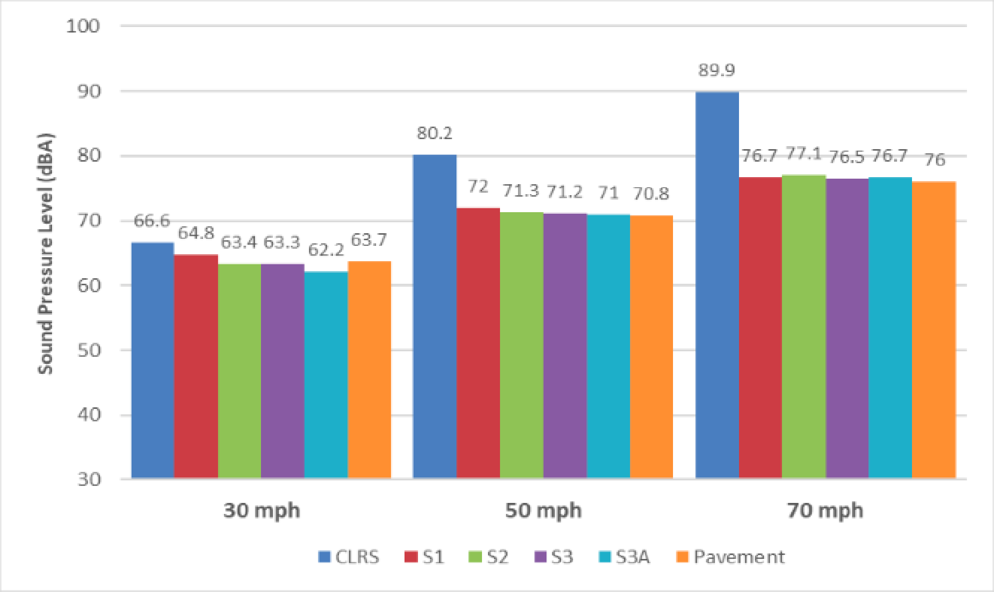


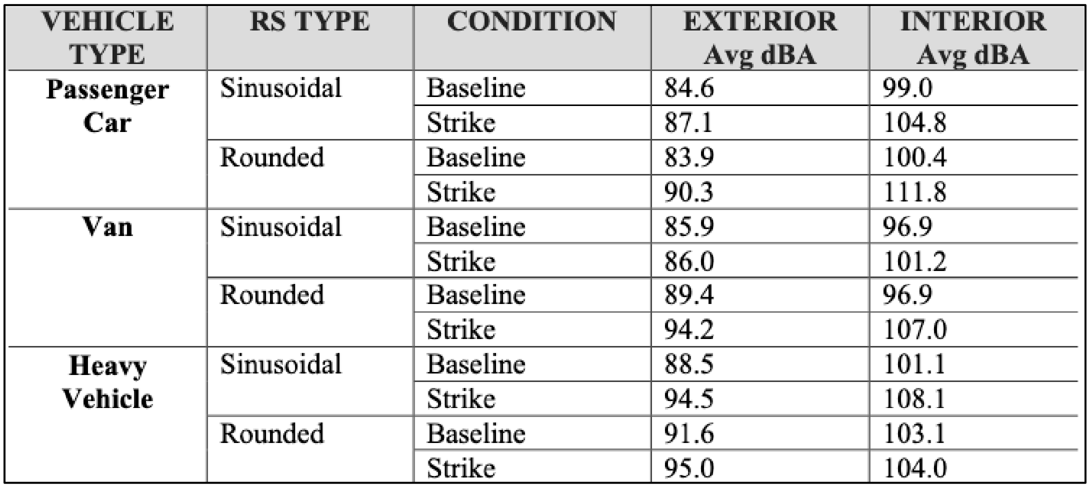
Figure 107. Graph. Sinusoidal and traditional rumble strip external noise levels for passenger vehicle.

Source: MDT 2019

Oregon DOT

Oregon DOT (ODOT) analyzed the performance of one sinusoidal and one traditional rumble strip designs based on their generated external and internal noise using three vehicles including passenger car, van, and heavy vehicle (ODOT 2019). For the three tested vehicles, ODOT reported that the external noise from sinusoidal rumble strips is 0.5 to 8.2 dBA quieter than traditional rumble strips, as shown in Table 25 (ODOT 2019). In addition, the sinusoidal rumble strips generated internal noise level increases that ranged from 4.3 to 7.0 dBA for three vehicles, as shown in Table 25. The increase in internal noise generated by all vehicles satisfies the FHWA requirements of 3 to 15 dBA. It should be noted that the rounded design was incapable of producing the FHWA minimum requirement for internal noise levels for the heavy truck, while the sinusoidal design produced a desirable 7.0 dBA (ODOT 2019).

Table 25. Exterior and Interior Noise Levels for Sinusoidal and Rounded Rumble Strips (ODOT 2019)



VEHICLE TYPE	RS TYPE	CONDITION	EXTERIOR Avg dBA	INTERIOR Avg dBA
Passenger Car	Sinusoidal	Baseline	84.6	99.0
		Strike	87.1	104.8
	Rounded	Baseline	83.9	100.4
		Strike	90.3	111.8
Van	Sinusoidal	Baseline	85.9	96.9
		Strike	86.0	101.2
	Rounded	Baseline	89.4	96.9
		Strike	94.2	107.0
Heavy Vehicle	Sinusoidal	Baseline	88.5	101.1
		Strike	94.5	108.1
	Rounded	Baseline	91.6	103.1
		Strike	95.0	104.0

Washington DOT

Washington DOT (WSDOT) analyzed the performance of one sinusoidal and three traditional rumble strip designs based on their generated external and internal noise using one passenger car (Laughlin & Donahue 2018). In this study, the external noise was measured at a distance of 25 and 50 feet from the center of the travel lane. The measured external noise results show that the sinusoidal rumble strip was 5 to 11 dBA quieter than traditional rumble strips for the passenger car, as shown in Figure 108 (Laughlin & Donahue 2018). In addition, the sinusoidal rumble strips generated internal noise level increases of 8 dBA for the test vehicle, as shown in Figure 108. The increase in internal noise generated by the sinusoidal rumble strip satisfies the FHWA requirements of 3 to 15 dBA.

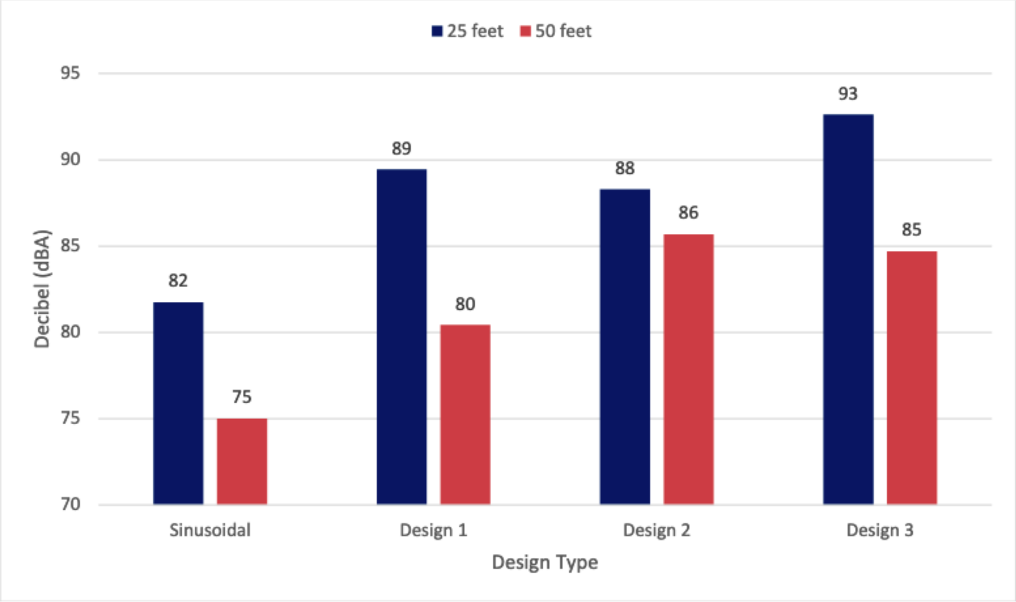


Figure 108. Graph. External noise levels for sinusoidal and traditional rumble strips.

Source: Laughlin & Donahue 2018

<u>NCHRP Research Project 1107</u>

NCHRP research project 1107 analyzed the performance of twenty-five sinusoidal and one traditional rumble strip designs in four different states: (1) three sinusoidal designs in Indiana; (2) one sinusoidal design in Michigan; (3) twenty sinusoidal designs in Washington; and (4) one sinusoidal and one traditional design in California. The twenty-five sinusoidal designs were evaluated based on their generated external and internal noise using twenty passenger cars (10 sedans and 10 SUVs) and one pick-up truck (NCHRP 1107, 2024). The rumble strip generated external noise was mainly measured at a distance of 25 feet from the vehicle centerline when tires are on rumble strips. The baseline pavement external noise on the other hand was measured at 25 feet from the center of travel lane. The internal and external noise measurements were measured at two different traveling speeds of 45 mph and 60 mph. A comprehensive internal and external noise measurements was conducted for twenty longitudinal designs and their results are summarized in Tables 26 and 27.

Table 26. Noise Measurements of Sinusoidal Rumble Strips at 60 mph (NCHRP 1107, 2024)

Site	Measured Dimensions			On/Off Increments			
	Wavelength (in.)	Amplitude (in.)	Recess (in.)	CC Mic. (dB)	ST Accel. (dB)	Interior Avg (dB)	Pass-by Mic. (dB)
EB6	24	1/8	0	3.2	6.9	5.05	0
EB8	17	1/8	0	4.5	7.1	5.8	0.9
EB7	14	5/16	0	5.7	6.8	6.25	1.5
WB3	18	1/8	1/8	4.6	8.1	6.35	0
WB7	12	1/8	1/8	5.9	9.7	7.8	6.4
WB5	15	5/16	0	6.3	10.4	8.35	0.8
EB11	15	5/16	1/8	7.5	9.6	8.55	4.3
WB4	16	5/16	0	6.8	10.4	8.6	1.4
WB1	14	1/8	1/8	8	9.4	8.7	3.6
WB2	16	1/8	1/8	7.3	10.2	8.75	0.6
EB5	14	7/16	1/8	7.8	9.9	8.85	5.4
EB4	16	1/8	0	8.5	11.1	9.8	1.6
EB1	14	5/16	0	10.1	11.2	10.65	8.7
WB8	14	7/16	0	10	12.1	11.05	7.6
WB9	14	1/2	1/8	10.3	11.8	11.05	10.2
EB2	14	5/16	0	10.5	11.6	11.05	9.9
EB9	13	5/16	0	11.6	10.8	11.2	5.7
WB6	16	1/2	0	9.7	13.3	11.5	2.7
EB10	15	7/16	0	11.7	13.1	12.4	4.7
EB3	14	1/2	0	12.6	14.2	13.4	5.5

Table 27. Noise Measurement of Sinusoidal Rumble Strips at 45 mph (NCHRP 1107, 2024)

Site	Measured Dimensions			On/Off Increments			
	Wavelength (in.)	Amplitude (in.)	Recess (in.)	CC Mic. (dB)	ST Accel. (dB)	Interior Avg (dB)	Pass-by Mic. (dB)
WB7	12	3/8	1/8	2.5	8.2	5.4	1.3
WB6	16	1/2	0	2.7	8.5	5.6	0.0
EB9	13	5/16	0	5.3	7.0	6.1	0.8
EB5	14	7/16	1/8	5.2	8.1	6.6	0.0
EB7	14	5/16	0	5.8	9.9	7.9	0.0
EB6	24	3/8	0	5.6	10.2	7.9	0.0
EB4	16	3/8	0	5.8	10.2	8.0	0.0
EB3	14	1/2	0	4.9	12.1	8.5	0.0
WB5	15	5/16	0	5.2	12.0	8.6	0.0
EB2	14	5/16	0	6.8	10.6	8.7	0.5
WB8	14	7/16	0	8.0	9.7	8.9	0.0
WB9	14	1/2	1/8	7.1	10.7	8.9	2.1
WB4	16	5/16	0	6.4	12.5	9.4	1.7
EB8	17	3/8	0	7.2	12.9	10.0	0.2
EB11	15	5/16	1/8	6.8	13.6	10.2	3.0
WB2	16	3/8	1/8	6.9	14.5	10.7	1.8
EB10	15	7/16	0	7.3	14.6	10.9	2.5
WB1	14	3/8	1/8	8.2	14.5	11.4	3.7
EB1	14	5/16	0	9.3	13.8	11.5	0.7
WB3	18	3/8	1/8	9.9	17.0	13.5	1.3

Best Performing Sinusoidal Rumble Strips

This section analyzes the reported internal and external noise generated by varying designs of sinusoidal rumble strips that were tested by other state DOTs to identify and rank the top six performing sinusoidal rumble strip designs that can be used in the planned field tests in this study. California, Indiana, Minnesota, Montana, Oregon, and Washington DOTs studied the generated noise of thirteen sinusoidal rumble strip designs using passenger cars and heavy vehicles, as shown in Tables 28 and 29. These thirteen different sinusoidal rumble strips designs were analyzed to identify and rank the top six performing designs in (1) satisfying the FHWA recommended increase in internal noise of 3 to 15 dBA, and (2) producing the least external noise to minimize complaints from nearby residents for both passenger cars and heavy vehicles, as shown in Table 30. The top ranked sinusoidal rumble strip was the reported design by Indiana DOT that satisfied the FHWA recommendations for internal noise while producing the least external noise, as shown in Table 30.

Table 28. External and Interior Noise Levels for Sinusoidal Rumble Strips and Passenger Vehicles

Sinusoidal Design	Delta External	Delta Interior	Speed	Distance	Car Type
California	5.8 dBA	12.8 dBA	60 mph	25′ away	Honda Civic
California	4.5 dBA	11.8 dBA	60 mph	25′ away	Ford Fusion
California	7.1 dBA	19.1 dBA	60 mph	25′ away	Chevy Malibu
Minnesota 1	4.5 dBA	14.9 dBA	60 mph	50′ away	Ford Fusion
Minnesota 2	6.4 dBA	15.2 dBA	60 mph	50′ away	Ford Fusion
Minnesota 3	5.9 dBA	14.7 dBA	60 mph	50′ away	Ford Fusion
Minnesota 4	2.3 dBA	12.5 dBA	60 mph	50′ away	Ford Fusion
Montana 1	1.2 dBA	N/A	50 mph	50′ away	Toyota 4Runner
Montana 2	0.5 dBA	N/A	50 mph	50′ away	Toyota 4Runner
Montana 3	0.4 dBA	N/A	50 mph	50′ away	Toyota 4Runner
Montana 3A	0.2 dBA	N/A	50 mph	50′ away	Toyota 4Runner
Oregon	2.5 dBA	5.8 dBA	55 mph	Average of 25′ and 50′	Ford Focus Hatchback
Indiana 1	-0.5 dBA	12.5 dBA	50 mph	50′ away	Impala
Indiana 2	3.0 dBA	5.5 dBA	50 mph	50′ away	Impala
Indiana 3	1.0 dBA	5.0 dBA	50 mph	50′ away	Impala
Washington	4.0 dBA	8.0 dBA	60 mph	50′ away	Ford Explorer
Washington	6.0 dBA	8.0 dBA	60 mph	25′ away	Ford Explorer

Table 29. External and Interior Noise levels for Sinusoidal Rumble Strips and Heavy Trucks

Sinusoidal Design	Delta Exterior	Delta Interior	Speed	Distance	Heavy Vehicle Type
California	3.7 dBA	2.6 dBA	60 mph	25′ away	Dump Truck
Minnesota 1	-0.4 dBA	0.8 dBA	60 mph	50′ away	Sterling Class 35 tandem
Minnesota 2	3.0 dBA	2.7 dBA	60 mph	50′ away	Sterling Class 35 tandem
Minnesota 3	2.5 dBA	1.4 dBA	60 mph	50′ away	Sterling Class 35 tandem
Minnesota 4	1.8 dBA	1.2 dBA	60 mph	50′ away	Sterling Class 35 tandem
Montana 1	0.0 dBA	N/A	50 mph	50′ away	Volvo Truck Tractor
Montana 2	-0.7 dBA	N/A	50 mph	50′ away	Volvo Truck Tractor
Montana 3	-0.8 dBA	N/A	50 mph	50′ away	Volvo Truck Tractor
Montana 3A	2.0 dBA	N/A	50 mph	50′ away	Volvo Truck Tractor
Oregon	6.0 dBA	7.0 dBA	55 mph	Average of 25′ and 50′	Volvo Truck
Indiana 1	1.5 dBA	3.0 dBA	50 mph	50′ away	Tandem Axle
Indiana 2	0.5 dBA	-9.5 dBA	50 mph	50′ away	Tandem Axle
Indiana 3	-1.0 dBA	-9.0 dBA	50 mph	50′ away	Tandem Axle
Washington	N/A				

Table 30. Analysis and Ranking of Tested Sinusoidal Rumble Strips by Other State DOTs

Rank	Sinusoidal Design	Delta Exterior	Delta Interior	Speed	Distance	Vehicle Type
1	Indiana 1	-0.5 dBA	12.5 dBA	50 mph	50′ away	Passenger Vehicle
		1.5 dBA	3.0 dBA	50 mph	50′ away	Heavy Truck
2	Oregon	2.5 dBA	5.8 dBA	55 mph	Average of 25′ and 50′	Passenger Vehicle
		6.0 dBA	7.0 dBA	55 mph	Average of 25′ and 50′	Heavy Truck
3	California	4.5 dBA	11.8 dBA	60 mph	25′ away	Passenger Vehicle
		3.7 dBA	2.6 dBA	60 mph	25′ away	Heavy Truck
4	Minnesota 2	6.4 dBA	15.2 dBA	60 mph	50′ away	Passenger Vehicle
		3.0 dBA	2.7 dBA	60 mph	50′ away	Heavy Truck
5	Washington	4.0 dBA	8.0 dBA	60 mph	50′ away	Passenger Vehicle
		N/A				Heavy Truck
6	Montana 3A	0.2 dBA	N/A	50 mph	50′ away	Passenger Vehicle
		2.0 dBA	N/A	50 mph	50′ away	Heavy Truck

Bituminous Surface Treatment

Bituminous surface treatment (BST) also known as a chip seal, is a thin protective wearing surface that is applied to a pavement or base course, as shown in Figure 109 (Pavement Interactive 2022). This 0.5-inch type of road treatment is usually applied to low-volume roads (Constructor 2021). The application of one layer of chip seal produces shallower rumble strips without the need for reconstruction, with the rumble strip remaining functional until the life of the newly applied chip seal

(PennDOT 2014 and ODOT 2022). FHWA reported that applying a BST overlay on an existing strip retains the shape of the rumble but can lose some of the cross-section, however, the aggregates from the chip seal can increase the noise vibration of the rumble (FHWA 2015f). Nebraska DOT reported that a 1/8-inch reduction in milled rumble strip depth using BST did not reduce the rumble strip effectiveness at producing audible and tactile warnings to alert drivers (Tufuor et al. 2017). On the other hand, FHWA reported that the chip seal treatments may negatively impact the effectiveness of rumble strips due to the reduction in its depth resulting from the added thickness of the chip seal (FHWA 2015d). To address this, a number of state DOTs such as Michigan mill their rumble strips before the application of chip seal, while others such as Montana perform the re-milling after the application (FHWA 2015d and Tufuor et al. 2017).

Figure 109. Photo. Chip seal application.

Source: BETA Group 2022

Epoxy-Filled Rumble Strips

Epoxy-filled transverse rumble strips were studied by the Oregon DOT to reduce external noise generated by rumble strips and minimize noise complaints from nearby residents, as shown in Figure 110 (ODOT 2019). In this study, ODOT investigated the noise produced by the traditional transverse design, epoxy-filled transverse design, and a fully paved transverse rumble strip. The epoxy-filled transverse rumble strip design was identical to their traditional design with an addition of 1/4 inches of epoxy layer, which reduced the depth from 1/2 inches to 1/4 inches. This reduction in depth reduced the external noise by 3.5 dBA from 87.5 dBA, which was produced by the traditional transverse device, as shown in Figure 111 (ODOT 2019). The study reported that switching to a shallower transverse rumble strip would reduce a significant amount of external noise since the depth of the transverse rumble strip has a large influence on the amount of additional noise generated by rumble strip strikes (Miles et al. 2007, ODOT 2019).

Figure 110. Photo. Epoxy-filled transverse rumble strip.

Source: ODOT 2019

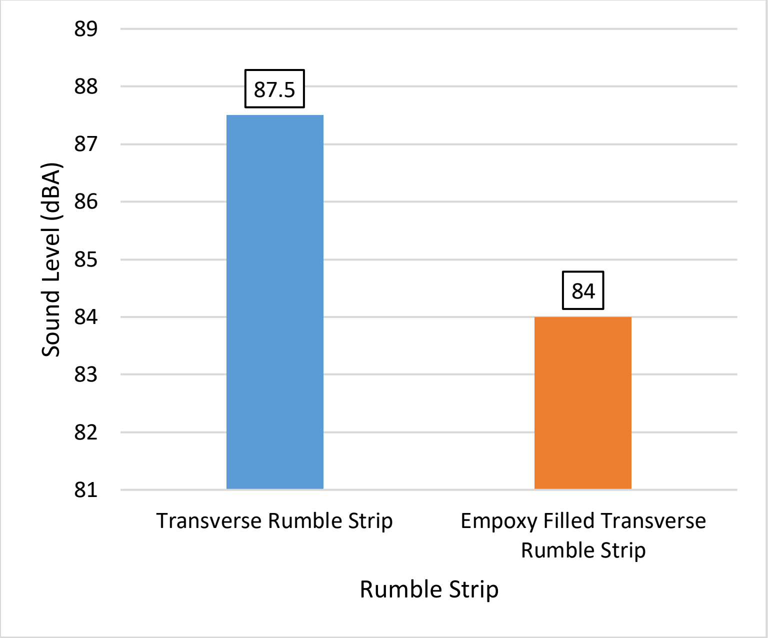


Figure 111. Graph. External noise produced by epoxy-filled transverse rumble strip.

Source: ODOT 2019

Buffer Zones

A number of state DOTs such as California, Florida, and Minnesota utilize a minimum buffer zone of 650 feet between the location of rumble strips and residential areas to minimize noise complaints from nearby residents (FDOT n.d. FHWA 2016b and Caltrans 2018).

APPENDIX A5: RUMBLE STRIP NOISE AND VIBRATION TESTING PROCEDURE

This section presents a concise review of external and internal noise testing procedures for measuring noise generated by rumble strips. The following sections focus on (1) external noise testing procedures, (2) internal noise testing procedures, (3) internal vibration testing procedures, and (4) noise testing procedures used by state DOTs.

External Noise Testing Procedures

The American Association of State Highway and Transportation Officials (AASHTO) provides detailed testing procedures for measuring the external noise generated by rumble strips: (1) Testing Provisional 389 for statistical isolated pass-by (SIP), and (2) Testing Provisional 390 for continuous-flow traffic time-integrated method (CTIM).

Testing Provisional 389

AASHTO Testing Provisional 389 or the statistical isolated pass-by (SIP) is a test method used to measure the influence of road surfaces, such as rumble strips, on highway traffic noise (AASHTO 2021). This testing procedure is conducted using an isolated vehicle, free of any noise contamination that may be produced by other vehicles. The testing procedure involves placing two microphones at a distance of 25 ft and 50 ft from the center of the travel lane to record pavement baseline and rumble strip strike sound levels in order to provide a clear comparison of the increase/decrease in noise level, as shown in Figure 112 (AASHTO 2021). The rumble strip needs to span at least 100 feet before and after where the microphone is located on a straight open space road free of any extraneous material. Additionally, the site must be located away from intrusive noise sources, intersections, and lane mergers. The SIP method recommends a minimum of 30 pass-by events per vehicle category with 100 being the desired amount. Further considerations include documenting the air temperature, wind speed, sky condition, and pavement conditions (AASHTO 2021).

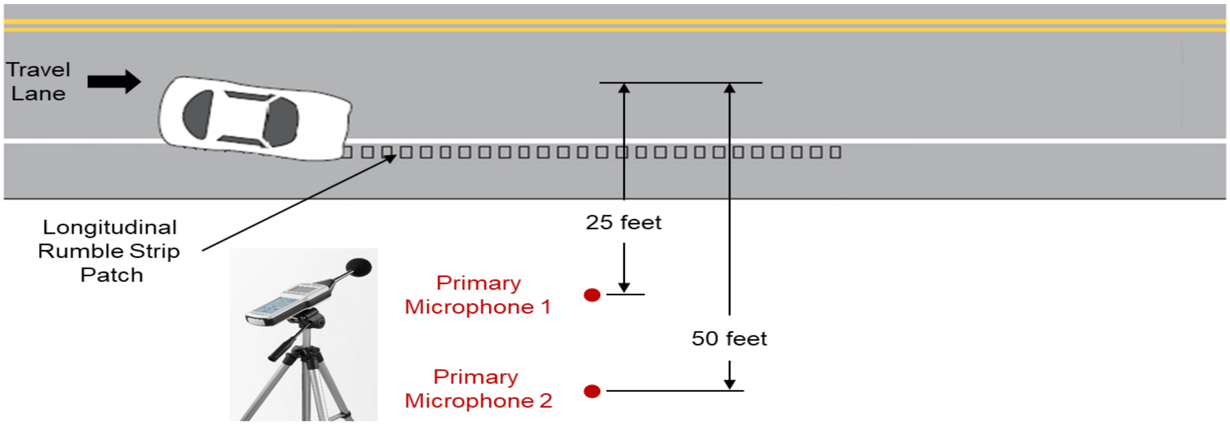


Figure 112. Illustration. External noise set-up for TP 389.

Testing Provisional 390

AASHTO Testing Provisional 390 or the continuous-flow traffic time-integrated method (CTIM) is a test method used to measure the influence of road surfaces, such as rumble strips, on highway traffic noise (AASHTO 2020). This testing procedure is conducted on an active road with traffic, where the noise produced by all vehicles in all lanes is measured from a nearby location. TP 390 is to be used on roadways where single vehicle pass-by events would be too difficult due to the dense traffic volume. The testing procedure involves placing a microphone at a preferred distance of 50 ft or at an alternate position 50 – 100 ft from the center of the travel lane if the 50 is not permissible. The microphones record the pavement baseline and rumble strip strike sound levels in order to provide a clear comparison of the increase/decrease in noise level, as shown in Figure 113 (AASHTO 2020). The rumble strip needs to span, in both directions, at least 4 times the distance from the center of the travel lane to the microphone on a straight open space road free of any extraneous material. Additionally, the site must be located away from intrusive noise sources, intersections, and lane mergers. Further considerations include documenting the air temperature, wind speed, sky condition, and pavement conditions (AASHTO 2020). TP 390 recommends that continuous noise measurements should be conducted for a period that captures enough data to properly represent the site. Furthermore, Section 4.3 of TP 390 states that “this procedure does not currently allow for site-to-site comparison” and should only be used to determine “the difference in sound levels before and after the application of a new surface on the highway” (AASHTO 2020).

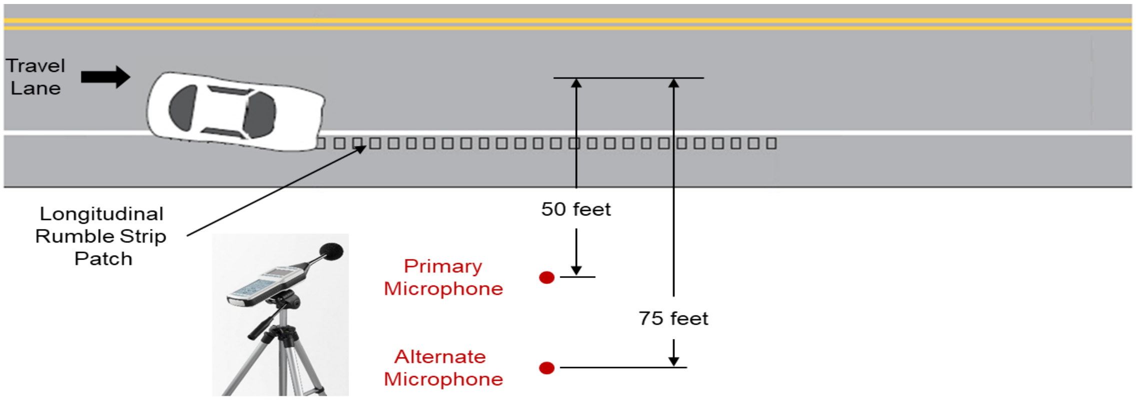


Figure 113. Illustration. External noise set-up for TP 390.

Internal Noise Testing Procedures

The Society of Automotive Engineers (SAE) provides a detailed testing procedure (J1477) for the measurement of interior sound levels of light vehicles (SAE 2000). This SAE testing procedure details the test procedure, environment, instrumentation, and data analyses for comparing interior sound level of passenger cars, multipurpose vehicles, and light trucks having gross vehicle weight rating (GVWR) of 10,000 lb (4540 kg) or less (SAE 2000). The testing procedure involves placing two microphones inside the cabin: (1) over the shoulder of the driver, and (2) at the headrest level of the passenger seat, as shown in Figure 114. The microphones record the pavement baseline and rumble strip strike sound levels in order to provide a clear comparison of the increase/decrease in internal noise levels (SAE 2000). Additionally, the testing procedure requires that (a) all windows and ventilating systems inside the vehicle shall be closed and shutoff, and (b) no accessories, such as windshield wipers, should be running at the time of the test. It should be noted that during the testing procedure only the driver and the instruments operator are allowed to be in the testing vehicle.

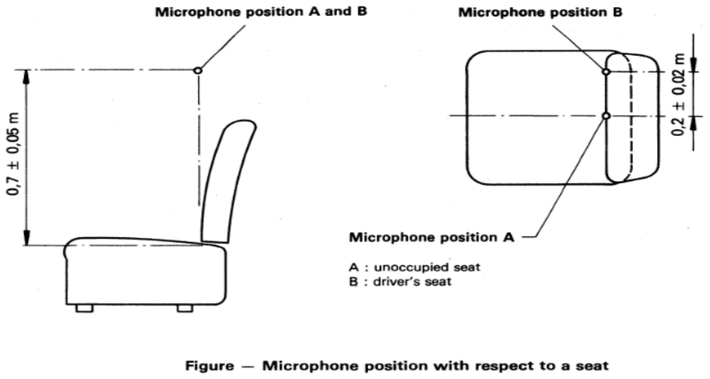


Figure 114. Illustration. Internal noise set up for SAE J1477.

Source: SAE 2000

Internal Vibration Testing Procedures

Several state DOTs including California, Indiana, and Oregon have conducted studies to measure the internal vibration generated by rumble strips (Caltrans 2018, ODOT 2019, and INDOT 2019). The testing procedure was very similar in the three studies and it used a triaxial accelerometer mounted on top of the steering column or on the driver seat track using adhesive to ensure an adequate measurement of the vibration experienced by drivers, as shown in Figure 115. The accelerometer works by measuring acceleration along the three dimensions (X, Y, and Z) which is used to calculate the resulting force experienced by the driver (Caltrans 2018, ODOT 2019, and INDOT 2019). During the pass-by drive, the collected data by the accelerometer is stored and analyzed in a laptop computer. It should be noted that the Y-axis, X-axis, and Z-axis of the accelerometer should be placed facing the driver, parallel to the dashboard, and aligned vertically, respectively (ODOT 2019).

Figure 115. Photo. Accelerometer placement.

Source: Caltrans 2018

Testing Procedures Used by State Dots

State DOTs have conducted studies to measure external noise generated by rumble strips using AASHTO TP 389 and TP 390. The TP 389 was used by California, Delaware, Indiana, Minnesota, Montana, New Hampshire, Oregon, and Washington DOTs when measuring noise levels produced by rumble strips, while the TP 390 was used only by the North Carolina DOT, as shown in Figure 116 (MnDOT 2016, NHDOT 2017, Caltrans 2018, Washington 2018, DelDOT 2019, INDOT 2019, Big Sky Acoustics 2019, ODOT 2019, Findley et al. 2020). The equipment used by state DOTS in their noise and vibration measurement studies included sound level meters, accelerometers, video cameras, windscreens, weather stations, and elevation equipment such as tripods.

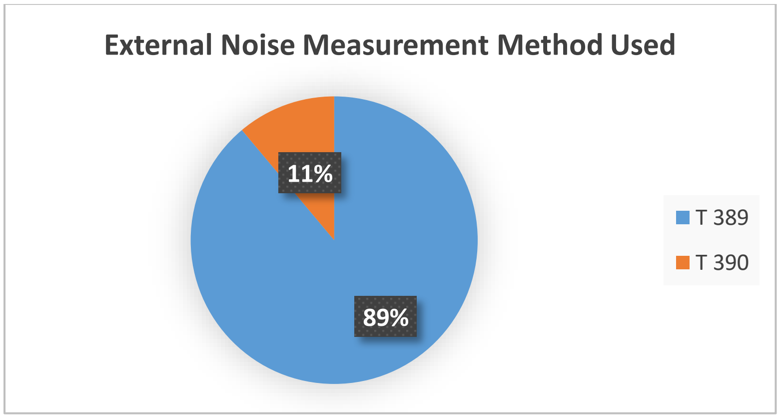


Figure 116. Graph. External noise measurement testing procedure used by state DOTs.

APPENDIX A6: RUMBLE STRIP CHALLENGES AND MAINTENANCE

This chapter presents the reported challenges and maintenance requirements of rumble strips by other state DOTs.

Rumble Strip Challenges

The section highlights the reported challenges of longitudinal and transverse rumble strips. The FHWA has reported several rumble strip challenges including (1) noise, (2) road winter maintenance, and (3) bicyclist accommodations (Ahmed et al. 2015).

Noise

State DOTs including Washington, Minnesota, North Carolina, and Oregon have reported that many nearby residents of rumble strips have filed complaints about the generated noise levels of rumble strips (MnDOT 2016, Findley et al. 2020, ODOT 2019, and Anund et al. 2017). To address these complaints, several state DOTs have conducted studies to minimize rumble strip noise for nearby residential areas and wildlife habitats (Caltrans 2018, WSDOT 2019, and ODOT 2019). These noise complaints are often caused by the low frequency sounds generated by traditional rumble strips that travel farther in distance compared to high frequency sounds (FHWA 2015e). To address this, North Carolina DOT reported that sinusoidal rumble strips generate external noise at a higher frequency of 525 Hz compared to traditional rumble strips that generate noise at a frequency of 122.5Hz (Findley et al. 2020). The external noise generated by traditional rumble strips, their related complaints, and their mitigation techniques are described in more detail in Chapter 4.

Road Winter Maintenance

The use of raised rumble strips was reported to cause challenges during snow removal and winter maintenance operations (FHWA 2016a). Snowplowing activities often damage or completely remove raised rumble strips which prompted several state DOTs including Idaho, Pennsylvania, and Utah DOTs to restrict the use of raised rumble strips in areas that require snow removal activities (Pigman & Barclay 1981 and FHWA 2015d). On the other hand, milled rumble strips are not damaged or removed by snow removal activities and therefore are often preferred over raised rumble strips in northern states with heavy annual levels of snowfall. FHWA reported that snowplow drivers have come to depend on shoulder rumble strips to help them find the edge of the travel lane during heavy snow and low visibility conditions (FHWA 2015d).

Bicyclist Accommodation

State DOTs have reported that rumble strips often cause rideability issues and safety hazards for bicyclists because of the extreme vibration experienced by bicyclists that may lead to loss of control and injuries (Ahmed et al. 2015 and FHWA 2017a). The American League of Bicyclist reported that riding over rumble strips can damage bike wheels, cause flat tires, and shake loose parts off bicycles (Flushe 2010). To address this, state DOTs have adopted flexible design criteria for areas with large bicycle communities such as bicycle gaps, offset rumble strips, and smaller rumble strips (FHWA 2015d). First, bicycle gaps use a typical gap of 10-12 feet for every 40-60 feet of shoulder line rumble strips that allows bicyclists riding on the shoulder to safely maneuver, avoid debris, make turns, and pass other bicyclists, as shown in Figure 95. Second, state DOTs often accommodate bicyclists by using edge line rumble strips instead of shoulder line rumble strips to provide more space for bicyclists riding on the shoulder, as shown in Figure 117. Third, state DOTs reduce their typical 16-inch or 12-inch length to 12-inches or 8-inches, and sometimes as narrow as 6-inches when necessary. Reducing the depth of the rumble strip may also reduce the jarring effect should a bicyclist need to cross the rumble strips. It should be noted that reducing the rumble strip length and/or depth dimensions can significantly reduce the alerting noise and associated safety effectiveness of the rumble strip for motorists (FHWA 2015d). For example, Colorado DOT recommends installing shoulder line rumble strips with a 12-foot bicycle gap and decreasing the depth of the rumble strip to accommodate the challenges faced by bicyclists (FHWA 2017a).

Figure 117. Photo. Shoulder line to edge line rumble strip bicycle accommodation.

Source: FHWA 2015d

Rumble Strip Maintenance

The maintenance of rumble strips is commonly performed during the scheduled maintenance operations of a given roadway (Watson et al. 2008, FHWA 2015e, and Johnson 2020). Rumble strips are considered to be a self-cleaning roadway element since it has the ability to discard accumulated rain, ice, snow, or sand due to the generated wind by passing vehicles. Raised rumble strips may require maintenance, particularly those that include raised pavement markers that can become loose over time (FHWA 2015f). Multiple state DOTs including Missouri, South Carolina, Pennsylvania, and Washington reported not using any form of preventative maintenance treatments for rumble strips (FHWA 2015f).

State DOTs have reported a number of rumble strip maintenance techniques to ensure their effectiveness including (1) fog sealing, (2) re-milling rumble strips after the application of shoulder surface treatments, and (3) crack sealing (Watson et al. 2008, FHWA 2015f, MDT 2015, WSDOT 2019 and Johnson 2020). First, fog sealing an asphalt emulsion coat is often recommended to reduce oxidation and moisture penetration due to the concern of accelerated pavement deterioration from milling. Fog sealing is typically applied in locations where the installation of rumble strips may have impacted the pavement such as a pavement joint (PBOT n.d. and CAIT 2021). Fog sealing over the rumble strip solely or the entire shoulder is the most commonly reported form of preventive maintenance for rumble strips, as shown in Figure 118 (Watson et al. 2008, FHWA 2015d, and Johnson 2020).

Figure 118. Photo. Fog seal application on rumble strips.

Source: FHWA 2015d

Second, re-milling rumble strips after the application of shoulder surface treatments was reported to be used by Montana and Wisconsin DOTs (MDT 2015 and WSDOT 2019). These shoulder surface treatments including chip-sealing, ultra-thin hot-mix asphalt, and micro-surface often reduce the depth of rumble strips and therefore may reduce their effectiveness (FHWA 2011b) To address this, Montana and Wisconsin DOTs have reported re-milling rumble strips after the application of shoulder surface treatments (MDT 2015 and WSDOT 2019). Third, crack sealing was reported to be used by Minnesota DOT as a maintenance procedure for rumble strips to seal the damaged areas adjacent to rumble strips and slow the growth of these cracks into the rumble strips, as shown in Figure 119 (Watson et al. 2008).

Figure 119. Photo. Crack sealing Application.

Source: West-Can Sealing Inc

APPENDIX B: NATIONAL SURVEY OF STATE DOTS

Quantification of the Effectiveness and External Noise of Rumble Strip Designs

The **Illinois Department of Transportation** is sponsoring an ongoing research project to study the **effectiveness and external noise of rumble strip designs**. This online survey is designed to take less than 15 minutes to complete. Your valuable feedback will assist in evaluating the designs of rumble strips used to alert motorists on roadways. We would appreciate it if you can complete the survey by Friday, March 4th, 2022.

The research team will be glad to share the findings of this survey with you upon completion. If you have any questions or comments, please contact the Principal Investigator (PI) of this research project:

Khaled El-Rayes, Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
E-mail: elrayes@illinois.edu

Thank you in advance for your time.

Background Information

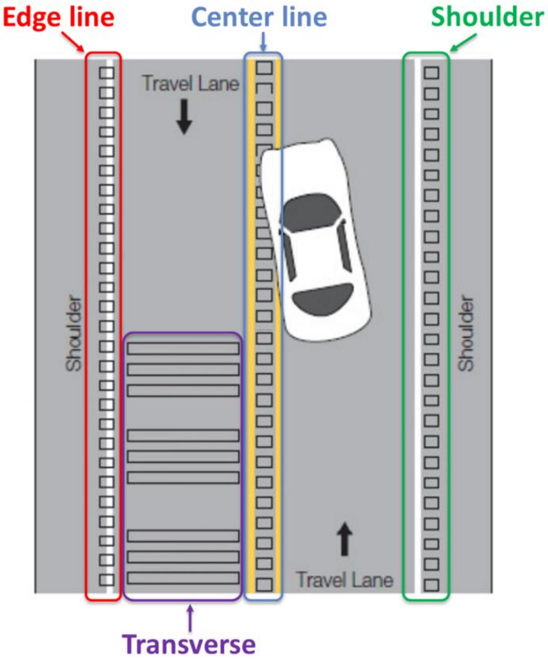
1. What is your name? (Optional)

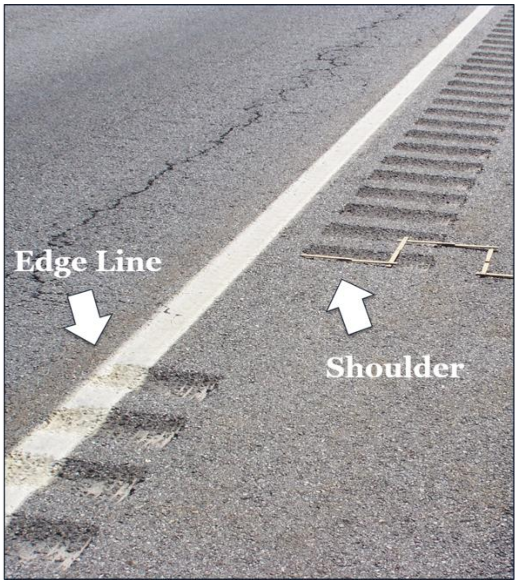
2. What state do you represent? (Required)

3. What is your current job title? (Optional)

Rumble Strip Design and Type

4. Please select the rumble strips designs currently used in your state. (Select all that apply)





- ☐ Shoulder Line
- ☐ Edgeline
- ☐ Centerline
- ☐ Transverse

5. Please select the rumble strip types currently used in your state. (Select all that apply)

- ☐ Milled rumble strips
- ☐ Rolled rumble strips
- ☐ Formed rumble strips
- ☐ Raised rumble strips Sinusoidal or “Mumble Strips”

6. If your state does not currently utilize sinusoidal rumble strips (mumble strips), does your state plan to consider using them for the following applications? (Select all that apply)

- ☐ Traditional longitudinal rumble strips (shoulder line, edge line, and center line)
- ☐ Transverse rumble strips
- ☐ May consider using them in the future after additional research/experience
- ☐ No current plans

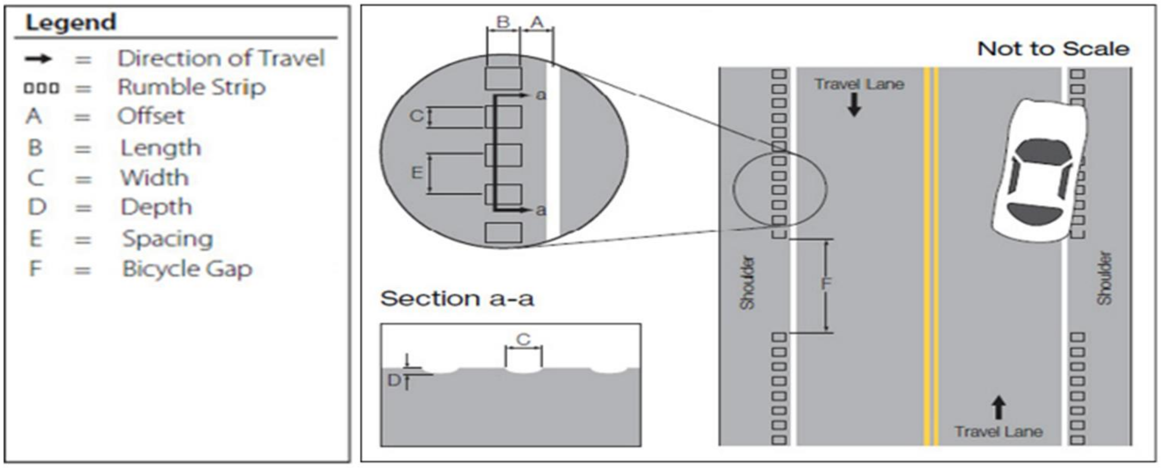
7. Does your state utilize alternative/non-traditional rumble strip designs? (Select all that apply)

- ☐ Angled or Fishbone (rumble strips not installed 90 degrees to roadway, instead installed askew)
- ☐ Gapped or Non-continuous rumble strips for bicyclists and pedestrians
- ☐ Increasing or Decreasing (Variable) spacing between rumble strips
- ☐ Shallower Designs for roadways in populated areas to minimize external noise
- ☐ Other (please specify)

8. Can you provide an online link to your DOT design specifications for rumble strips?

- ○ No (please enter your design specifications in the following questions on the next page)
- ○ Yes (please provide online link)

9. Please enter the following **specifications** for your **Longitudinal Shoulder Line** Rumble Strip Designs (see Figure below).



Please enter all dimensions in inches

A: Offset (if applicable)

B: Length

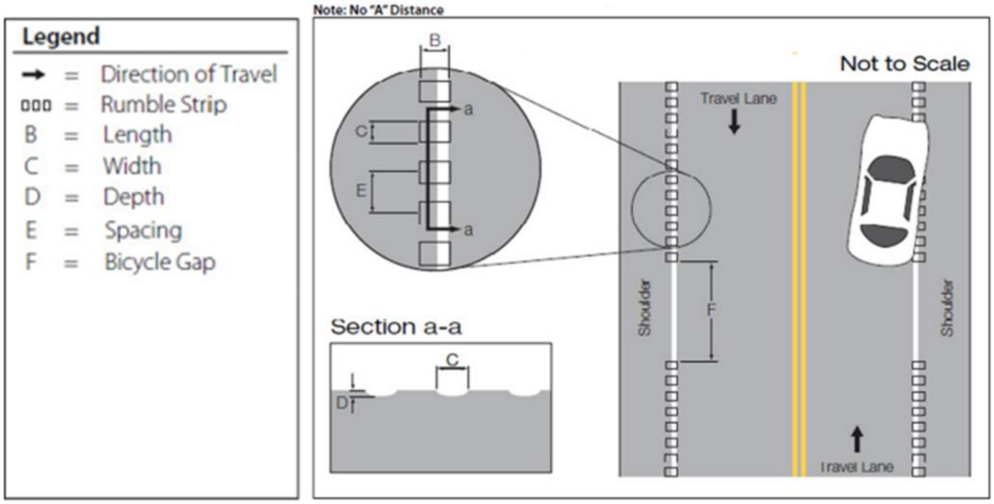
C: Width

D: Depth

E: Spacing

F: Bicycle Gap (if applicable)

10. Please enter the following **specifications** for your **Longitudinal Edge Line** Rumble Strip Designs (see Figure below).



B: Length

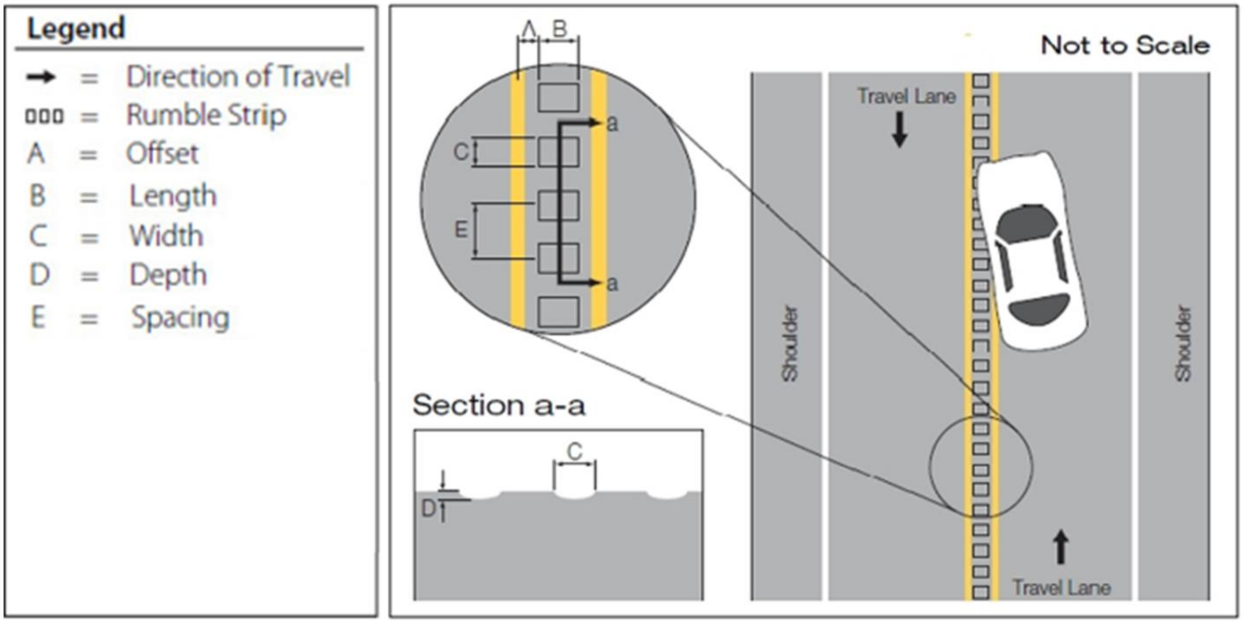
C: Width

D: Depth

E: Spacing

F: Bicycle Gap (if applicable)

11. Please enter the following **specifications** for your **Longitudinal Center Line** Rumble Strip Designs (see Figure below).



A: Offset (if applicable)

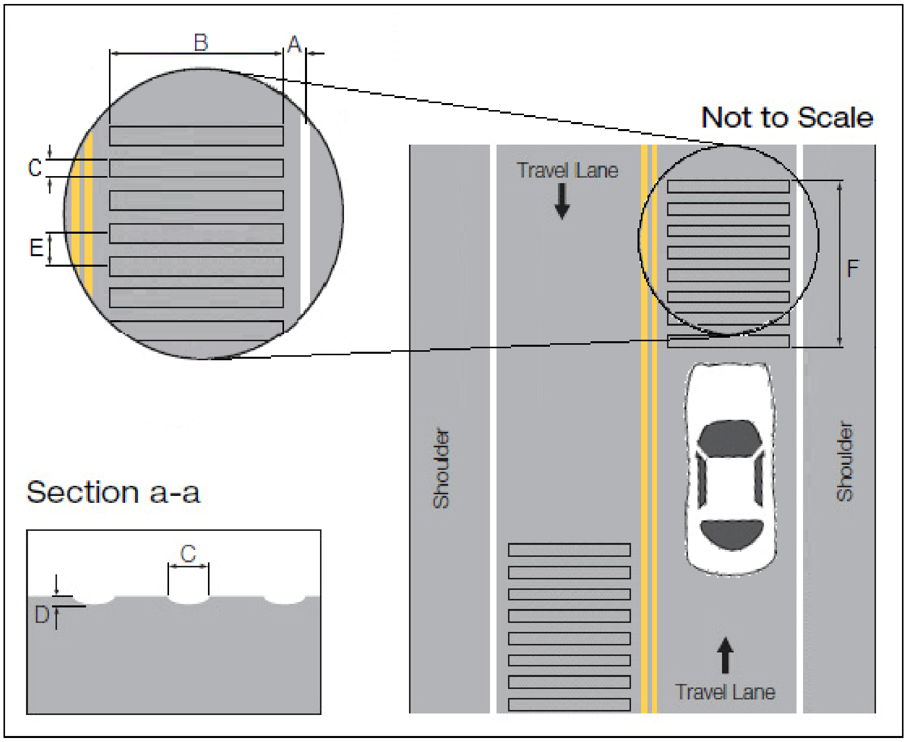
B: Length

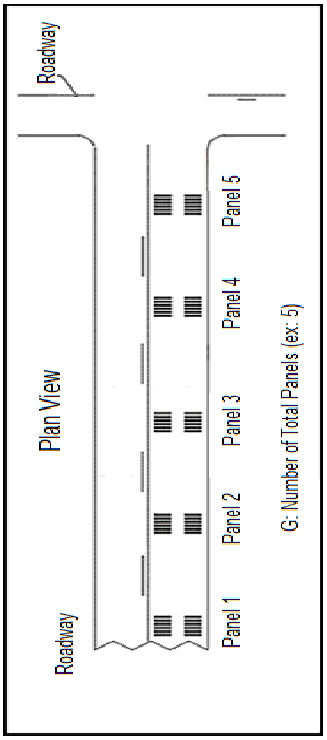
C: Width

D: Depth

E: Spacing

12. Please enter the following specifications for your **Transverse** Rumble Strips.





A: Offset (if applicable)

B: Length

C: Width

D: Depth

E: Spacing

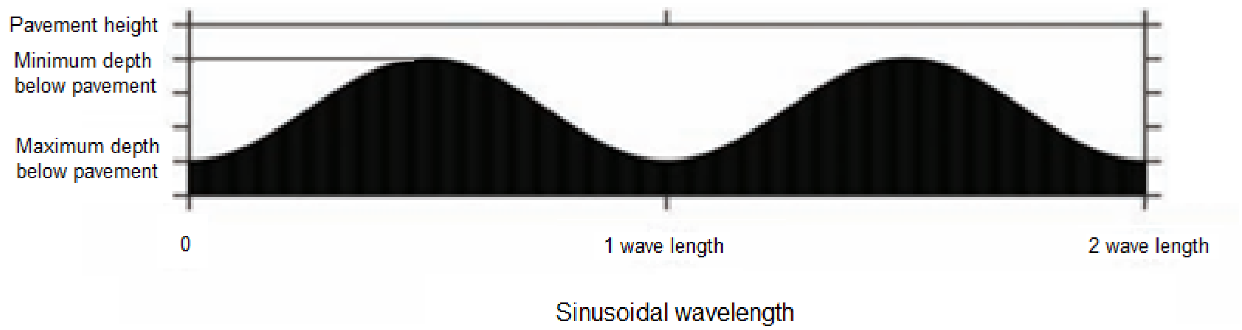
13. Please enter the following specifications for your **Sinusoidal Rumble Strips**.

Length of wave ☐

Width ☐

Min Depth below pavement ☐

Max Depth below pavement ☐



Benefits of Rumble Strips

14. Has your state experienced a **reduction in roadway crashes** through the utilizing **traditional longitudinal** rumble strips?

- ○ Yes
- ○ No

15. Has your state experienced a **reduction in roadway crashes** through utilizing **transverse** rumble strips?

- ○ Yes
- ○ No

16. Has your state experienced a **reduction in roadway crashes** through the utilizing **sinusoidal** rumble strips?

- ○ Yes
- ○ No

17. Please report experienced reduction in roadway crashes (%), or provide links to documented crash reduction, if available

☐

18. Has your state **conducted studies** to measure the internal noise and vibration experienced by drivers when alerted by **traditional longitudinal** rumble strips?

- ○ Yes
- ○ No

19. Has your state **conducted studies** to measure the internal noise and vibration experienced by drivers when alerted by **transverse** rumble strips?

- ○ Yes
- ○ No

20. Has your state **conducted studies** to measure the internal noise and vibration experienced by drivers when alerted by **sinusoidal** rumble strips?

- ○ Yes
- ○ No

21. Please provide links to conducted studies to measure internal noise and vibration, if available

22. If **transverse rumble strips** are used in your state, can you please rate its **effectiveness** in alerting drivers to slow down or stop in locations such as approaches to intersections, toll plazas, horizontal curves, and/or work zones.

- ○ Very effective
- ○ Somewhat effective
- ○ Not effective

External Noise Generated by Rumble Strips

23. Has your state received noise complaints from residents that live near traditional longitudinal rumble strips?

- ○ Yes
- ○ No

24. Has your state received noise complaints from residents that live near transverse rumble strips?

- ○ Yes
- ○ No

25. Has your state **received noise complaints from residents that live near sinusoidal** rumble strips?

- ○ Yes
- ○ No

26. Has your state performed any **remediation to rumble strips** in highly populated areas or areas that have received numerous noise complaints? **(Select all that apply)**

- ○ No Noise Remediation or Changes in Design
- ○ Removal of Rumble Strips
- ○ Altered Design of Rumble Strips
- ○ Installation of Noise Barriers
- ○ Other – Please specify and provide a brief description

27. How likely is your state to **modify the design** of the rumble strips **to address noise complaints** while maintaining effectiveness?

- ○ Modification in progress
- ○ Very likely
- ○ Somewhat likely
- ○ Not likely

28. What specific **design aspect(s)** would your state likely consider in revising the current design of the **transverse** rumble strips (if any)?

- ○ Sinusoidal (mumble) rumble strip design
- ○ Groove cross-section
- ○ Number of strips in each panel
- ○ Panel details and distances
- ○ Angle of the strips (slanted/skewed vs perpendicular to wheel path)
- ○ Other (please specify)

29. Has your state **conducted studies** to evaluate the effectiveness of **traditional longitudinal** rumble strips and measured their generated external noise?

- ○ Yes
- ○ No

30. Has your state **conducted studies** to evaluate the effectiveness of **transverse** rumble strips and measured their generated external noise?

- ○ Yes
- ○ No

31. Has your state **conducted studies** to evaluate the effectiveness of **sinusoidal** rumble strips and measured their generated external noise?

- ○ Yes
- ○ No

32. Please provide links to conducted studies to evaluate the effectiveness of rumble strips and measured generated noise, if available

Challenges of Rumble Strips

33. Does your state have **special roadway maintenance operation requirements** for pavements with rumble strips?

- ○ No
- ○ Yes, please explain or provide online link

34. Has your state encountered any **problems or challenges** with **traditional longitudinal** rumble strips? **(Select all that apply)**

- ☐ No problems
- ☐ Noise Complaints from Nearby Residents
- ☐ Accelerated Pavement Degradation
- ☐ Accelerated Pavement Degradation due to Rumble Strip Placement On/Near Joint
- ☐ Water Pooling, Freezing, and Degrading Rumble Strips due to freeze/thaw
- ☐ Rideability or Safety Complaints from Bicyclists, Motorcyclists, Pedestrians, etc.
- ☐ Decreased Effectiveness due to Accumulation or Dirt, Debris, Packed Snow, etc.
- ☐ Other, Please Explain

35. Has your state encountered any **problems or challenges** with **transverse** rumble strips? **(Select all that apply)**

- ☐ No problems
- ☐ Noise Complaints from Nearby Residents
- ☐ Accelerated Pavement Degradation
- ☐ Accelerated Pavement Degradation due to Rumble Strip Placement On/Near Joint
- ☐ Water Pooling, Freezing, and Degrading Rumble Strips due to freeze/thaw
- ☐ Rideability or Safety Complaints from Bicyclists, Motorcyclists, Pedestrians, etc.
- ☐ Decreased Effectiveness due to Accumulation or Dirt, Debris, Packed Snow, etc.
- ☐ Other, Please Explain

36. Has your state encountered any **problems or challenges** with **sinusoidal** rumble strips? **(Select all that apply)**

- ☐ No problems
- ☐ Noise Complaints from Nearby Residents
- ☐ Accelerated Pavement Degradation
- ☐ Accelerated Pavement Degradation due to Rumble Strip Placement On/Near Joint
- ☐ Water Pooling, Freezing, and Degrading Rumble Strips due to freeze/thaw
- ☐ Rideability or Safety Complaints from Bicyclists, Motorcyclists, Pedestrians, etc.
- ☐ Decreased Effectiveness due to Accumulation or Dirt, Debris, Packed Snow, etc.
- ☐ Other, Please Explain

Additional Feedback

37. Can you suggest any additional alternative rumble strip designs or techniques that were not listed and have the potential to reduce external noise while maintaining sufficient internal noise and vibration to alert drivers?

38. Please list any additional comments regarding rumble strip designs

39. Would you be willing to provide more information, if needed?

- ○ No
- ○ Yes, please provide e-mail address)

40. Are you interested in receiving the main findings of this survey upon completion?

- ○ No
- ○ Yes, please provide e-mail address)

APPENDIX C: RUMBLE STRIP DESIGNS

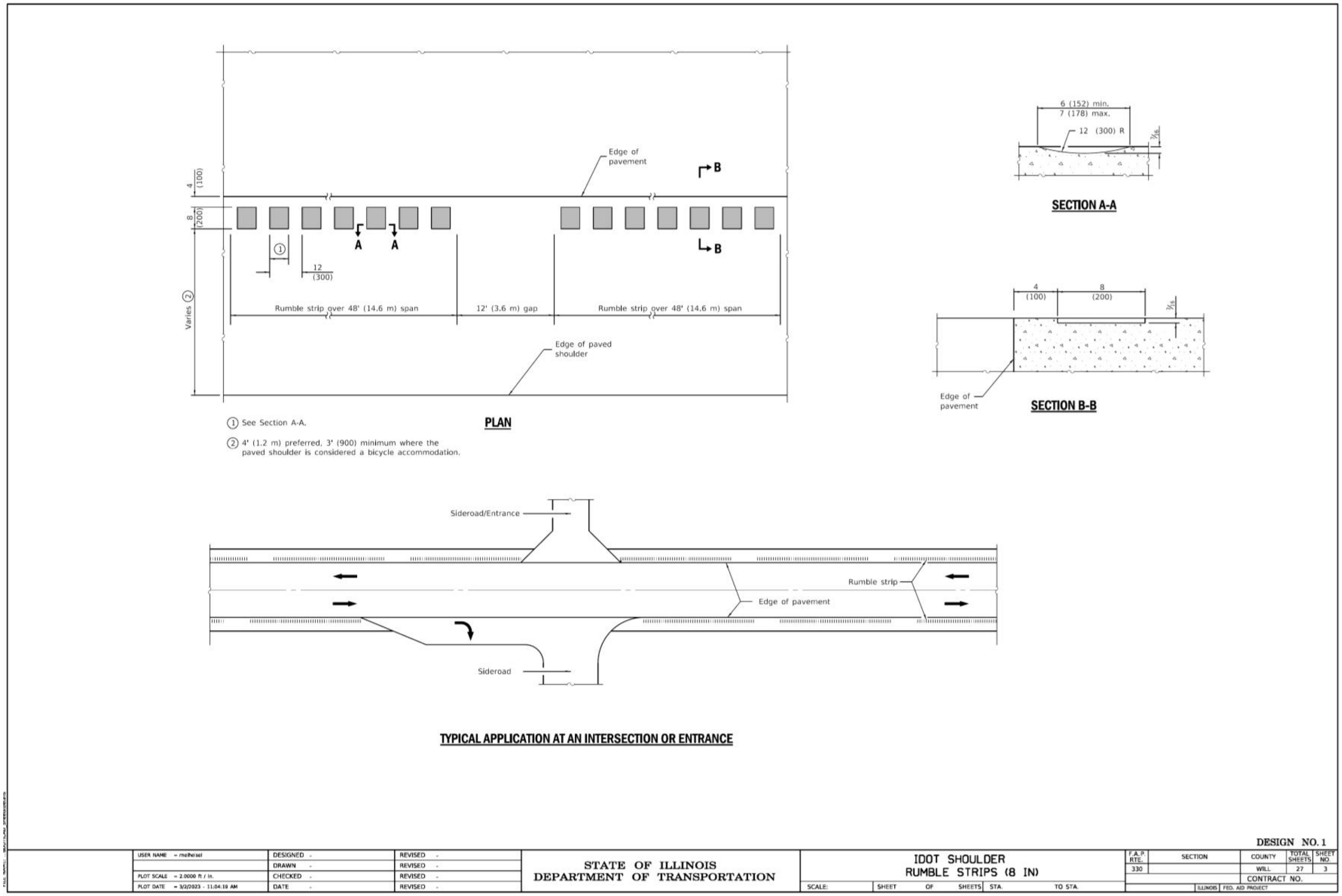


Figure 120. Illustration. Longitudinal traditional design 1: IDOT shoulder (8”).

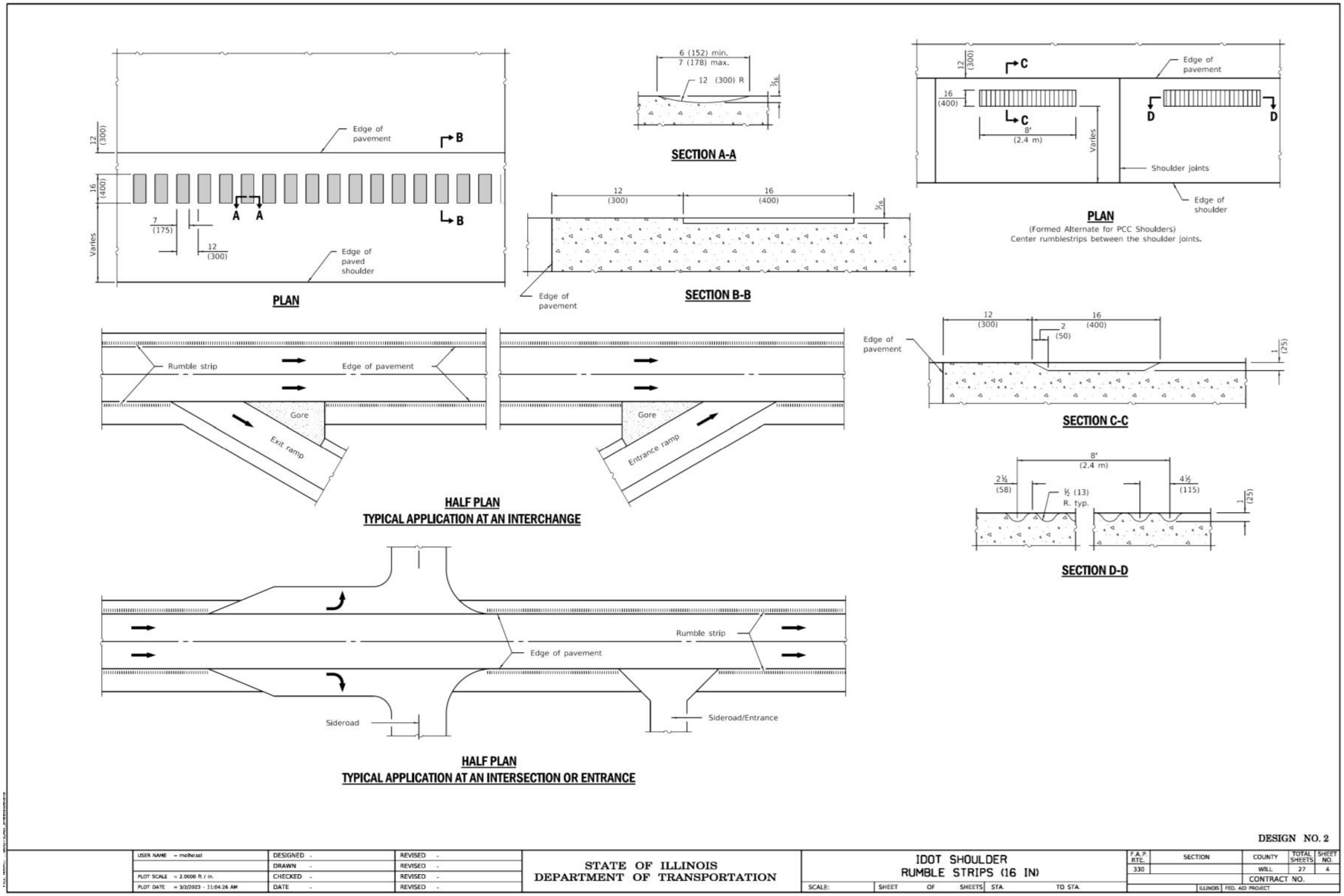


Figure 121. Illustration. Longitudinal traditional design 2: IDOT interstate shoulder (16”).

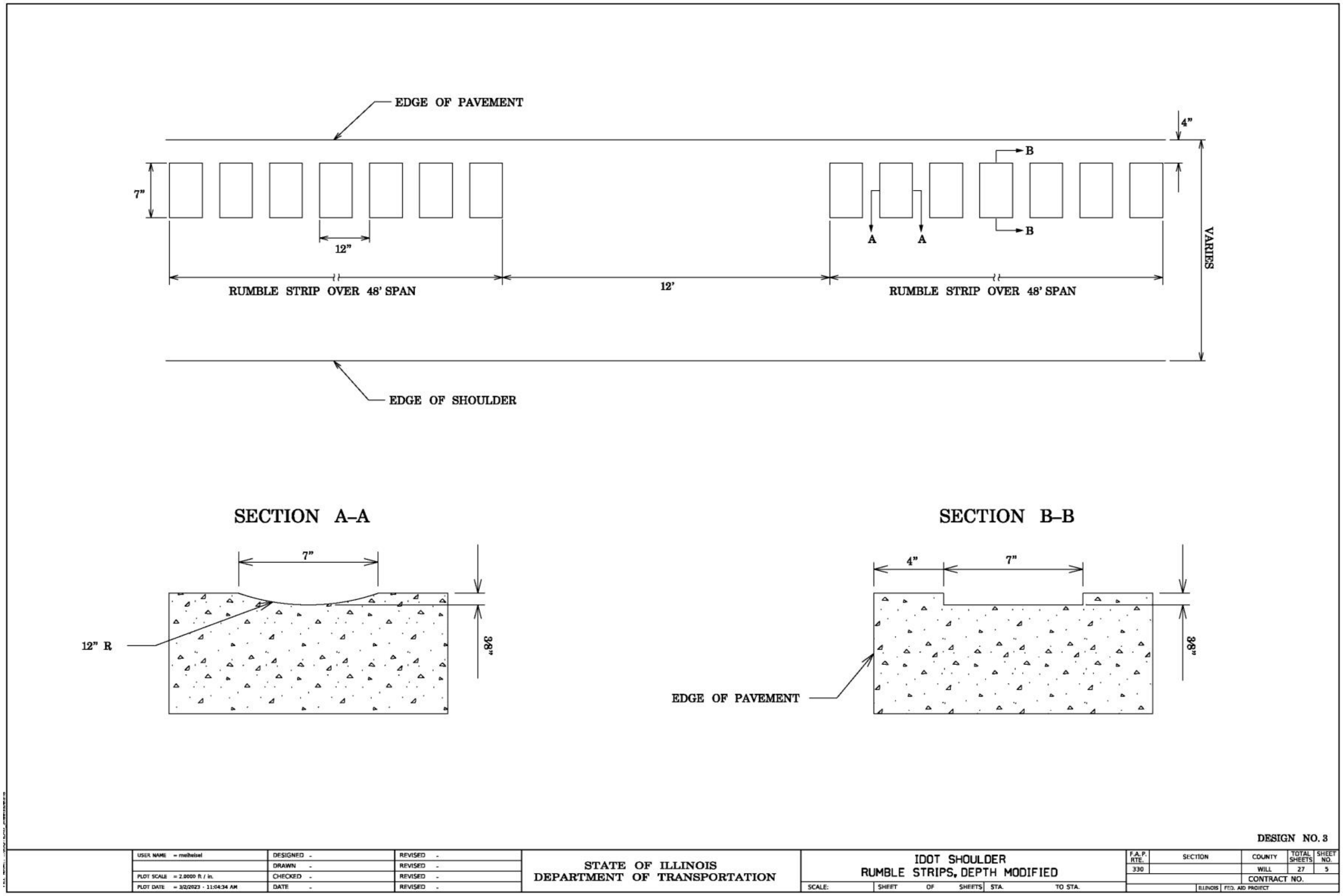


Figure 122. Illustration. Longitudinal traditional design 3: IDOT shoulder (modified).

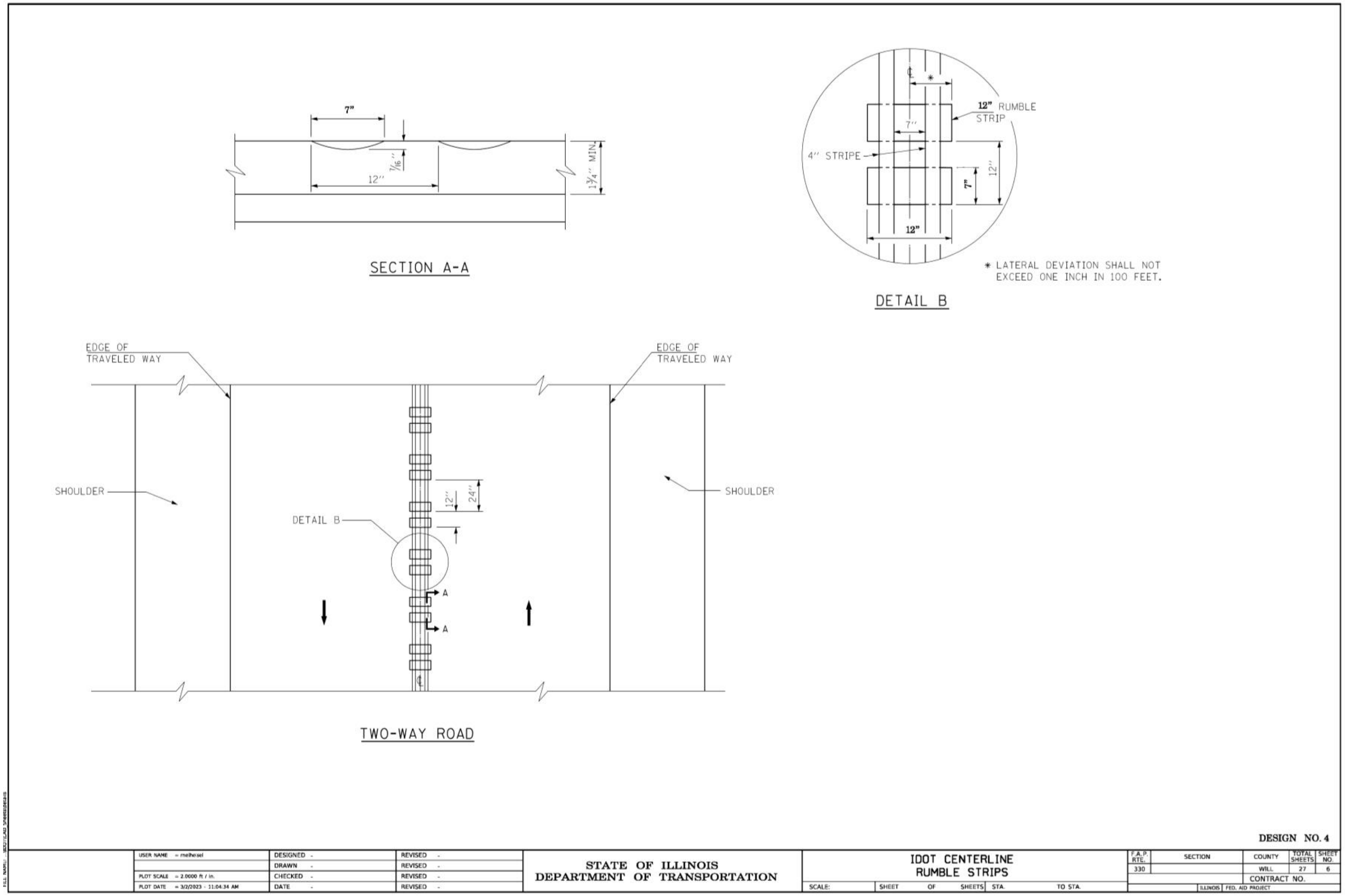


Figure 123. Illustration. Longitudinal traditional design 4: IDOT centerline.

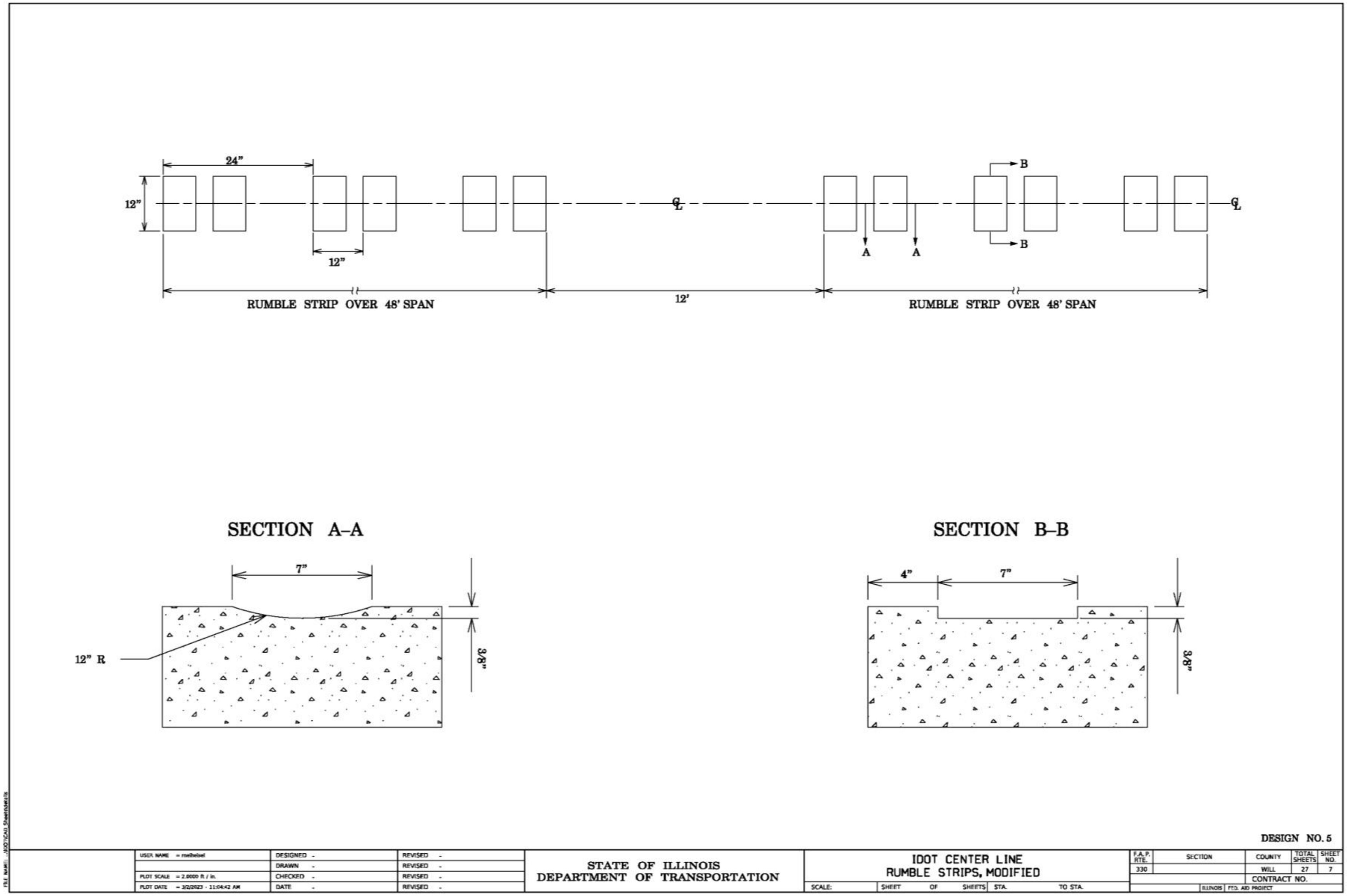


Figure 124. Illustration. Longitudinal traditional design 5: IDOT centerline with paired gap.

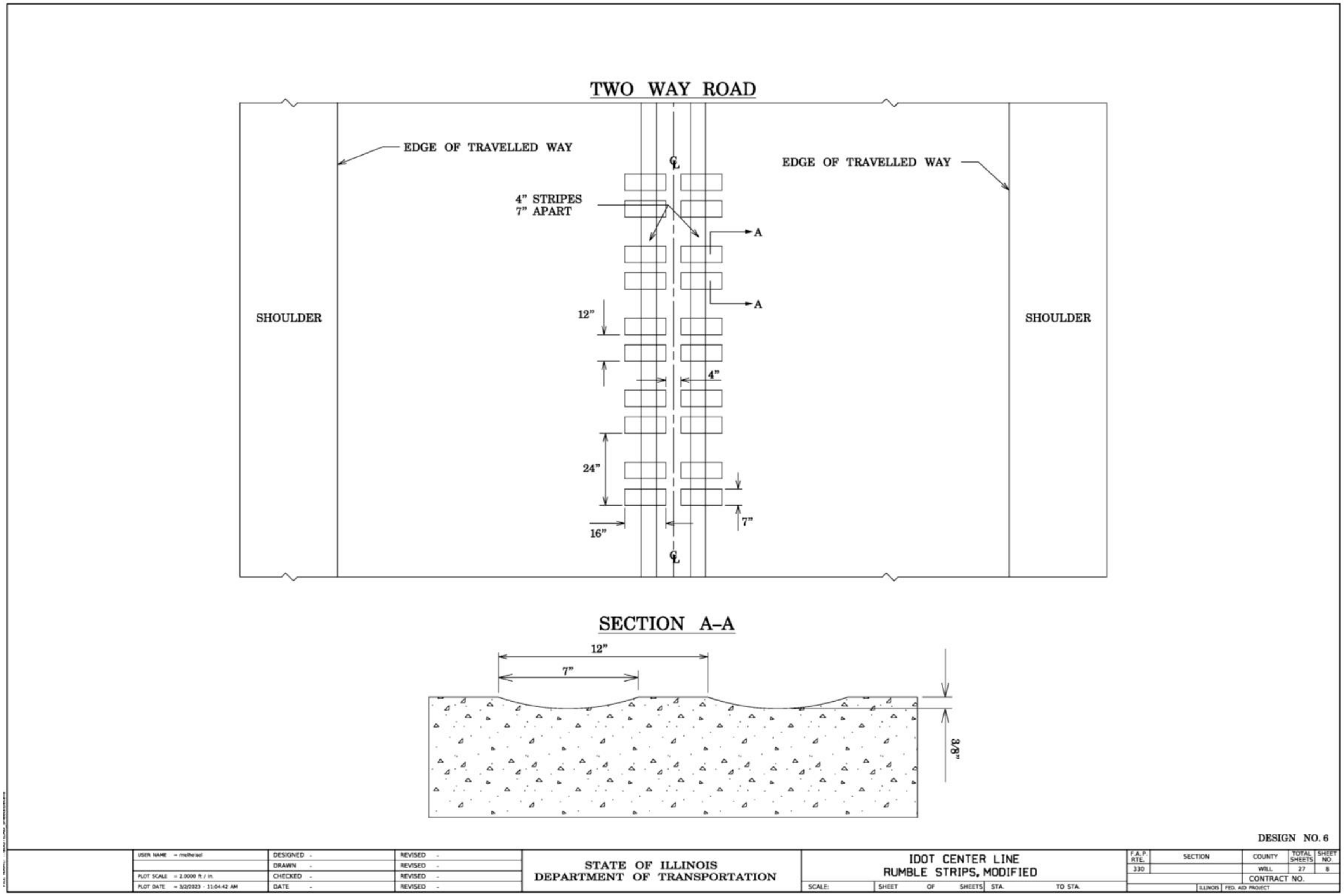
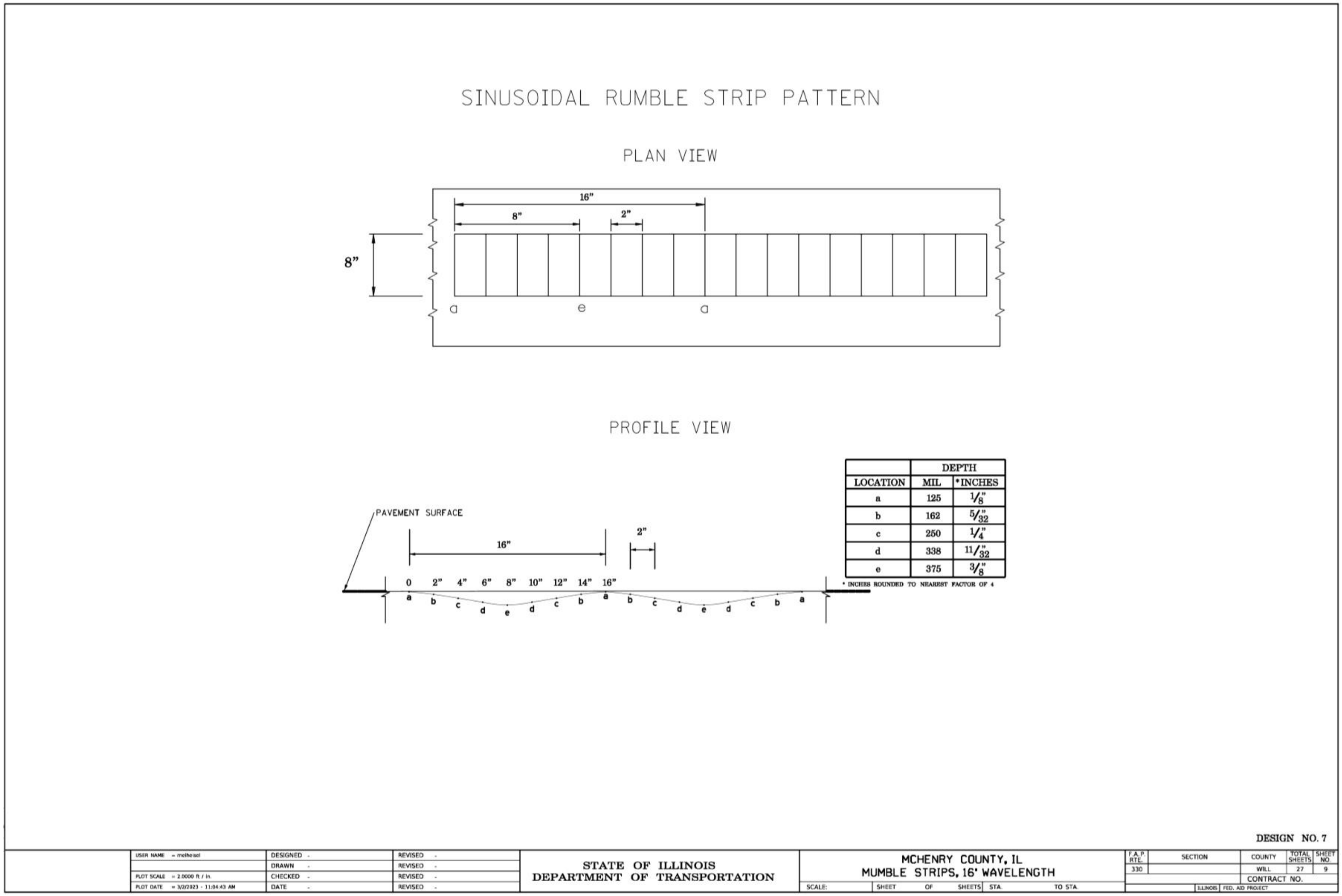


Figure 125. Illustration. Longitudinal traditional design 6: IDOT centerline reduced depth.



	DEPTH	
LOCATION	MIL	*INCHES
a	125	$1/8$"
b	162	$5/32$"
c	250	$1/4$"
d	338	$11/32$"
e	375	$3/8$"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

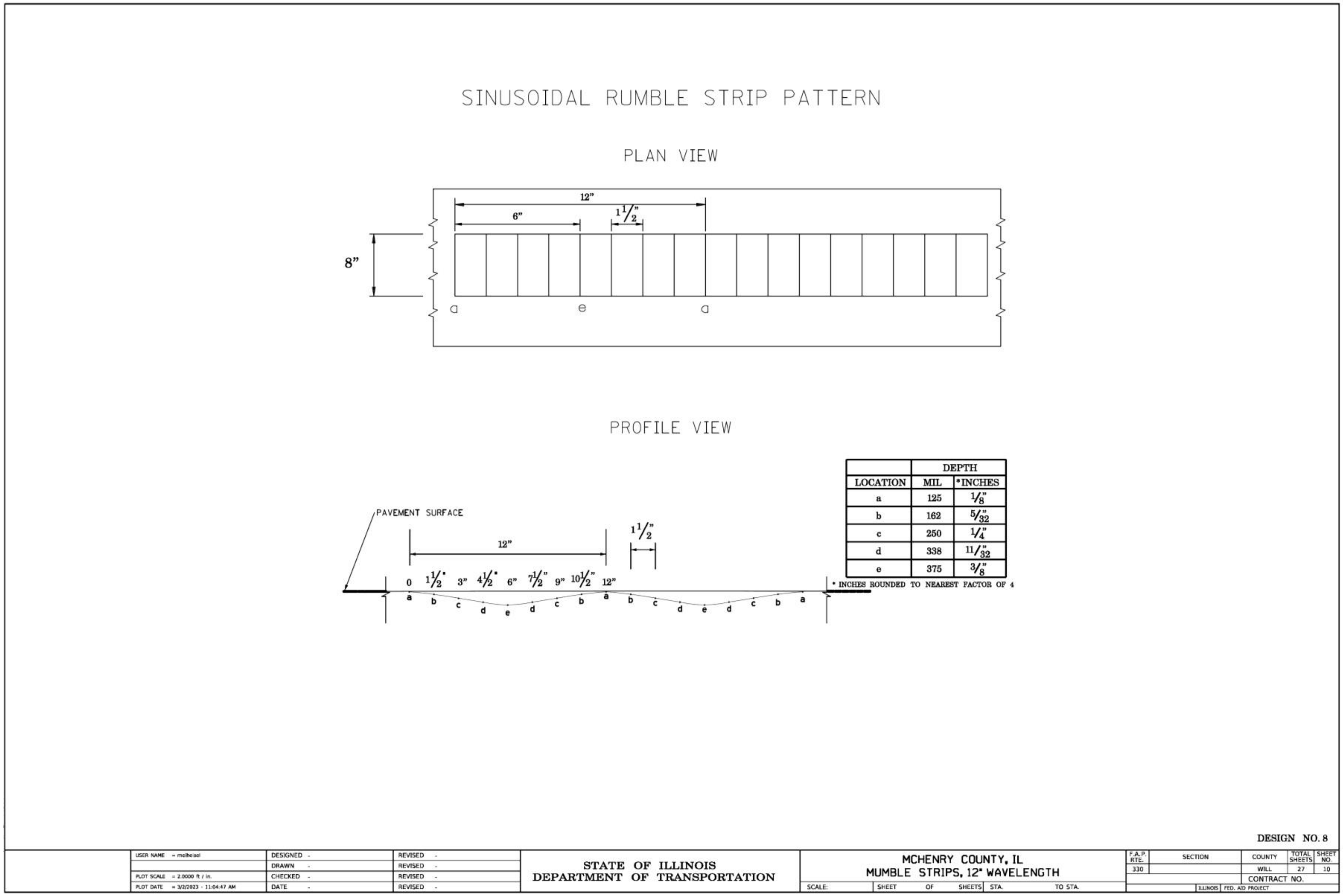
USER NAME = melheisel	DESIGNED -	REVISED -	STATE OF ILLINOIS DEPARTMENT OF TRANSPORTATION
	DRAWN -	REVISED -	
PLOT SCALE = 2.0000 ft / in.	CHECKED -	REVISED -	
PLOT DATE = 3/2/2023 - 11:04:43 AM	DATE -	REVISED -	

MCHENRY COUNTY, IL
MUMBLE STRIPS, 16' WAVELENGTH
SCALE: SHEET OF SHEETS STA. TO STA.

F.A.P. RTE.	SECTION	COUNTY	TOTAL SHEETS	SHEET NO.
330		WILL	27	9

CONTRACT NO.
ILLINOIS FED. AID PROJECT

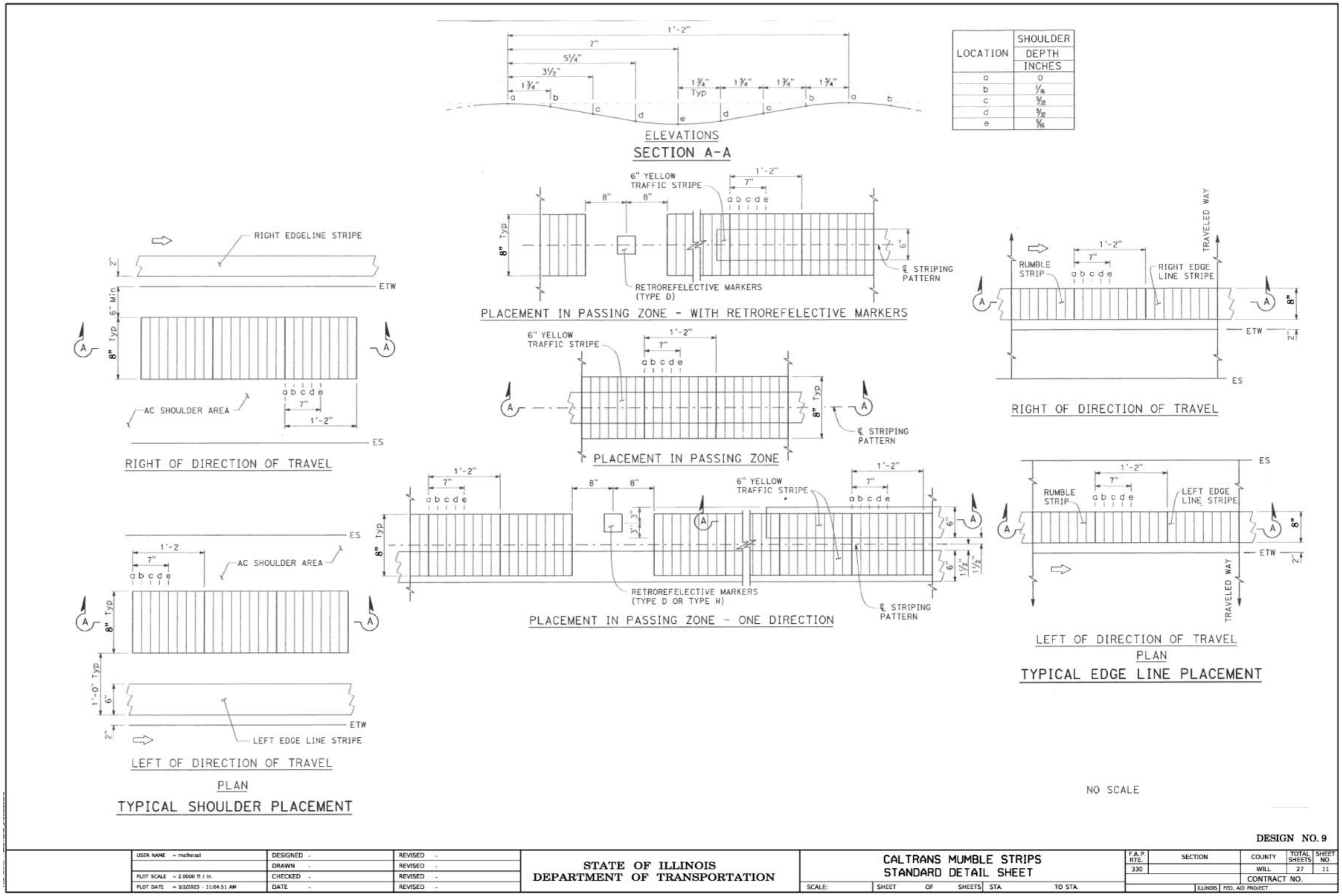
Figure 126. Illustration. Longitudinal sinusoidal design 7: IDOT McHenry 1.



	DEPTH	
LOCATION	MIL	*INCHES
a	125	$\frac{1}{8}$"
b	162	$\frac{5}{32}$"
c	250	$\frac{1}{4}$"
d	338	$\frac{11}{32}$"
e	375	$\frac{3}{8}$"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

Figure 127. Illustration. Longitudinal sinusoidal design 8: IDOT McHenry 2.



LOCATION	SHOULDER DEPTH INCHES
a	0
b	1/16
c	5/32
d	9/32
e	5/16

Figure 128. Illustration. Longitudinal sinusoidal design 9: Caltrans.

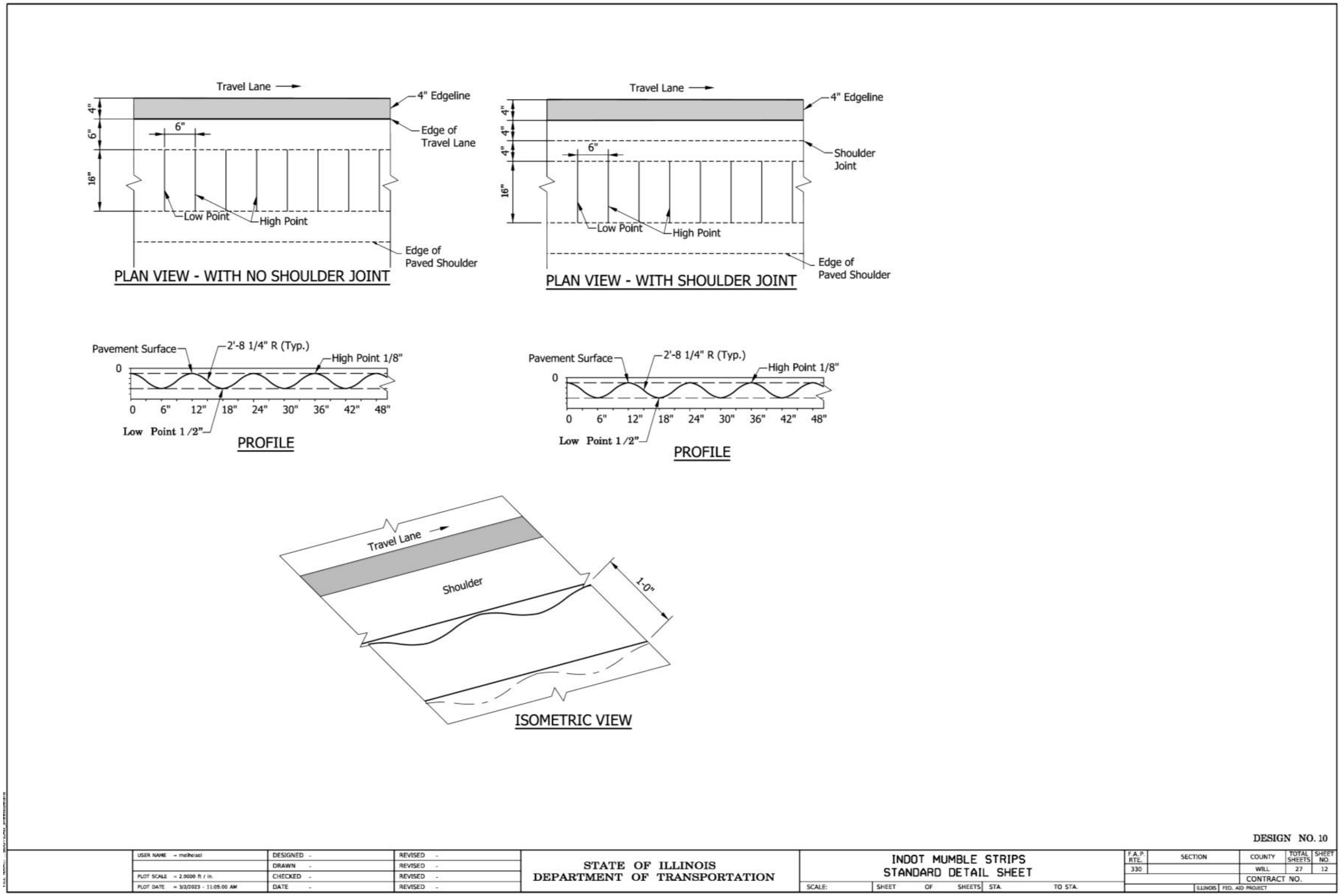
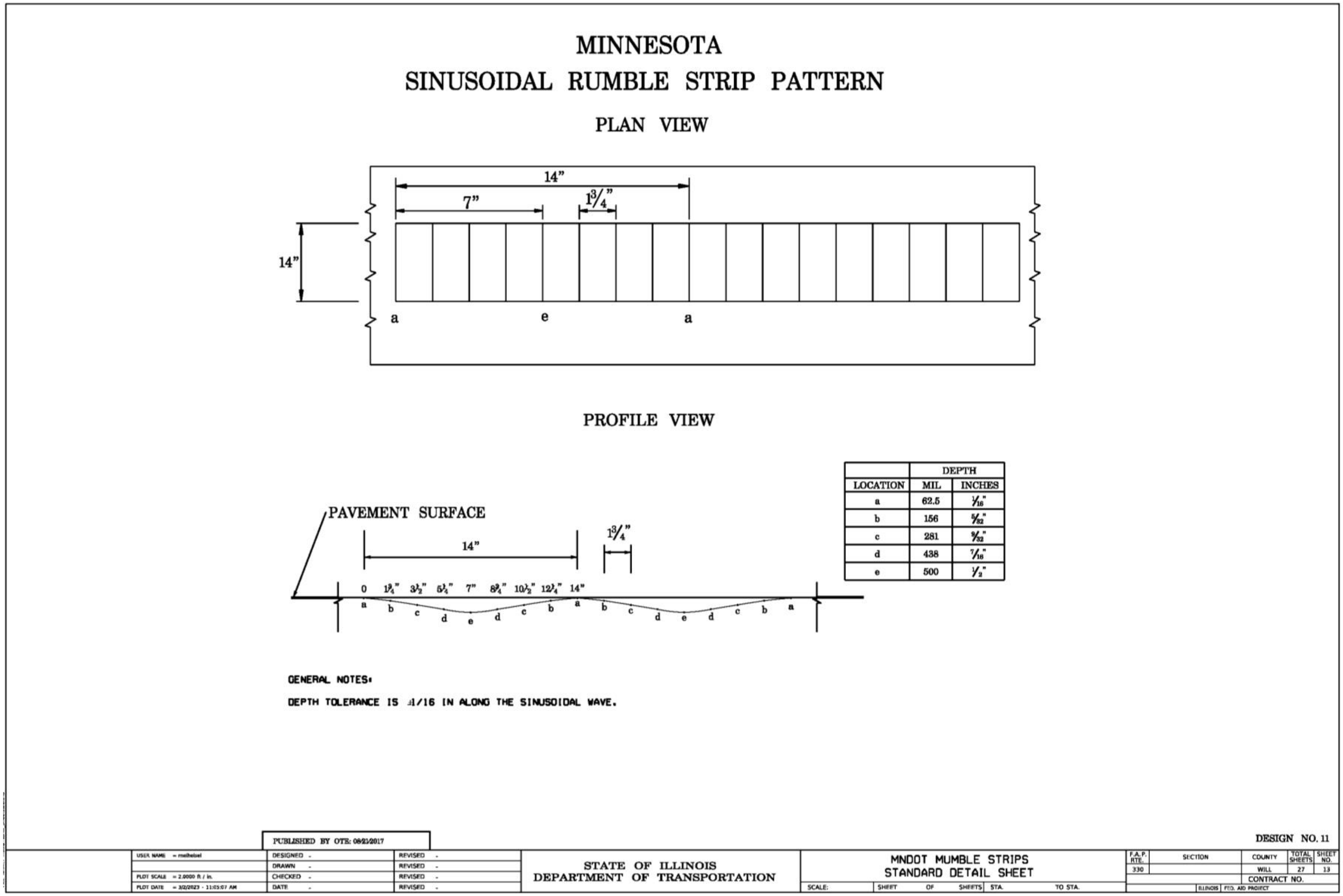


Figure 129. Illustration. Longitudinal sinusoidal design 10: Indiana DOT.



	DEPTH	
LOCATION	MIL	INCHES
a	62.5	$\frac{1}{16}$"
b	156	$\frac{5}{32}$"
c	281	$\frac{9}{32}$"
d	438	$\frac{7}{16}$"
e	500	$\frac{1}{2}$"

GENERAL NOTES:

DEPTH TOLERANCE IS ±1/16 IN ALONG THE SINUSOIDAL WAVE.

Figure 130. Illustration. Longitudinal sinusoidal design 11: Minnesota DOT.

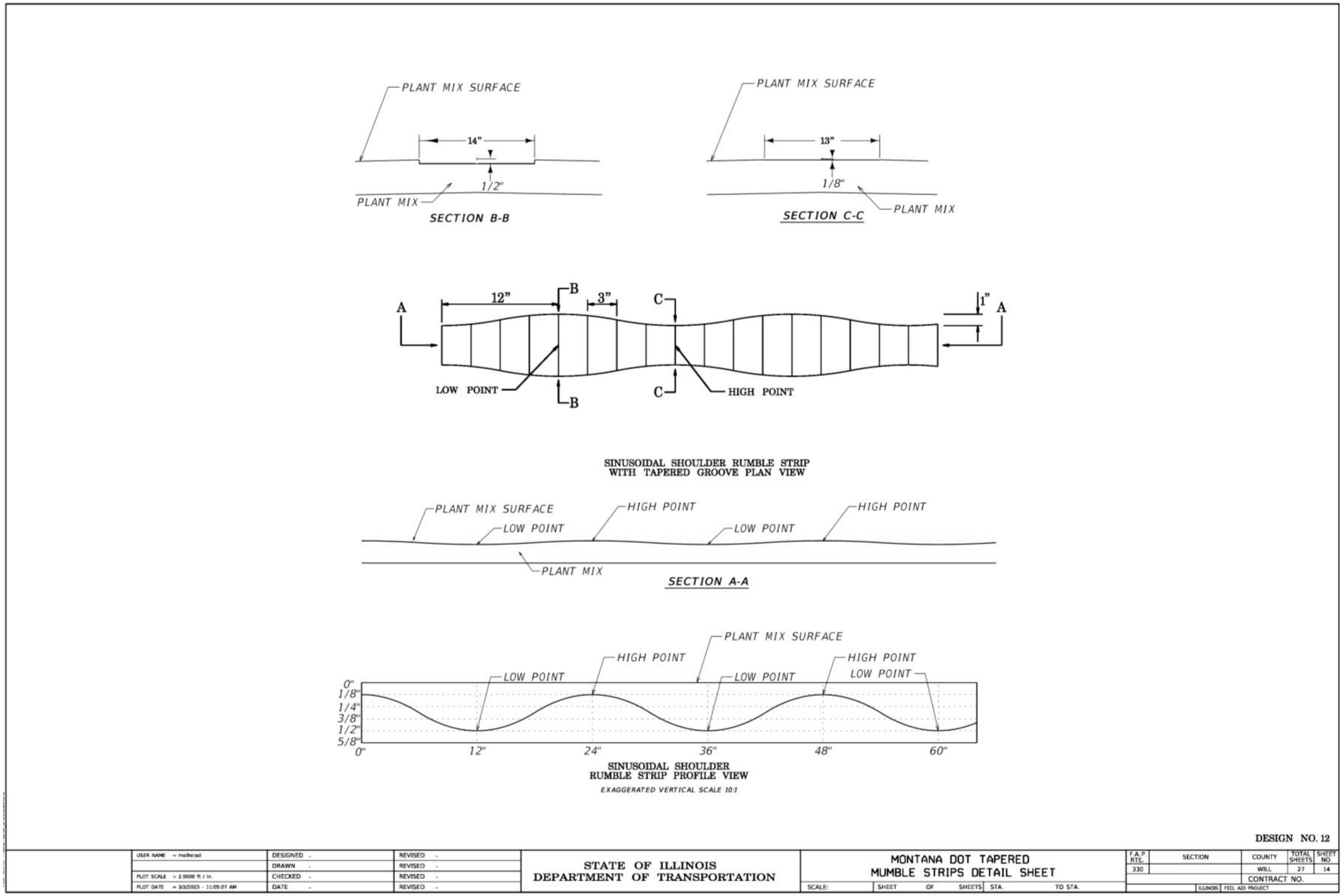
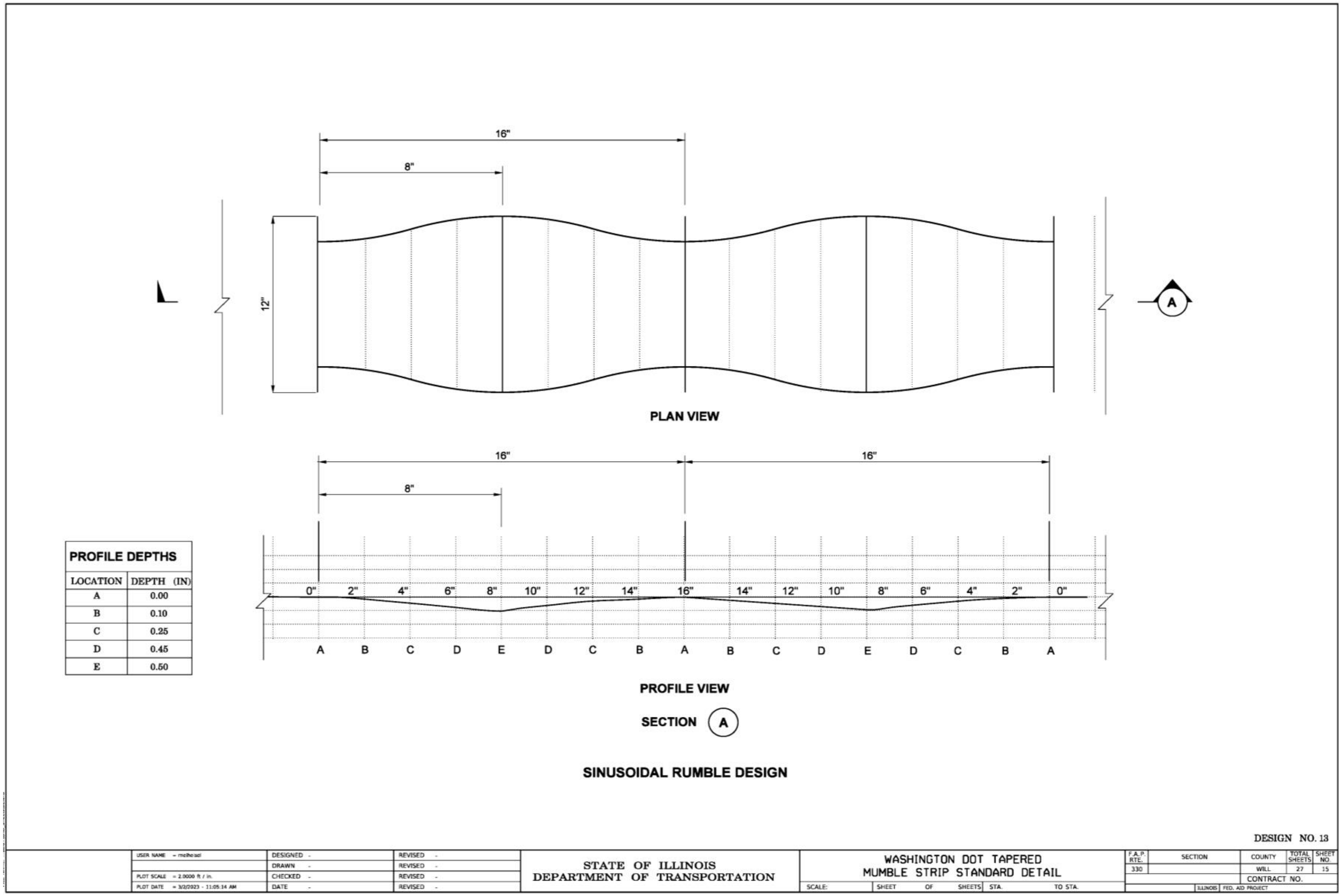


Figure 131. Illustration. Longitudinal sinusoidal design 12: Montana DOT.



PROFILE DEPTHS

LOCATION	DEPTH (IN)
A	0.00
B	0.10
C	0.25
D	0.45
E	0.50

Figure 132. Illustration. Longitudinal sinusoidal design 13: Washington DOT.

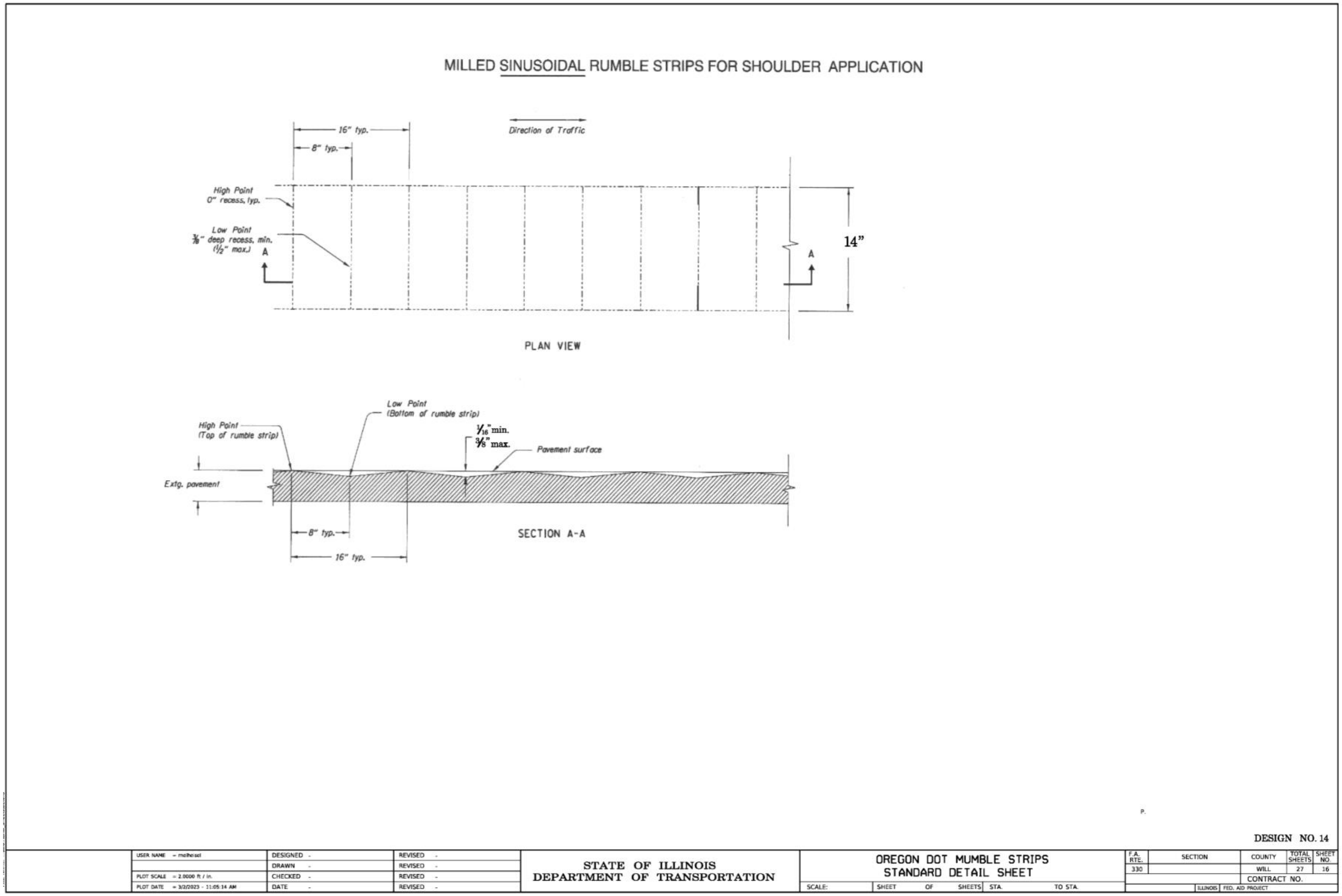
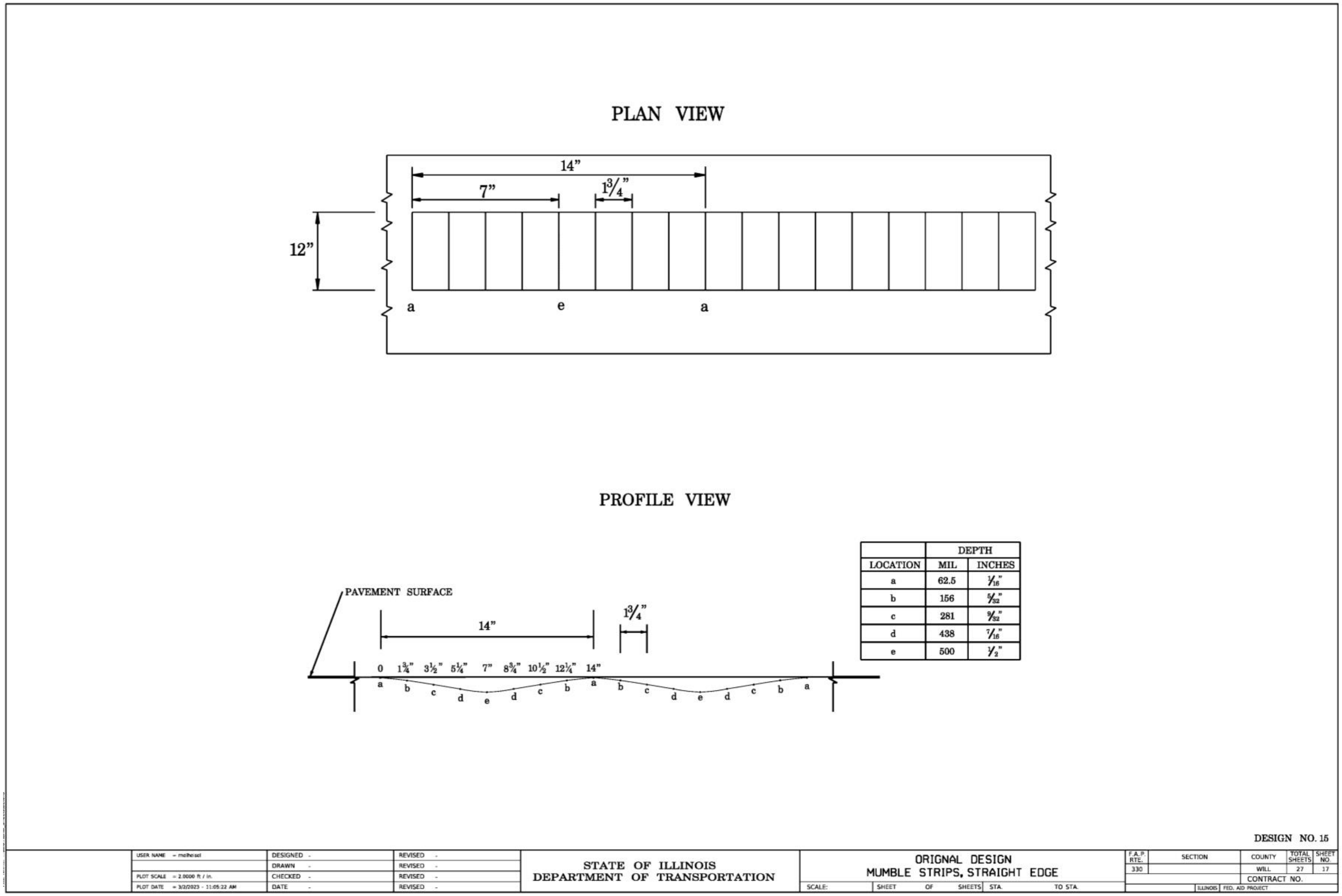
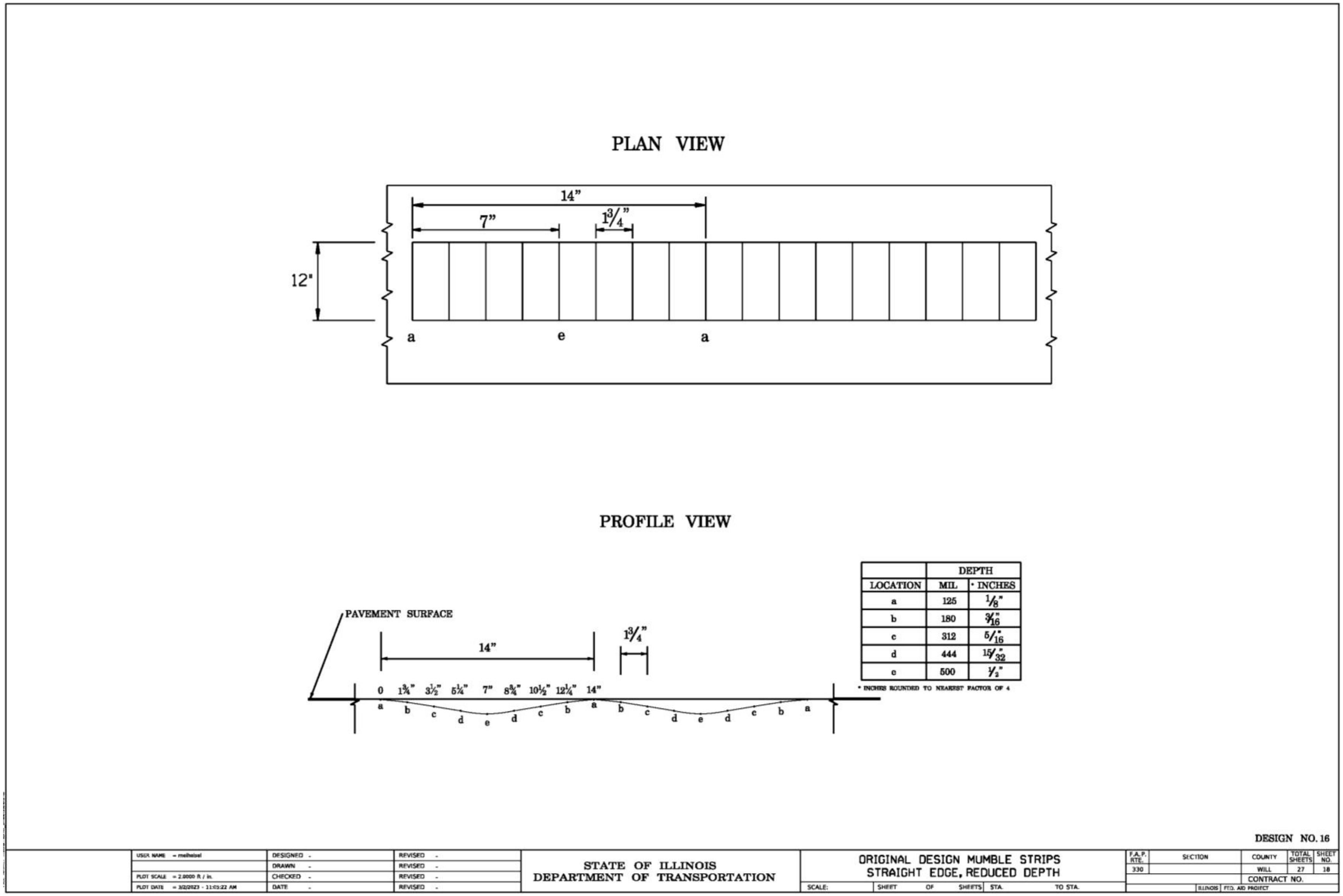


Figure 133. Illustration. Longitudinal sinusoidal design 14: Oregon DOT.



	DEPTH	
LOCATION	MIL	INCHES
a	62.5	1/16”
b	156	5/32”
c	281	9/32”
d	438	7/16”
e	500	1/2”

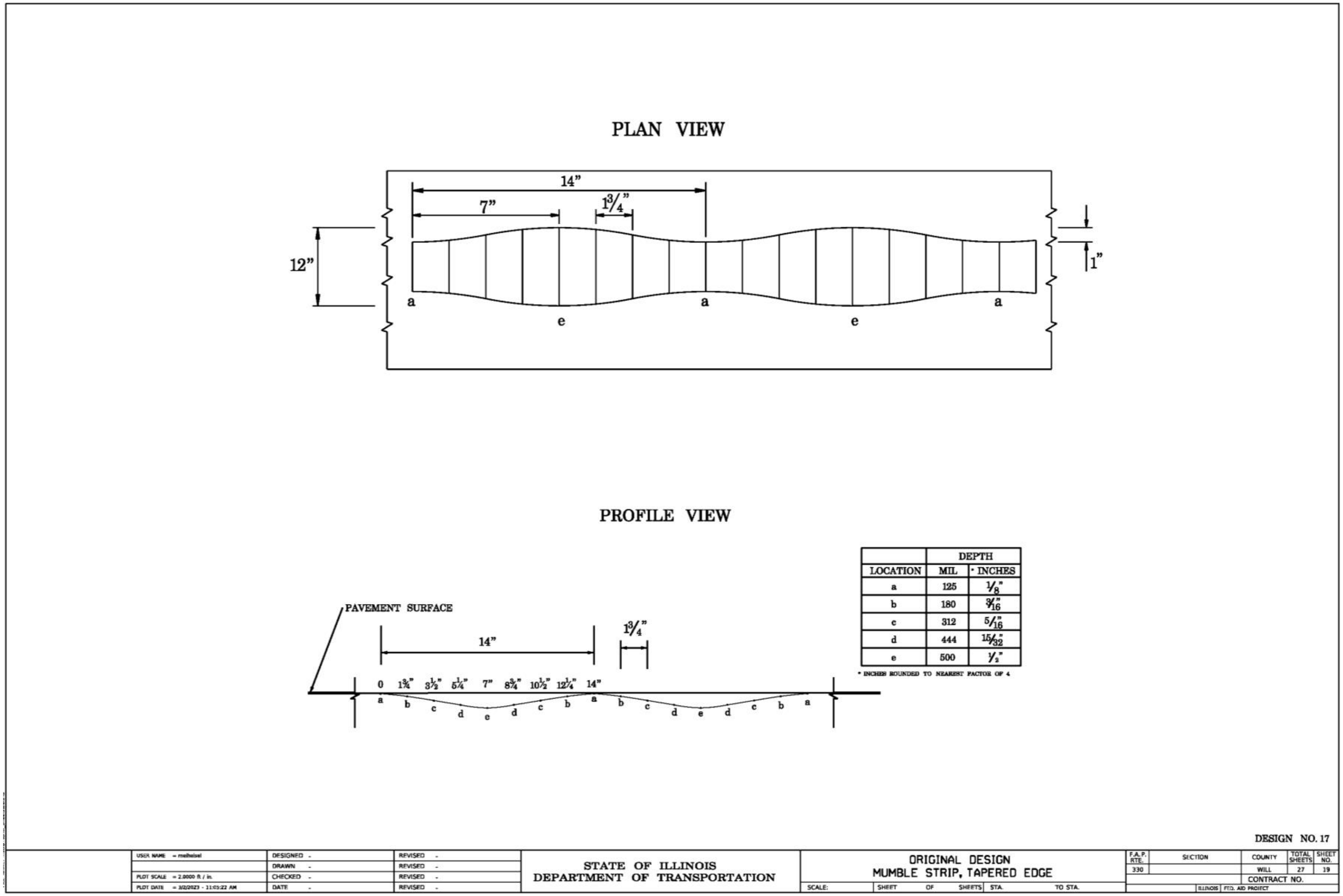
Figure 134. Illustration. Longitudinal sinusoidal design 15: straight edge 12” SRS.



	DEPTH	
LOCATION	MIL	* INCHES
a	125	⅛"
b	180	3/16"
c	312	5/16"
d	444	15/32"
e	500	½"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

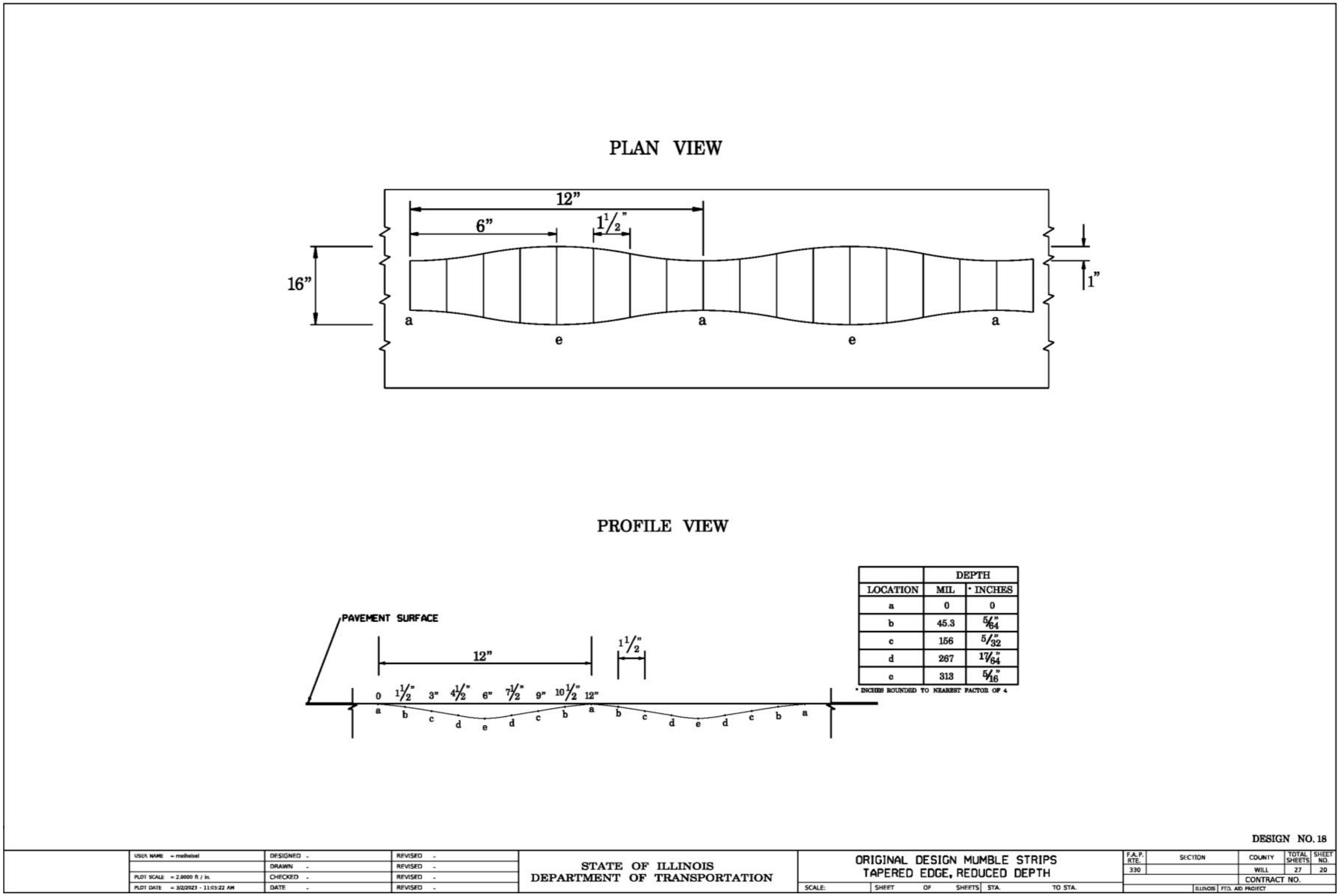
Figure 135. Illustration. Longitudinal sinusoidal design 16: reduced profile straight 12″ SRS.



	DEPTH	
LOCATION	MIL	* INCHES
a	125	1/8"
b	180	3/16"
c	312	5/16"
d	444	15/32"
e	500	1/2"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

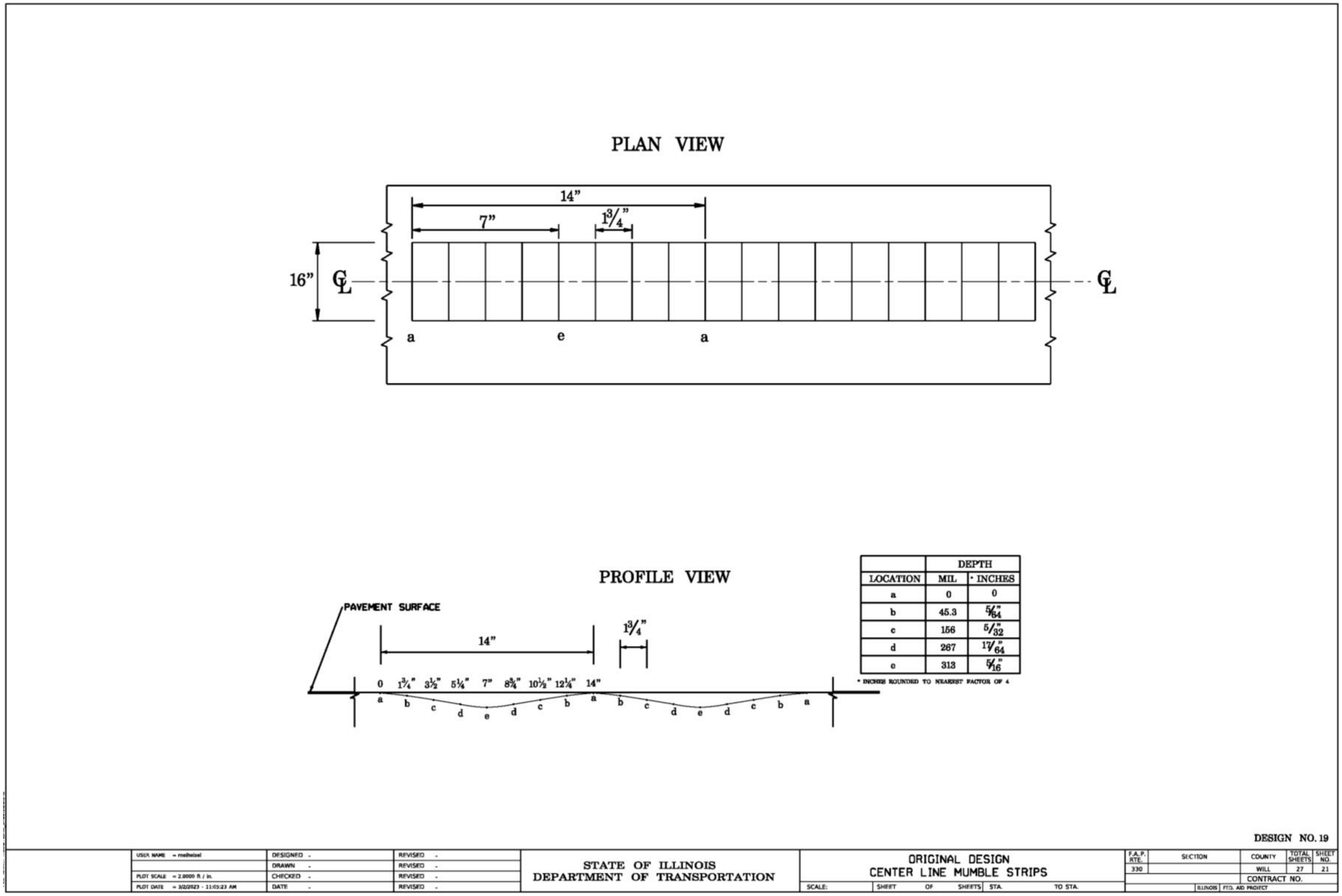
Figure 136. Illustration. Longitudinal sinusoidal design 17: tapered edge 12" SRS.



	DEPTH	
LOCATION	MIL	* INCHES
a	0	0
b	45.3	5/64"
c	156	5/32"
d	267	17/64"
e	313	5/16"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

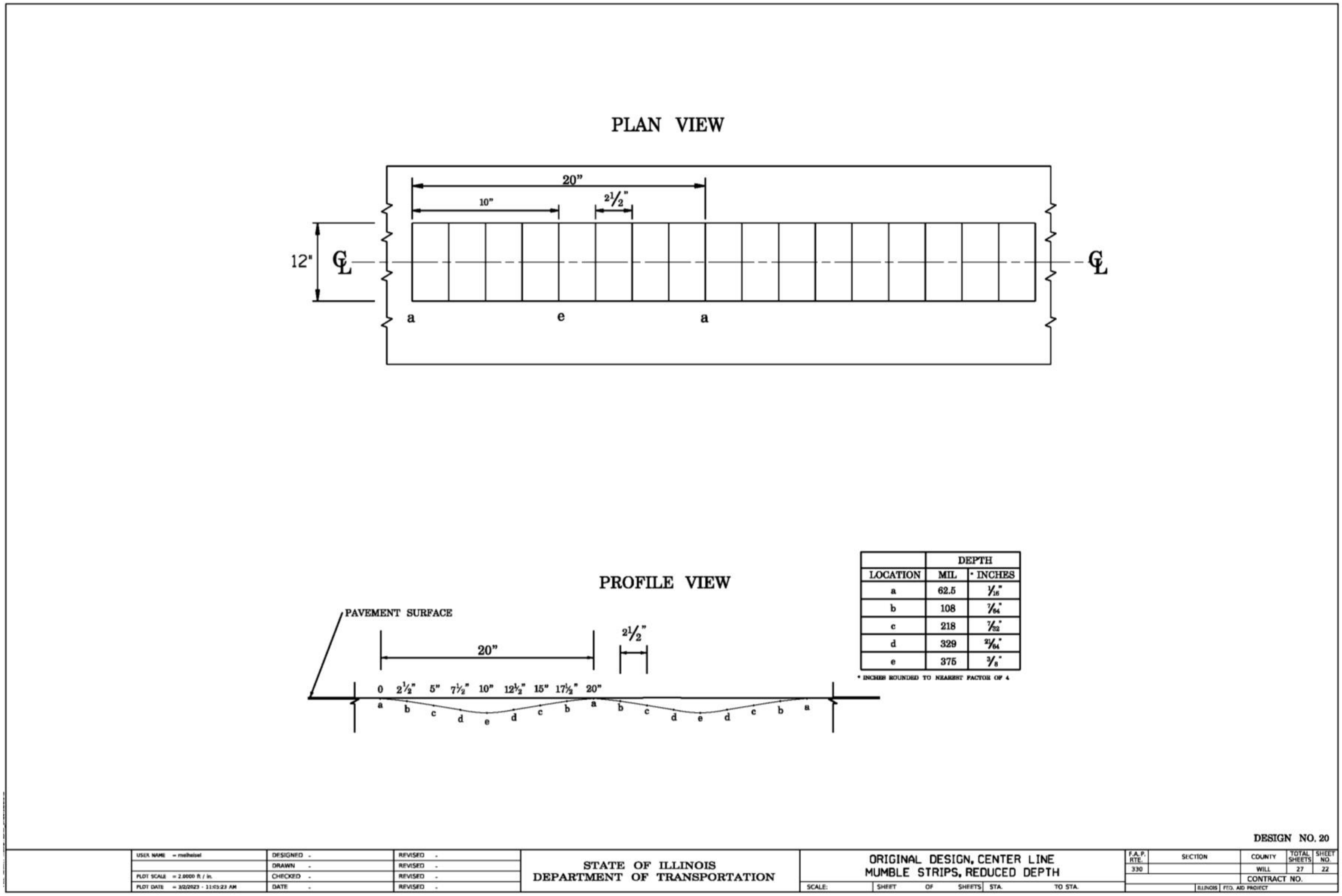
Figure 137. Illustration. Longitudinal sinusoidal design 18: reduced profile tapered 16" SRS.



	DEPTH	
LOCATION	MIL	* INCHES
a	0	0
b	45.3	5/64"
c	156	5/32"
d	267	17/64"
e	313	5/16"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

Figure 138. Illustration. Longitudinal sinusoidal design 19: reduced profile straight 16" SRS.



	DEPTH	
LOCATION	MIL	* INCHES
a	62.5	1/16"
b	108	7/64"
c	218	7/32"
d	329	21/64"
e	375	3/8"

* INCHES ROUNDED TO NEAREST FACTOR OF 4

Figure 139. Illustration. Longitudinal sinusoidal design 20: extended wavelength 12” SRS.

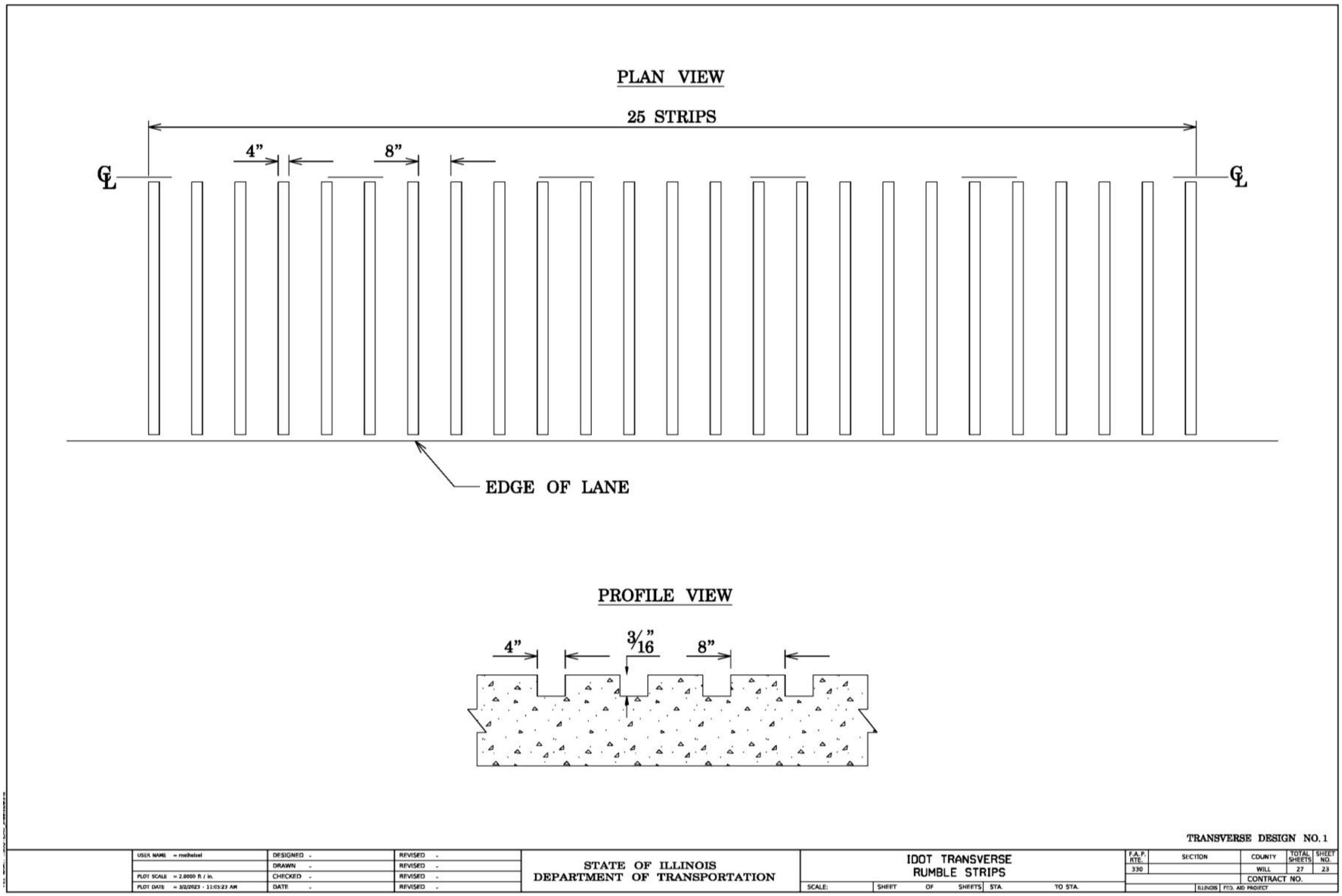


Figure 140. Illustration. Transverse design 1: IDOT traditional design.

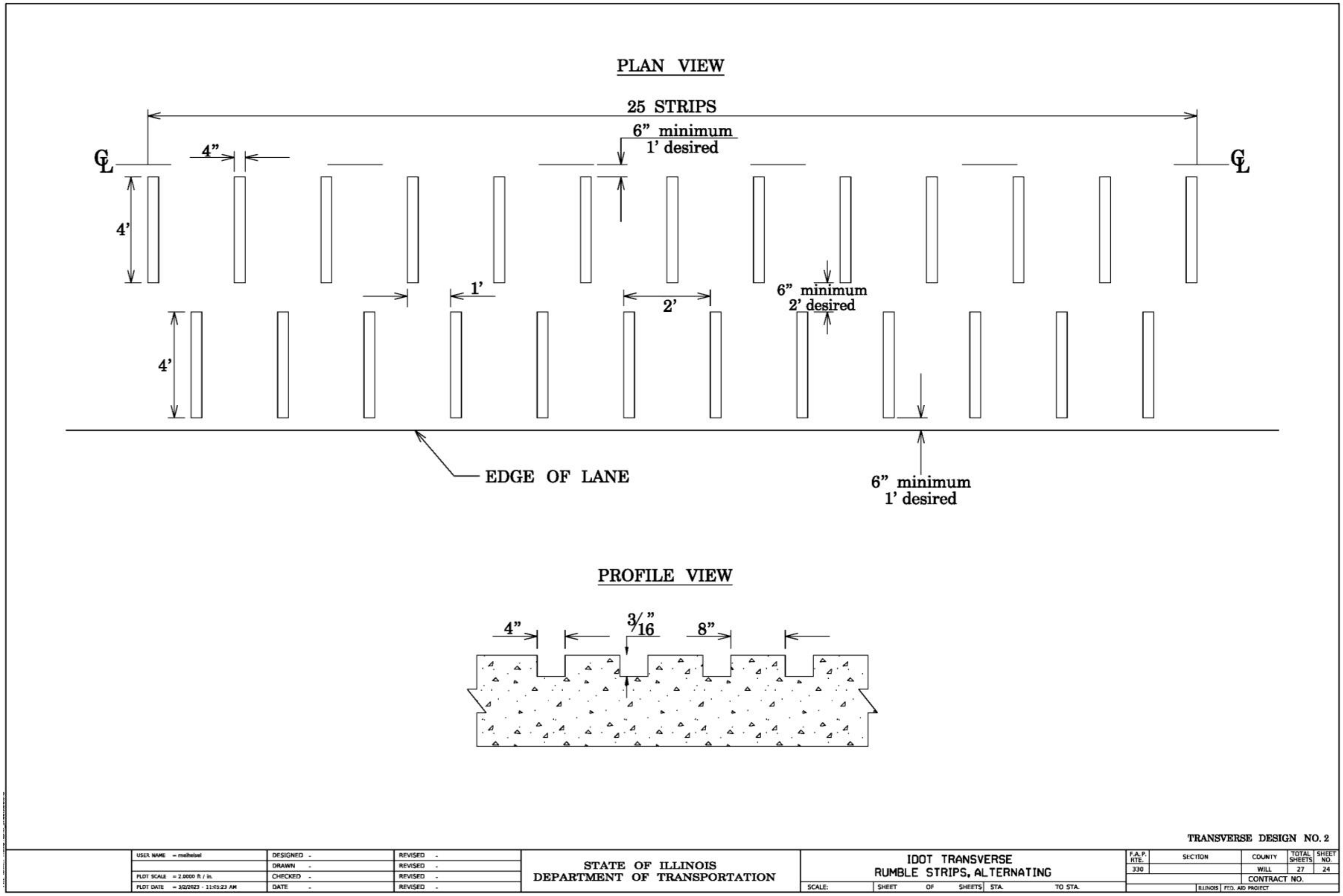
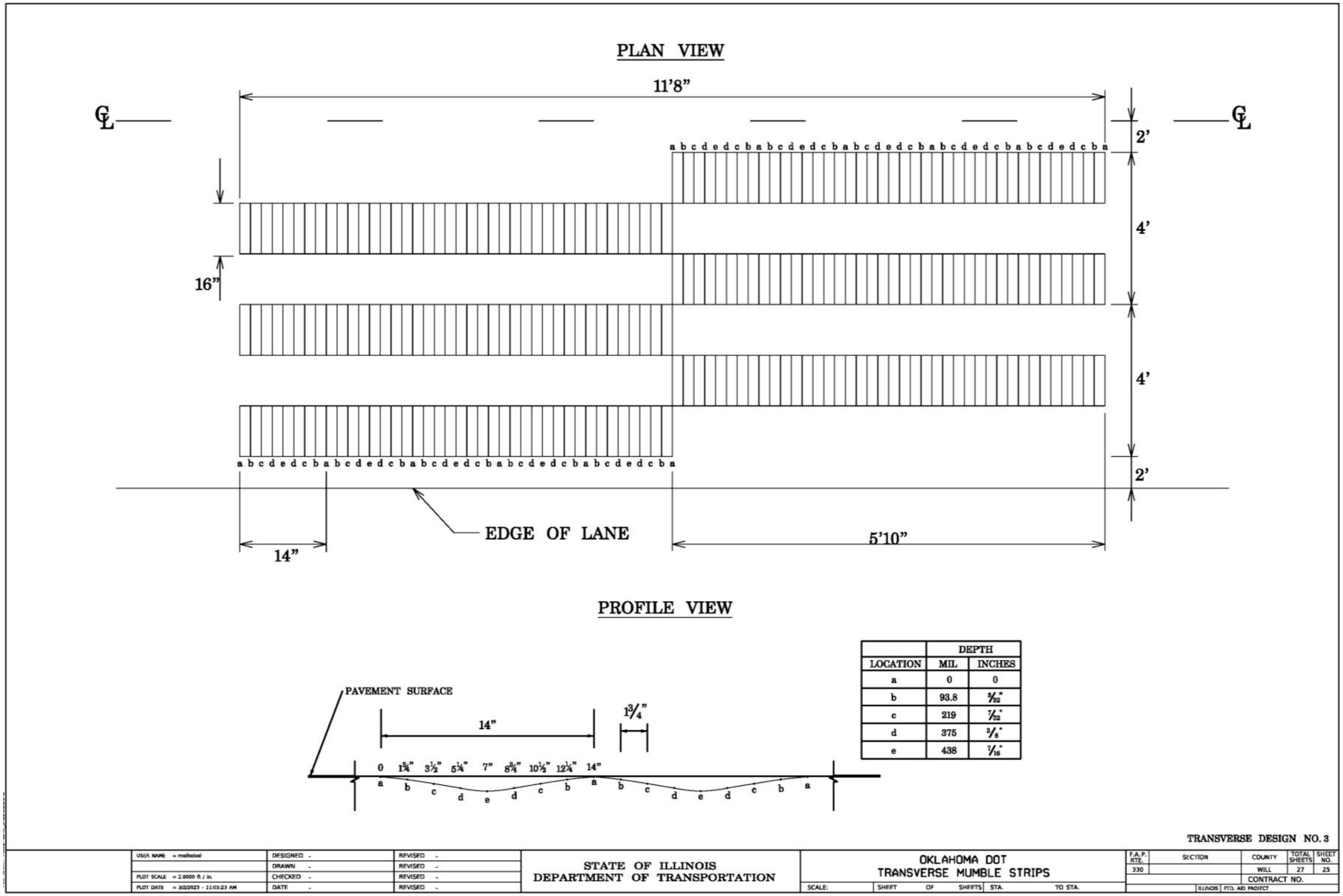


Figure 141. Illustration. Transverse design 2: IDOT traditional with alternate placement.



	DEPTH	
LOCATION	MIL	INCHES
a	0	0
b	93.8	3/32"
c	219	7/32"
d	375	3/8"
e	438	7/16"

Figure 142. Illustration. Transverse design 3: OKDOT sinusoidal design.

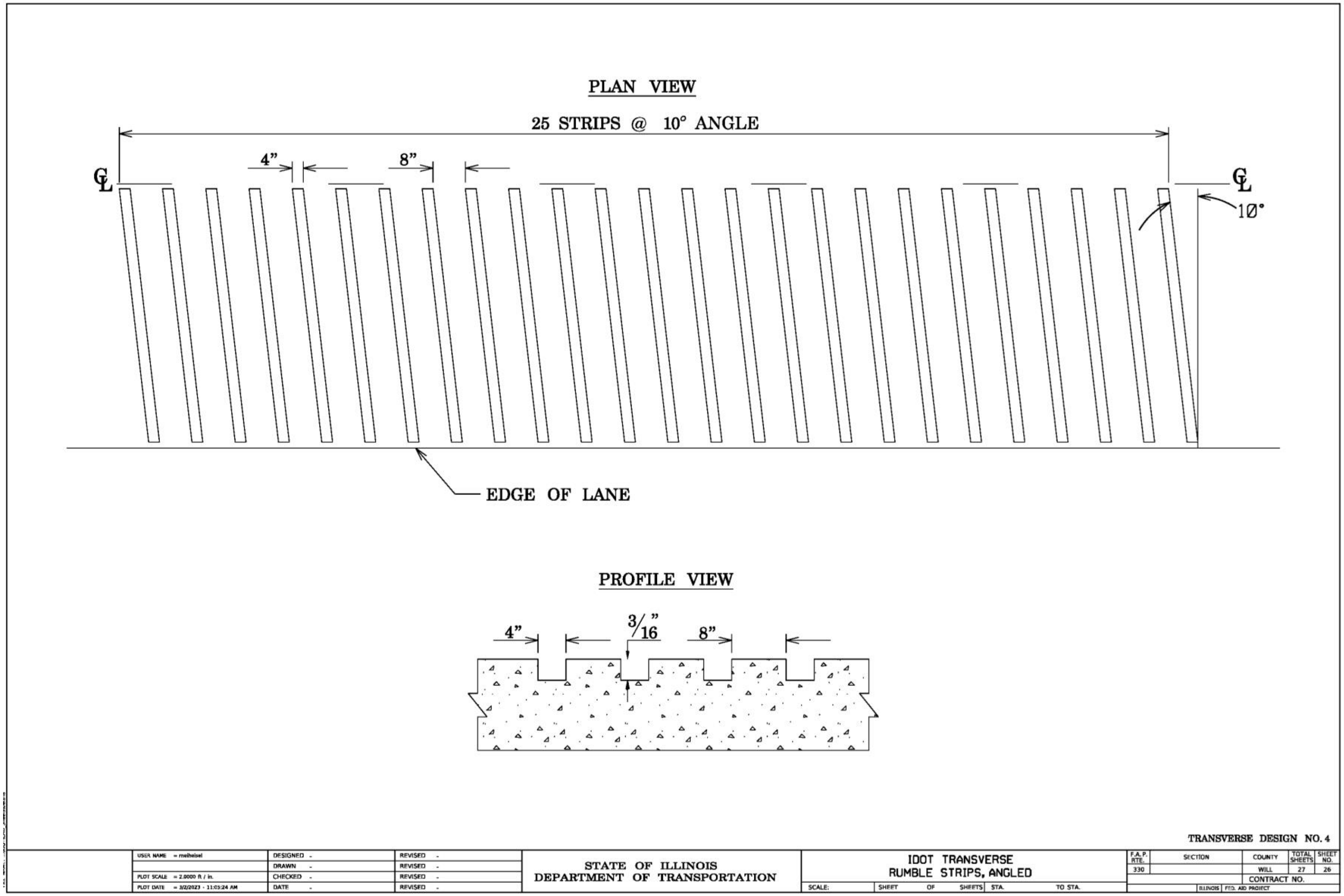


Figure 143. Illustration. Transverse design 4: angled transverse.

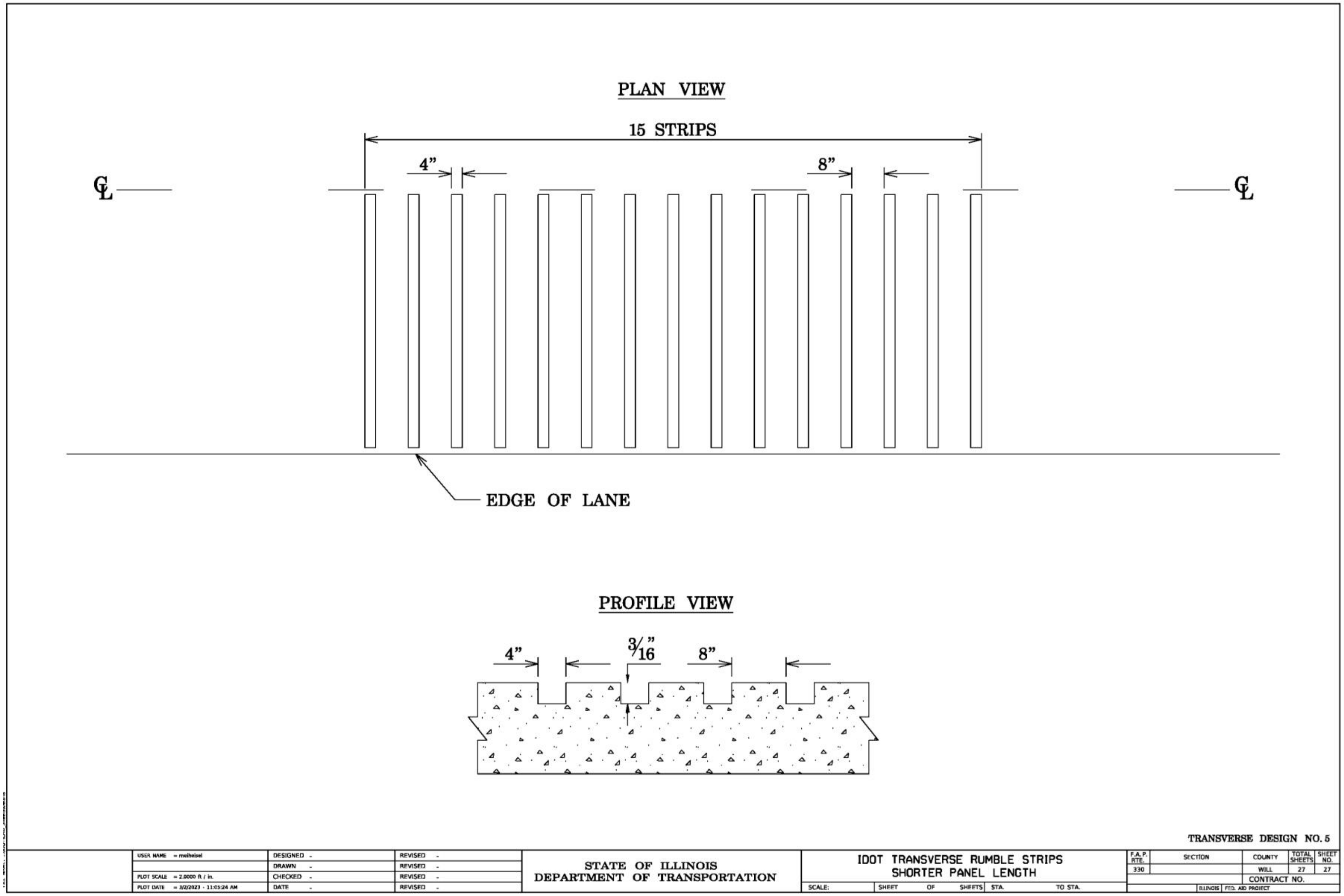


Figure 144. Illustration. Transverse design 5: IDOT traditional shorter design.

APPENDIX D: RESULTS OF NOISE DATA ANALYSIS FOR INITIAL ROUND OF TESTING

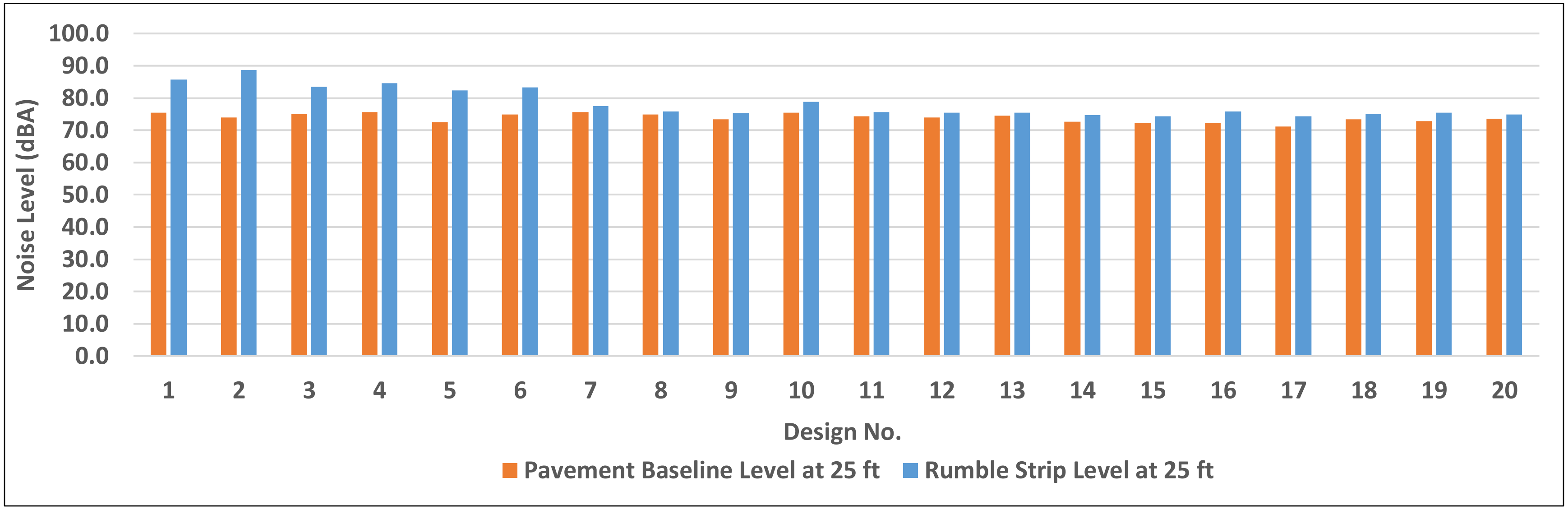


Figure 145. Graph. External noise of sedan and longitudinal rumble strips at 25 ft.

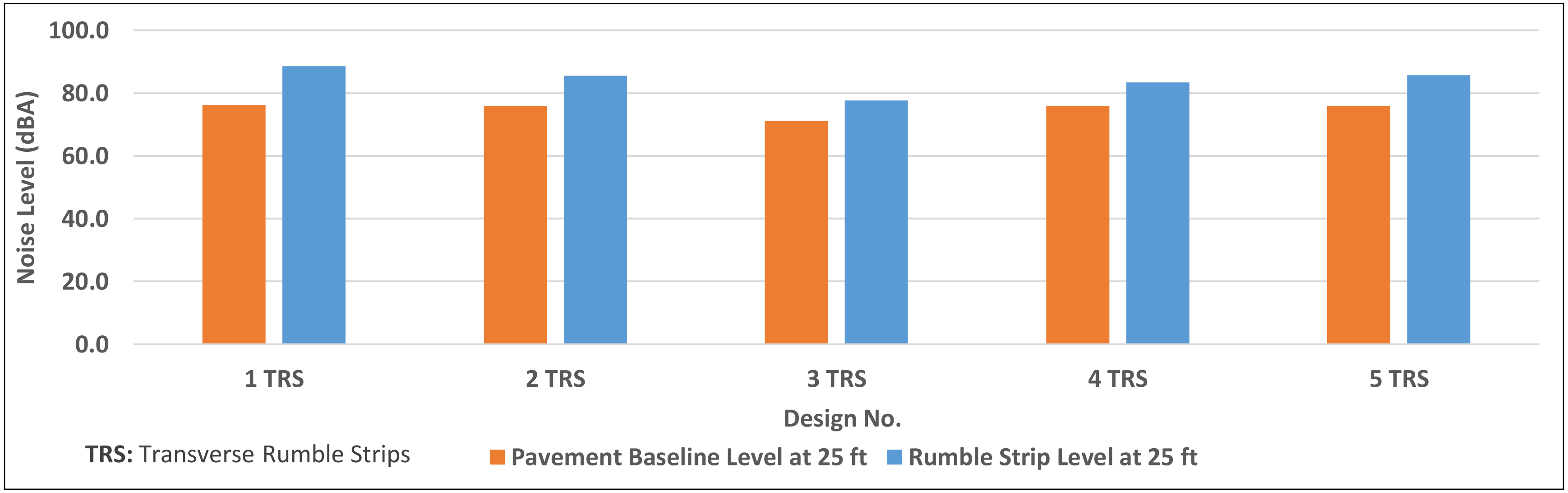


Figure 146. Graph. External noise of sedan and transverse rumble strips at 25 ft.

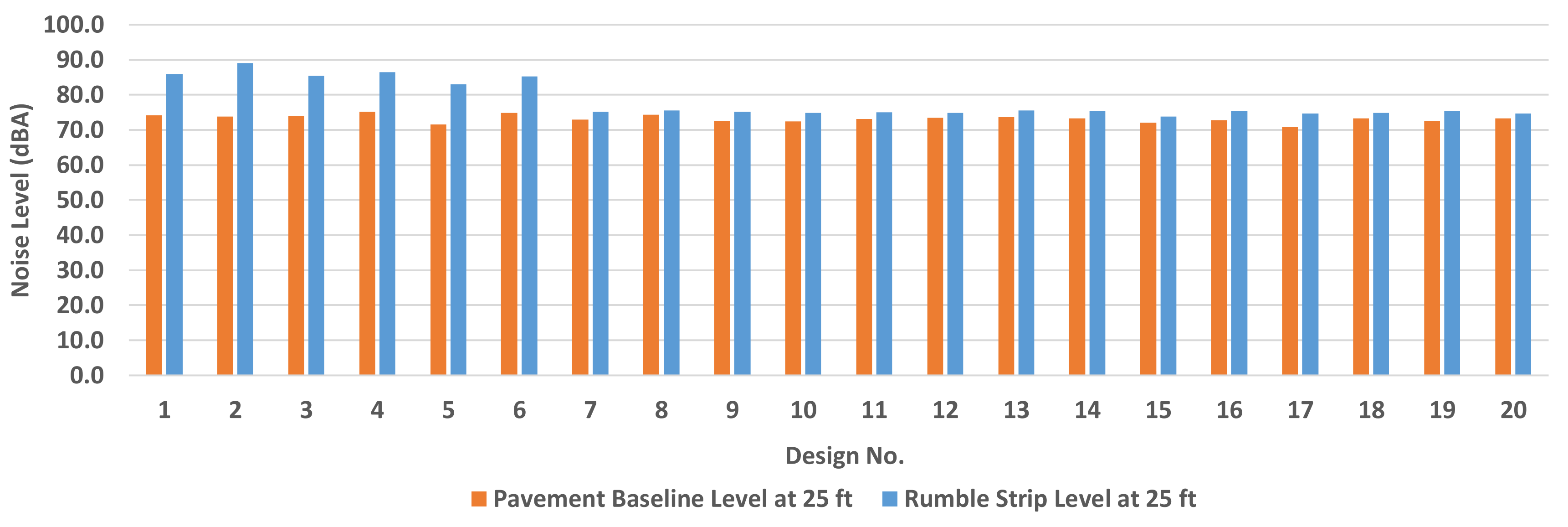


Figure 147. External noise of SUV and longitudinal rumble strips at 25 ft.

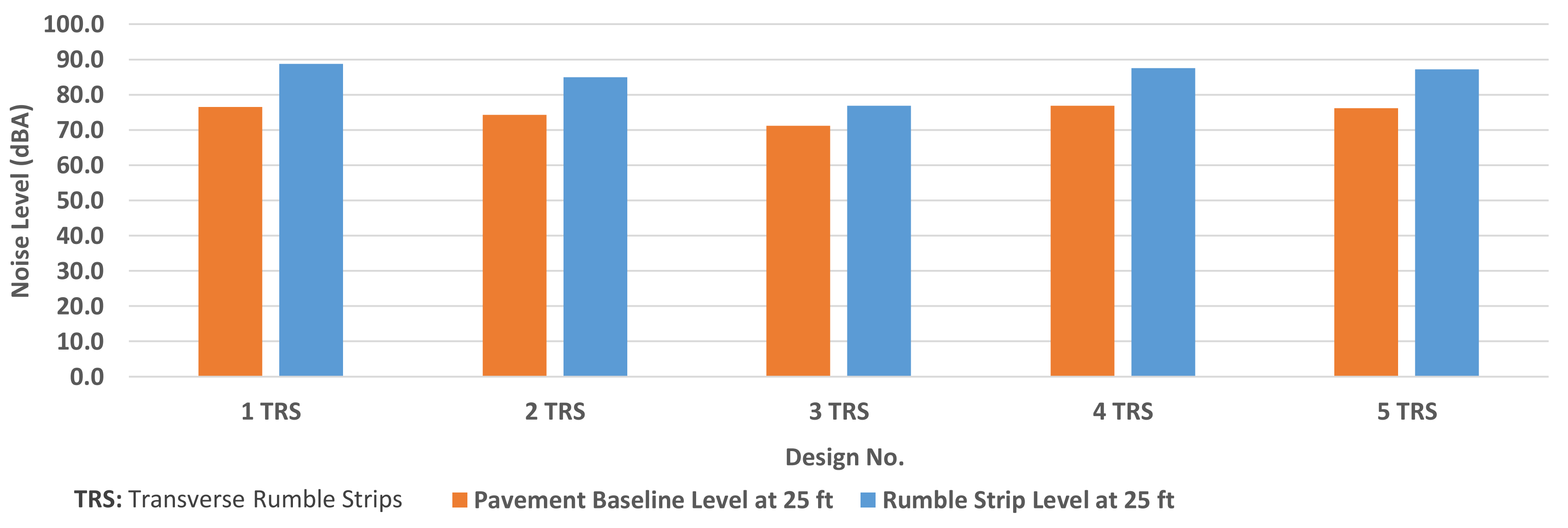


Figure 148. Graph. External noise of SUV and transverse rumble strips at 25 ft.

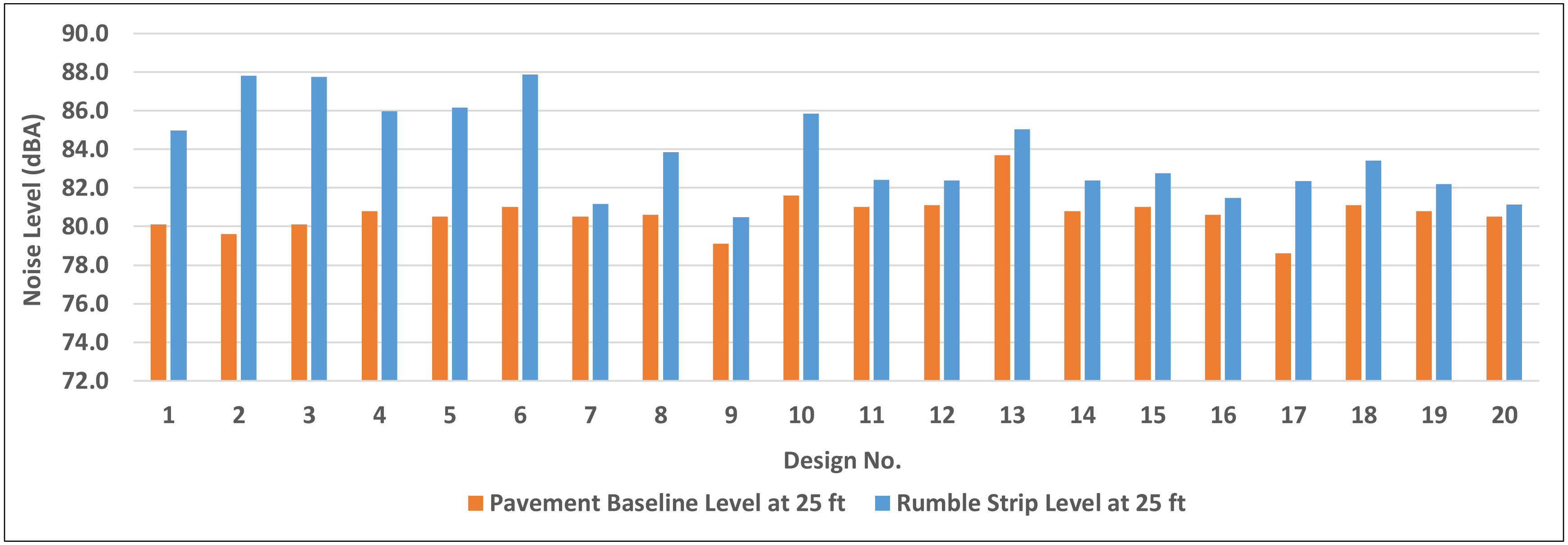


Figure 149. Graph. External noise of medium truck and longitudinal rumble strips at 25 ft.

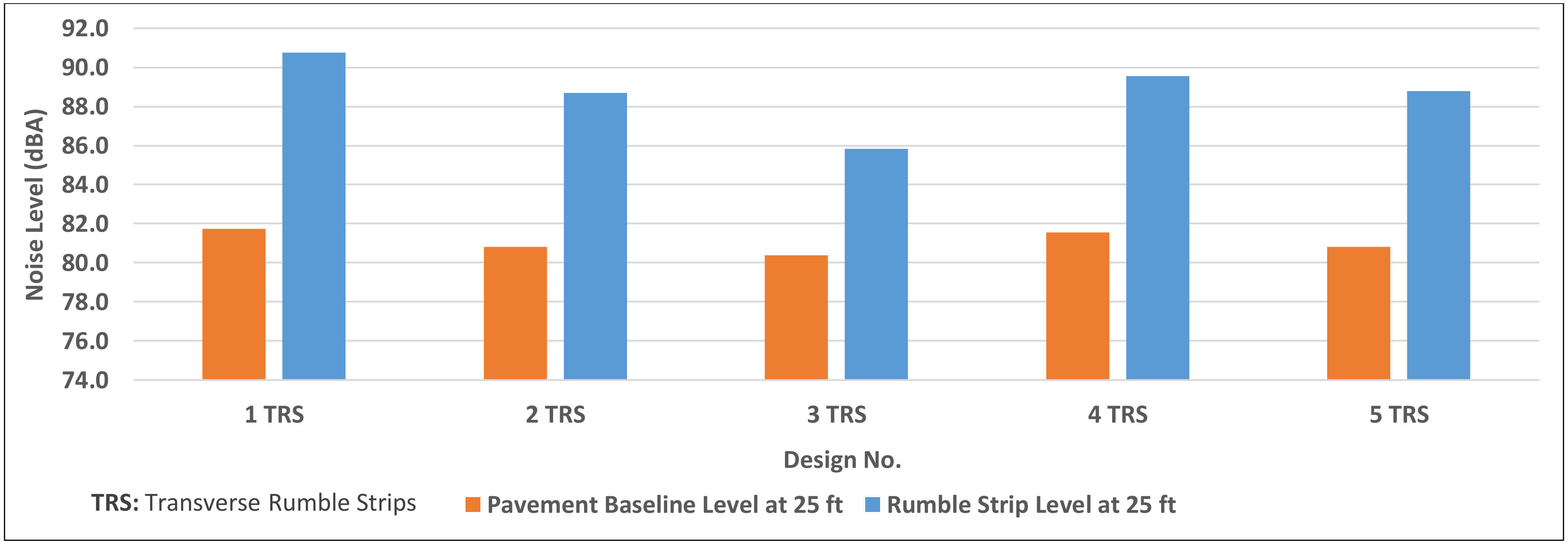


Figure 150. Graph. External noise of medium truck and transverse rumble strips at 25 ft.

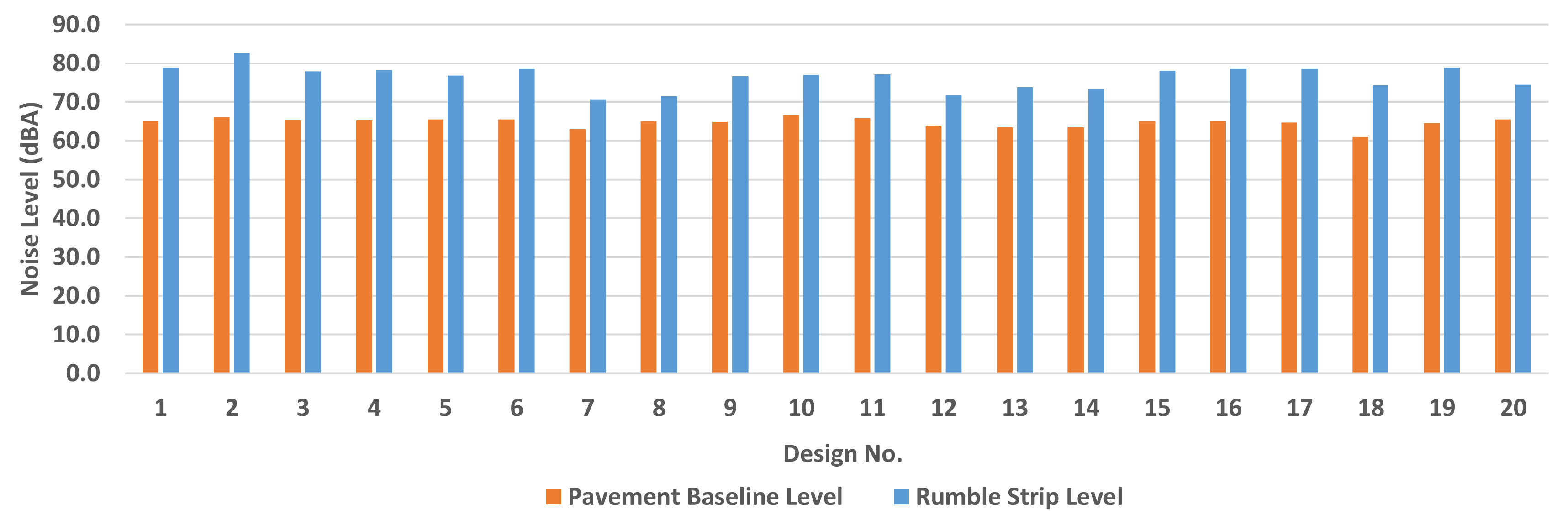


Figure 151. Graph. Internal noise of SUV and longitudinal rumble strips.

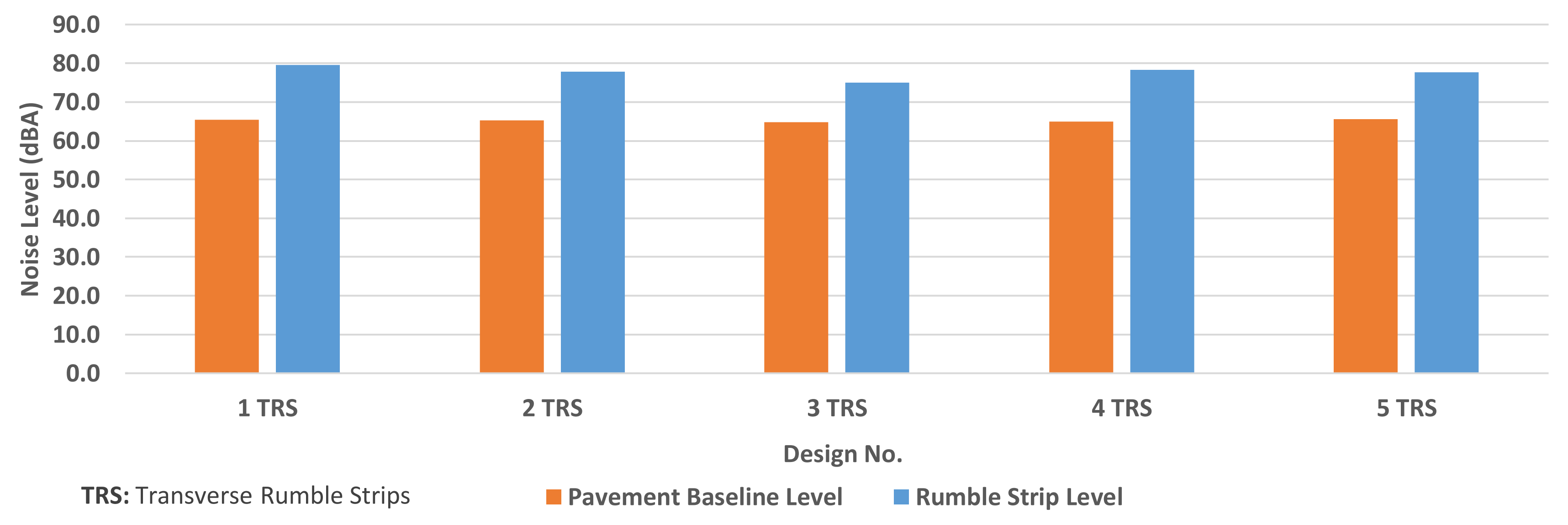


Figure 152. Graph. Internal noise of SUV and transverse rumble strips.

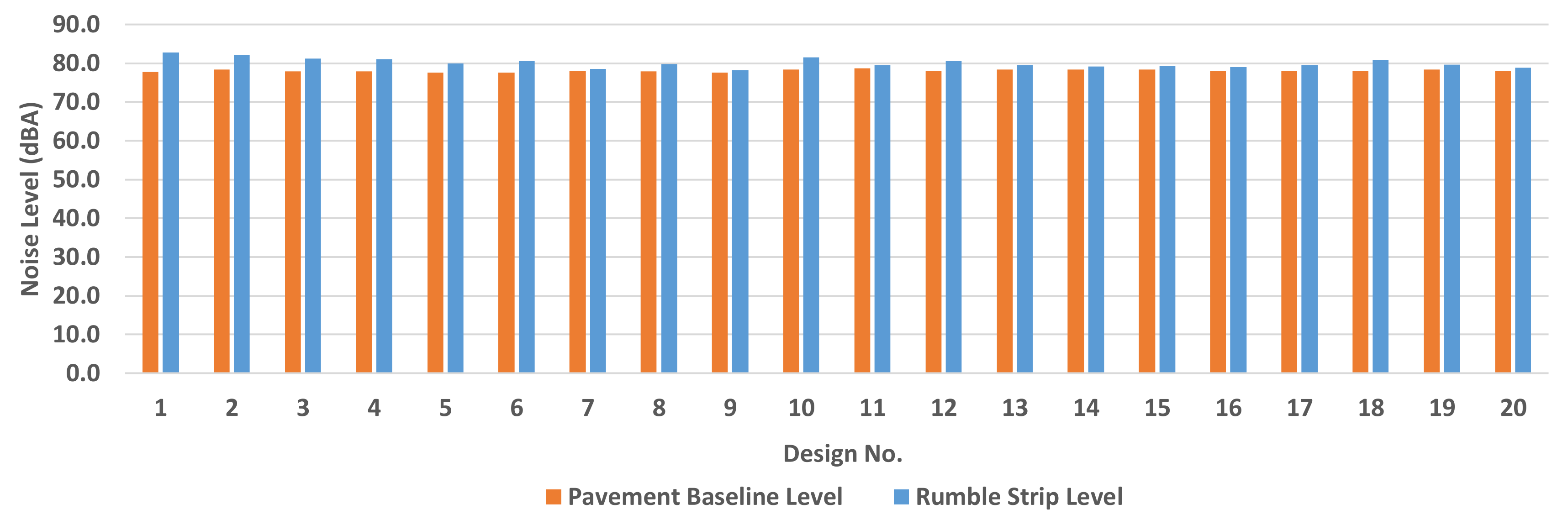


Figure 153. Graph. Internal noise of medium truck and longitudinal rumble strips.

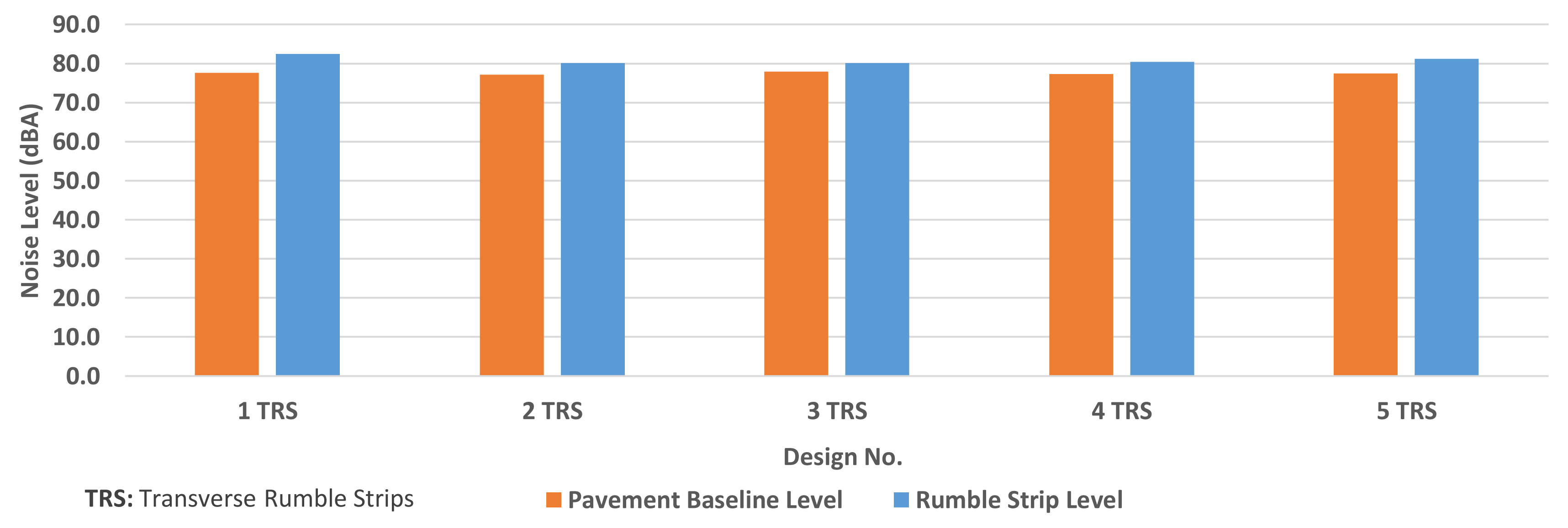


Figure 154. Graph. Internal noise of medium truck and transverse rumble strips.

Table 31. Initial Round Evaluation External Noise Levels of Longitudinal Rumble Strips at 50 ft

		Noise Levels (dBA)																			
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Sedan	**Sample Size**	33	33	30	30	38	31	35	31	33	31	31	32	30	32	30	36	30	35	30	30
	Average	79.8	84.0	77.0	79.2	77.6	78.6	73.3	70.3	72.9	74.6	70.5	70.6	70.1	70.0	68.9	71.8	70.8	71.2	71.3	69.0
	Standard Deviation	1.2	0.5	1.2	0.9	3.2	1.3	2.6	1.1	1.8	1.3	1.7	1.5	0.6	0.4	0.8	1.9	2.0	1.0	1.8	1.2
SUV	**Sample Size**	30	31	30	30	31	31	30	30	30	30	30	31	30	30	30	31	30	30	30	30
	Average	81.3	84.6	80.9	81.1	77.3	80.1	71.2	70.4	71.3	70.2	70.1	69.7	70.5	70.2	68.1	70.6	69.1	70.4	70.4	70.3
	Standard Deviation	1.0	0.7	0.7	0.6	1.0	0.7	1.8	0.5	1.3	0.9	1.1	0.5	0.5	0.8	0.4	1.2	0.7	0.7	1.0	0.6
Truck	**Sample Size**	5	4	4	4	4	5	4	5	4	4	5	4	4	5	4	4	7	4	4	4
	Average	80.4	84.2	81.1	81.1	81.3	82.3	76.9	77.9	76.1	81.2	78.1	78.0	80.8	77.0	77.5	77.3	77.7	79.3	77.8	76.7
	Standard Deviation	1.0	0.8	0.9	1.2	0.5	0.3	2.0	0.5	0.2	0.8	0.9	1.2	0.2	0.7	0.3	0.9	1.3	0.7	0.5	1.0

Table 32. Initial Round Evaluation External Baseline Noise Levels of Longitudinal Rumble Strips at 50 ft

		Baseline Noise Levels (dBA)																			
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Sedan	**Sample Size**	5	4	4	5	6	7	5	5	5	4	5	5	5	6	4	5	3	6	3	5
	Average	70.3	70.2	70.0	70.9	68.2	70.5	71.4	69.9	71.1	72.1	70.0	70.2	69.6	68.8	67.5	70.7	69.7	70.5	70.1	68.3
	Standard Deviation	0.4	0.2	0.6	0.3	0.3	0.9	0.4	0.2	0.6	0.8	0.5	0.2	0.1	0.2	0.4	0.9	0.6	0.2	1.3	0.3
SUV	**Sample Size**	4	5	6	4	6	3	5	5	5	5	5	4	5	5	5	5	5	5	4	5
	Average	70.0	70.1	70.0	70.8	66.7	70.2	70.0	69.8	69.9	69.0	69.5	69.3	69.4	69.0	67.1	69.3	68.0	69.8	69.0	69.6
	Standard Deviation	0.9	0.3	0.5	0.3	0.3	0.6	0.2	0.7	0.4	0.4	0.4	0.2	0.3	0.2	0.4	0.5	0.2	0.4	0.3	0.4
Truck	**Sample Size**	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
	Average	75.6	76.2	75.4	76.2	76.4	75.5	76.1	75.5	75.2	76.9	76.8	77.0	80.2	75.4	76.4	76.4	75.3	76.9	76.2	76.2
	Standard Deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 33. Initial Round Evaluation External Noise Levels of Transverse Rumble Strips at 50 ft

		Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Sedan	**Sample**	30	30	31	33	30
	Average	83.8	81.2	72.8	78.7	80.8
	Standard Deviation	0.8	0.9	0.8	0.6	0.9
SUV	**Sample**	33	30	32	30	32
	Average	84.6	79.3	71.3	81.5	82.1
	Standard Deviation	0.8	1.0	0.8	1.1	1.5
Truck	**Sample**	4	4	4	4	4
	Average	85.0	83.4	78.7	83.3	82.5
	Standard Deviation	0.5	1.3	0.2	0.4	0.5

Table 34. Initial Round Evaluation External Baseline Noise Levels of Transverse Rumble Strips at 50 ft

		Baseline Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Sedan	**Sample**	14	6	18	20	14
	Average	73.5	74.9	69.8	73.0	74.3
	Standard Deviation	1.4	0.8	0.7	1.5	2.0
SUV	**Sample**	22	7	32	28	32
	Average	75.4	71.1	69.4	72.7	74.1
	Standard Deviation	2.5	2.2	0.4	2.3	2.2
Truck	**Sample**	4	4	4	4	4
	Average	76.8	76.5	75.1	76.5	75.8
	Standard Deviation	1.1	1.0	1.2	1.2	0.9

Table 35. Initial Round Evaluation External Noise Levels of Longitudinal Rumble Strips at 25 ft

		Noise Levels (dBA)																			
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Sedan	**Sample Size**	33	34	31	32	38	32	36	30	33	31	31	32	30	32	30	36	31	35	31	32
	Average	85.6	88.6	83.5	84.6	82.4	83.3	77.6	75.8	75.2	78.8	75.7	75.5	75.5	74.7	74.4	75.7	74.4	75.1	75.4	74.8
	Standard Deviation	1.8	0.9	1.9	1.4	3.8	1.8	2.6	0.7	1.3	1.1	0.8	0.5	0.6	0.9	0.4	1.7	1.2	0.6	1.7	1.1
SUV	**Sample Size**	30	31	30	31	30	31	30	31	30	32	32	31	31	30	30	31	30	30	33	30
	Average	86.0	89.0	85.4	86.4	83.1	85.2	75.2	75.6	75.2	74.9	75.0	74.9	75.5	75.3	73.8	75.3	74.6	74.8	75.3	74.7
	Standard Deviation	2.5	1.0	1.0	0.9	1.1	1.7	0.8	0.4	0.3	0.5	2.0	0.4	0.5	0.5	0.5	0.8	0.6	0.5	0.4	0.4
Truck	**Sample Size**	5	4	4	4	4	5	4	4	4	4	5	4	4	5	4	4	5	4	4	4
	Average	85.0	87.8	87.8	86.0	86.2	87.9	81.2	83.9	80.5	85.9	82.4	82.4	85.0	82.4	82.8	81.5	82.3	83.4	82.2	81.2
	Standard Deviation	1.5	1.0	1.1	1.6	0.2	0.3	1.1	0.6	0.1	0.6	0.5	1.2	0.2	0.3	0.1	0.3	1.2	0.9	0.3	0.5

Table 36. Initial Round Evaluation External Baseline Noise Levels of Longitudinal Rumble Strips at 25 ft

		Baseline Noise Levels (dBA)																			
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Sedan	**Sample Size**	5	4	4	5	6	7	4	6	5	4	5	6	5	6	5	5	3	6	3	5
	Average	75.5	74.0	75.1	75.5	72.4	75.0	75.6	74.8	73.4	75.5	74.4	73.9	74.5	72.7	72.3	72.2	71.2	73.5	72.8	73.6
	Standard Deviation	0.4	0.3	0.4	0.7	0.3	0.2	0.2	0.3	0.7	1.2	0.3	0.9	0.1	0.5	0.3	2.3	0.6	0.6	1.3	0.4
SUV	**Sample Size**	5	6	5	5	6	5	5	5	5	5	5	4	5	4	5	5	5	5	4	5
	Average	74.1	73.8	74.0	75.3	71.5	74.9	73.0	74.3	72.6	72.5	73.2	73.4	73.6	73.3	72.1	72.8	70.9	73.4	72.7	73.3
	Standard Deviation	0.5	0.4	0.4	0.4	0.4	0.5	1.1	0.4	0.4	0.7	0.4	0.3	0.3	0.6	0.4	0.9	1.2	0.3	0.9	0.2
Truck	**Sample Size**	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Average	80.1	79.6	80.1	80.8	80.5	81.0	80.5	80.6	79.1	81.6	81.0	81.1	83.7	80.8	81.0	80.6	78.6	81.1	80.8	80.5
	Standard Deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 37. Initial Round Evaluation External Noise Levels of Transverse Rumble Strips at 25 ft

		Noise Levels (dBA)				
Design No.		1 TRS	2 TRS	3 TRS	4 TRS	5 TRS
Sedan	Sample	30	30	31	31	30
	Average	88.6	85.6	77.7	83.5	85.8
	Standard Deviation	1.0	0.7	0.5	0.7	1.1
SUV	Sample	30	30	32	30	31
	Average	88.8	84.9	76.9	87.6	87.1
	Standard Deviation	1.7	1.0	0.5	1.0	1.9
Truck	Sample	4	4	4	4	4
	Average	90.8	88.7	85.8	89.6	88.8
	Standard Deviation	0.9	0.9	0.2	0.7	1.1

Table 38. Initial Round Evaluation External Baseline Noise Levels of Transverse Rumble Strips at 25 ft

		Baseline Noise Levels (dBA)				
Design No.		1 TRS	2 TRS	3 TRS	4 TRS	5 TRS
Sedan	Sample	16	10	14	20	20
	Average	76.1	76.0	71.1	76.0	76.0
	Standard Deviation	1.1	1.8	0.7	1.8	1.9
SUV	Sample	26	15	32	28	31
	Average	76.6	74.2	71.1	76.8	76.1
	Standard Deviation	1.6	1.2	0.9	2.2	1.6
Truck	Sample	4	4	4	4	4
	Average	81.8	80.8	80.4	81.6	80.8
	Standard Deviation	0.3	0.2	1.0	1.4	1.0

Table 39. Initial Round Evaluation Internal Noise Levels of Longitudinal Rumble Strips

		Noise Levels (dBA)																			
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Sedan	**Sample Size**	6	6	6	7	22	9	19	7	12	6	6	9	6	6	7	18	8	9	6	7
	Average	78.6	81.9	77.2	78.3	73.0	77.6	70.8	73.7	66.1	77.8	72.1	71.5	71.6	70.6	75.4	71.6	73.8	76.3	74.1	71.5
	Standard Deviation	0.8	0.5	1.0	1.3	3.7	1.0	0.6	1.6	1.5	0.4	0.5	0.5	1.1	0.5	0.8	0.7	0.8	2.1	0.3	0.3
SUV	**Sample Size**	6	6	6	6	6	7	7	6	6	6	6	7	8	6	6	5	7	7	8	6
	Average	78.8	82.6	77.9	78.1	76.7	78.5	70.7	71.5	76.6	77.0	77.2	71.8	73.8	73.3	78.1	78.5	78.5	74.2	78.8	74.4
	Standard Deviation	1.2	0.2	1.2	0.4	0.4	0.6	0.7	0.4	1.1	0.8	0.7	0.5	0.4	1.9	2.8	0.3	1.1	0.5	0.7	0.7
Truck	**Sample Size**	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Average	82.8	82.2	81.1	81.1	79.9	80.6	78.6	79.8	78.3	81.5	79.5	80.5	79.4	79.1	79.3	79.0	79.5	80.9	79.7	78.9
	Standard Deviation	0.3	0.4	0.4	0.0	0.5	0.2	0.3	0.3	0.2	0.4	0.2	0.3	0.3	0.3	0.3	0.1	0.3	0.7	0.4	0.1

Table 40. Initial Round Evaluation Internal Baseline Noise Levels of Longitudinal Rumble Strips

		Baseline Noise Levels (dBA)																			
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Sedan	**Sample Size**	6	6	6	7	22	9	19	7	12	6	6	9	6	6	7	18	8	9	6	7
	Average	65.1	66.4	64.7	65.7	61.5	64.4	62.9	65.0	57.4	65.4	64.9	65.3	65.0	65.6	64.6	62.1	65.1	65.2	65.6	64.6
	Standard Deviation	0.9	0.5	0.4	0.7	2.9	1.0	0.5	0.9	0.9	0.4	0.5	0.6	0.3	0.3	1.5	0.5	0.7	0.9	0.4	0.3
SUV	**Sample Size**	6	6	6	6	6	7	7	6	6	6	6	7	8	6	6	5	7	7	8	6
	Average	65.2	66.2	65.3	65.4	65.5	65.5	62.9	65.0	64.9	66.6	65.8	64.0	63.4	63.4	65.0	65.2	64.7	61.0	64.5	65.5
	Standard Deviation	0.1	0.1	0.1	0.2	0.2	0.3	0.5	0.5	0.3	1.0	0.5	0.6	0.8	0.6	0.2	0.7	0.3	0.6	0.4	0.3
Truck	**Sample Size**	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Average	77.7	78.3	77.9	77.8	77.6	77.6	78.0	78.0	77.7	78.4	78.7	78.1	78.4	78.4	78.3	78.1	78.1	78.0	78.4	78.1
	Standard Deviation	0.7	0.3	0.3	0.0	0.2	0.4	0.2	0.0	0.2	0.5	0.2	0.2	0.2	0.2	0.1	0.1	0.3	0.1	0.5	0.2

Table 41. Initial Round Evaluation Internal Noise Levels of Transverse Rumble Strips

		Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Sedan	**Sample**	9	7	5	7	8
	Average	79.5	77.5	75.9	78.3	77.8
	Standard Deviation	2.2	1.7	2.1	2.3	3.1
SUV	**Sample**	5	5	5	8	5
	Average	79.6	77.8	75.0	78.4	77.7
	Standard Deviation	1.1	1.0	1.5	2.6	0.8
Truck	**Sample**	3	3	3	3	3
	Average	82.4	80.1	80.1	80.4	81.1
	Standard Deviation	1.2	0.5	0.4	1.5	0.4

Table 42. Initial Round Evaluation Internal Baseline Noise Levels of Transverse Rumble Strips

		Baseline Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Sedan	**Sample**	9	7	5	7	8
	Average	65.5	64.9	65.4	65.4	65.3
	Standard Deviation	0.3	0.6	0.30	0.2	0.2
SUV	**Sample**	5	5	5	8	5
	Average	65.5	65.3	64.8	65.0	65.5
	Standard Deviation	0.1	0.4	0.3	0.7	0.3
Truck	**Sample**	3	3	3	3	3
	Average	77.6	77.1	78.0	77.4	77.5
	Standard Deviation	0.3	0.2	0.1	0.1	0.2

APPENDIX E: RESULTS OF NOISE DATA ANALYSIS FOR SECOND ROUND OF TESTING

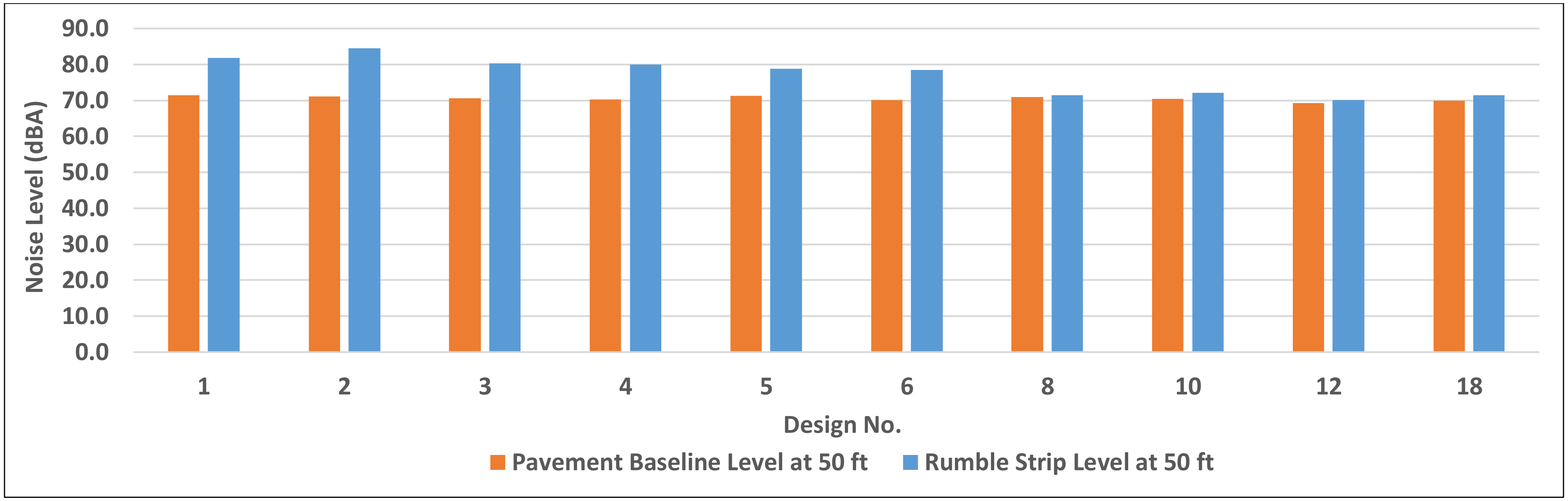


Figure 155. Graph. External noise of full-size sedan and longitudinal rumble strips at 50 ft.

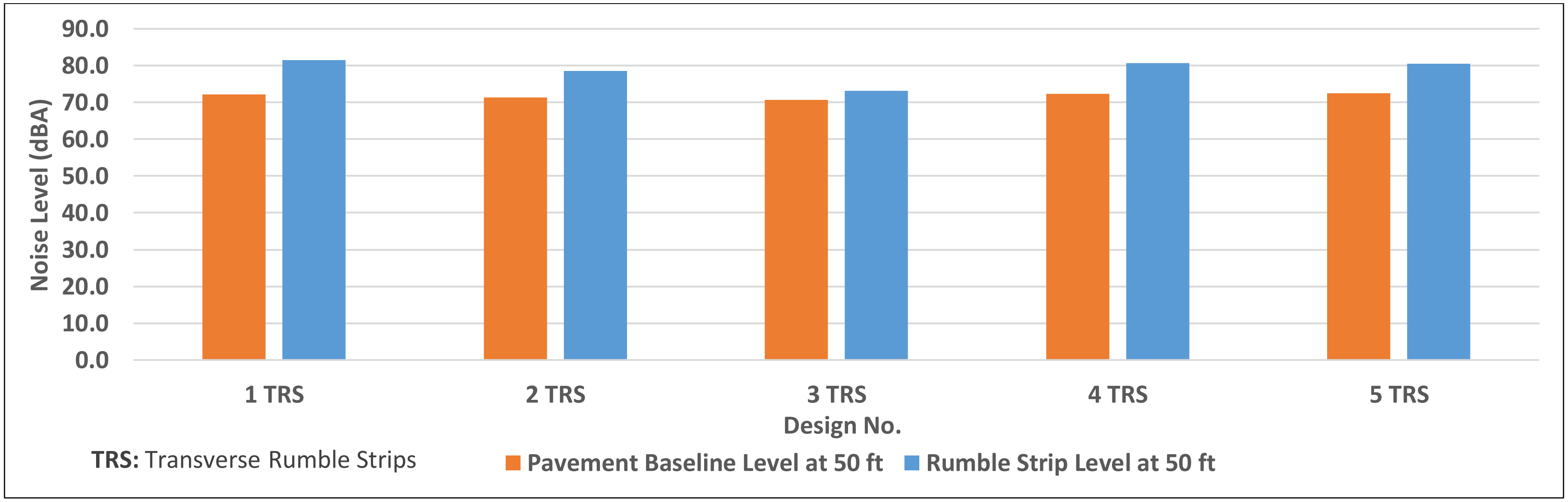


Figure 156. Graph. External noise of full-size sedan and transverse rumble strips at 50 ft.

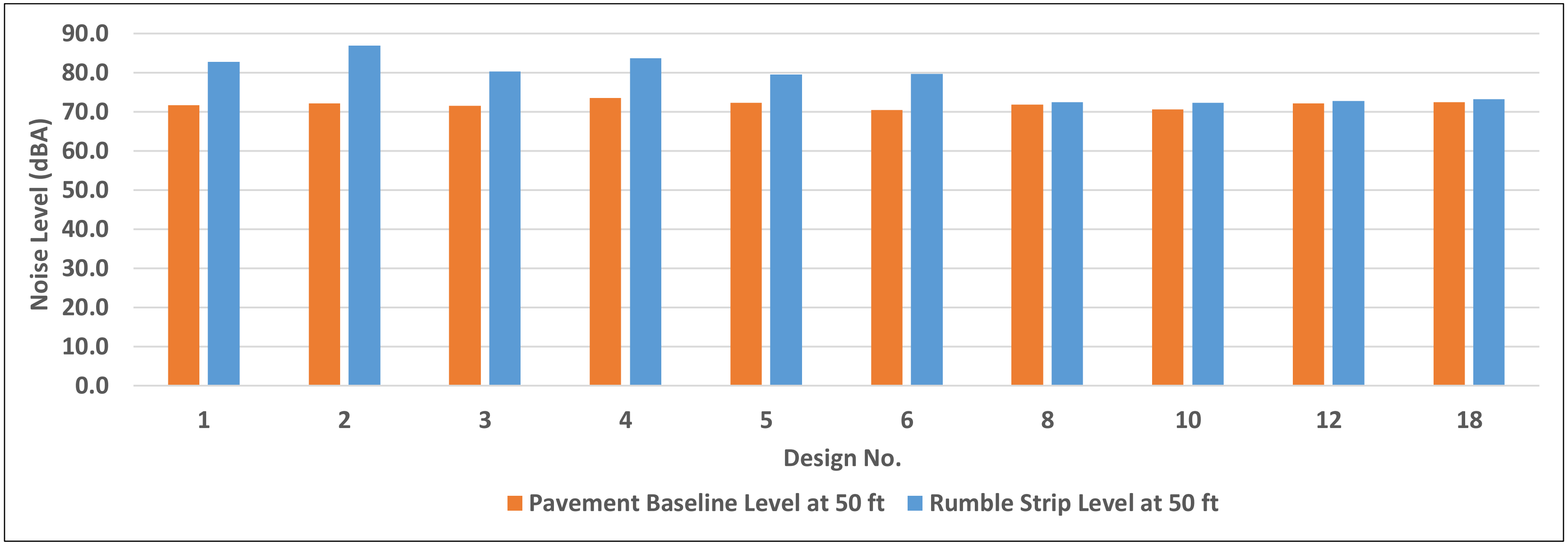


Figure 157. Graph. External noise of electric sedan and longitudinal rumble strips at 50 ft.

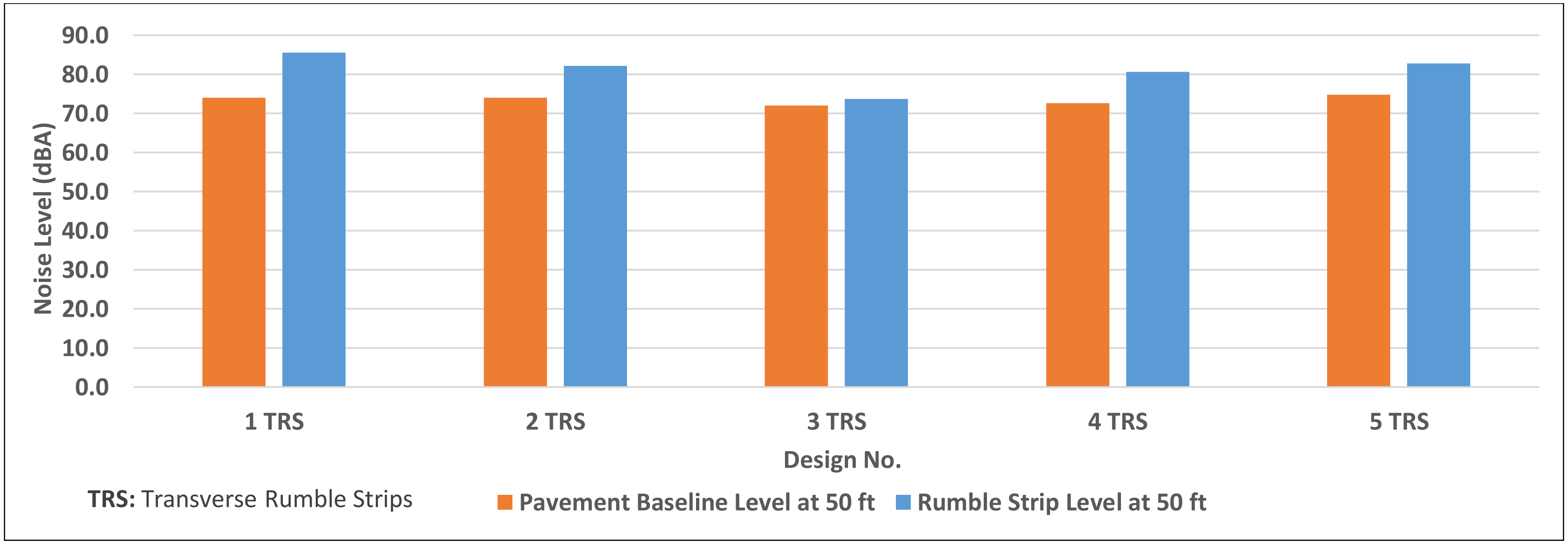


Figure 158. Graph. External noise of electric sedan and transverse rumble strips at 50 ft.

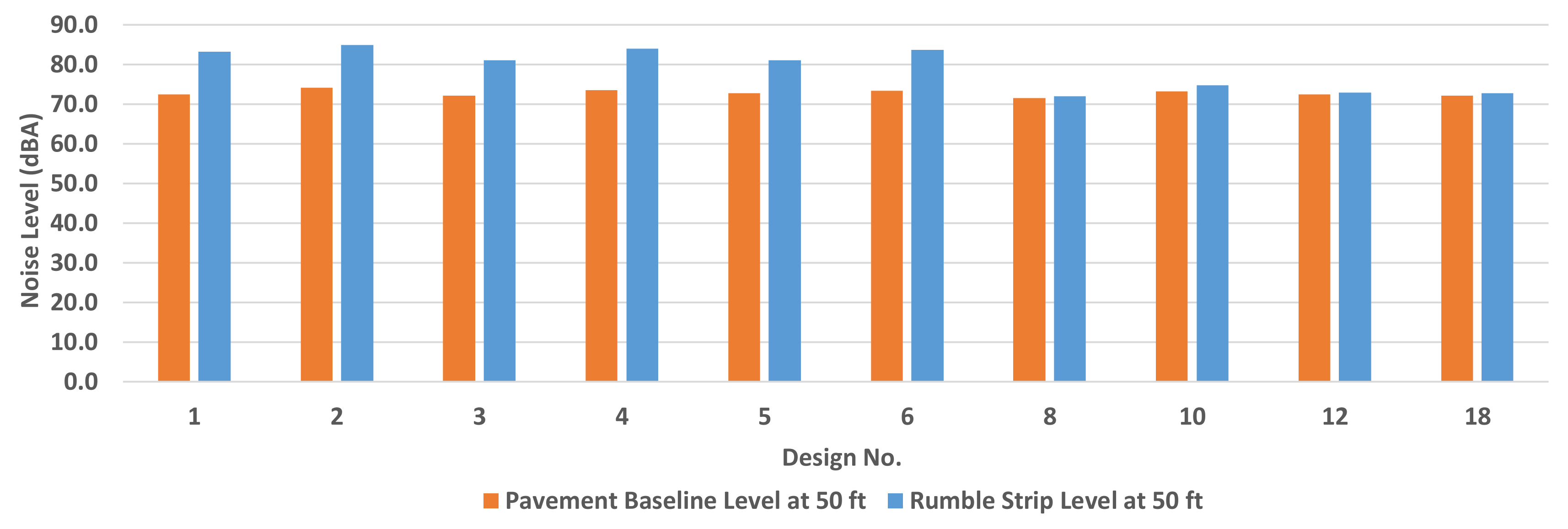


Figure 159. Graph. External noise of full-size SUV and longitudinal rumble strips at 50 ft.

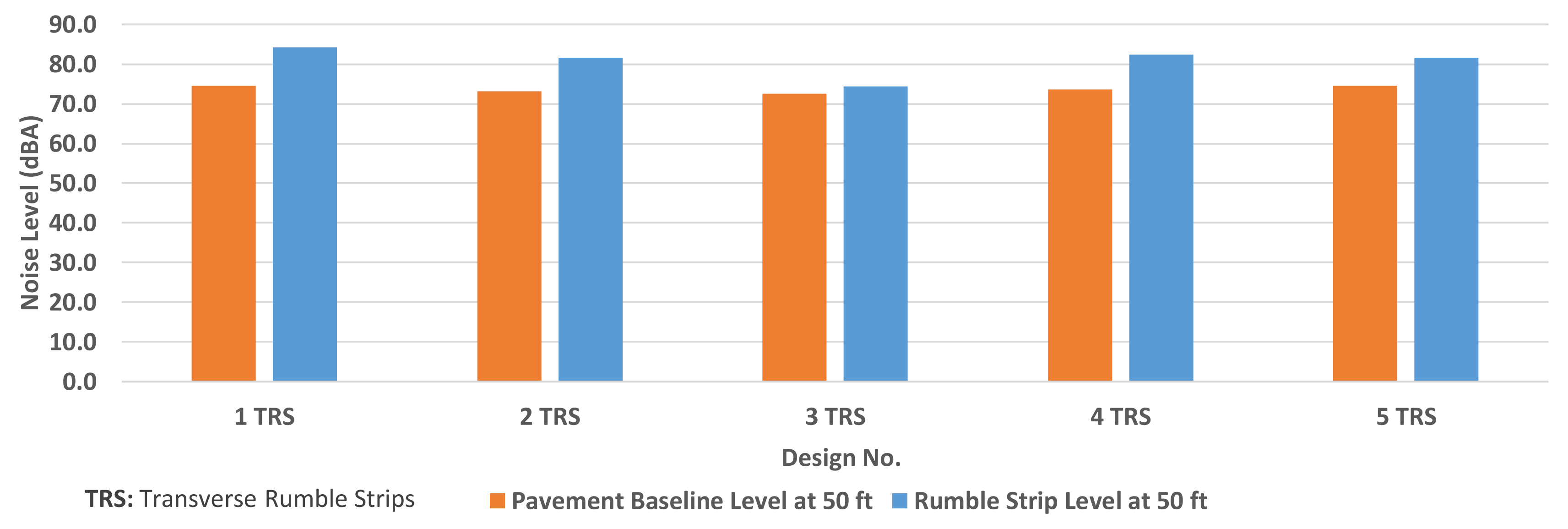


Figure 160. Graph. External noise of full-size SUV and transverse rumble strips at 50 ft.

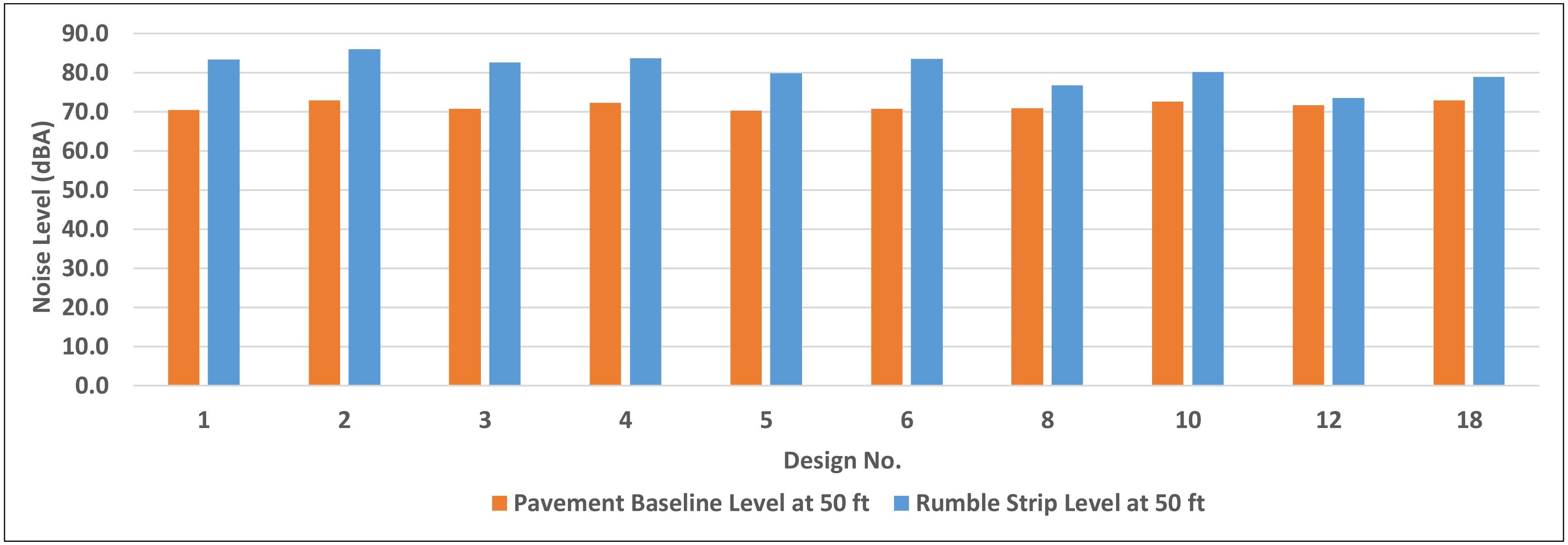


Figure 161. Graph. External noise of minivan and longitudinal rumble strips at 50 ft.

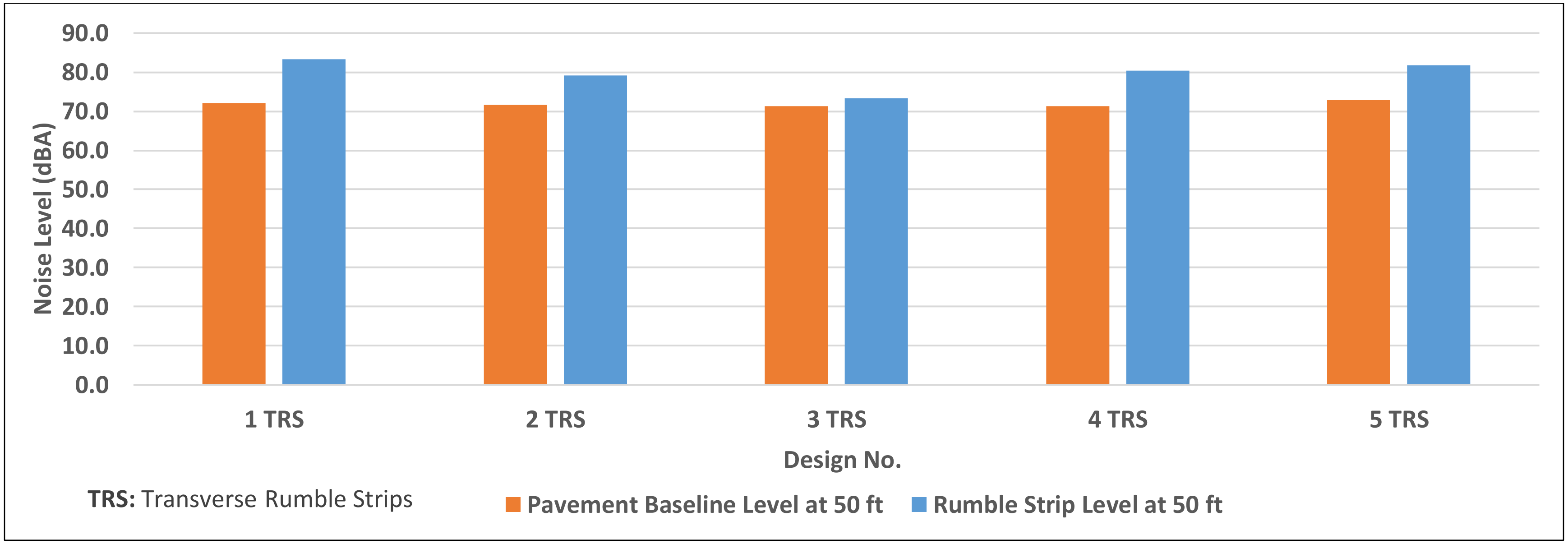


Figure 162. Graph. External noise of minivan and transverse rumble strips at 50 ft.

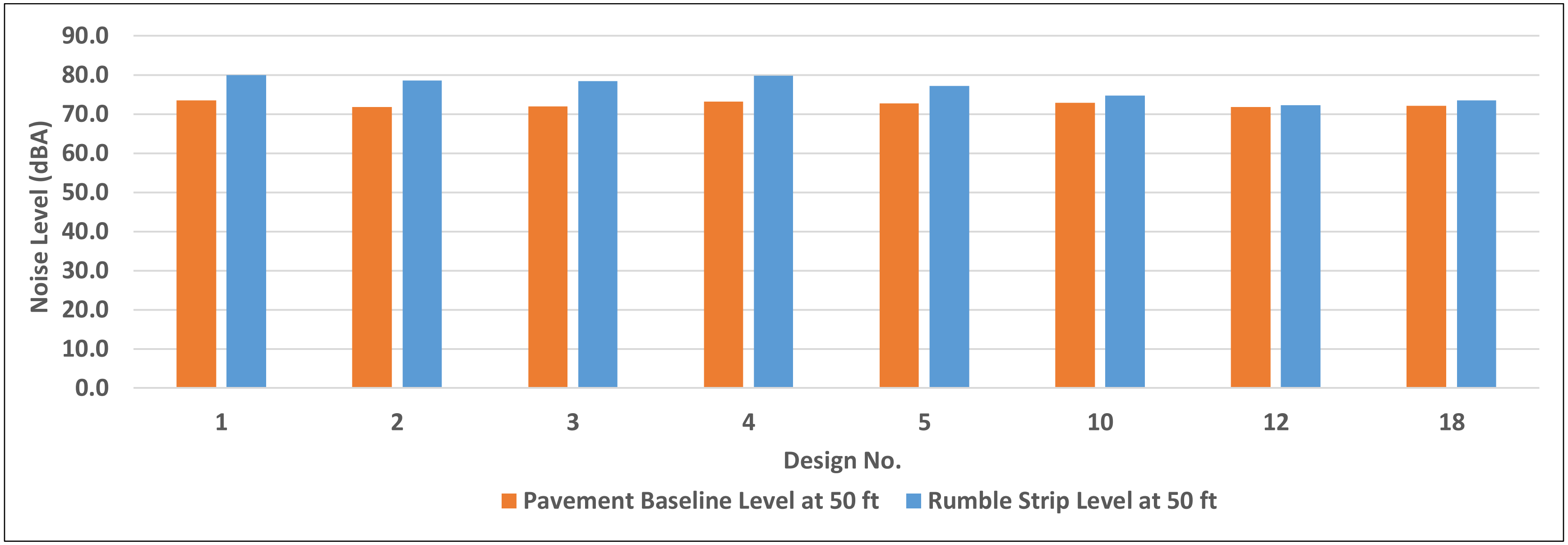


Figure 163. Graph. External noise of standard pick-up truck and longitudinal rumble strips at 50 ft.

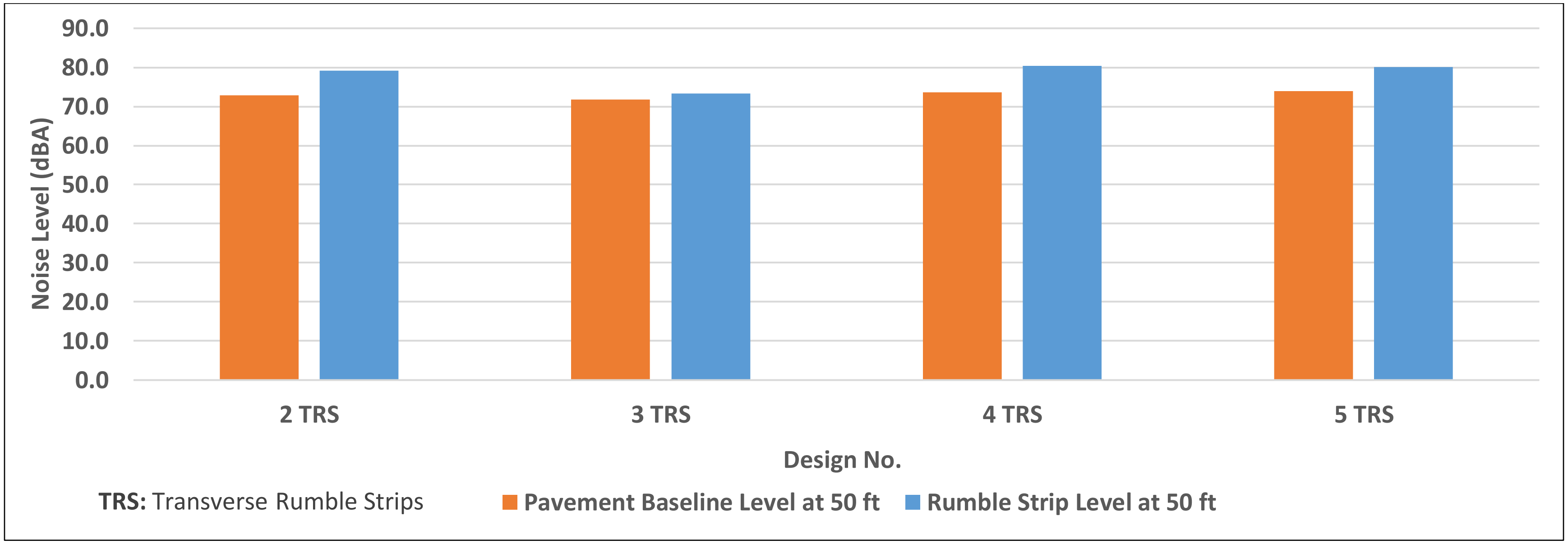


Figure 164. Graph. External noise of standard pick-up truck and transverse rumble strips at 50 ft.

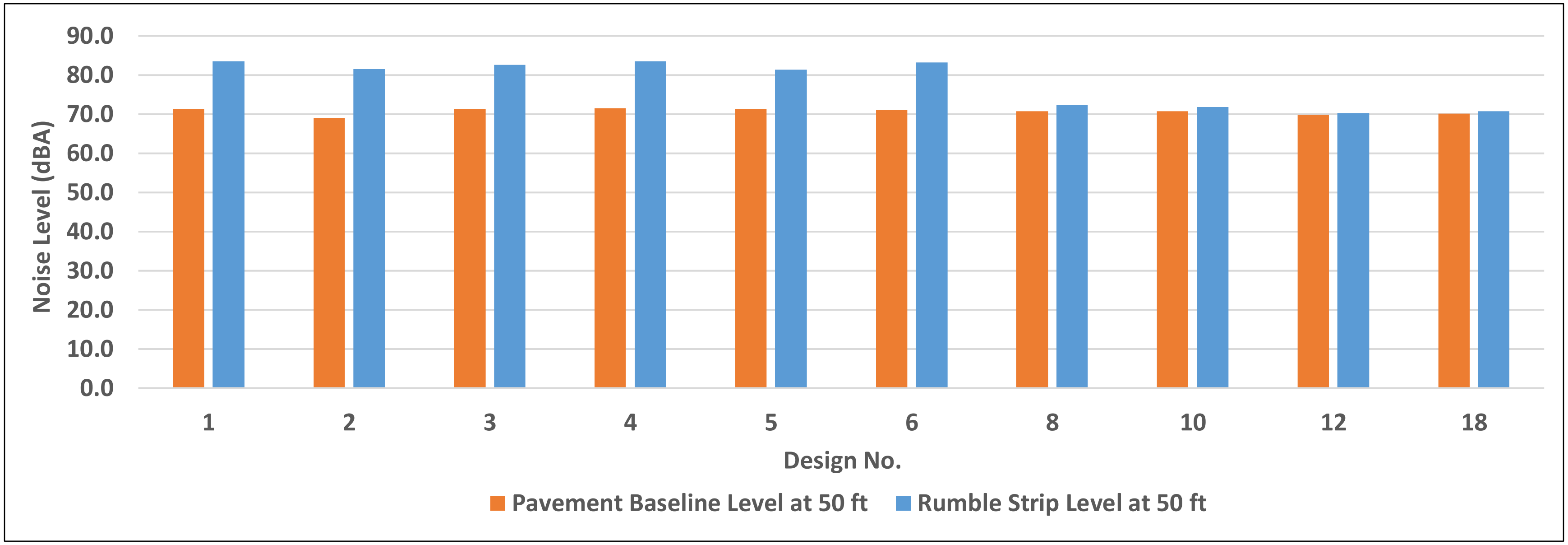


Figure 165. Graph. External noise of 1/2 ton pick-up truck and longitudinal rumble strips at 50 ft.

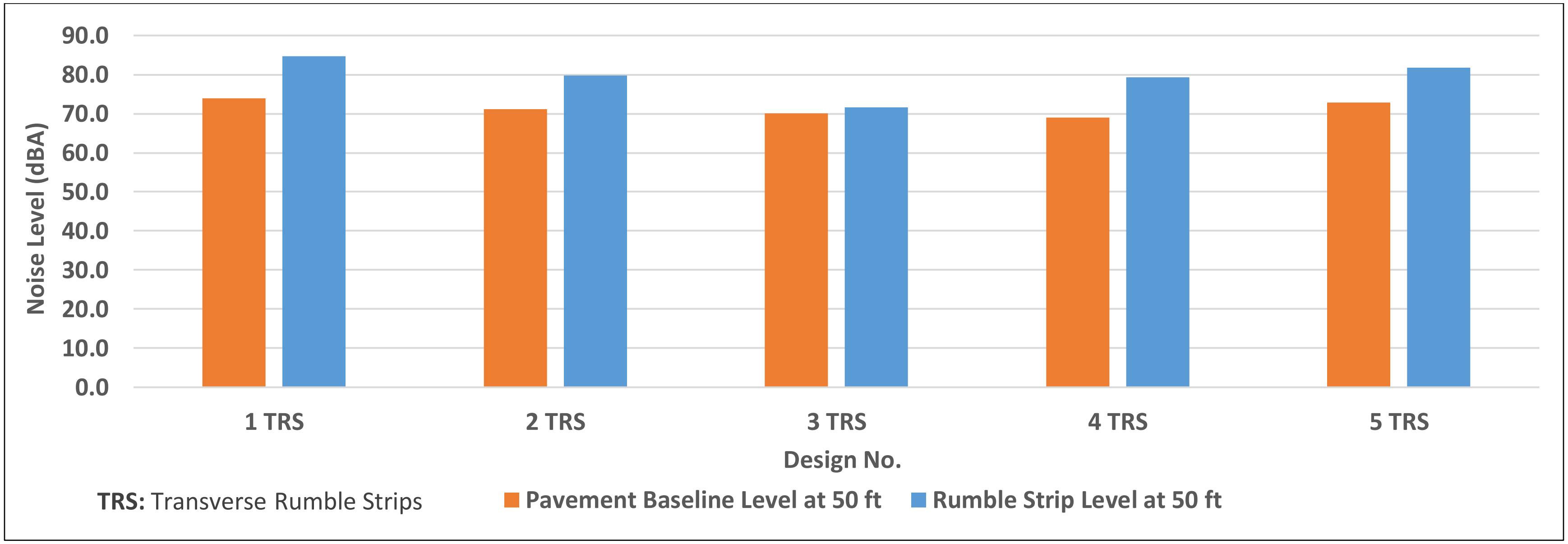


Figure 166. Graph. External noise of 1/2 ton pick-up truck and transverse rumble strips at 50 ft.

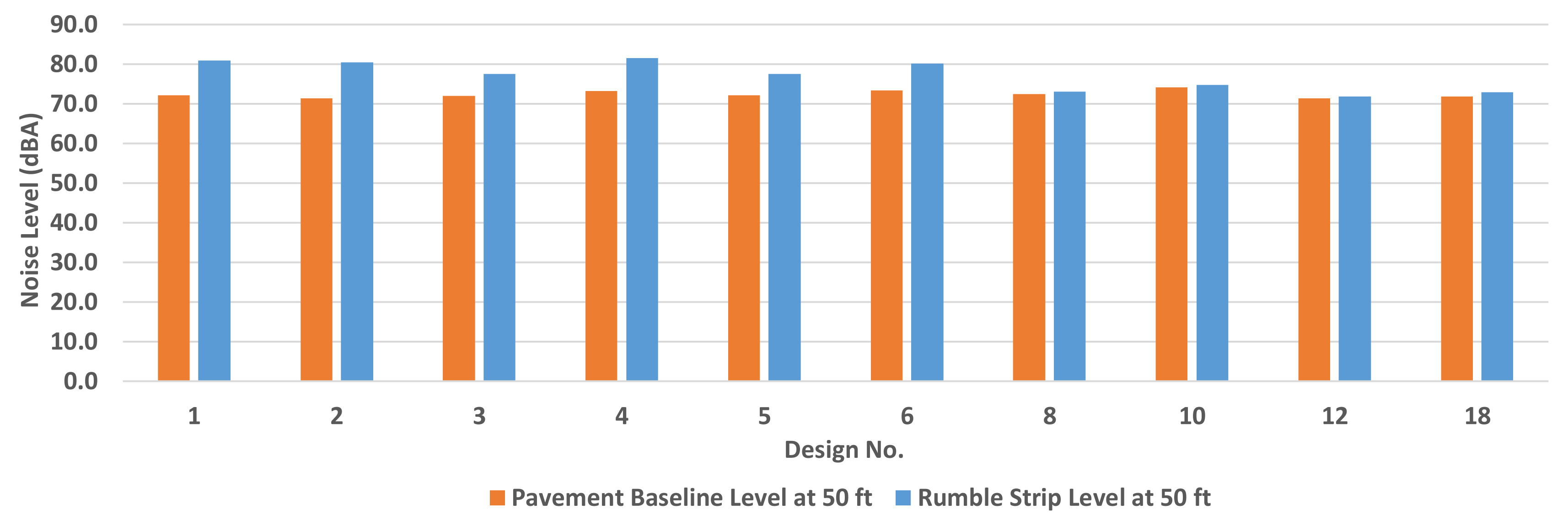


Figure 167. Graph. External noise of box truck and longitudinal rumble strips at 50 ft.

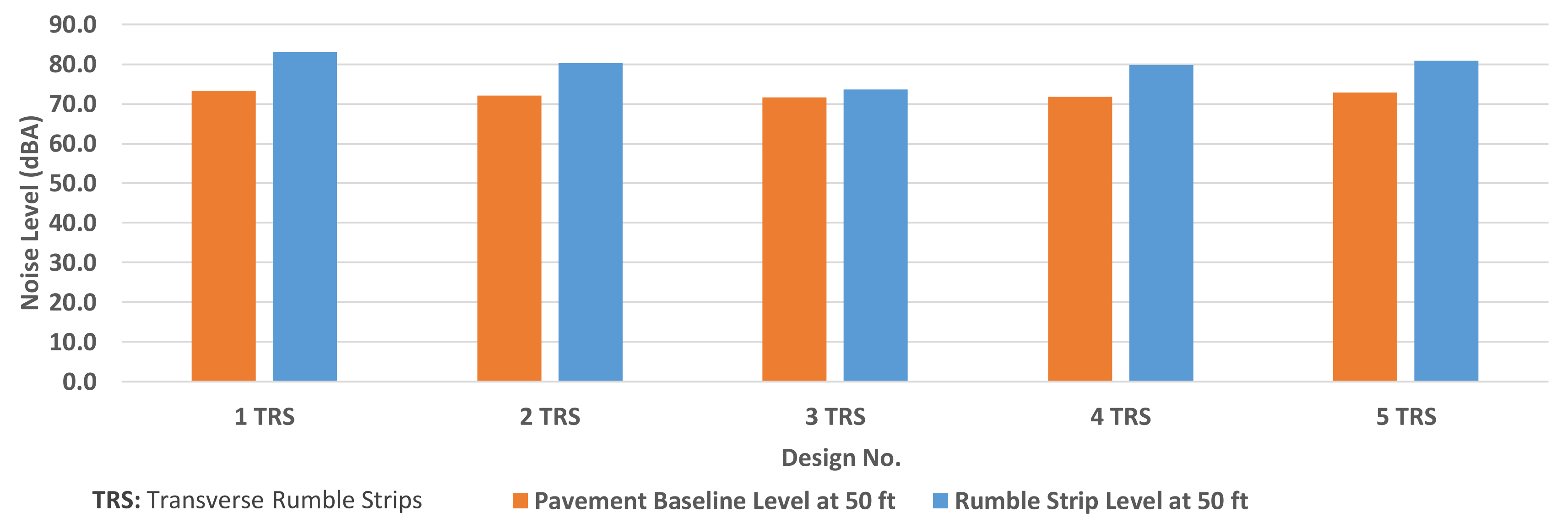


Figure 168. Graph. External noise of box truck and transverse rumble strips at 50 ft.

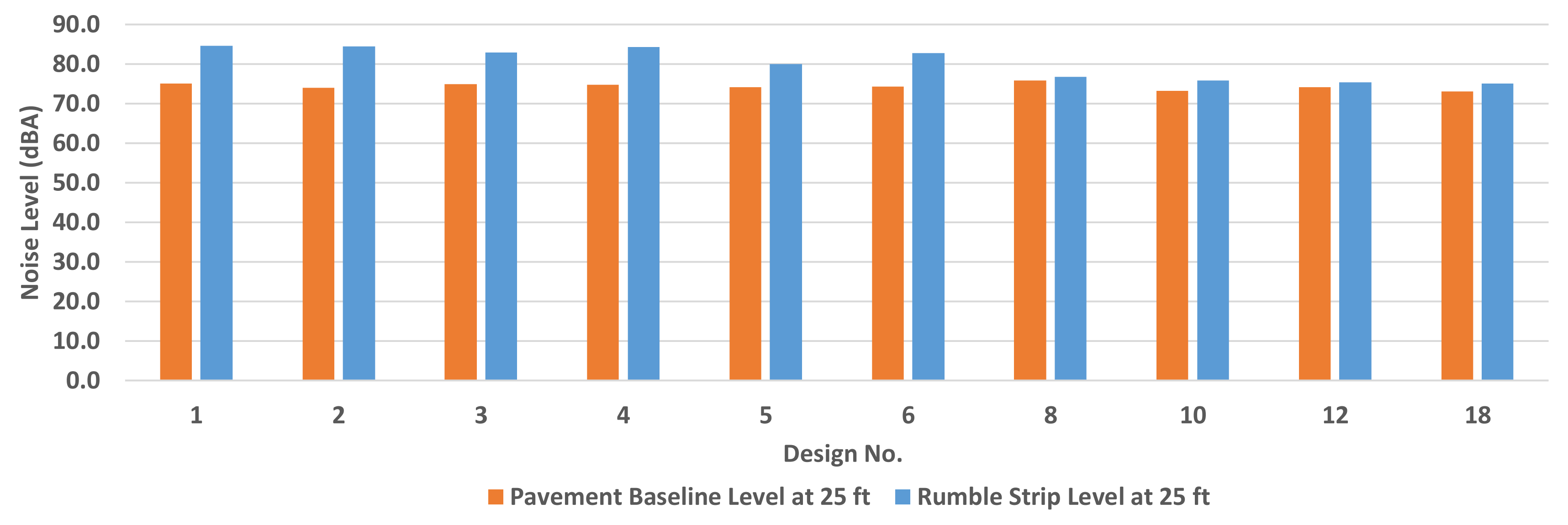


Figure 169. Graph. External noise of compact sedan and longitudinal rumble strips at 25 ft.

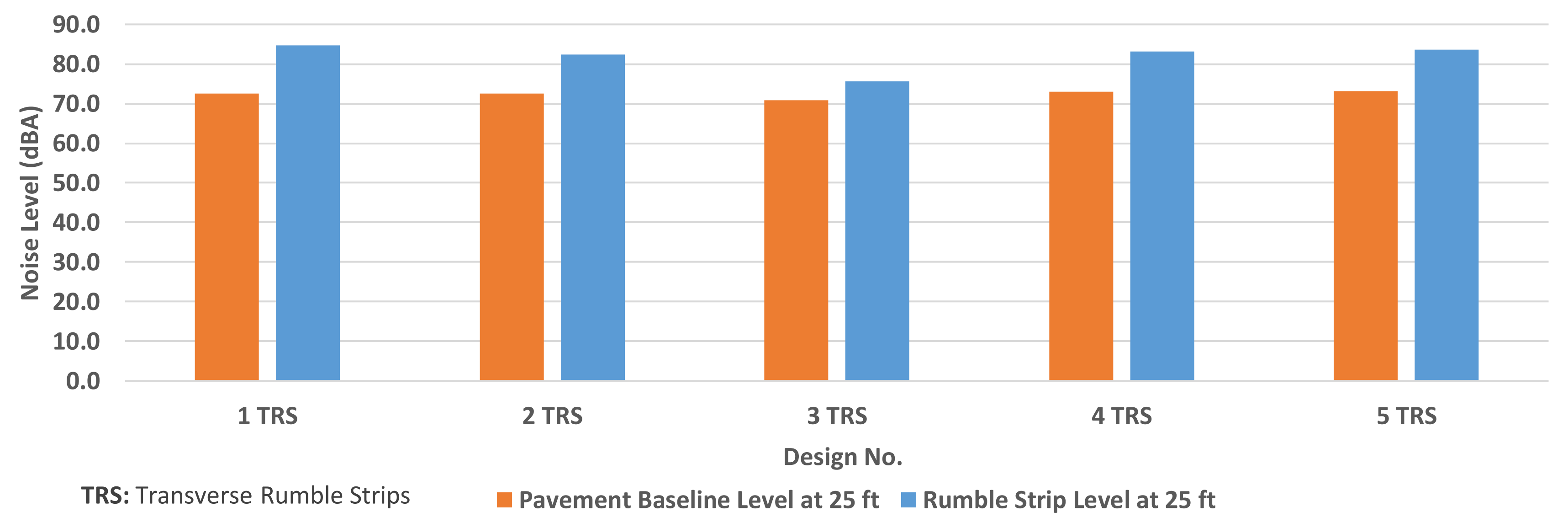


Figure 170. Graph. External noise of compact sedan and transverse rumble strips at 25 ft.

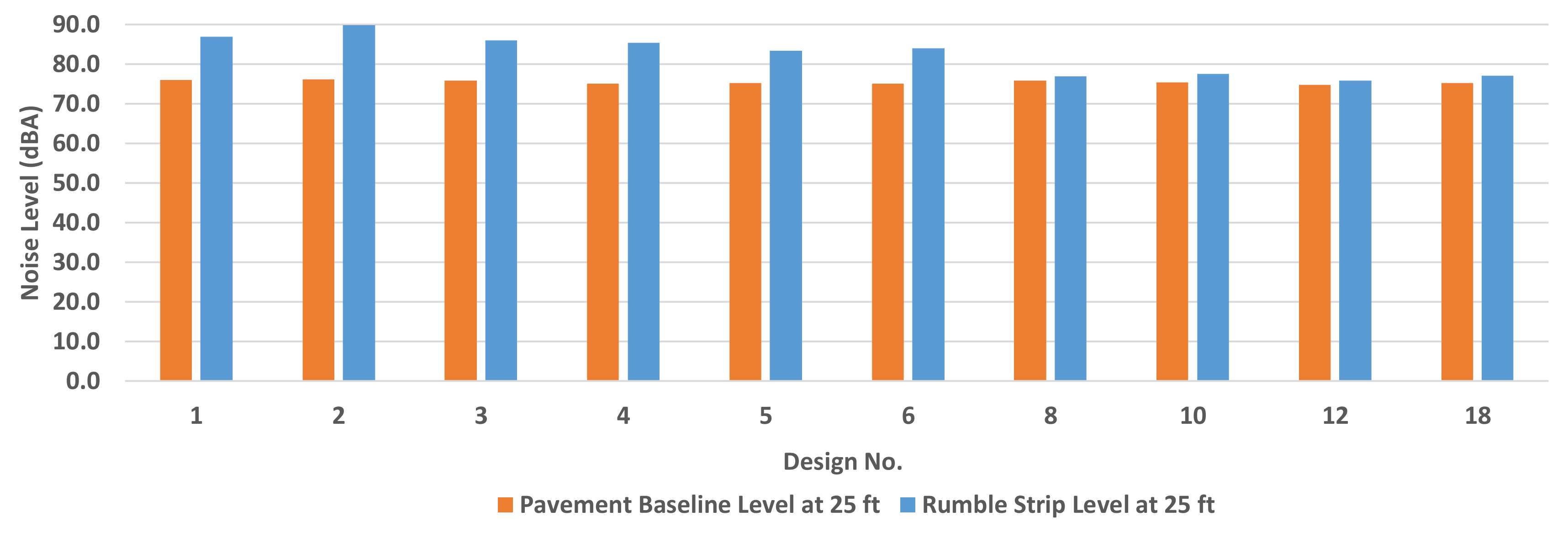


Figure 171. Graph. External noise of full-size sedan and longitudinal rumble strips at 25 ft.

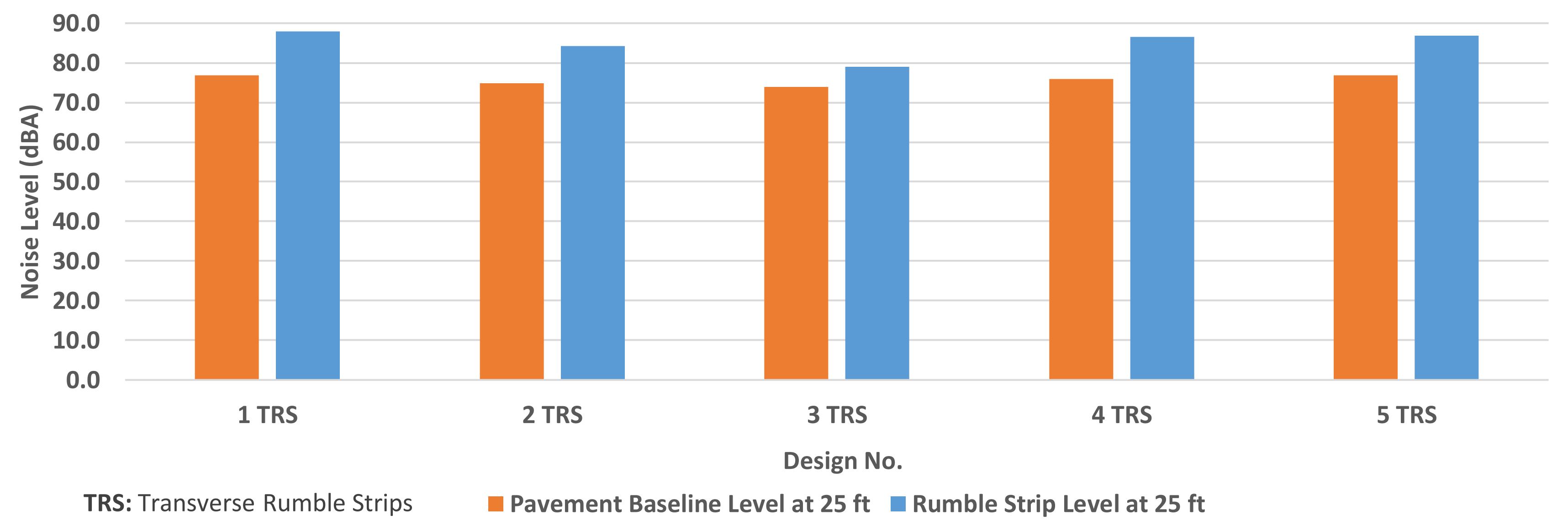


Figure 172. Graph. External noise of full-size sedan and transverse rumble strips at 25 ft.

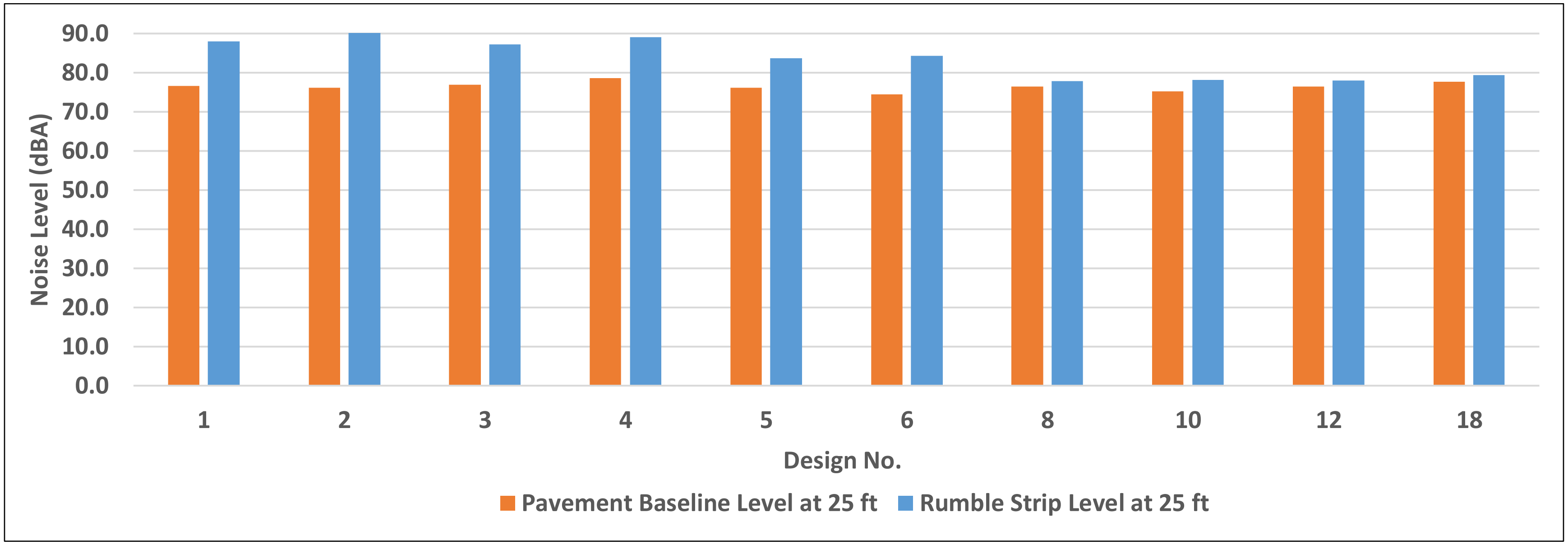


Figure 173. Graph. External noise of electric sedan and longitudinal rumble strips at 25 ft.

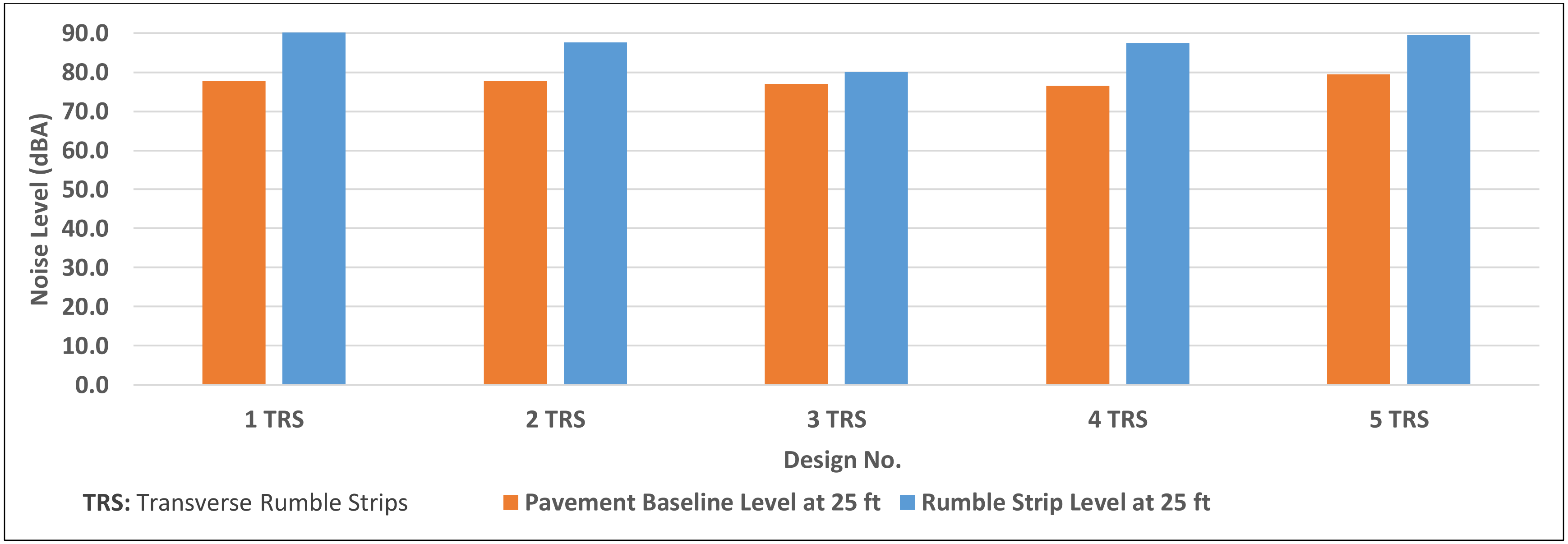


Figure 174. Graph. External noise of electric sedan and transverse rumble strips at 25 ft.

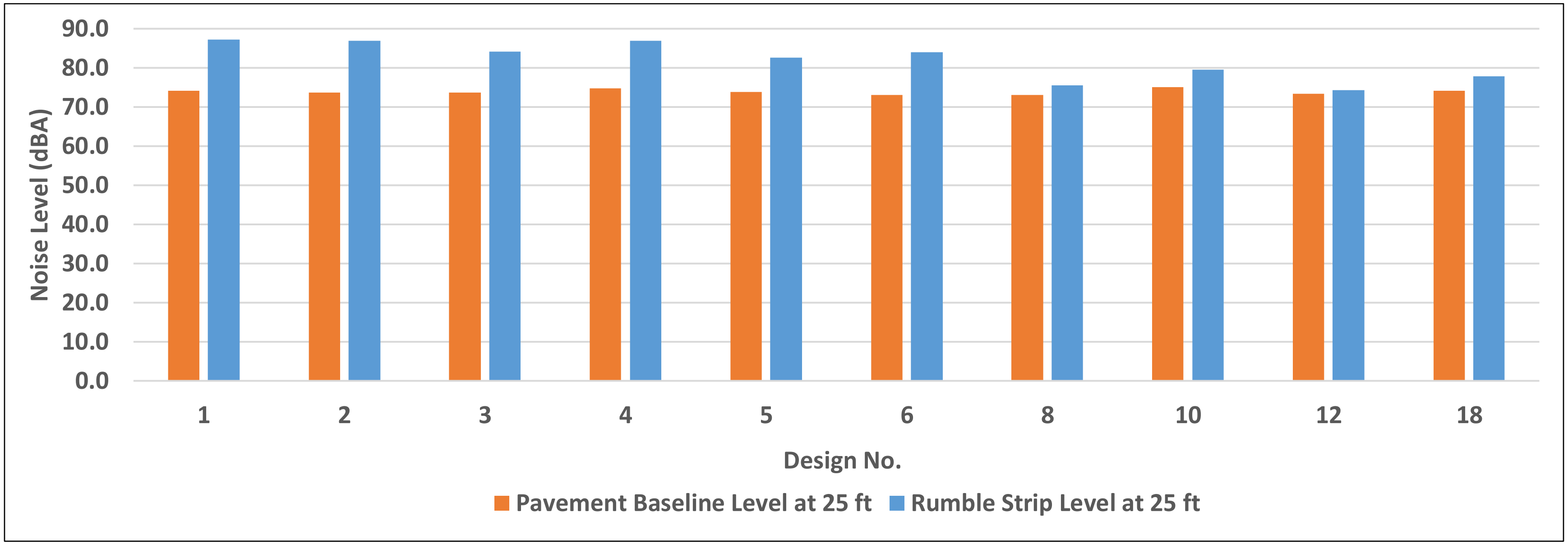


Figure 175. Graph. External noise of compact SUV and longitudinal rumble strips at 25 ft.

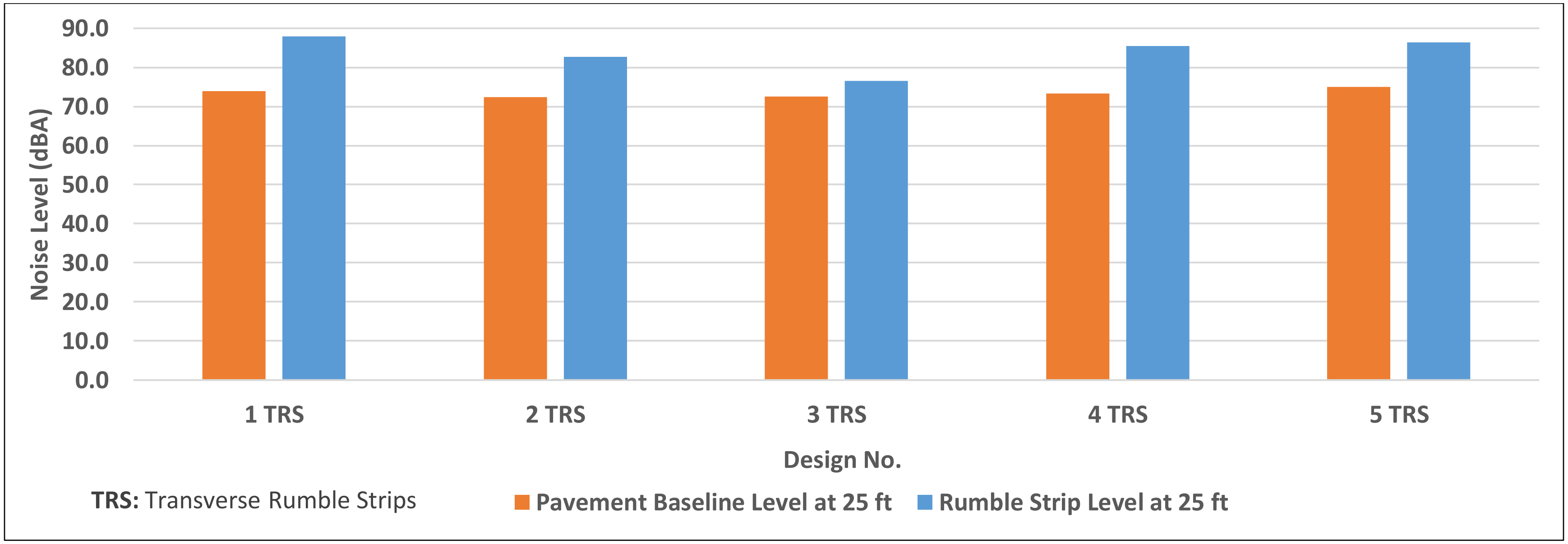


Figure 176. Graph. External noise of compact SUV and transverse rumble strips at 25 ft.

Figure 177. Graph. External noise of full-size SUV and longitudinal rumble strips at 25 ft.

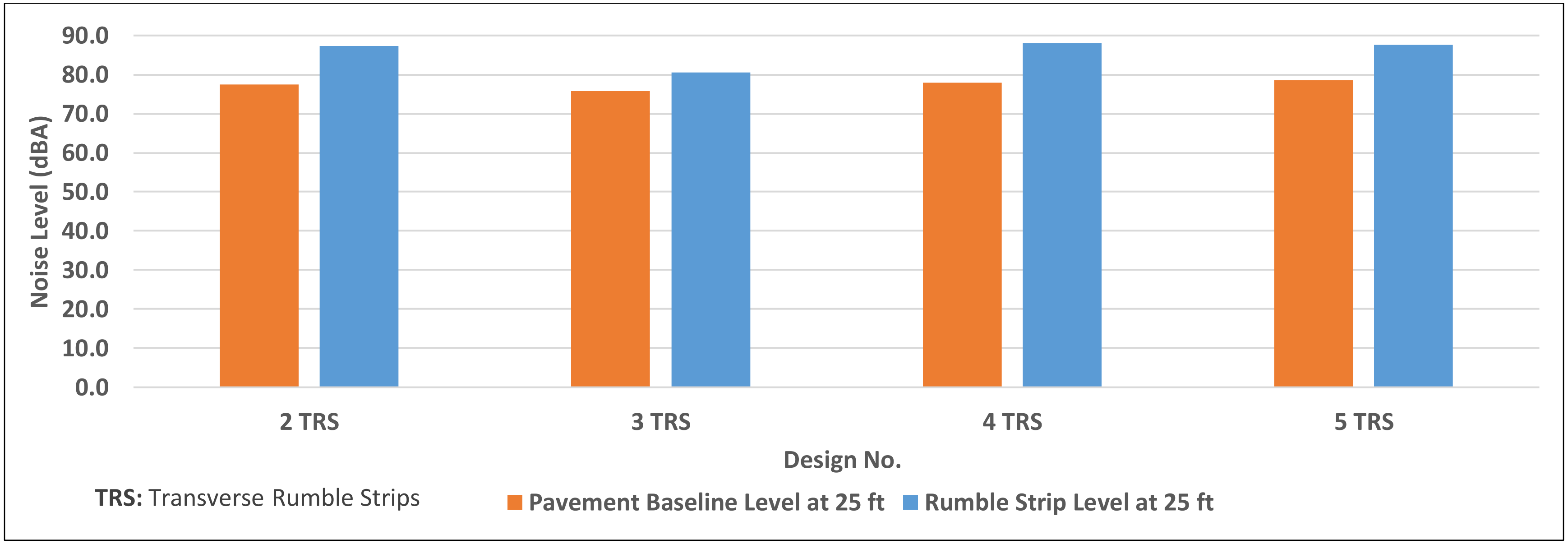


Figure 178. Graph. External noise of full-size SUV and transverse rumble strips at 25 ft.

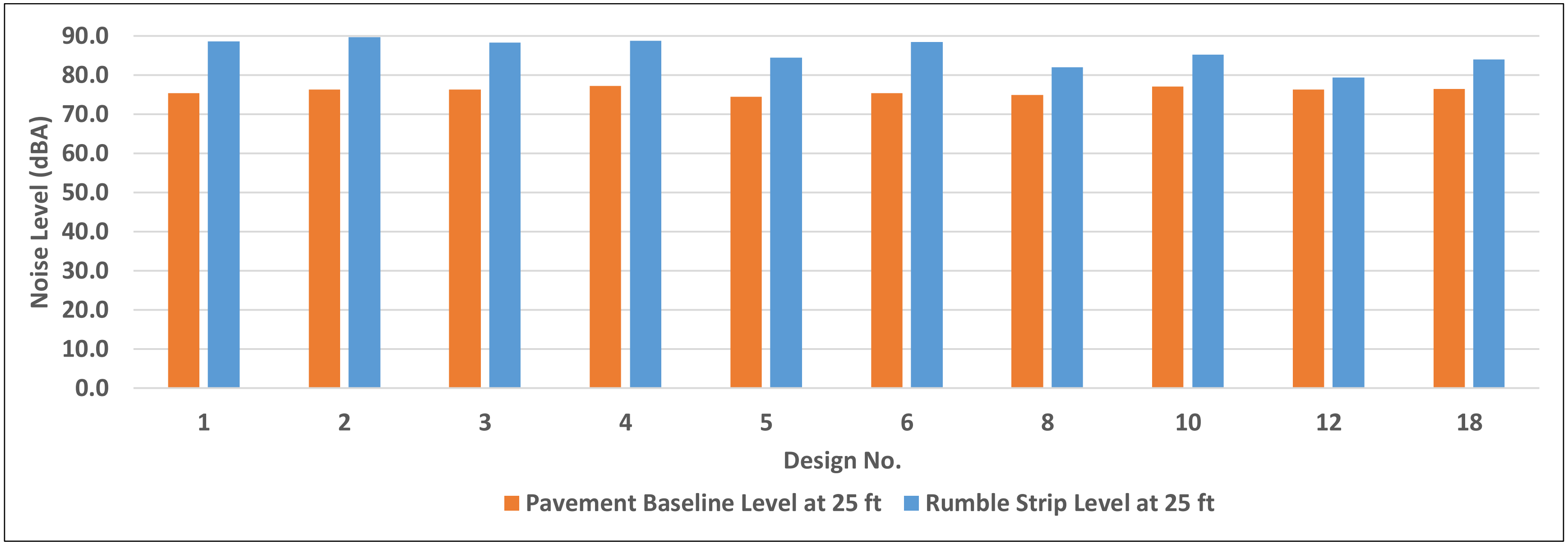


Figure 179. Graph. External noise of minivan and longitudinal rumble strips at 25 ft.

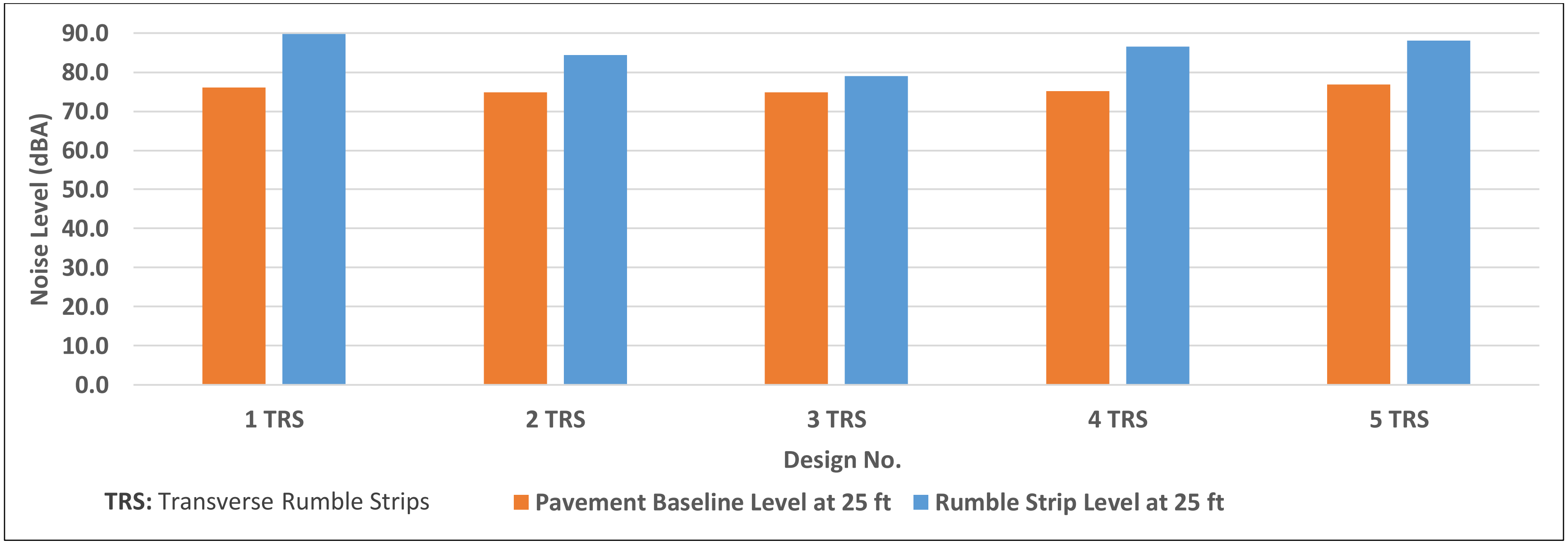


Figure 180. Graph. External noise of minivan and transverse rumble strips at 25 ft.

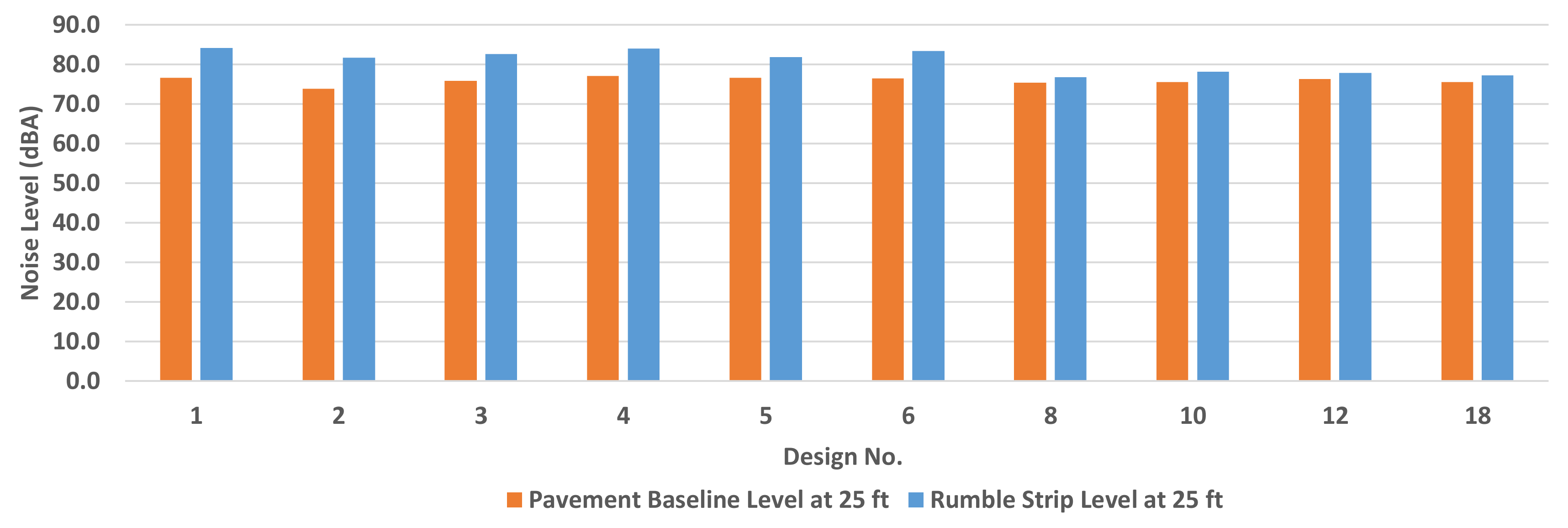


Figure 181. Graph. External noise of standard pick-up truck and longitudinal rumble strips at 25 ft.

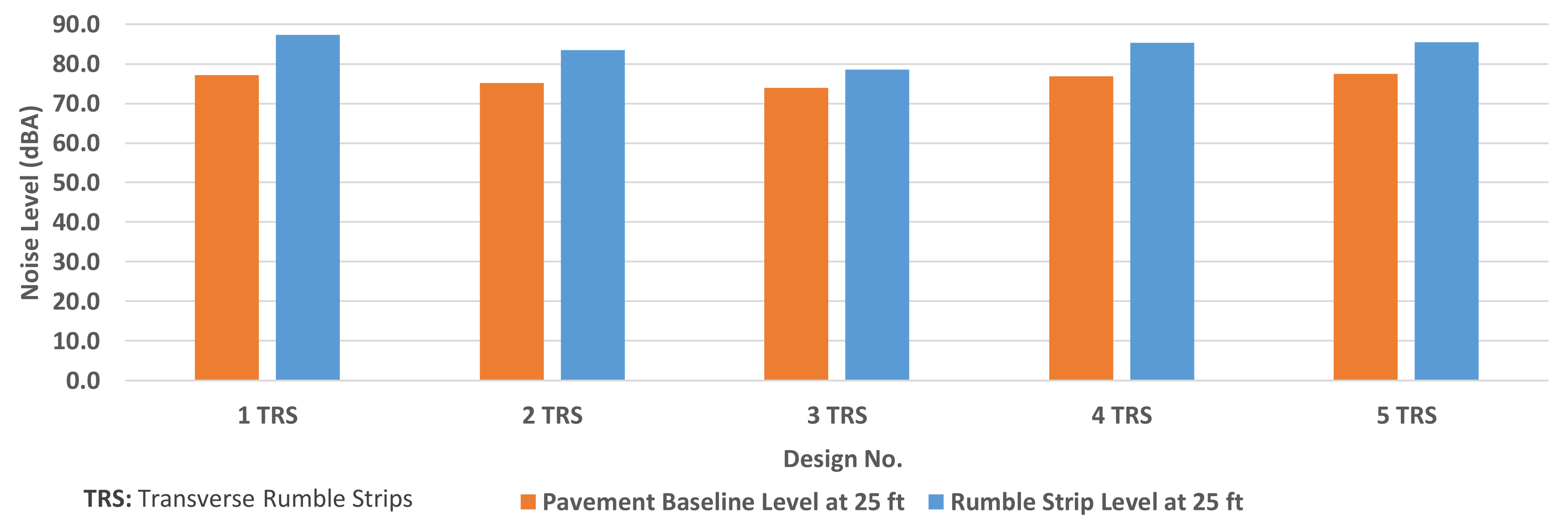


Figure 182. Graph. External noise of standard pick-up truck and transverse rumble strips at 25 ft.

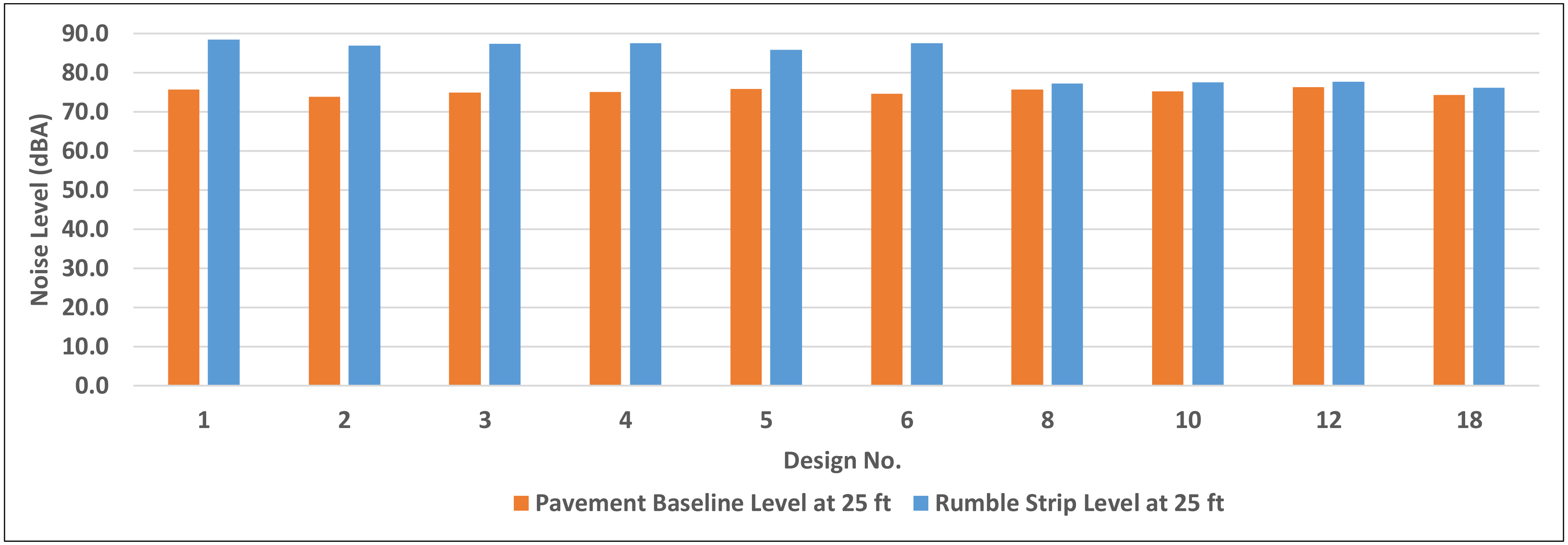


Figure 183. Graph. External noise of 1/2 ton pick-up truck and longitudinal rumble strips at 25 ft.

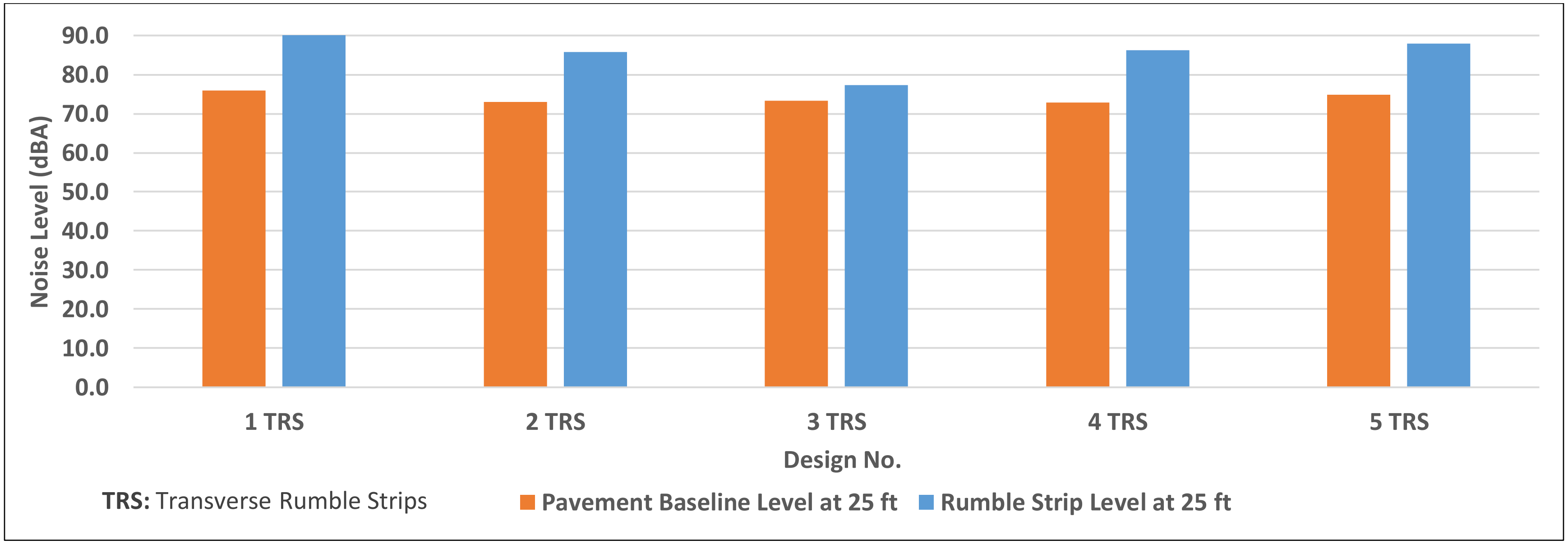


Figure 184. Graph. External noise of 1/2 ton pick-up truck and transverse rumble strips at 25 ft.

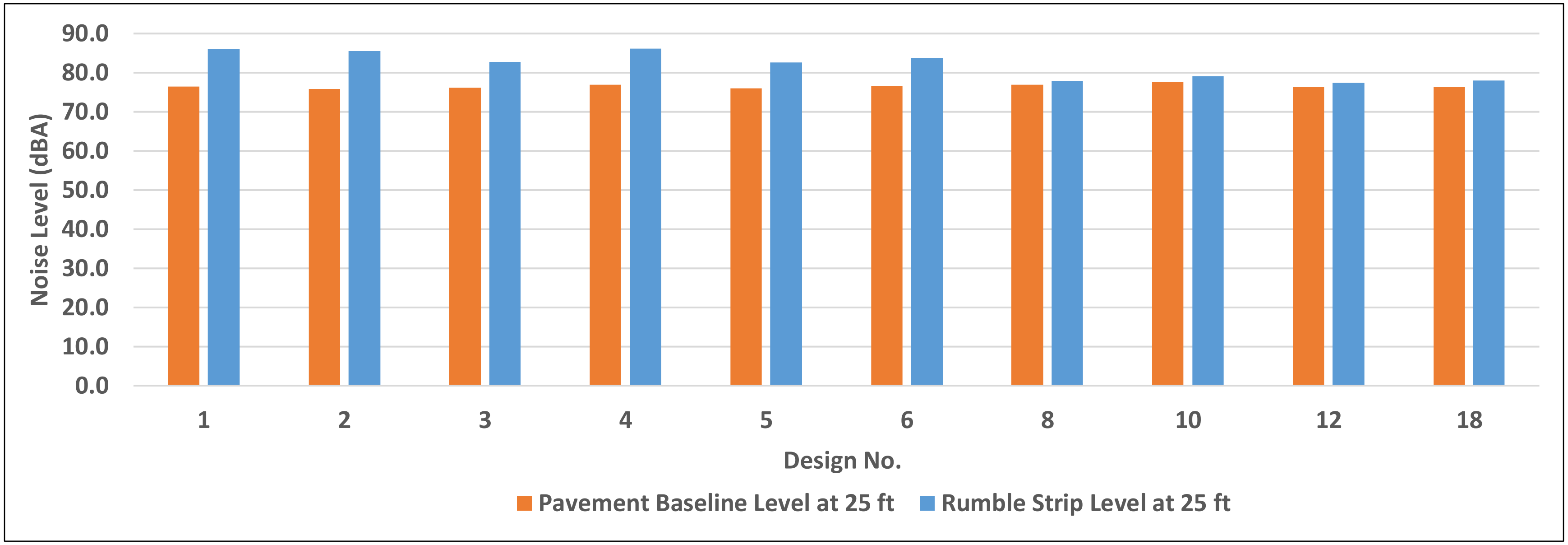


Figure 185. Graph. External noise of box truck and longitudinal rumble strips at 25 ft.

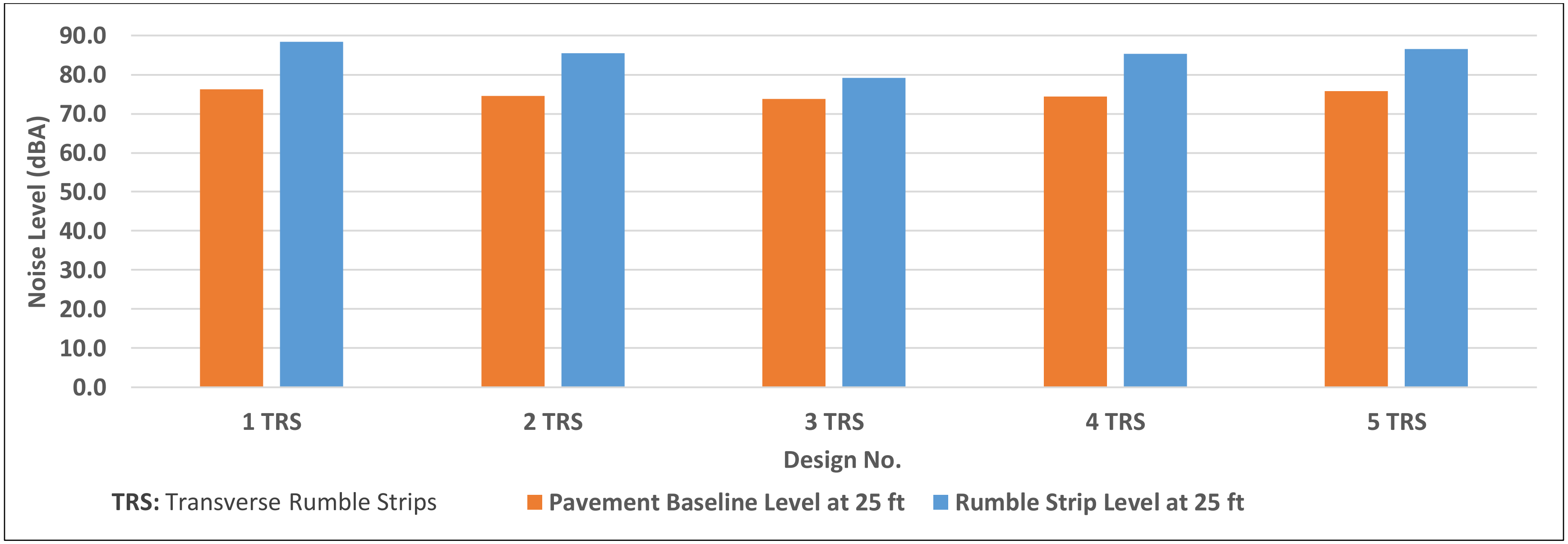


Figure 186. Graph. External noise of box truck and transverse rumble strips at 25 ft.

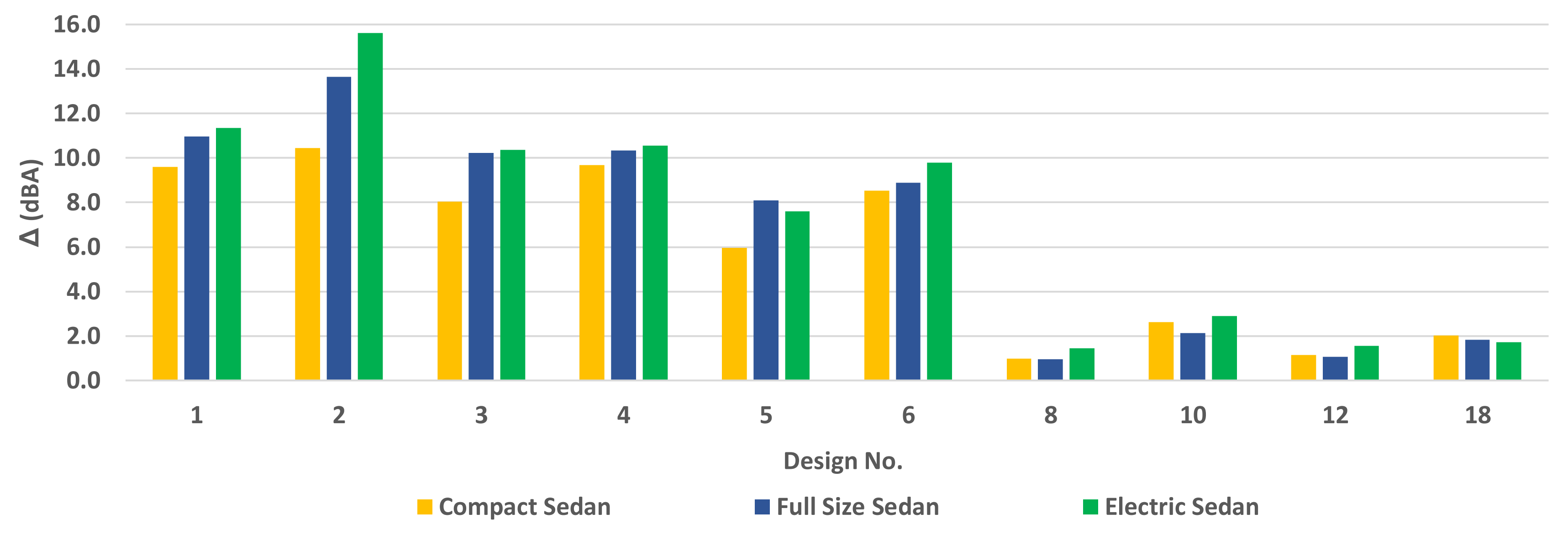


Figure 187. Graph. External noise increase (Δ) at 25 ft of sedans and longitudinal rumble strips.

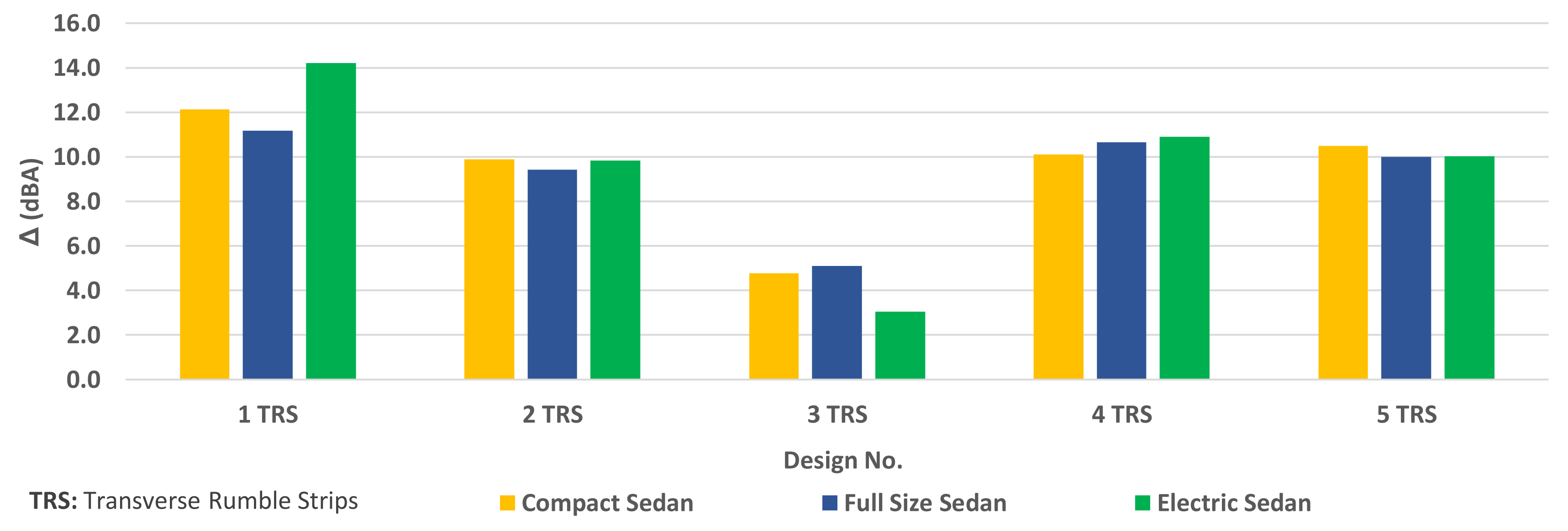


Figure 188. Graph. External noise increase (Δ) at 25 ft of sedans and transverse rumble strips.

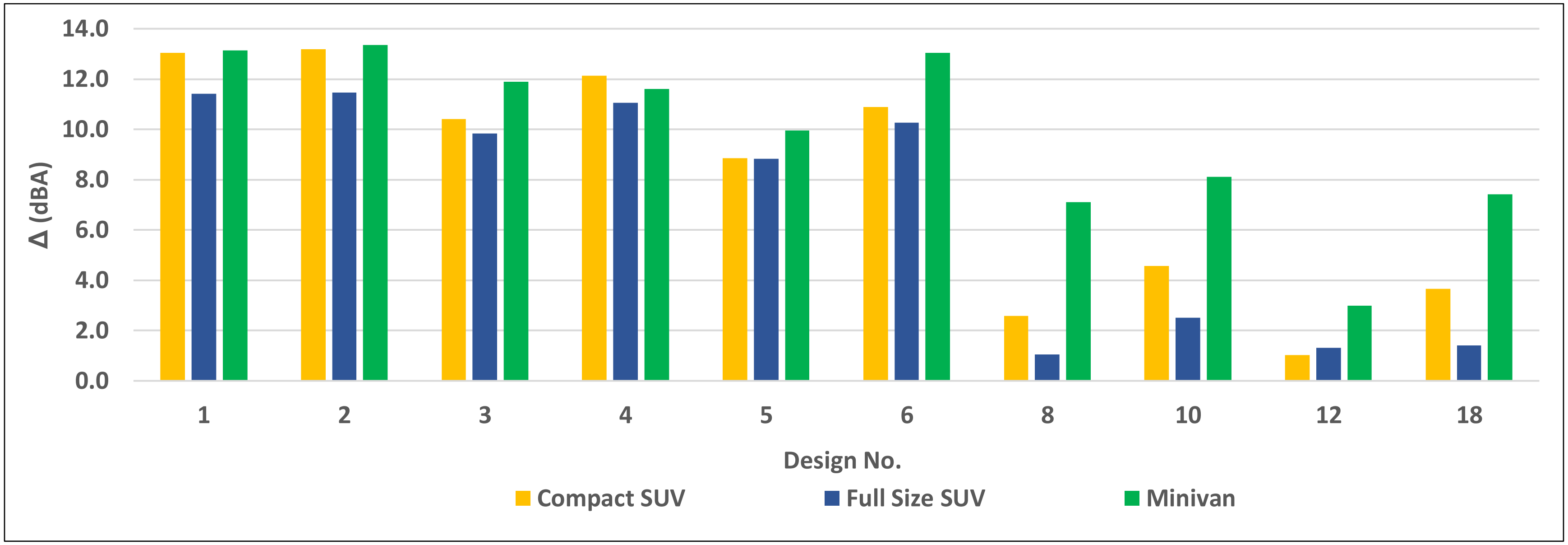


Figure 189. Graph. External noise increase (Δ) at 25 ft of SUVs, minivan, and longitudinal rumble strips.

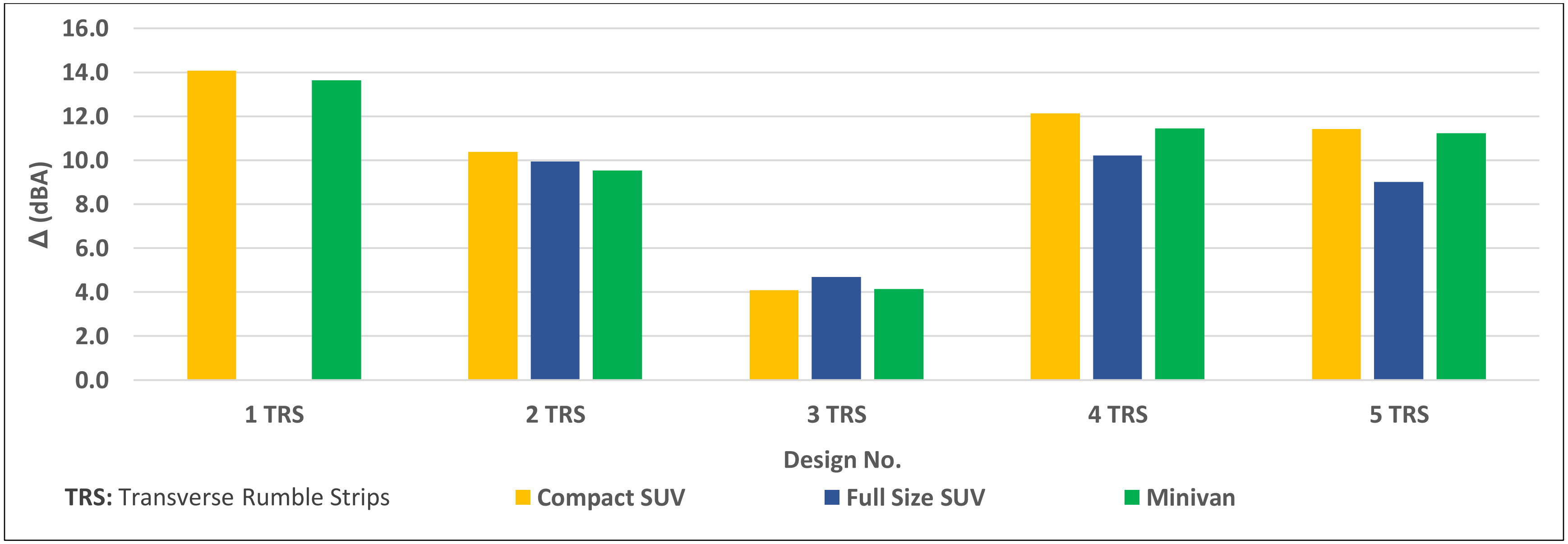


Figure 190. Graph. External noise increase (Δ) at 25 ft of SUVs, minivan, and transverse rumble strips.

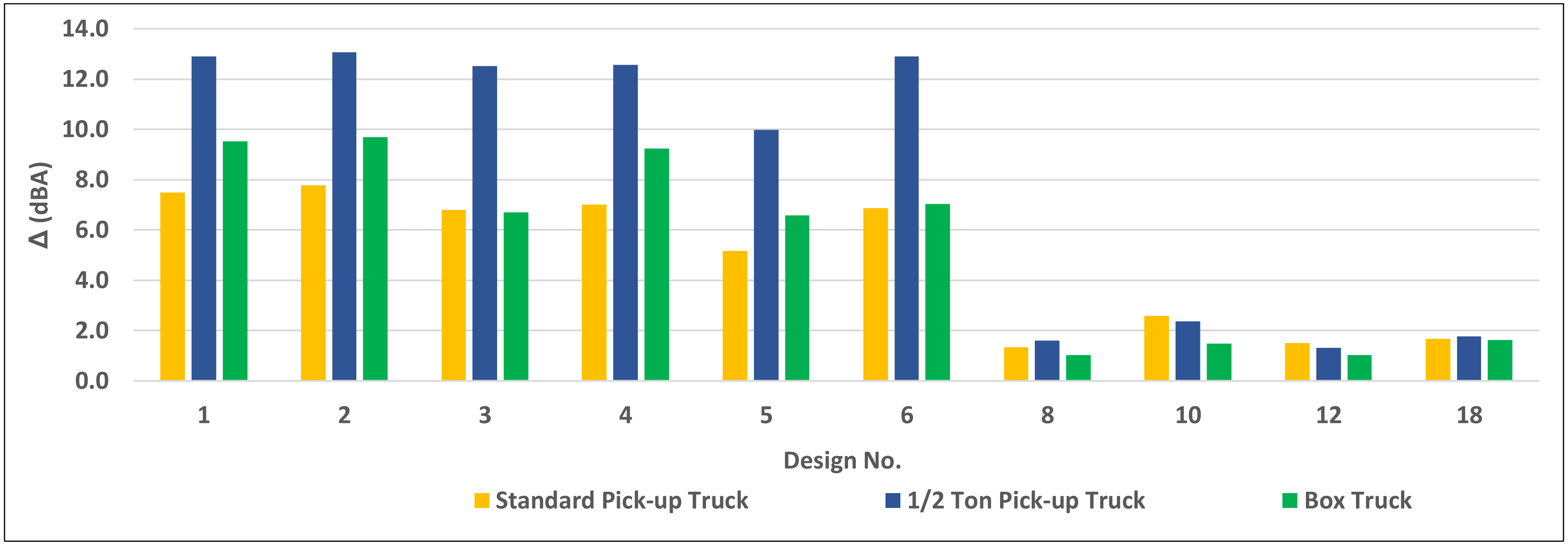


Figure 191. Graph. External noise increase (Δ) at 25 ft of pick-up, box trucks and longitudinal rumble strips.

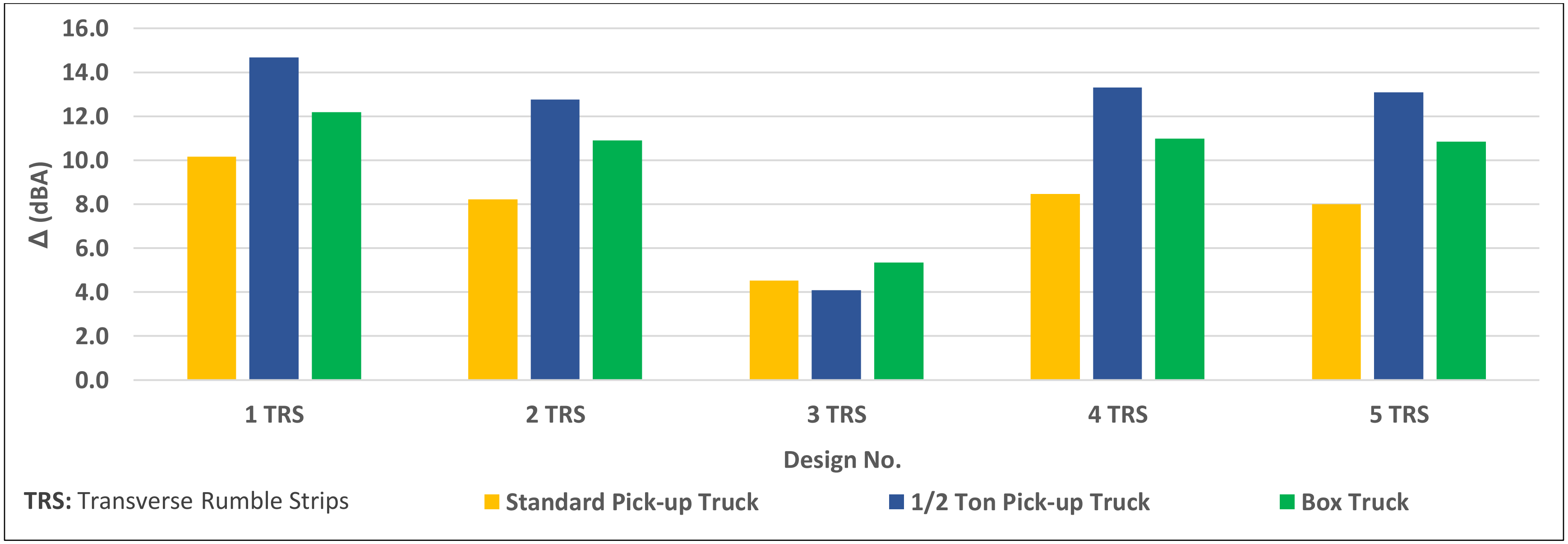


Figure 192. Graph. External noise increase (Δ) at 25 ft of pick-up, box trucks and transverse rumble strips.

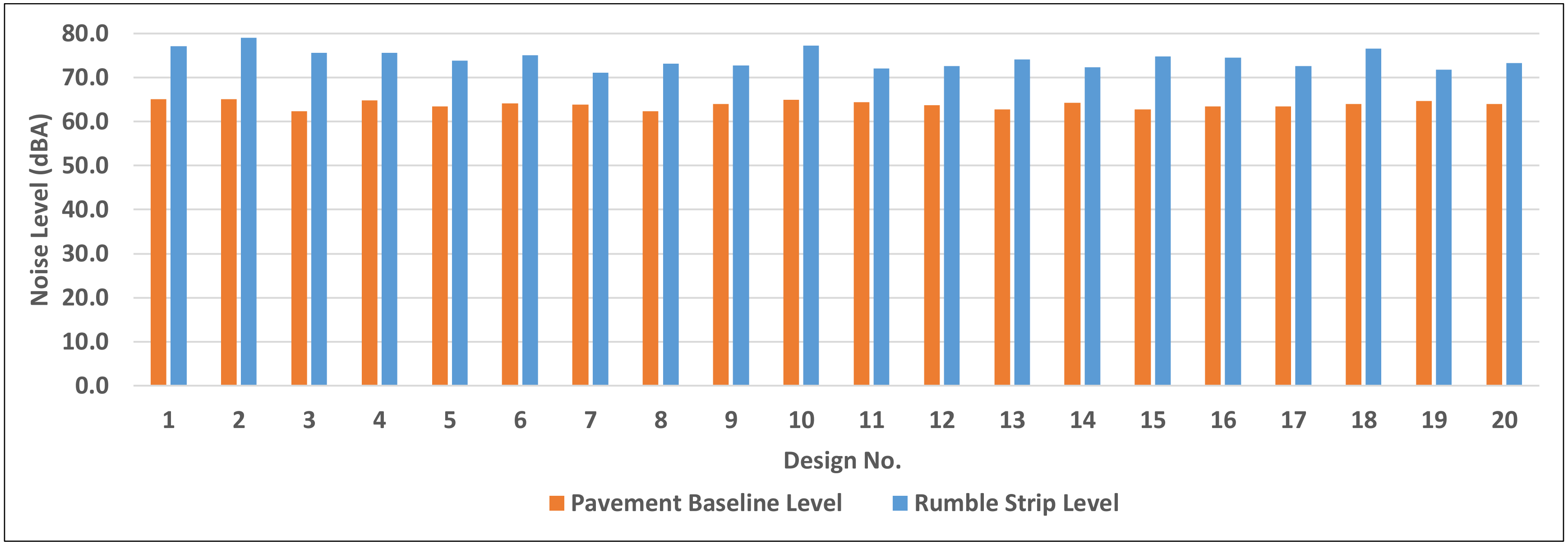


Figure 193. Graph. Internal noise of full-size sedan and longitudinal rumble strips.

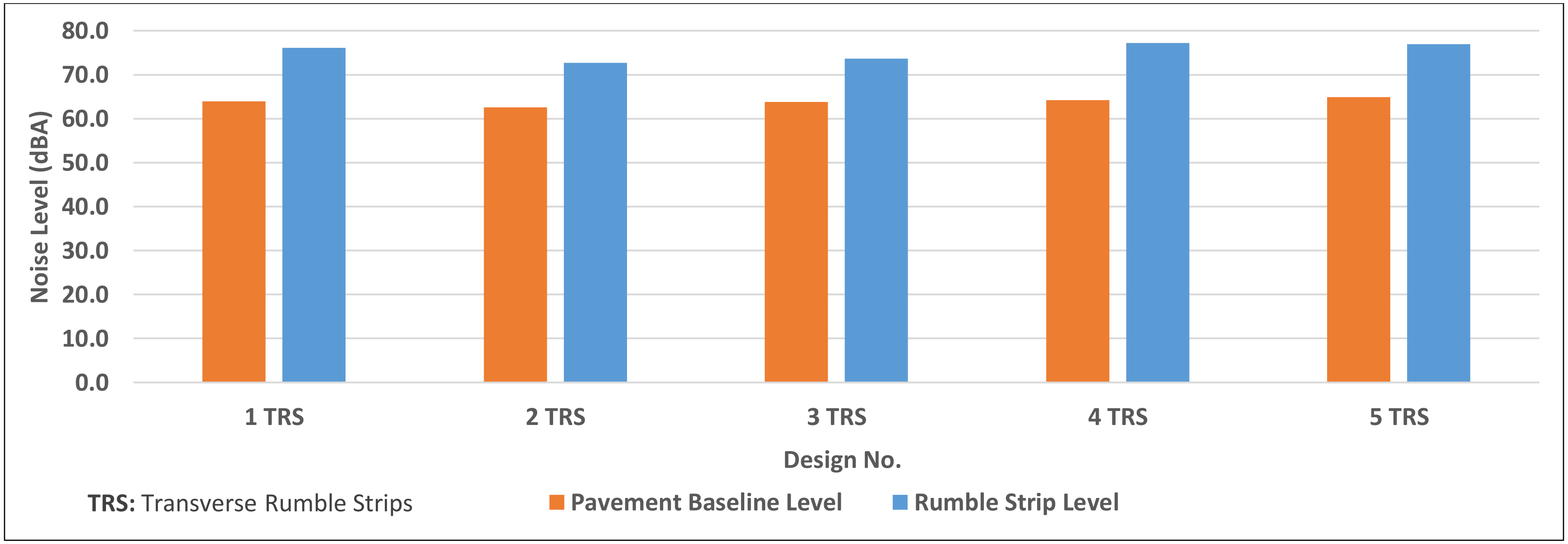


Figure 194. Graph. Internal noise of full-size sedan and transverse rumble strips.

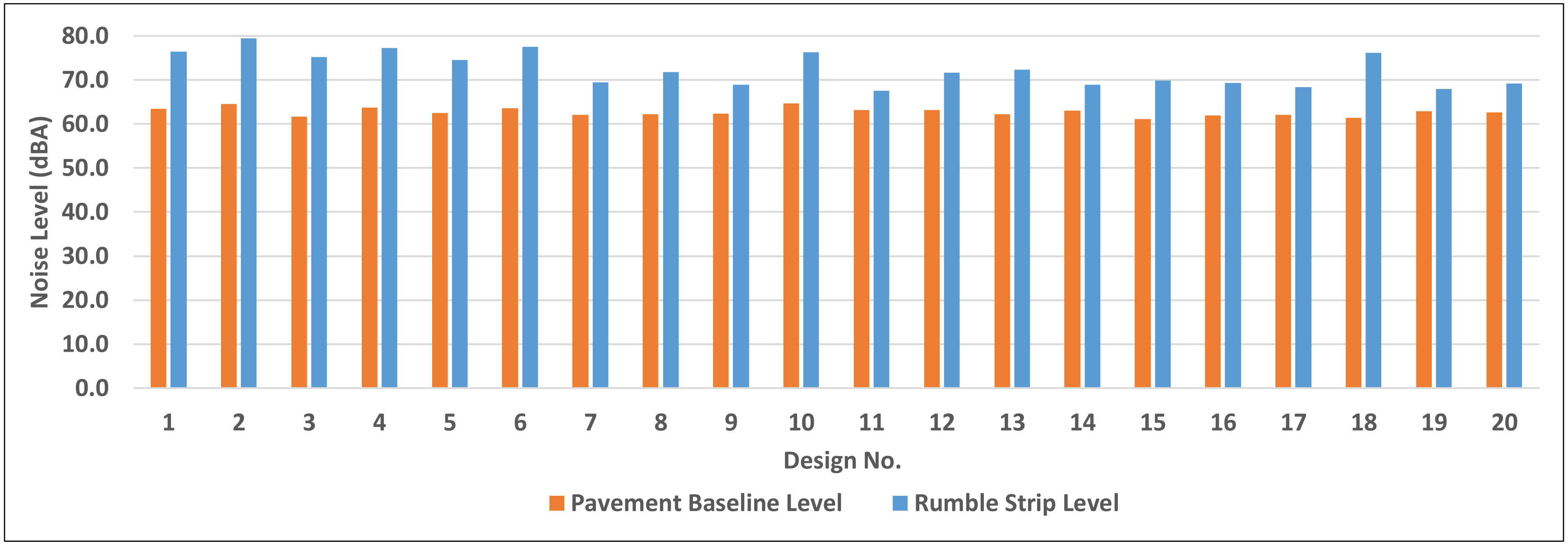


Figure 195. Graph. Internal noise of electric sedan and longitudinal rumble strips.

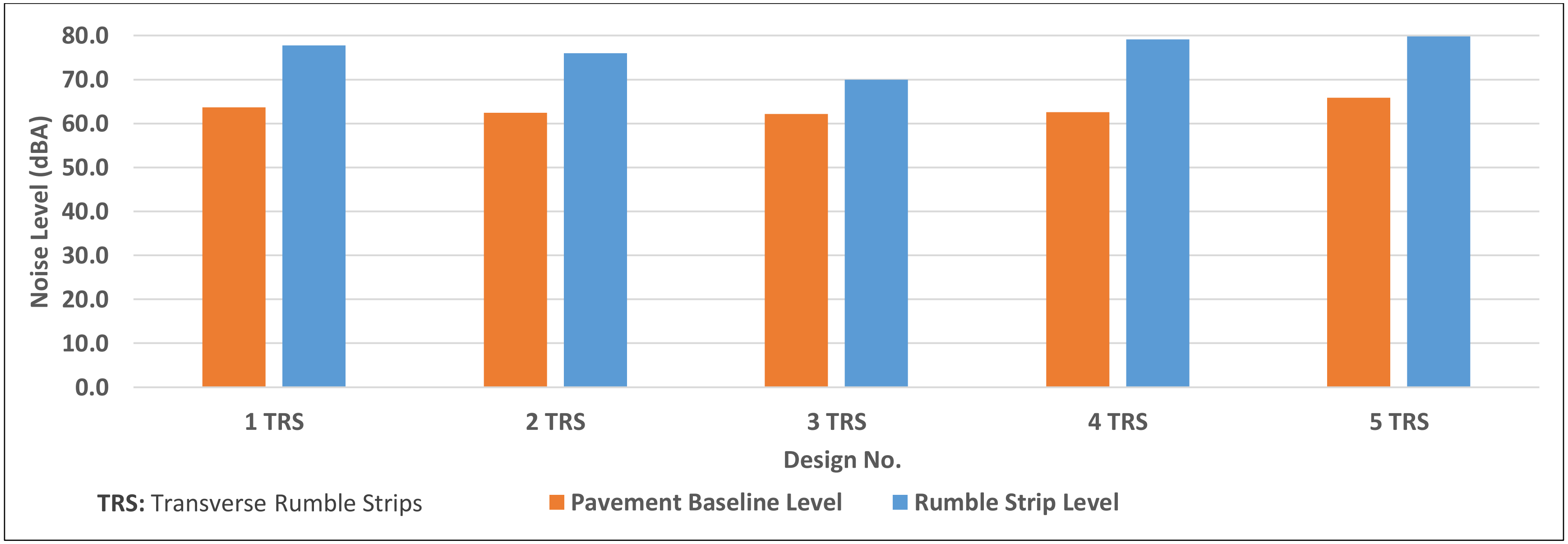


Figure 196. Graph. Internal noise of electric sedan and transverse rumble strips.

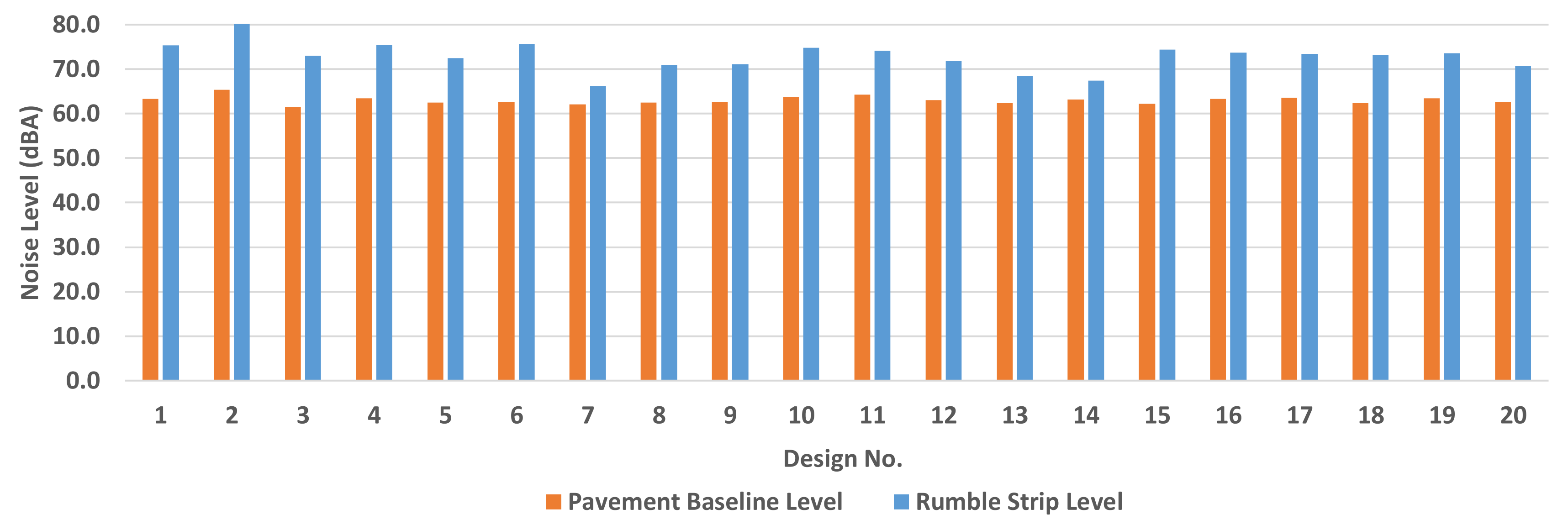


Figure 197. Graph. Internal noise of full-size SUV and longitudinal rumble strips.

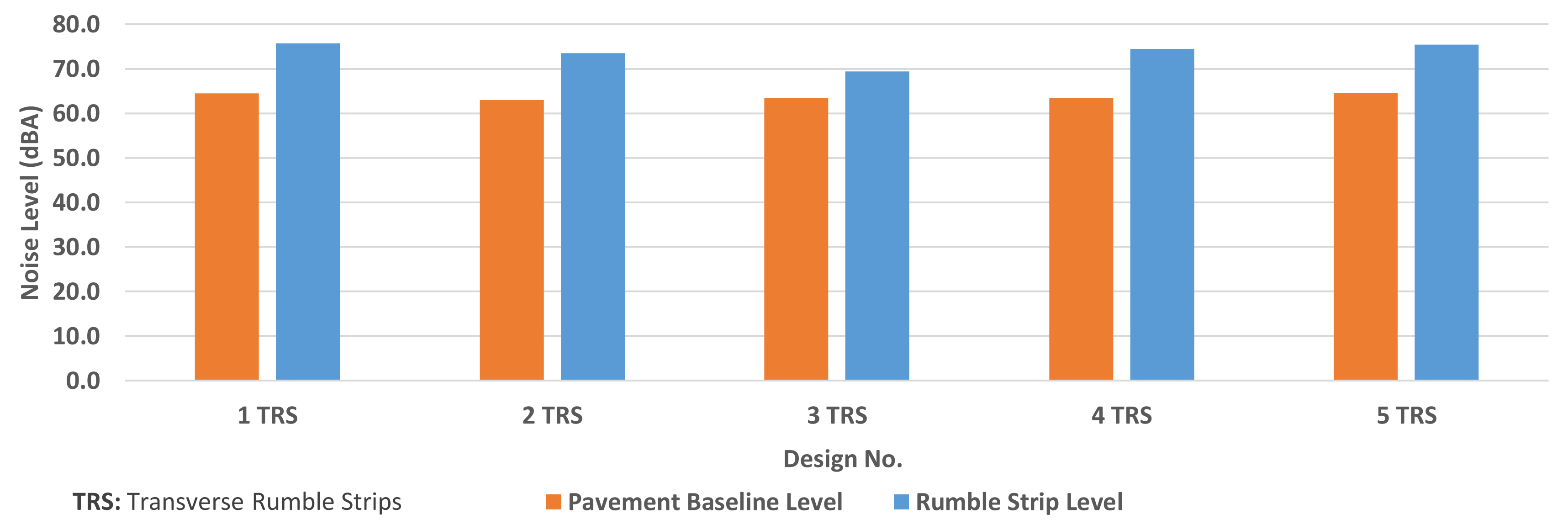


Figure 198. Graph. Internal noise of full-size SUV and transverse rumble strips.

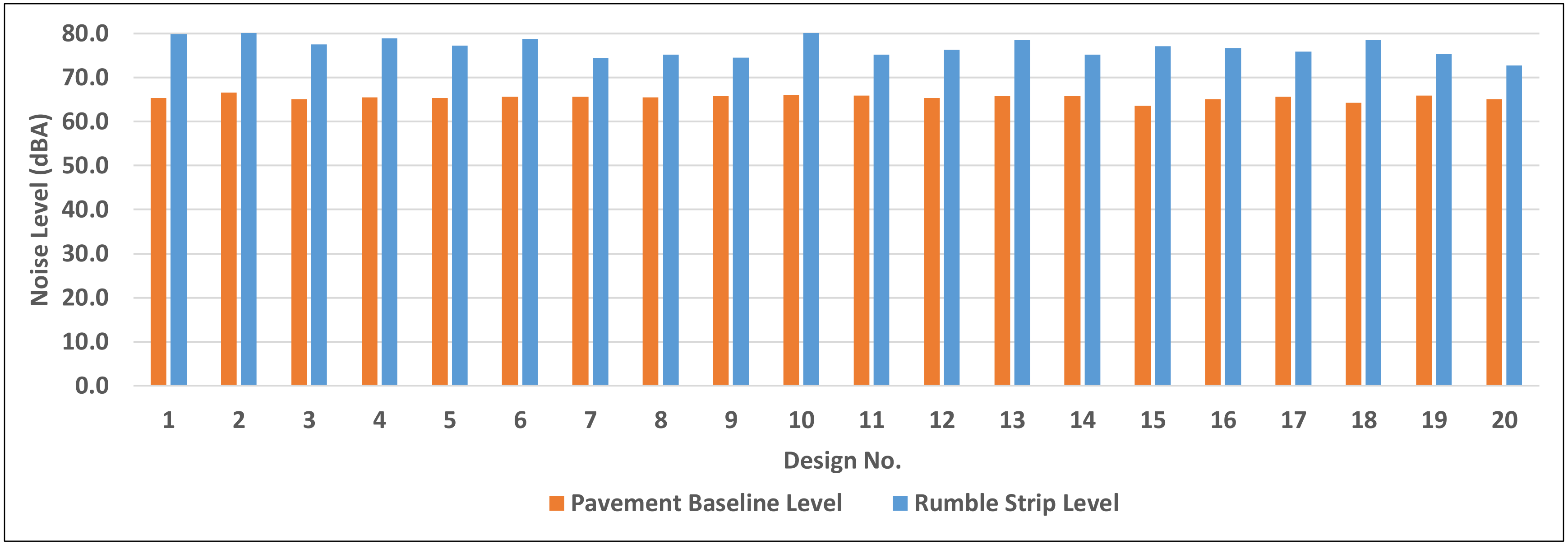


Figure 199. Graph. Internal noise of minivan and longitudinal rumble strips.

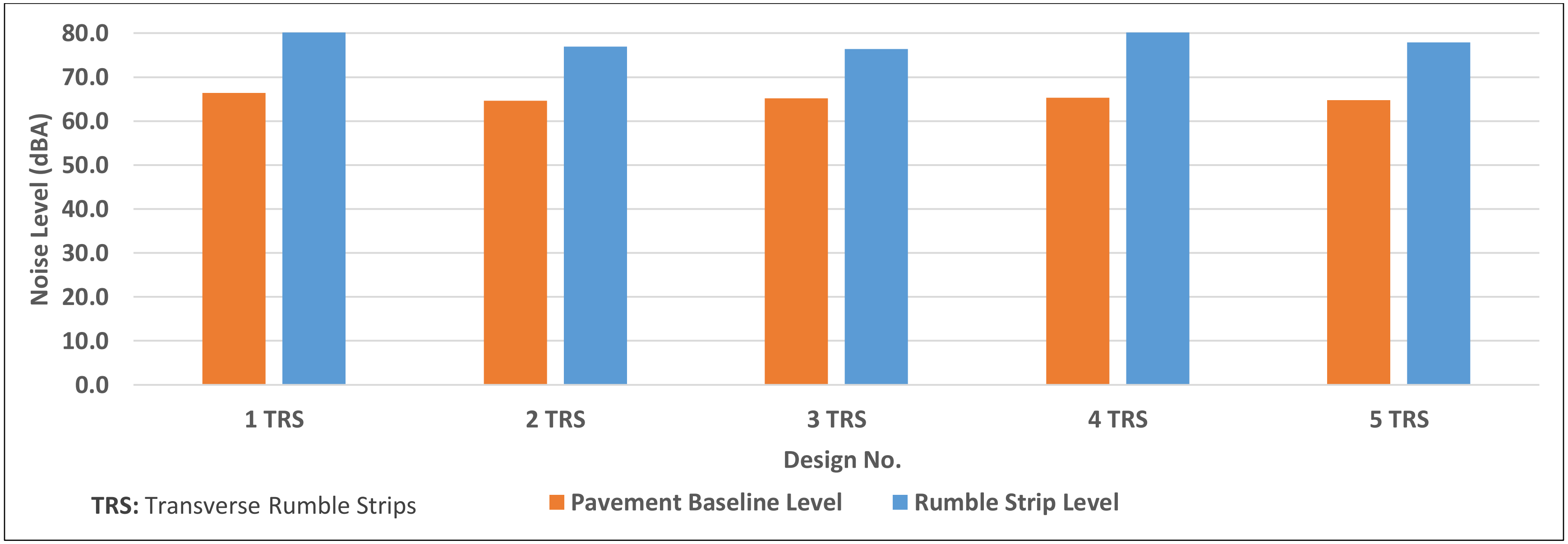


Figure 200. Graph. Internal noise of minivan and transverse rumble strips.

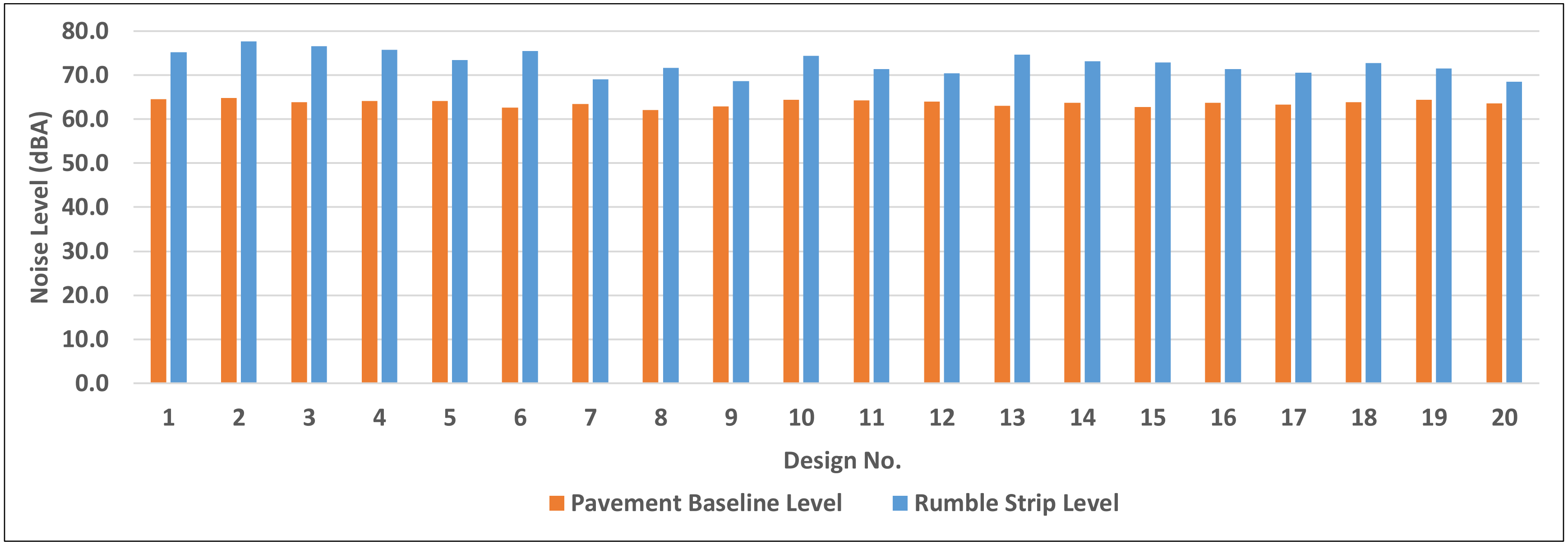


Figure 201. Graph. Internal noise of standard pick-up truck and longitudinal rumble strips.

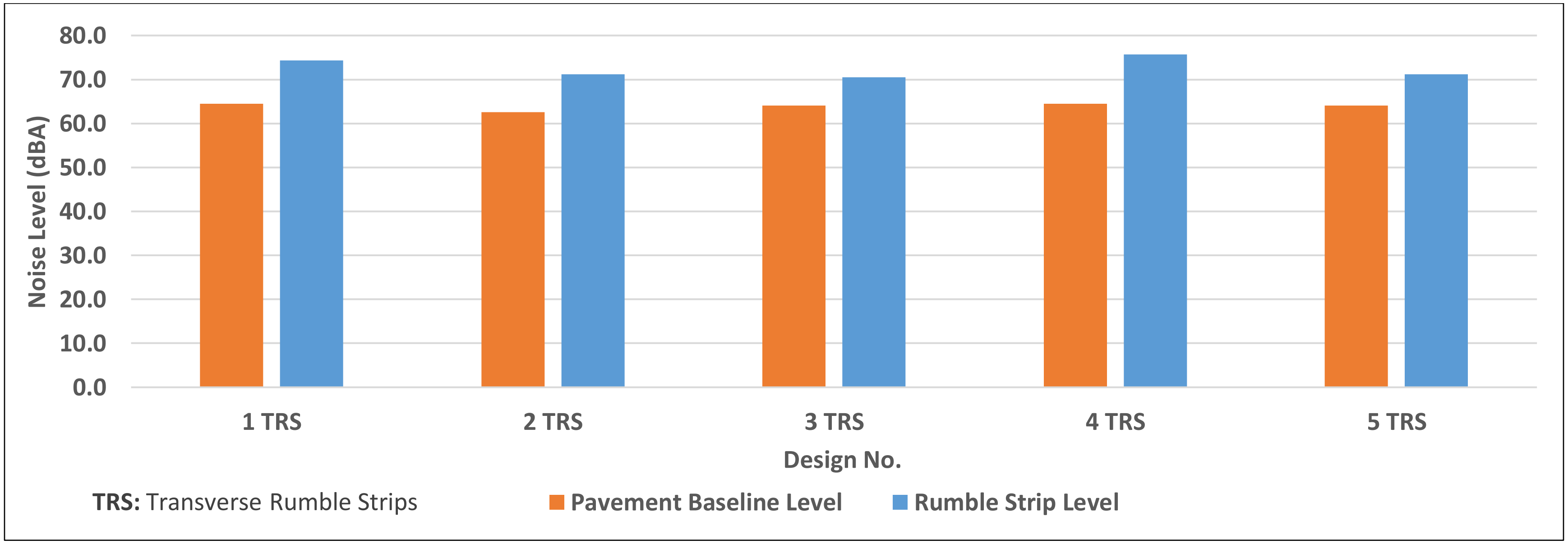


Figure 202. Graph. Internal noise of standard pick-up truck and transverse rumble strips.

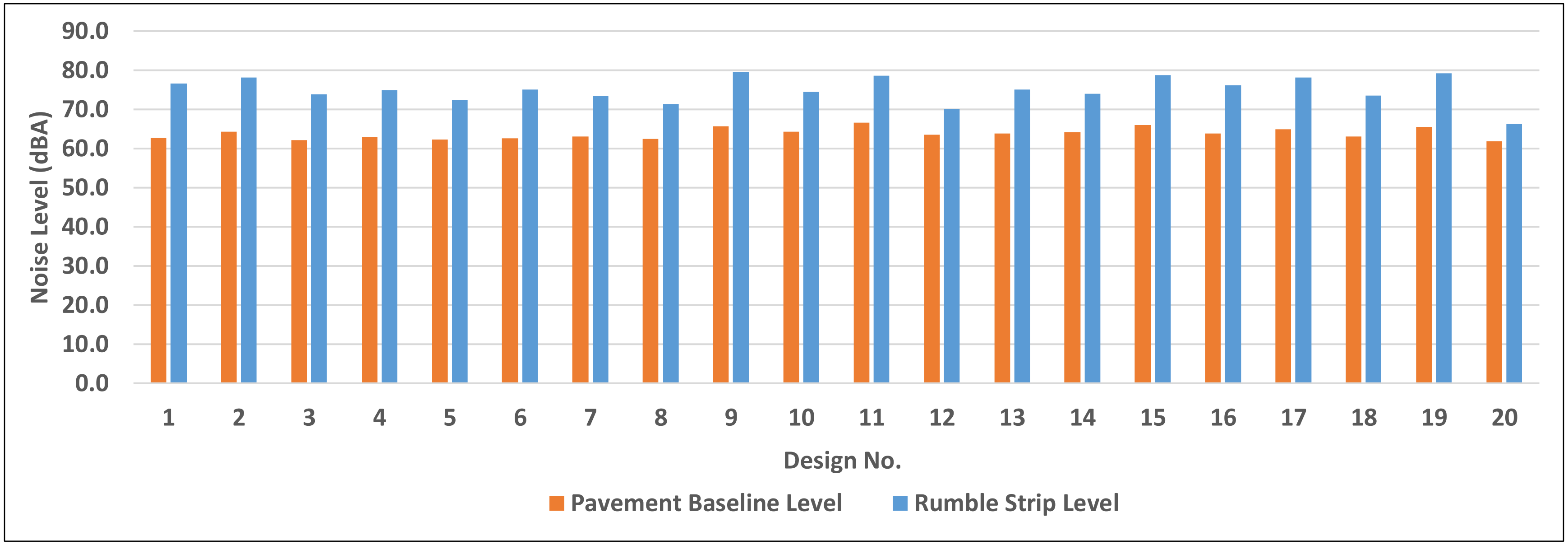


Figure 203. Graph. Internal noise of 1/2 ton pick-up truck and longitudinal rumble strips.

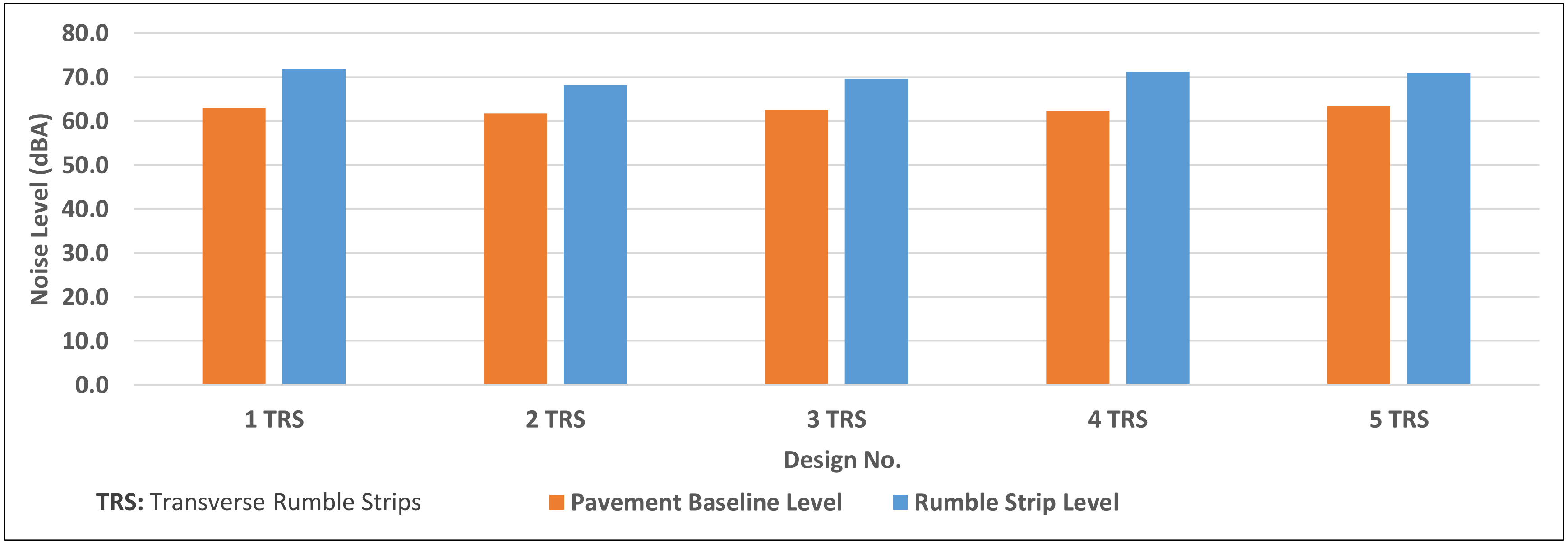


Figure 204. Graph. Internal noise of 1/2 ton pick-up truck and transverse rumble strips.

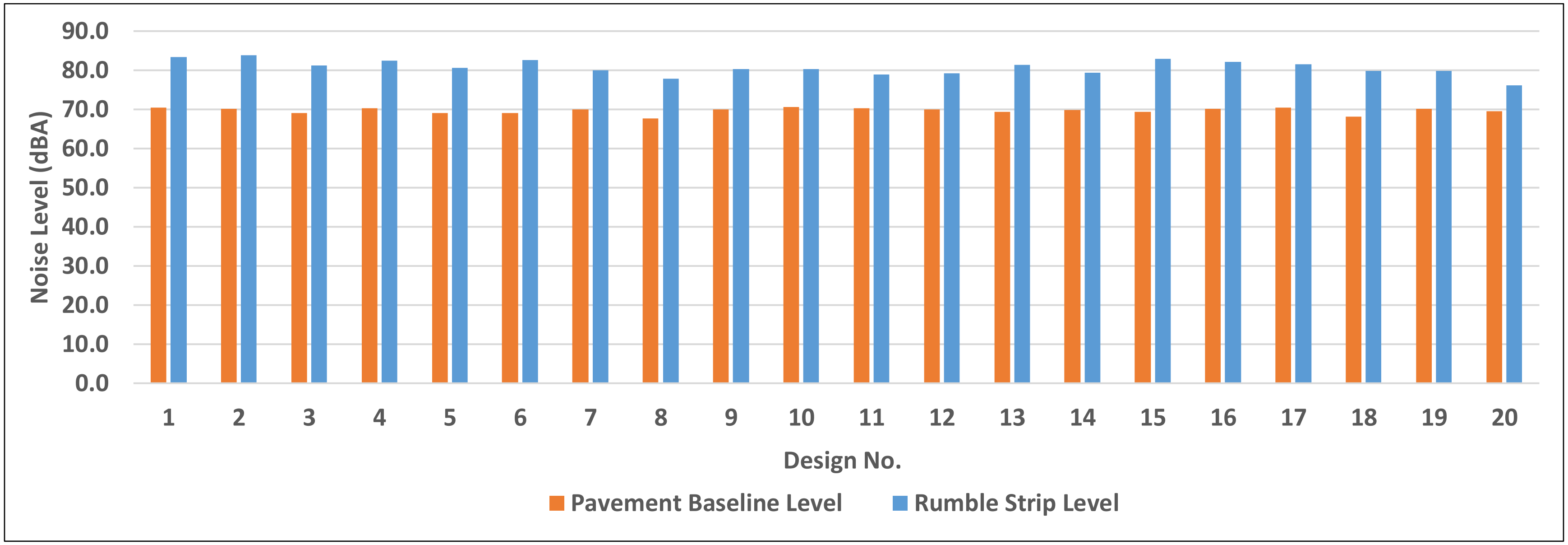


Figure 205. Graph. Internal noise of box truck and longitudinal rumble strips.

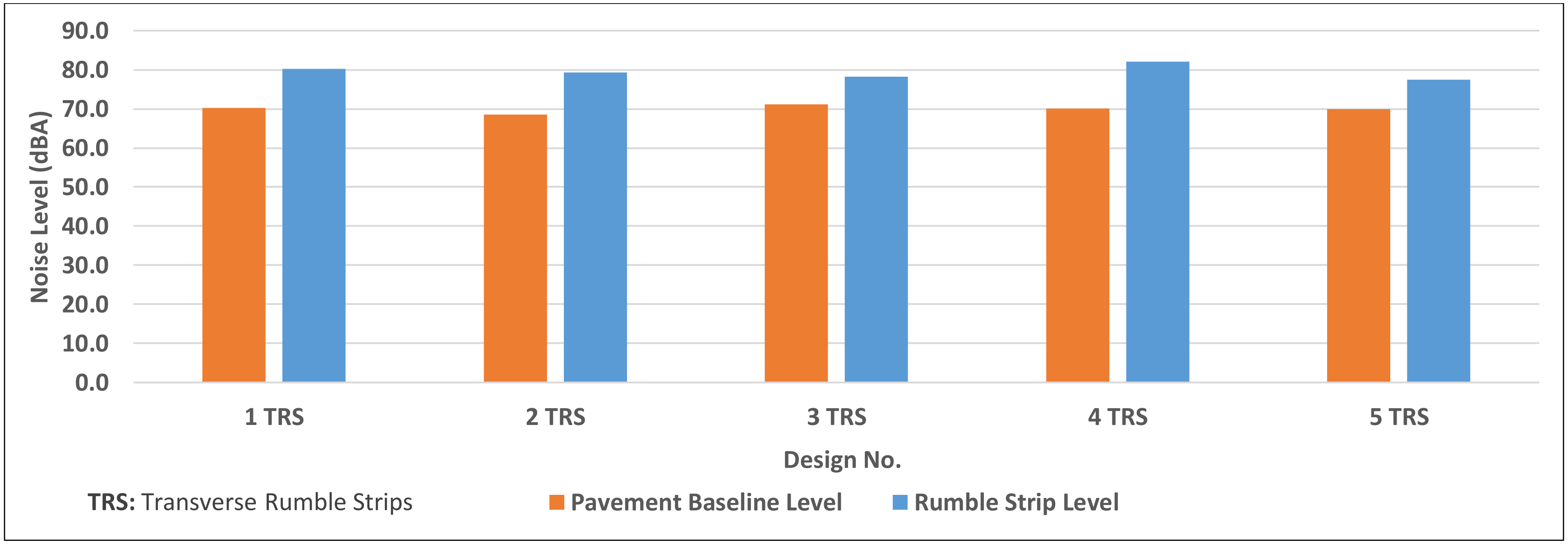


Figure 206. Graph. Internal noise of box truck and transverse rumble strips.

Table 43. Second Round Evaluation External Noise Levels of Longitudinal Rumble Strips at 50 ft

		Noise Levels (dBA)									
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**18**
Semi-Trailer Truck	**Sample Size**	3	3	3	3	3	3	3	3	3	3
	Average	87.2	90.9	84.9	85.4	85.6	87.4	81.4	85.8	81.3	82.7
	Standard Deviation	0.7	0.1	0.6	1.4	1.0	0.2	1.2	0.4	0.5	0.5
Compact Sedan	**Sample Size**	12	12	13	12	12	14	12	12	11	12
	Average	79.7	81.6	79.2	80.6	76.4	78.6	72.9	72.9	71.8	71.9
	Standard Deviation	1.5	1.2	0.9	0.6	0.8	1.0	1.1	0.7	0.8	0.8
0.5 Ton Pick-up Truck	**Sample Size**	5	5	5	5	5	5	5	5	5	8
	Average	83.6	81.5	82.7	83.5	81.3	83.3	72.2	71.8	70.3	70.8
	Standard Deviation	0.7	0.9	1.2	0.7	0.7	0.7	0.5	0.4	0.8	0.6
Full Size SUV	**Sample Size**	12	12	12	12	12	13	12	12	12	12
	Average	83.2	84.9	81.1	83.9	81.0	83.7	72.0	74.7	72.9	72.7
	Standard Deviation	1.5	1.3	1.4	0.9	0.8	0.7	0.6	0.5	1.0	0.6
Box Truck	**Sample Size**	3	5	4	3	3	3	3	3	5	6
	Average	80.9	80.4	77.6	81.5	77.6	80.2	73.0	74.7	71.8	72.9
	Standard Deviation	0.8	0.8	1.1	0.6	0.6	0.7	0.5	0.8	0.7	0.7
Standard Pick-up Truck	**Sample Size**	12	12	12	12	12	N/A	N/A	12	12	12
	Average	80.0	78.6	78.5	79.8	77.2	N/A	N/A	74.7	72.3	73.5
	Standard Deviation	1.0	1.0	0.5	0.8	0.7	N/A	N/A	0.5	0.5	1.2
Minivan	**Sample Size**	12	12	12	12	12	12	12	12	12	12
	Average	83.4	85.9	82.6	83.6	79.9	83.5	76.7	80.2	73.5	78.8
	Standard Deviation	1.0	1.0	0.9	0.8	0.7	0.9	1.0	0.6	0.5	1.1
Compact SUV	**Sample Size**	13	12	12	12	12	13	15	12	12	12
	Average	82.5	82.6	79.3	81.4	78.2	79.7	70.7	74.0	69.1	72.2
	Standard Deviation	1.3	1.1	0.7	0.7	1.2	0.6	0.7	0.4	0.7	0.6
Electric Vehicle	**Sample Size**	12	12	12	12	12	12	13	13	13	12
	Average	82.7	86.9	80.3	83.7	79.6	79.7	72.4	72.3	72.7	73.3
	Standard Deviation	1.0	0.8	0.8	0.9	0.9	0.6	0.5	0.7	0.6	0.3
Full Size Sedan	**Sample Size**	12	12	12	12	13	12	12	12	12	14
	Average	81.9	84.5	80.3	80.0	78.7	78.4	71.5	72.1	70.0	71.5
	Standard Deviation	0.8	0.8	1.0	1.0	0.6	0.7	0.6	0.5	0.2	0.3

N/A: Analysis results are not available because collected noise data is corrupted.

Table 44. Second Round Evaluation External Baseline Noise Levels of Longitudinal Rumble Strips at 50 ft

		Baseline Noise Levels (dBA)									
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**18**
Semi-Trailer Truck	**Sample Size**	2	2	2	2	2	2	2	2	2	2
	Average	82.2	81.5	81.7	82.1	82.2	81.5	78.7	83	80.4	80.6
	Standard Deviation	0	0.3	0.2	0.0	0.6	0.5	0.3	0.0	0.1	0.1
Compact Sedan	**Sample Size**	3	4	2	3	3	3	3	3	3	3
	Average	70.5	72.0	71.5	71.3	70.9	70.3	72.0	70.9	71.3	71.1
	Standard Deviation	0.5	0.9	0.3	0.4	0.7	0.2	0.5	0.4	0.1	0.6
0.5 Ton Pick-up Truck	**Sample Size**	3	3	3	3	3	3	3	3	3	3
	Average	71.3	69.1	71.3	71.6	71.4	71.1	70.7	70.7	69.9	70.1
	Standard Deviation	0.1	0.1	0.4	0.3	0.3	0.8	0.1	0.2	0.4	0.2
Full Size SUV	**Sample Size**	3	3	3	3	3	4	3	4	3	3
	Average	72.4	74.1	72.2	73.5	72.7	73.4	71.6	73.3	72.5	72.1
	Standard Deviation	0.6	0.3	0.3	0.4	0.2	0.6	0.1	0.2	0.6	0.1
Box Truck	**Sample Size**	4	3	3	3	3	4	4	3	3	3
	Average	72.2	71.4	71.9	73.2	72.1	73.3	72.5	74.1	71.3	71.9
	Standard Deviation	0.6	0.2	0.5	0.5	0.6	0.1	0.3	0.5	0.2	0.2
Standard Pick-up Truck	**Sample Size**	2	3	3	3	3	N/A	N/A	3	3	3
	Average	73.4	71.8	72.0	73.2	72.7	N/A	N/A	72.9	71.8	72.1
	Standard Deviation	1.5	0.5	0.2	0.2	0.6	N/A	N/A	0.3	0.2	0.4
Minivan	**Sample Size**	4	3	3	3	3	3	3	3	5	4
	Average	70.5	72.9	70.8	72.3	70.2	70.7	70.9	72.6	71.7	72.9
	Standard Deviation	0.5	0.7	0.5	0.3	0.5	0.4	0.5	0.4	0.2	0.1
Compact SUV	**Sample Size**	3	3	3	4	4	3	4	4	3	4
	Average	69.8	69.8	69.3	69.5	69.5	69.3	68.4	70.7	68.4	68.8
	Standard Deviation	0.4	0.2	0.5	0.4	0.8	0.7	0.2	0.7	0.2	0.5
Electric Vehicle	**Sample Size**	3	2	4	4	3	4	3	3	3	3
	Average	71.7	72.2	71.6	73.5	72.2	70.5	71.9	70.6	72.1	72.4
	Standard Deviation	0.3	0.4	0.4	0.3	0.8	0.3	0.7	0.2	0.2	0.3
Full Size Sedan	**Sample Size**	3	4	3	3	3	4	4	4	3	4
	Average	71.4	71.1	70.6	70.2	71.3	70.1	71.0	70.5	69.3	70.0
	Standard Deviation	0.2	0.2	0.5	0.2	0.4	0.3	0.5	0.8	0.7	0.4

N/A: Analysis results are not available because collected noise data is corrupted.

Table 45. Second Round Evaluation External Noise Levels of Transverse Rumble Strips at 50 ft

		Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Semi-Trailer Truck	**Sample Size**	5	5	5	4	4
	Average	91.1	90.1	83.4	90.6	89.8
	Standard Deviation	1.2	0.8	0.4	1.0	1.1
Compact Sedan	**Sample Size**	12	13	12	13	12
	Average	82.3	78.0	72.5	79.4	80.3
	Standard Deviation	0.9	0.9	0.9	0.6	0.8
0.5 Ton Pick-up Truck	**Sample Size**	5	6	5	5	5
	Average	84.7	79.9	71.6	79.4	81.8
	Standard Deviation	0.7	0.8	0.6	0.7	0.7
Full Size SUV	**Sample Size**	12	12	12	12	12
	Average	84.3	81.6	74.4	82.4	81.7
	Standard Deviation	0.9	0.7	0.5	1.1	1.0
Box Truck	**Sample Size**	4	4	4	4	5
	Average	83.0	80.3	73.7	79.9	80.9
	Standard Deviation	0.2	0.9	0.4	0.4	0.8
Standard Pick-up Truck	**Sample Size**	N/A	12	12	12	12
	Average	N/A	79.1	73.3	80.4	80.0
	Standard Deviation	N/A	0.3	0.7	0.8	0.9
Minivan	**Sample Size**	12	12	13	12	12
	Average	83.3	79.2	73.3	80.4	81.8
	Standard Deviation	0.8	0.6	1.0	0.8	0.8
Compact SUV	**Sample Size**	12	12	13	12	12
	Average	82.6	77.2	70.8	79.4	80.0
	Standard Deviation	0.9	0.9	0.7	0.6	0.8
Electric Vehicle	**Sample Size**	14	12	12	12	12
	Average	85.6	82.1	73.8	80.7	82.8
	Standard Deviation	0.9	1.1	0.6	0.7	0.8
Full Size Sedan	**Sample Size**	12	12	13	12	12
	Average	81.5	78.6	73.2	80.6	80.5
	Standard Deviation	0.6	0.5	0.4	0.7	0.8

N/A: Analysis results are not available because collected noise data is corrupted.

Table 46. Second Round Evaluation External Baseline Noise Levels of Transverse Rumble Strips at 50 ft

		Baseline Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Semi-Trailer Truck	**Sample Size**	5	5	5	4	4
	Average	83.7	83.3	80.4	83.5	83.5
	Standard Deviation	1.6	0.9	0.9	1.3	0.7
Compact Sedan	**Sample Size**	12	13	12	13	12
	Average	72.2	71.0	69.8	71.2	71.7
	Standard Deviation	0.7	0.7	0.7	0.9	0.8
0.5 Ton Pick-up Truck	**Sample Size**	5	6	5	5	5
	Average	74.0	71.2	70.1	68.9	72.9
	Standard Deviation	0.3	0.6	0.1	0.3	0.2
Full Size SUV	**Sample Size**	12	12	12	12	12
	Average	74.5	73.2	72.6	73.6	74.6
	Standard Deviation	0.6	0.9	0.7	0.9	0.8
Box Truck	**Sample Size**	4	4	4	4	5
	Average	73.4	72.2	71.6	71.7	72.9
	Standard Deviation	0.2	0.9	0.6	0.3	0.6
Standard Pick-up Truck	**Sample Size**	N/A	3	12	12	12
	Average	N/A	72.8	71.8	73.6	74.0
	Standard Deviation	N/A	0.3	0.9	1.0	0.8
Minivan	**Sample Size**	12	12	13	12	12
	Average	72.1	71.6	71.3	71.3	72.9
	Standard Deviation	0.8	0.6	0.7	0.9	0.6
Compact SUV	**Sample Size**	12	12	13	12	12
	Average	70.9	68.6	68.5	69.5	70.3
	Standard Deviation	0.9	0.6	0.8	0.7	0.6
Electric Vehicle	**Sample Size**	14	12	12	12	12
	Average	74.0	74.1	72.0	72.7	74.7
	Standard Deviation	0.6	0.7	0.6	0.4	0.4
Full Size Sedan	**Sample Size**	12	12	13	12	12
	Average	72.2	71.3	70.7	72.4	72.6
	Standard Deviation	0.4	0.8	0.6	0.4	0.8

N/A: Analysis results are not available because collected noise data is corrupted.

Table 47. Second Round Evaluation External Noise Levels of Longitudinal Rumble Strips at 25 ft

		Noise Levels (dBA)									
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**18**
Compact Sedan	**Sample Size**	12	12	13	12	12	14	12	12	12	12
	Average	84.6	84.4	82.9	84.4	80.1	82.8	76.7	75.8	75.3	75.0
	Standard Deviation	1.7	1.4	0.7	0.8	0.8	1.2	0.8	0.5	0.6	0.9
0.5 Ton Pick-up Truck	**Sample Size**	5	5	5	8	5	5	5	5	5	10
	Average	88.5	86.9	87.4	87.6	85.9	87.5	77.3	77.6	77.6	76.1
	Standard Deviation	0.7	0.8	0.5	1.5	1.2	0.8	0.6	0.3	0.3	0.6
Full Size SUV	**Sample Size**	12	12	12	12	12	12	12	12	13	12
	Average	89.1	88.8	87.2	89.5	85.8	88.3	77.4	81.2	78.1	78.5
	Standard Deviation	1.7	1.6	1.4	1.4	0.9	0.9	0.6	0.8	0.5	0.6
Box Truck	**Sample Size**	3	3	3	3	3	3	3	4	3	6
	Average	86.0	85.5	82.8	86.1	82.6	83.6	77.9	79.1	77.4	78.0
	Standard Deviation	1.0	0.9	0.7	0.6	0.8	0.5	0.6	0.5	0.8	0.4
Standard Pick-up Truck	**Sample Size**	12	12	12	12	12	12	12	12	12	12
	Average	84.1	81.6	82.6	84.0	81.8	83.4	76.8	78.1	77.9	77.3
	Standard Deviation	1.6	1.0	0.8	0.9	0.9	1.2	0.4	0.4	0.5	0.8
Minivan	**Sample Size**	12	12	12	12	12	12	12	12	12	12
	Average	88.6	89.6	88.2	88.8	84.4	88.4	82.0	85.2	79.3	83.9
	Standard Deviation	0.8	1.0	0.9	1.2	1.1	0.9	1.0	0.6	0.4	0.8
Compact SUV	**Sample Size**	13	12	12	12	12	13	15	12	12	12
	Average	87.1	86.8	84.2	86.9	82.6	84.0	75.6	79.6	74.4	77.9
	Standard Deviation	1.1	0.7	0.8	1.0	1.2	0.7	1.1	0.5	0.4	0.6
Electric Vehicle	**Sample Size**	12	12	12	12	12	12	13	13	13	12
	Average	88.0	91.7	87.2	89.1	83.7	84.2	77.9	78.1	78.0	79.4
	Standard Deviation	1.2	0.6	1.0	1.1	0.9	0.5	0.5	0.7	0.5	0.4
Full Size Sedan	**Sample Size**	12	12	12	12	13	12	12	12	12	14
	Average	86.9	89.9	86.0	85.4	83.4	84.0	76.9	77.6	75.8	77.1
	Standard Deviation	0.9	0.9	0.7	0.9	1.0	0.8	0.6	0.3	0.4	0.5

Table 48. Second Round Evaluation External Baseline Noise Levels of Longitudinal Rumble Strips at 25 ft

		Baseline Noise Levels (dBA)									
Design No.		**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**18**
Compact Sedan	**Sample Size**	3	4	2	3	3	3	3	3	3	3
	Average	75.0	74.0	74.9	74.7	74.1	74.3	75.8	73.2	74.2	73.0
	Standard Deviation	0.6	0.2	0.2	0.4	0.2	0.3	0.2	0.2	0.2	0.6
0.5 Ton Pick-up Truck	**Sample Size**	3	3	3	3	3	3	3	3	3	3
	Average	75.6	73.9	74.9	75.0	75.9	74.6	75.7	75.2	76.3	74.3
	Standard Deviation	0.1	0.1	0.3	0.1	0.5	0.2	0.1	0.4	0.5	0.2
Full Size SUV	**Sample Size**	3	3	3	3	3	1	3	4	3	3
	Average	77.6	77.3	77.3	78.5	77.0	78.0	76.3	78.7	76.8	77.1
	Standard Deviation	0.3	0.2	0.4	0.1	0.7	0.0	0.4	0.5	0.3	0.1
Box Truck	**Sample Size**	4	3	3	3	3	4	4	3	3	3
	Average	76.5	75.8	76.1	76.9	76.0	76.6	76.9	77.6	76.3	76.4
	Standard Deviation	0.7	0.7	0.6	0.3	0.6	0.4	0.3	0.3	0.5	0.1
Standard Pick-up Truck	**Sample Size**	4	3	3	3	3	4	3	3	3	3
	Average	76.6	73.9	75.8	77.0	76.7	76.5	75.4	75.6	76.4	75.6
	Standard Deviation	0.2	0.3	0.2	0.5	0.5	0.3	0.2	0.7	0.4	0.4
Minivan	**Sample Size**	4	3	3	3	3	3	3	3	5	4
	Average	75.5	76.3	76.3	77.2	74.4	75.4	74.9	77.1	76.3	76.5
	Standard Deviation	0.4	0.5	0.1	0.5	0.3	0.6	0.4	0.6	0.4	0.6
Compact SUV	**Sample Size**	3	3	3	4	4	3	4	4	3	4
	Average	74.1	73.7	73.7	74.8	73.8	73.1	73.0	75.0	73.3	74.2
	Standard Deviation	0.7	0.4	0.2	0.3	0.6	0.1	0.3	0.3	0.5	0.2
Electric Vehicle	**Sample Size**	3	3	4	4	3	4	3	3	3	3
	Average	76.6	76.1	76.9	78.6	76.1	74.4	76.4	75.2	76.4	77.7
	Standard Deviation	0.1	0.4	0.6	0.3	0.7	0.5	0.1	0.3	0.4	0.4
Full Size Sedan	**Sample Size**	3	4	3	3	3	4	4	4	3	4
	Average	75.9	76.2	75.8	75.1	75.3	75.1	75.9	75.5	74.7	75.3
	Standard Deviation	0.1	0.2	0.1	0.6	0.2	0.4	0.3	0.7	0.6	0.3

Table 49. Second Round Evaluation External Noise Levels of Transverse Rumble Strips at 25 ft

Design No.		Noise Levels (dBA)				
		1 TRS	2 TRS	3 TRS	4 TRS	5 TRS
Compact Sedan	Sample Size	12	13	12	13	12
	Average	84.7	82.4	75.6	83.1	83.6
	Standard Deviation	1.4	1.2	0.9	1.0	1.2
0.5 Ton Pick-up Truck	Sample Size	5	6	5	5	5
	Average	90.6	85.8	77.3	86.2	87.9
	Standard Deviation	0.4	0.6	0.3	0.3	0.8
Full Size SUV	Sample Size	N/A	12	12	12	12
	Average	N/A	87.3	80.5	88.2	87.6
	Standard Deviation	N/A	0.8	0.4	1.1	0.8
Box Truck	Sample Size	4	4	4	4	5
	Average	88.4	85.5	79.2	85.4	86.5
	Standard Deviation	0.6	0.7	0.7	0.1	0.9
Standard Pick-up Truck	Sample Size	12	12	12	12	12
	Average	87.3	83.4	78.5	85.4	85.5
	Standard Deviation	0.6	0.7	0.7	0.8	0.8
Minivan	Sample Size	12	12	13	12	12
	Average	89.7	84.4	79.0	86.6	88.1
	Standard Deviation	0.9	0.6	0.6	0.9	0.7
Compact SUV	Sample Size	12	12	13	12	12
	Average	88.0	82.7	76.6	85.4	86.4
	Standard Deviation	0.8	0.8	0.4	0.4	0.8
Electric Vehicle	Sample Size	14	12	12	12	12
	Average	92.0	87.6	80.1	87.4	89.4
	Standard Deviation	1.0	0.8	0.3	0.8	0.9
Full Size Sedan	Sample Size	12	12	13	12	12
	Average	88.0	84.2	79.0	86.5	86.9
	Standard Deviation	1.0	0.5	0.2	0.5	0.8

N/A: Analysis results are not available because collected noise data is corrupted.

Table 50. Second Round Evaluation External Baseline Noise Levels of Transverse Rumble Strips at 25 ft

		Baseline Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Compact Sedan	**Sample Size**	12	13	10	13	12
	Average	72.6	72.6	70.8	73.1	73.1
	Standard Deviation	1.5	1.1	0.8	1.0	1.2
0.5 Ton Pick-up Truck	**Sample Size**	5	6	5	5	5
	Average	75.9	73.0	73.2	72.9	74.8
	Standard Deviation	0.3	0.7	0.4	0.7	0.6
Full Size SUV	**Sample Size**	N/A	11	12	12	12
	Average	N/A	77.4	75.8	78.0	78.6
	Standard Deviation	N/A	0.7	0.8	0.8	0.7
Box Truck	**Sample Size**	4	4	4	4	5
	Average	76.3	74.6	73.8	74.4	75.7
	Standard Deviation	0.7	0.7	0.2	0.5	0.6
Standard Pick-up Truck	**Sample Size**	12	12	12	12	12
	Average	77.1	75.2	74.0	76.9	77.5
	Standard Deviation	0.9	0.8	1.0	0.7	0.8
Minivan	**Sample Size**	12	12	13	12	12
	Average	76.1	74.9	74.8	75.1	76.9
	Standard Deviation	0.7	0.5	0.7	0.7	0.9
Compact SUV	**Sample Size**	12	12	13	12	12
	Average	73.9	72.4	72.5	73.3	75.0
	Standard Deviation	0.6	0.6	0.5	0.9	0.5
Electric Vehicle	**Sample Size**	14	12	12	12	12
	Average	77.8	77.8	77.0	76.5	79.4
	Standard Deviation	0.9	0.9	0.7	0.7	0.9
Full Size Sedan	**Sample Size**	12	12	13	12	12
	Average	76.8	74.8	73.9	75.9	76.8
	Standard Deviation	1.0	0.6	0.8	0.9	0.8

N/A: Analysis results are not available because collected noise data is corrupted.

Table 51. Second Round Evaluation Internal Noise Levels (dBA) of Longitudinal Rumble Strips

Design No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Semi-Trailer Truck	**Sample Size**	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Average	79.9	85.1	80.3	80.8	79.2	80.9	76.3	78.9	78.8	79.3	78.2	77.9	78.0	78.4	78.6	78.6	77.6	79.0	77.7	75.2
	Standard Deviation	1.3	0.9	1.1	0.5	0.3	0.6	0.8	0.9	0.6	0.5	0.7	0.7	0.3	0.4	0.3	0.6	0.6	0.2	0.6	0.8
Compact Sedan	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	82.5	85.8	81.4	81.7	80.1	82.6	76.5	79.4	77.5	81.7	77.9	77.0	80.7	78.8	79.1	78.5	78.5	80.9	78.6	74.0
	Standard Deviation	2.8	0.4	0.5	1.5	0.5	0.6	1.0	0.9	1.3	1.1	1.2	0.3	0.8	0.9	1.0	1.8	1.0	1.7	0.6	1.4
0.5 Ton Pick-up Truck	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	76.6	78.1	73.8	74.8	72.4	75.0	73.4	71.3	79.5	74.4	78.5	70.2	75.0	74.0	78.8	76.1	78.2	73.5	79.2	66.3
	Standard Deviation	0.3	0.8	1.4	0.5	1.2	0.3	0.8	1.1	0.6	0.6	1.3	2.0	0.4	0.5	0.8	0.5	4.1	0.7	0.9	0.5
Full Size SUV	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	75.4	80.2	73.0	75.5	72.5	75.7	66.2	71.0	71.1	74.8	74.1	71.8	68.5	67.4	74.4	73.7	73.4	73.2	73.6	70.7
	Standard Deviation	1.9	0.3	1.6	0.7	1.5	0.4	0.6	0.6	1.5	0.7	0.5	0.9	0.5	0.6	0.7	0.4	1.7	1.2	0.3	0.9
Box Truck	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	83.4	83.8	81.2	82.4	80.6	82.6	80.0	77.9	80.3	80.3	79.0	79.3	81.3	79.3	82.9	82.2	81.5	79.8	79.8	76.1
	Standard Deviation	1.1	0.9	2.3	1.7	1.2	0.8	1.0	2.1	1.7	1.0	1.7	1.6	0.8	0.8	0.4	0.1	0.9	0.9	1.8	1.1
Standard Pick-up Truck	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	75.2	77.7	76.5	75.8	73.4	75.4	69.1	71.6	68.6	74.4	71.4	70.5	74.7	73.1	72.9	71.4	70.6	72.8	71.5	68.5
	Standard Deviation	2.1	0.8	0.8	0.3	0.5	0.4	1.6	1.0	0.7	1.1	0.5	0.8	0.9	0.9	0.5	1.5	1.0	0.7	0.4	0.7
Minivan	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	79.9	81.5	77.5	78.9	77.3	78.8	74.4	75.3	74.6	80.5	75.2	76.2	78.5	75.2	77.1	76.8	76.0	78.6	75.4	72.7
	Standard Deviation	1.5	0.4	1.3	0.6	0.7	0.5	0.8	1.1	0.6	0.5	0.4	0.3	1.0	0.5	0.3	0.8	0.4	1.5	0.2	0.6
Compact SUV	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	77.5	78.7	75.2	78.2	76.5	78.5	69.1	71.3	71.1	74.2	71.5	74.2	72.7	70.3	75.5	74.7	73.3	73.4	71.4	69.6
	Standard Deviation	1.0	0.4	0.2	0.5	1.7	0.6	0.8	0.7	0.4	0.8	0.5	0.1	0.8	0.6	0.5	0.4	0.3	0.2	0.2	0.8
Electric Vehicle	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	76.5	79.4	75.2	77.2	74.5	77.6	69.4	71.8	68.9	76.3	67.5	71.7	72.3	69.0	69.8	69.4	68.4	76.2	67.9	69.2
	Standard Deviation	1.4	0.5	2.1	0.4	1.1	0.4	0.7	0.7	0.6	0.5	0.4	0.5	0.6	0.5	0.5	0.6	0.3	0.3	0.5	0.6
Full Size Sedan	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	77.1	79.0	75.6	75.6	73.9	75.0	71.1	73.2	72.7	77.3	72.1	72.7	74.1	72.4	74.8	74.5	72.5	76.5	71.8	73.4
	Standard Deviation	0.6	0.5	1.2	1.0	0.6	0.3	1.5	1.4	0.8	1.2	0.2	1.7	0.9	0.6	1.1	0.8	0.8	1.0	0.8	1.1

Table 52. Second Round Evaluation Internal Baseline Noise Levels (dBA) of Longitudinal Rumble Strips

Design No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Semi-Trailer Truck	**Sample Size**	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Average	74.3	74.9	75.1	75.5	74.1	75.5	74.7	75.4	76.3	74.7	76.2	74.3	74.7	76.6	74.7	74.7	74.0	74.5	74.4	73.5
	Standard Deviation	0.7	0.4	1.0	0.4	0.2	0.2	0.4	0.8	0.4	0.4	0.8	0.4	0.7	0.3	0.4	0.5	0.5	0.3	0.6	1.0
Compact Sedan	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	67.5	69.0	67.5	67.7	67.1	67.7	66.6	68.9	67.5	68.6	68.4	68.1	68.9	69.4	66.6	67.8	68.3	68.1	68.7	66.8
	Standard Deviation	0.9	1.0	0.5	0.2	0.6	1.0	0.6	0.7	0.7	0.2	0.6	0.5	0.6	0.4	0.6	0.8	0.3	0.9	0.5	0.5
0.5 Ton Pick-up Truck	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	62.8	64.3	62.1	62.9	62.3	62.6	63.1	62.4	65.7	64.3	66.6	63.5	63.9	64.1	66.1	63.8	64.9	63.1	65.6	61.8
	Standard Deviation	0.2	0.2	0.4	0.7	0.7	1.0	0.6	0.5	0.9	0.6	0.5	1.1	0.7	0.5	0.5	0.5	1.1	1.0	1.8	0.5
Full Size SUV	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	63.2	65.4	61.6	63.5	62.5	62.7	62.1	62.5	62.6	63.8	64.3	63.0	62.3	63.1	62.2	63.3	63.6	62.4	63.5	62.6
	Standard Deviation	0.7	0.6	0.4	0.4	0.7	0.4	0.5	0.4	0.5	0.5	0.3	0.7	0.3	0.5	0.6	0.5	0.1	0.3	0.2	0.3
Box Truck	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	70.5	70.2	69.1	70.3	69.0	69.1	70.0	67.7	69.9	70.5	70.4	70.0	69.4	69.8	69.4	70.1	70.4	68.1	70.2	69.5
	Standard Deviation	1.0	0.4	0.8	0.7	1.0	1.5	1.0	1.0	1.1	0.3	0.5	0.8	1.1	0.5	1.0	0.9	0.5	0.8	0.6	1.1
Standard Pick-up Truck	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	64.5	64.9	63.8	64.1	64.1	62.7	63.4	62.0	62.9	64.4	64.3	64.0	63.0	63.7	62.8	63.7	63.3	63.8	64.3	63.6
	Standard Deviation	0.2	0.3	0.7	0.3	0.3	0.8	0.6	0.6	0.6	0.2	0.3	0.5	0.5	0.3	0.6	0.5	0.4	0.4	0.1	0.3
Minivan	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	65.4	66.5	65.2	65.5	65.3	65.7	65.6	65.5	65.8	66.0	65.9	65.3	65.8	65.8	63.6	65.0	65.6	64.3	66.0	65.2
	Standard Deviation	0.2	0.3	0.7	0.4	0.8	0.4	0.4	0.7	0.6	0.3	0.7	0.4	0.5	0.5	0.9	0.6	0.1	0.6	0.4	0.6
Compact SUV	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	64.6	65.0	63.0	65.3	64.4	65.3	63.7	62.5	62.4	64.9	65.0	64.9	63.3	64.8	64.1	64.6	64.0	63.8	64.7	64.2
	Standard Deviation	0.1	0.6	0.6	0.2	0.3	0.7	0.2	0.4	0.7	0.1	0.5	0.2	0.4	0.2	0.6	0.6	0.4	0.2	0.5	0.4
Electric Vehicle	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	63.4	64.5	61.7	63.7	62.6	63.6	62.0	62.2	62.4	64.6	63.2	63.2	62.2	63.1	61.2	62.0	62.1	61.4	63.0	62.7
	Standard Deviation	0.6	0.5	0.6	0.2	0.5	0.5	0.4	0.2	0.8	0.5	0.4	0.4	0.6	0.4	0.6	0.6	0.3	1.1	0.6	0.6
Full Size Sedan	**Sample Size**	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Average	65.0	65.1	62.4	64.8	63.4	64.2	63.8	62.4	64.0	64.9	64.4	63.8	62.8	64.3	62.7	63.4	63.4	63.9	64.7	63.9
	Standard Deviation	0.4	0.5	0.4	0.3	0.3	0.6	0.5	0.8	0.6	0.7	0.2	0.2	0.2	0.3	0.3	0.8	0.4	0.9	0.4	0.1

Table 53. Second Round Evaluation Internal Noise Levels of Transverse Rumble Strips

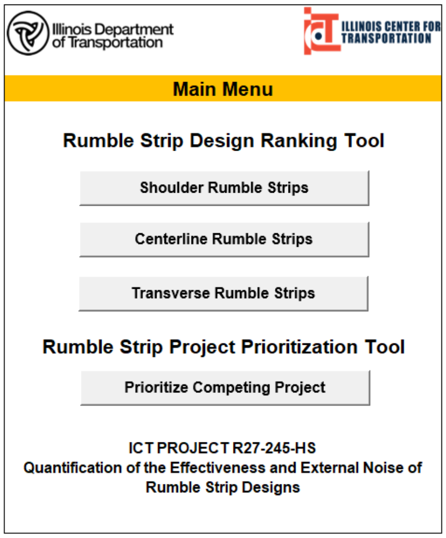
		Noise Levels (dBA)				
Design No.		**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Semi-Trailer Truck	**Sample Size**	4	4	4	4	4
	Average	84.1	77.8	77.0	78.6	81.4
	Standard Deviation	0.7	0.2	0.7	1.6	1.8
Compact Sedan	**Sample Size**	6	6	6	6	6
	Average	86.4	79.4	77.3	84.4	83.2
	Standard Deviation	0.8	2.7	4.4	1.7	1.7
0.5 Ton Pick-up Truck	**Sample Size**	6	6	6	6	6
	Average	71.9	68.2	69.6	71.2	71.0
	Standard Deviation	0.7	0.8	2.3	1.0	0.6
Full Size SUV	**Sample Size**	6	6	6	6	6
	Average	75.7	73.6	69.4	74.4	75.4
	Standard Deviation	1.2	1.9	1.7	2.0	2.6
Box Truck	**Sample Size**	6	6	6	6	6
	Average	80.2	79.3	78.3	82.0	77.5
	Standard Deviation	2.6	2.2	1.1	3.5	1.8
Standard Pick-up Truck	**Sample Size**	6	6	6	6	6
	Average	74.4	71.1	70.5	75.7	71.2
	Standard Deviation	2.2	1.7	2.2	3.1	2.3
Minivan	**Sample Size**	6	6	6	6	6
	Average	81.4	77.0	76.3	80.4	77.9
	Standard Deviation	2.1	2.9	2.5	3.4	5.7
Compact SUV	**Sample Size**	6	6	6	6	6
	Average	80.6	79.3	76.7	74.3	70.1
	Standard Deviation	1.8	1.8	2.5	1.1	3.1
Electric Vehicle	**Sample Size**	6	6	6	6	6
	Average	77.7	75.9	69.9	79.1	79.8
	Standard Deviation	3.0	3.5	1.2	4.0	2.2
Full Size Sedan	**Sample Size**	6	6	6	6	6
	Average	76.1	72.7	73.7	77.3	77.0
	Standard Deviation	2.8	1.4	1.5	1.3	2.0

Table 54. Second Round Evaluation Internal Baseline Noise Levels of Transverse Rumble Strips

Design No.		Baseline Noise Levels (dBA)				
		1 TRS	2 TRS	3 TRS	4 TRS	5 TRS
Semi-Trailer Truck	Sample Size	4	4	4	4	4
	Average	76.4	73.6	74.3	73.8	75.1
	Standard Deviation	0.8	0.4	0.6	0.8	0.7
Compact Sedan	Sample Size	6	6	6	6	6
	Average	68.0	64.5	66.9	66.3	68.0
	Standard Deviation	0.8	1.1	0.5	0.6	0.2
0.5 Ton Pick-up Truck	Sample Size	6	6	6	6	6
	Average	62.9	61.8	62.6	62.3	63.4
	Standard Deviation	0.6	0.2	0.1	0.9	0.4
Full Size SUV	Sample Size	6	6	6	6	6
	Average	64.5	62.9	63.3	63.4	64.6
	Standard Deviation	0.6	0.8	0.6	0.5	0.4
Box Truck	Sample Size	6	6	6	6	6
	Average	70.2	68.5	71.2	70.1	69.9
	Standard Deviation	0.5	1.6	0.5	0.6	0.9
Standard Pick-up Truck	Sample Size	6	6	6	6	6
	Average	64.4	62.6	64.1	64.5	64.1
	Standard Deviation	0.6	1.0	0.4	0.6	0.4
Minivan	Sample Size	6	6	6	6	6
	Average	66.4	64.7	65.1	65.4	64.8
	Standard Deviation	0.5	0.4	0.5	0.8	0.4
Compact SUV	Sample Size	6	6	6	6	6
	Average	65.6	65.3	65.2	62.9	64.5
	Standard Deviation	0.4	0.8	0.5	0.3	0.3
Electric Vehicle	Sample Size	6	6	6	6	6
	Average	63.7	62.4	62.2	62.5	65.9
	Standard Deviation	0.3	0.9	0.5	0.8	0.6
Full Size Sedan	Sample Size	6	6	6	6	6
	Average	63.9	62.6	63.8	64.2	64.8
	Standard Deviation	0.2	1.1	0.5	0.4	0.5

APPENDIX F: DECISION SUPPORT TOOL FOR RANKING RUMBLE STRIP DESIGNS

This appendix describes the development and use of a decision support tool (DST) for ranking the 15 top-performing rumble strip designs that were identified in the initial and second rounds of field evaluations. The DST is designed to rank these top-performing rumble strip designs based on (a) collected internal and external noise levels generated by each rumble strip design; (b) roadway traffic distribution in terms of percentage of passenger cars, single- unit trucks, and multiple unit trucks; (c) type of roadway and whether it is a freeway; and (d) type of activities in the surrounding area of the roadway and its sensitivity to external noise generated by rumble strips. The rumble strip design ranking tool enables IDOT to rank the top-performing shoulder, centerline, and transverse rumble strip designs, as shown in Figure 207. The following three sections describe the required input data, ranking methods, and output data of the rumble strip design ranking tool.

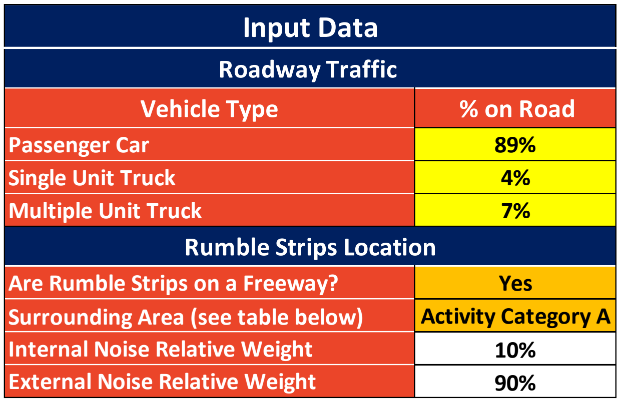


ICT PROJECT R27-245-HS
Quantification of the Effectiveness and External Noise of Rumble Strip Designs

Figure 207. Screenshot. Rumble strip design ranking and project prioritization tools.

APPENDIX F1: REQUIRED INPUT DATA

To enable the ranking of the top-performing rumble strip designs, this tool requires IDOT to provide the following roadway project input data: (1) percentage of each vehicle type (passenger car, single unit truck, and multiple unit truck) on the roadway segment; (2) type of roadway (freeway or non-freeway); and (3) type of activities in the surrounding area of rumble strips, as shown in the yellow and orange cells in Figure 208. First, the percentage of each vehicle type on the roadway is used for calculating a weighted overall internal and external noise performance utility score for each design alternative based on the proportions of different types of vehicles on the roadway, which is described in more detail in the next section. Second, the type of roadway is needed to differentiate between the internal noise performance score of each rumble strip design on freeways and non-freeways based on NCHRP 641 (2009) recommendations: “On roadways where bicyclists are not expected, such as on freeways, it is recommended that rumble strip patterns be designed to generate approximately 10 to 15 dBA above the ambient in-vehicle sound level, but for roadways where bicyclists may be expected, it is recommended that rumble strip patterns be designed to generate between 6 to 12 dBA above the ambient in-vehicle sound level.” Third, the type of activities in the surrounding area of rumble strips is needed to analyze the sensitivity of nearby areas to the external noise generated by the rumble strip designs. The type of activities in this tool utilizes the classification of FHWA (2023) Noise Abatement Criteria (NAC), 23 CFR Part 772, Procedures for Abatement of Highway Traffic Noise and Construction Noise, as shown in Table 55. In this tool, the designer-specified type of activity in the surrounding area is used to specify the relative importance/weights of generated internal and external rumble strip noise levels based on a default set of weights that can be adjusted by IDOT, as shown in Table 56. For example, the default relative weight of internal and external noise levels is specified to be 10% and 90%, respectively, for rumble strips located in type A areas where serenity and quiet are of extraordinary significance, as shown in Table 56. The default relative weights of internal and external noise performance for the remaining categories are summarized in Table 56. The tool is designed to extract and display the relative importance/weights of internal and external noise levels based on the user-specified type of the surrounding area, as shown in Figure 208.



Input Data	
Roadway Traffic	
Vehicle Type	**% on Road**
Passenger Car	89%
Single Unit Truck	4%
Multiple Unit Truck	7%
Rumble Strips Location	
Are Rumble Strips on a Freeway?	Yes
Surrounding Area (see table below)	Activity Category A
Internal Noise Relative Weight	10%
External Noise Relative Weight	90%

Figure 208. Screenshot. Example of required input data for rumble strip design ranking tool.

Table 55. Activity Categories According to FHWA Noise Abatement Criteria (2023)

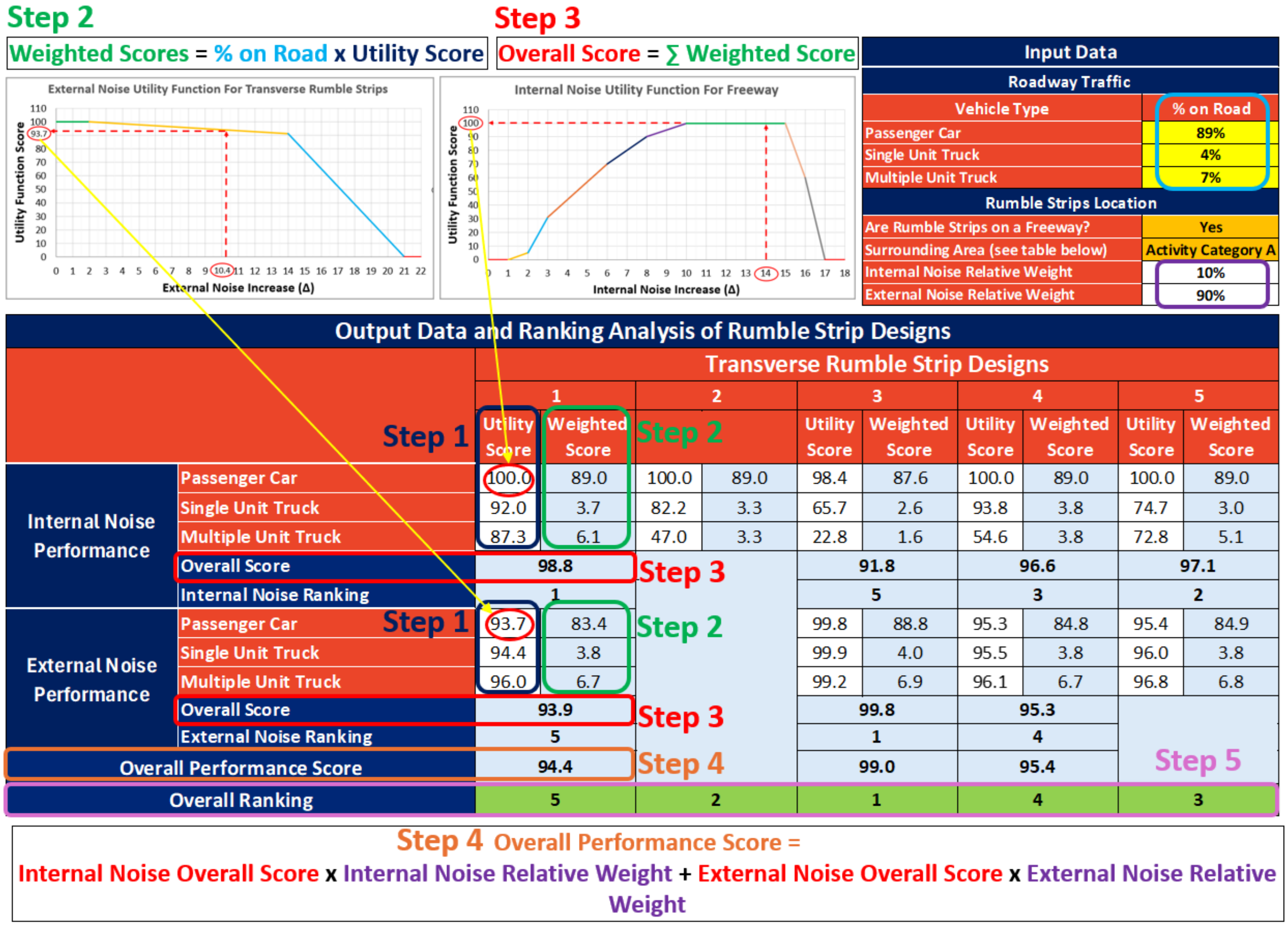
Activity Category	Description of Activity Category
A	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and the preservation of those qualities are essential.
B	Residential and undeveloped lands, permitted for residential activities.
C	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, schools, television studios, trails and trail crossings.
E	Hotels, motels, offices, restaurants/bars, and other developed lands, properties or activities not included in categories A, B, C, or F.
F	Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities, and warehousing.
G	Undeveloped lands that are not permitted.

Table 56. Default Relative Weights of Internal and External Noises

Activity Category	Default Internal Noise Relative Weight	Default External Noise Relative Weight
A	10%	90%
B	30%	70%
C	40%	60%
E	75%	25%
F	95%	5%
G	100%	0%

APPENDIX F2: RANKING METHODS

This rumble strip design ranking tool utilizes multi-attribute utility theory (Rueda-Benavides, et al., 2022) to rank the top-performing rumble strip designs based on their overall performance score (P_i) following five steps, as shown in Figure 209.



Input Data	
Roadway Traffic	
Vehicle Type	**% on Road**
Passenger Car	89%
Single Unit Truck	4%
Multiple Unit Truck	7%
Rumble Strips Location	
Are Rumble Strips on a Freeway?	Yes
Surrounding Area (see table below)	Activity Category A
Internal Noise Relative Weight	10%
External Noise Relative Weight	90%

Output Data and Ranking Analysis of Rumble Strip Designs

		Transverse Rumble Strip Designs									
		1		2		3		4		5	
	Step 1	Utility Score	Weighted Score	Step 2		Utility Score	Weighted Score	Utility Score	Weighted Score	Utility Score	Weighted Score
Internal Noise Performance	Passenger Car	100.0	89.0	100.0	89.0	98.4	87.6	100.0	89.0	100.0	89.0
	Single Unit Truck	92.0	3.7	82.2	3.3	65.7	2.6	93.8	3.8	74.7	3.0
	Multiple Unit Truck	87.3	6.1	47.0	3.3	22.8	1.6	54.6	3.8	72.8	5.1
	Overall Score	98.8		Step 3		91.8		96.6		97.1	
	Internal Noise Ranking	1				5		3		2	
External Noise Performance	Passenger Car Step 1	93.7	83.4	Step 2		99.8	88.8	95.3	84.8	95.4	84.9
	Single Unit Truck	94.4	3.8			99.9	4.0	95.5	3.8	96.0	3.8
	Multiple Unit Truck	96.0	6.7			99.2	6.9	96.1	6.7	96.8	6.8
	Overall Score	93.9		Step 3		99.8		95.3			
	External Noise Ranking	5				1		4			
Overall Performance Score		94.4		Step 4		99.0		95.4		Step 5	
Overall Ranking		5		2		1		4		3	

Step 4 Overall Performance Score =
Internal Noise Overall Score x Internal Noise Relative Weight + External Noise Overall Score x External Noise Relative Weight

Figure 209. Illustration. Example of rumble strip design ranking tool for transverse designs.

Step 1: Calculate internal (IU_{ij}) and external (EU_{ij}) noise utility scores of each rumble strip design (i) based on its generated internal (IN_{ij}) and external (EN_{ij}) noise level increases for each vehicle type (j) including passenger cars, single unit trucks, and multiple unit trucks. IN_{ij} and EN_{ij} were calculated for these three vehicle types by averaging the data of the collected internal and external noise level increases that were collected during the field evaluations (see Tables 11 and 12). For example, the average internal noise level increase for longitudinal design 1 and passenger car ($IN_{1,1}$ = 13.3 dBA) was calculated by averaging its generated noise increases for the tested compact sedan, sedan, full-size sedan, electric sedan, compact SUV, SUV, full-size SUV, and minivan that are listed in Table 11. Similarly, the internal (IN_{ij}) and external (EN_{ij}) noise level increases were calculated for the remaining designs and vehicle types, as shown in Tables 57, 58, 59, and 60. These internal (IN_{ij}) and external (EN_{ij}) noise level increases are then used to calculate their corresponding internal (IU_{ij}) and external (EU_{ij}) noise utility scores using newly developed utility functions that are described in the next section.

Table 57. Internal Noise Utility Scores of Longitudinal Rumble Strips

Shoulder and Centerline Rumble Strip Designs										
Design No. (i)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**18**
Internal Noise Increase Δ (IN_{ij}) in dBA										
Passenger Car (j = 1)	13.3	15.1	12.7	12.7	11.5	13.2	9.2	11.8	8.7	12.4
Single Unit Truck (j = 2)	10.6	11.0	10.0	9.8	8.3	10.5	7.6	8.2	6.2	8.5
Multiple Unit Truck (j = 3)	5.6	10.1	5.2	5.3	5.1	5.3	3.5	4.6	3.6	4.5
Internal Noise Utility Function Scores (IU_{ij}) for Freeways										
Passenger Car (j = 1)	100.0	95.1	100.0	100.0	100.0	100.0	95.8	100.0	93.3	100.0
Single Unit Truck (j = 2)	100.0	100.0	99.8	98.8	91.7	100.0	86.3	91.1	72.4	92.5
Multiple Unit Truck (j = 3)	64.7	100.0	59.9	60.3	58.8	61.5	37.1	51.9	38.7	50.2
Internal Noise Utility Function Scores (IU_{ij}) for Non-Freeways										
Passenger Car (j = 1)	96.0	81.6	97.9	97.8	100.0	96.5	100.0	100.0	100.0	98.8
Single Unit Truck (j = 2)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	92.4	100.0
Multiple Unit Truck (j = 3)	83.8	100.0	78.3	78.8	77.1	80.2	52.0	69.2	53.8	67.2

Table 58. Internal Noise Utility Scores of Transverse Rumble Strips

Transverse Rumble Strip Designs					
Design No. (i)	**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
Internal Noise Increase Δ (IN_{ij}) in dBA					
Passenger Car (j = 1)	14.2	12.6	9.7	13.9	11.9
Single Unit Truck (j = 2)	8.4	7.2	5.7	8.8	6.5
Multiple Unit Truck (j = 3)	7.7	4.2	2.7	4.8	6.3
Internal Noise Utility Function Scores (IU_{ij}) for Freeways					
Passenger Car (j = 1)	100.0	100.0	98.4	100.0	100.0
Single Unit Truck (j = 2)	92.0	82.2	65.7	93.8	74.7
Multiple Unit Truck (j = 3)	87.3	47.0	22.8	54.6	72.8
Internal Noise Utility Function Scores (IU_{ij}) for Non-Freeways					
Passenger Car (j = 1)	93.3	98.3	100.0	94.2	100.0
Single Unit Truck (j = 2)	100.0	100.0	85.0	100.0	94.7
Multiple Unit Truck (j = 3)	100.0	63.5	33.9	72.2	92.8

Table 59. External Noise Utility Scores at 50 ft for Longitudinal Rumble Strips

Shoulder and Centerline Rumble Strip Designs										
Design No. (i)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**18**
External Noise Increase at 50 ft Δ (EN_{ij}) in dBA										
Passenger Car (j = 1)	11.0	12.8	9.4	10.2	8.4	9.7	1.4	2.7	0.7	1.8
Single Unit Truck (j = 2)	8.1	9.0	7.3	7.9	6.2	8.6	1.5	1.9	0.6	1.4
Multiple Unit Truck (j = 3)	5.0	9.5	3.2	3.3	3.4	6.0	2.7	2.8	1.0	2.1
External Noise Utility Function Scores at 50 ft (EU_{ij})										
Passenger Car (j = 1)	96.4	95.7	97.1	96.7	97.5	96.9	100.0	99.7	100.0	100.0
Single Unit Truck (j = 2)	97.6	97.2	97.9	97.6	98.3	97.4	100.0	100.0	100.0	100.0
Multiple Unit Truck (j = 3)	98.8	97.0	99.5	99.5	99.4	98.4	99.7	99.7	100.0	100.0

Table 60. External Noise Utility Scores at 50 ft for Transverse Rumble Strips

Transverse Rumble Strip Designs					
Design No.	**1 TRS**	**2 TRS**	**3 TRS**	**4 TRS**	**5 TRS**
External Noise Increase at 50 ft Δ (EN_{ij}) in dBA					
Passenger Car (j = 1)	10.4	7.7	2.3	8.3	8.1
Single Unit Truck (j = 2)	9.5	7.5	2.2	8.1	7.4
Multiple Unit Truck (j = 3)	7.4	6.8	3.1	7.1	6.3
External Noise Utility Function Scores at 50 ft (EU_{ij})					
Passenger Car (j = 1)	93.7	95.7	99.8	95.3	95.4
Single Unit Truck (j = 2)	94.4	95.9	99.9	95.5	96.0
Multiple Unit Truck (j = 3)	96.0	96.4	99.2	96.1	96.8

Step 2: Compute internal (IS_{ij}) and external (ES_{ij}) noise weighted scores of each combination of rumble strip design (i) and vehicle type (j) based on the internal (IU_{ij}) and external (EU_{ij}) noise utility scores that were calculated in the previous step and the user-specified percentage of each vehicle type (W_j) on the roadway (see Figure 209), as illustrated in Figures 210 and 211.

$$\mathbf{IS_{ij}} = \mathbf{IU_{ij}} \times \mathbf{W_j}$$

Figure 210. Equation. Internal noise weighted score of a rumble strip design.

$$\mathbf{ES_{ij}} = \mathbf{EU_{ij}} \times \mathbf{W_j}$$

Figure 211. Equation. External noise weighted score of a rumble strip design.

Where

IS_{ij} is the internal noise weighted score of a rumble design (i) for a vehicle type (j)

IU_{ij} is the internal noise utility score of a rumble strip design (i) for a vehicle type (j)

ES_{ij} is the internal noise weighted score of a rumble design (i) for a vehicle type (j)

EU_{ij} is the external noise utility score of a rumble strip design (i) for a vehicle type (j)

W_j is the percentage of each vehicle type (j) on the roadway, where W_1, W_2, and W_3 represent the percentages of passenger cars, single unit trucks, and multiple unit trucks, respectively.

Step 3: Calculate internal (I_i) and external (E_i) noise overall scores for each rumble strip design (i) by summing all the internal (IS_{ij}) and external (ES_{ij}) noise weighted scores for each rumble strip design (i), as illustrated in Figures 212 and 213.

$$\mathbf{I_i} = \sum_{\mathbf{j=1}}^{\mathbf{j=3}} \mathbf{IS_{ij}}$$

Figure 212. Equation. Internal noise performance score of a rumble strip design.

$$\mathbf{E_i} = \sum_{\mathbf{j=1}}^{\mathbf{j=3}} \mathbf{ES_{ij}}$$

Figure 213. Equation. External noise performance score of a rumble strip design.

Where

I_i is the internal noise overall score of a rumble strip design (i)
E_i is the external noise overall score of a rumble strip design (i)

Step 4: Calculate overall performance score (P_i) of each rumble strip design (i) based on its internal (I_i) and external (E_i) noise overall scores that were calculated in the previous step and the relative importance/weight of internal and external noise levels in the project location based on the user-specified type of activities in the surrounding area of rumble strips, as shown in Figures 209 and 214.

$$\mathbf{P_i = I_i \times W_i + E_i \times W_e}$$

Figure 214. Equation. Noise overall performance score of a rumble strip design

Where

$\mathbf{P_i}$ is the noise overall performance score of a rumble strip design (n)

$\mathbf{W_i}$ is the relative weight of internal noise

$\mathbf{W_e}$ is the relative weight of external noise

Step 5: Rank the top-performing rumble strip designs based on the calculated overall performance score (P_i) for each rumble strip design (i), as shown in Figure 209.

As stated earlier, the internal (IU_{ij}) and external (EU_{ij}) noise utility scores of each rumble strip design (i) and vehicle type (j) were calculated based on the generated internal (IN_{ij}) and external (EN_{ij}) noise level increases and four newly developed utility functions. These utility functions were designed to transform each internal and external noise level increase to a corresponding performance score that ranges from 0 to 100, where 0 and 100 represent the worst and the best performances, respectively. These four utility functions were designed to assess the performance of varying levels of (1) internal noise on freeways, shown in Figure 215; (2) internal noise on non-freeways, shown in Figure 216; (3) external noise at 50 feet for longitudinal (shoulder and centerline) rumble strips, shown in Figure 218; and (4) external noise at 50 feet for transverse rumble strips, shown in Figure 219.

The internal noise performance utility functions for freeways and non-freeways were developed based on the NCHRP recommended range of 3 to 15 dBA for internal noise level increase (NCHRP 641, 2009). For freeways where bicyclists are not expected, NCHRP 641 (2009) recommends that "rumble strip patterns be designed to generate approximately 10 to 15 dBA above the ambient in-vehicle sound level." Accordingly, the internal performance utility function for freeways was designed to provide a score of 100 for all internal noise level increases within the range of 10–15 dBA, as shown in Figure 215. The performance score for internal noise levels that are outside of this recommended range (10–15 dBA) was designed to gradually decrease, as shown in Figure 215. The internal performance utility function for non-freeways was designed in a similar manner, as shown in Figure 216.

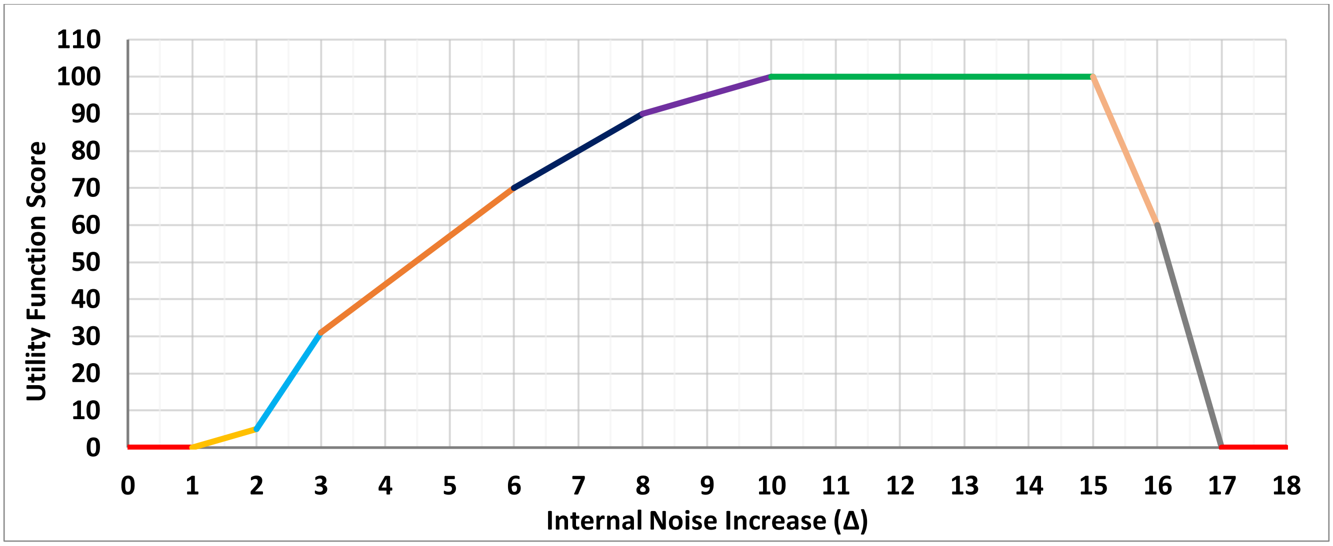


Figure 215. Graph. Internal noise performance utility function for freeways.

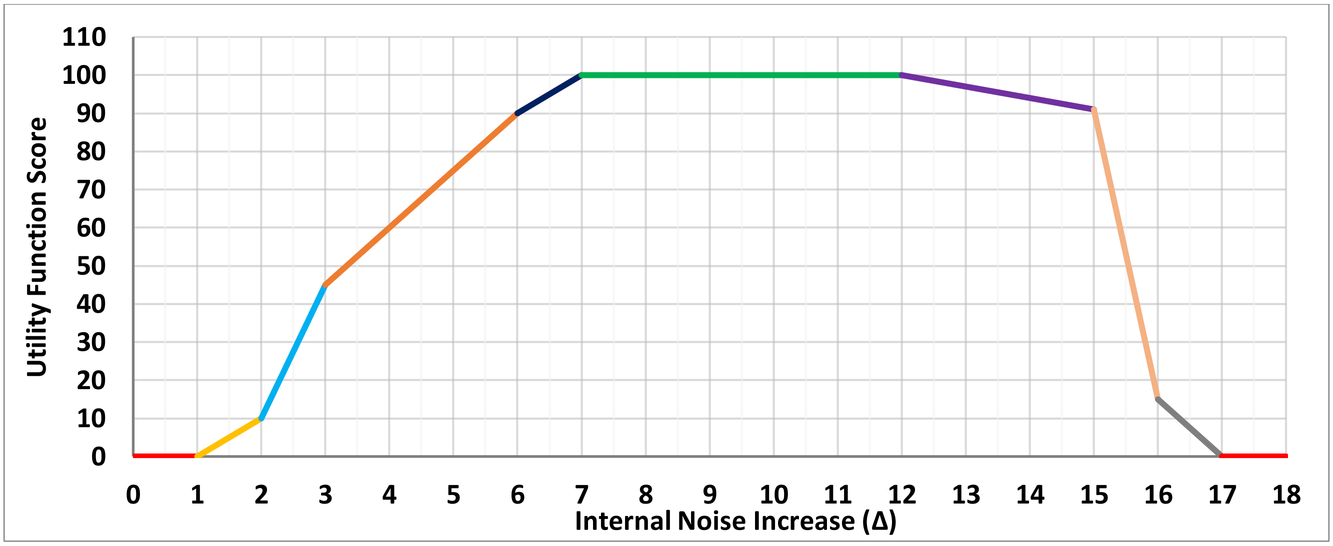


Figure 216. Graph. Internal noise performance utility function for non-freeways.

The external noise performance utility functions were designed based on IDOT noise policy, which specifies that the external noise level increase at the receptor must be less than 15 dBA (IDOT, 2017). In this tool, it is assumed that the closest distance between rumble strips and a receptor is 100 feet. The maximum allowable 15 dBA at a receptor located at 100 feet can be used to calculate a maximum allowable external noise level increase of 21 dBA at 50 feet using the noise spherical divergence equation (FHWA, 2000), as shown in Figure 217. Accordingly, the external noise utility function for longitudinal (shoulder and centerline) rumple strips was designed to provide a score of 100 for all external noise level increases that are lower than 2 dBA, slightly decline to a score of 95 at 14 dBA, and then significantly decline to a score of 0 at 21 dBA (equivalent to 15 dBA at a receptor ending at 100 feet), as shown in Figure 218. The external noise transverse utility function was designed in a similar manner with the only difference of assigning a score of 90 at 14 dBA (see Figure

219) because transverse rumble strips are continuously struck by all traveling vehicles unlike longitudinal rumble strips, which are occasionally struck by inattentive drivers.

$$\mathbf{L_2 = L_1 + 20 \times \log_{10}(\frac{d_1}{d_2})}$$

Figure 217. Equation. Noise spherical divergence equation for sound point sources.

Where

L₁ is the noise level in dBA at distance **d₁**

L₂ is the noise level in dBA at distance **d₂**

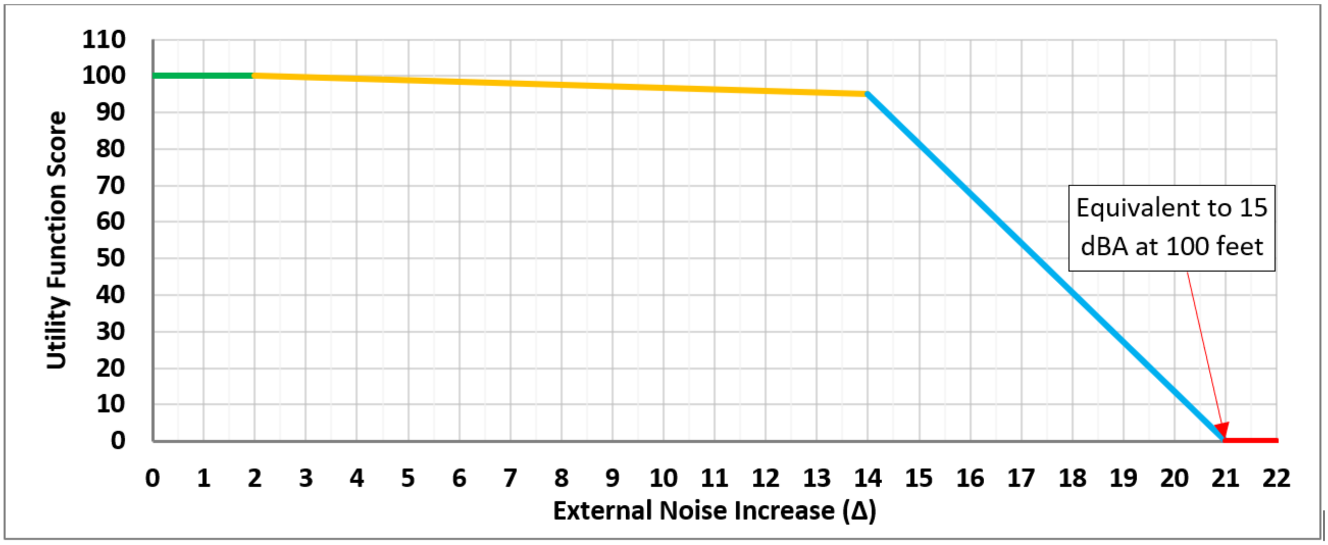


Figure 218. Graph. External noise utility function at 50 ft for longitudinal rumble strips.

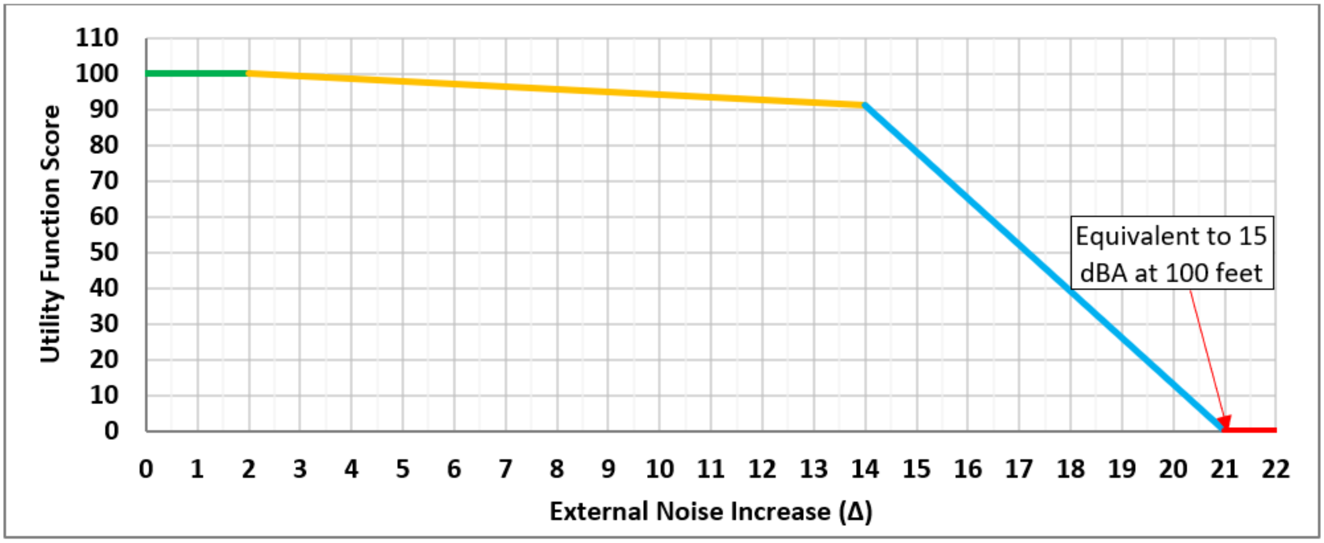


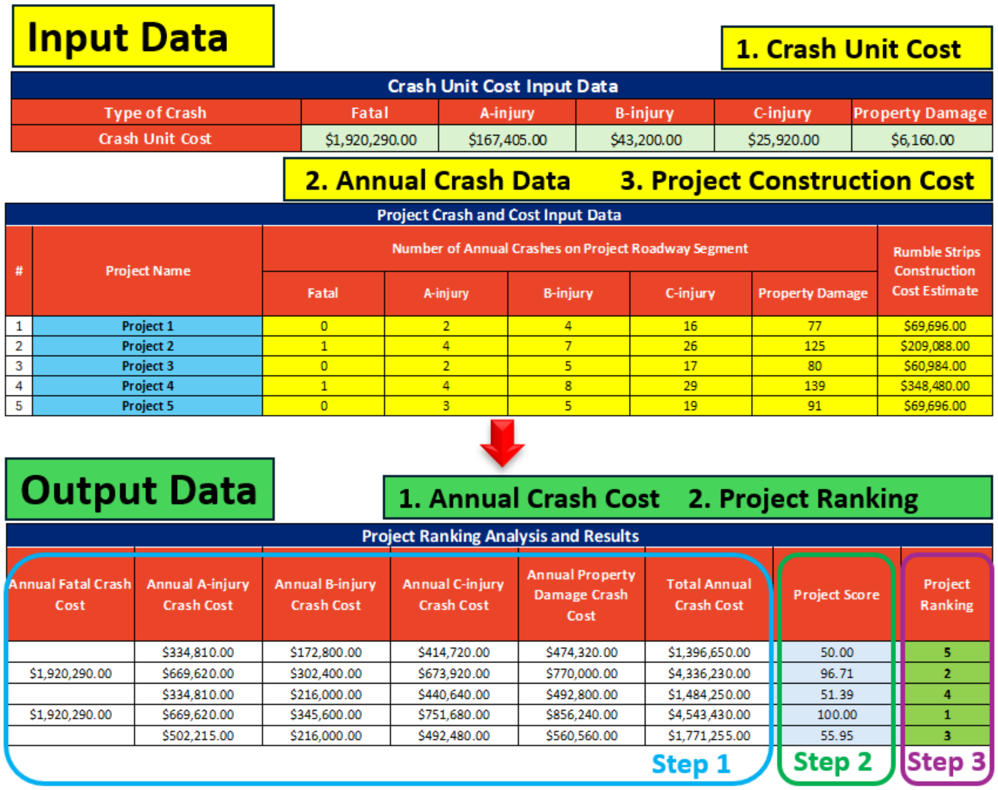
Figure 219. Graph. External noise utility function at 50 ft for transverse rumble strips.

APPENDIX G: OPTIMIZATION MODEL FOR PRIORITIZING RUMBLE STRIP PROJECTS

This appendix presents the development of an optimization model that is designed to support IDOT decision-makers in ranking and prioritizing competing rumble strip construction projects to maximize total roadway safety benefits while considering available budget for all rumble strip projects.

APPENDIX G1: RUMBLE STRIPS PROJECT RANKING

The rumble strip project ranking tool was designed to rank all competing projects based on designer-specified input data that consists of annual number of different types of crashes reported on the roadway segment within the project scope due to lack of rumble strips along with their unit crash costs that are included in the tool as default values based on 2022 IDOT crash unit costs (IDOT, 2022), as shown in Figure 220. This input data of annual number of crashes and their unit costs are required for fatal crashes, incapacitating injury (A-injury) crashes, non-incapacitating evident injury (B-injury) crashes, possible injury (C-injury) crashes, and property-damage-only crashes, as shown in Figure 220. The input data are then used by the tool to rank all competing rumble strip projects in three main steps that are designed to (1) calculate total annual crash cost (AC_i) of each rumble strip project (i), as shown in Figure 221; (2) assign a normalized project score (S_i) that ranges from 50 to 100 for each rumble strip project (i) based on its total annual crash cost; and (3) rank all competing rumble strip projects based on their normalized project scores, as shown in Figure 220.



Input Data

1. Crash Unit Cost

Crash Unit Cost Input Data

Type of Crash	Fatal	A-injury	B-injury	C-injury	Property Damage
Crash Unit Cost	$1,920,290.00	$167,405.00	$43,200.00	$25,920.00	$6,160.00

2. Annual Crash Data 3. Project Construction Cost

Project Crash and Cost Input Data

#	Project Name	Number of Annual Crashes on Project Roadway Segment					Rumble Strips Construction Cost Estimate
		Fatal	A-injury	B-injury	C-injury	Property Damage	
1	Project 1	0	2	4	16	77	$69,696.00
2	Project 2	1	4	7	26	125	$209,088.00
3	Project 3	0	2	5	17	80	$60,984.00
4	Project 4	1	4	8	29	139	$348,480.00
5	Project 5	0	3	5	19	91	$69,696.00

Output Data

1. Annual Crash Cost 2. Project Ranking

Project Ranking Analysis and Results

Annual Fatal Crash Cost	Annual A-injury Crash Cost	Annual B-injury Crash Cost	Annual C-injury Crash Cost	Annual Property Damage Crash Cost	Total Annual Crash Cost	Project Score	Project Ranking
	$334,810.00	$172,800.00	$414,720.00	$474,320.00	$1,396,650.00	50.00	5
$1,920,290.00	$669,620.00	$302,400.00	$673,920.00	$770,000.00	$4,336,230.00	96.71	2
	$334,810.00	$216,000.00	$440,640.00	$492,800.00	$1,484,250.00	51.39	4
$1,920,290.00	$669,620.00	$345,600.00	$751,680.00	$856,240.00	$4,543,430.00	100.00	1
	$502,215.00	$216,000.00	$492,480.00	$560,560.00	$1,771,255.00	55.95	3

Figure 220. Illustration. Rumble strip project ranking tool.

$$\mathbf{TC_i = FC_i \times F + AC_i \times A + BC_i \times B + CC_i \times C + PC_i \times P}$$

Figure 221. Equation. Total annual crash cost of rumble strip projects.

Where

TC_i is total annual crash cost associated of rumble strip project (i)

FC_i is annual number of fatal crashes within the scope of project (i)

F is unit cost of a fatal crash

AC_i is annual number of A-injury crashes within the scope of project (i)

A is unit cost of an A-injury crash

BC_i is annual number of B-injury crashes within the scope of project (i)

B is unit cost of a B-injury crash

CC_i is annual number of C-injury crashes within the scope of project (i)

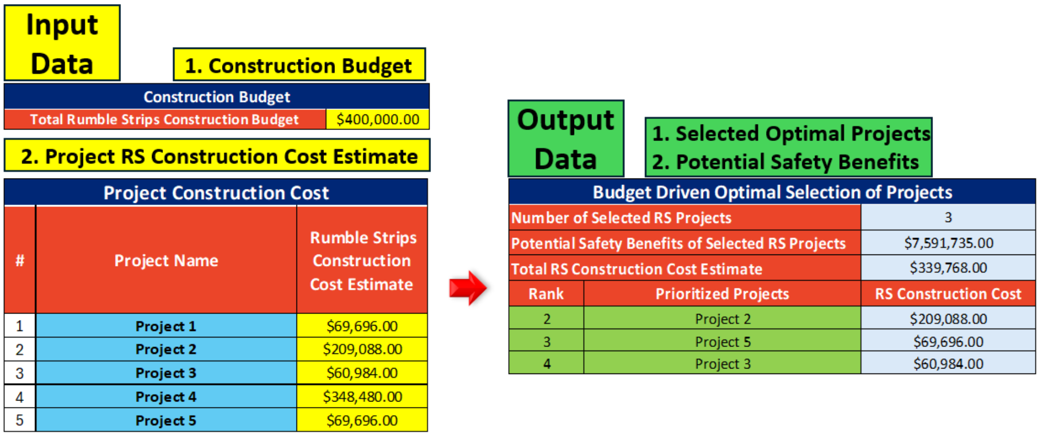
C is unit cost of a C-injury crash

PC_i is annual number of property-damage-only crashes within the scope of project (i)

P is unit cost of a property-damage-only crash

APPENDIX G2: OPTIMIZATION MODEL FOR PRIORITIZING RUMBLE STRIP CONSTRUCTION

The optimization model is designed to select an optimal set of rumble strip projects that maximizes roadway safety benefits (SB) while ensuring that their total construction cost estimates (CE) do not exceed the available construction budget (CB). The required input data in this model are total available construction budget (CB) and rumble strip construction cost estimate (CE_i) of each project (i), as shown in Figure 222. The model utilizes this input data to maximize potential roadway safety benefits (SB) by selecting an optimal set of rumble strip projects (i = 1 to n), as shown in Figure 223. The potential roadway safety benefits (SB_i) of each project (i) is calculated in this model based on its potential impact on the total annual crash cost (TC_i) resulting from the lack of rumble strips within the scope of project (i), as shown in Figure 220. The main decision variable in this optimization model (X_i) is a binary variable that represents whether each competing project (i) is selected ($X_i = 1$) or not ($X_i = 0$). The model is designed to comply with practical constraints including the limited availability of construction budget (CB), as shown in Figure 224. The model computations are performed using genetic/evolutionary algorithms that are supported by MS Excel Solver.



Input Data

1. Construction Budget

Construction Budget	
Total Rumble Strips Construction Budget	$400,000.00

2. Project RS Construction Cost Estimate

Project Construction Cost		
#	Project Name	Rumble Strips Construction Cost Estimate
1	Project 1	$69,696.00
2	Project 2	$209,088.00
3	Project 3	$60,984.00
4	Project 4	$348,480.00
5	Project 5	$69,696.00

Output Data

1. Selected Optimal Projects
2. Potential Safety Benefits

Budget Driven Optimal Selection of Projects		
Number of Selected RS Projects		3
Potential Safety Benefits of Selected RS Projects		$7,591,735.00
Total RS Construction Cost Estimate		$339,768.00
Rank	Prioritized Projects	RS Construction Cost
2	Project 2	$209,088.00
3	Project 5	$69,696.00
4	Project 3	$60,984.00

Figure 222. Illustration. Optimizing the selection of rumble strip construction projects.

$$\text{Maximize SB} = \sum_{i=1}^{i=n} SB_i = \sum_{i=1}^{i=n} TC_i.X_i$$

Figure 223. Equation. Optimization objective function.

$$\sum_{i=1}^{i=n} EC_i.X_i \leq CB$$

Figure 224. Equation. Optimization constraint.

Where

EC_i is construction cost estimate of rumble strip project (i)

X_i is binary decision variable that represents selection of project (i) ($X_i = 1$ if selected, $X_i = 0$ otherwise)

CB is available construction budget for all rumble strip projects

SB_i is potential safety benefits of rumble strip project (i)

SB is total potential safety benefits of all selected rumble strip projects

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