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16. Abstract

This report describes the methodology and results of analyses performed to (1) evaluate the impact of shoulder rumble strips (SRS) and centerline rumble strips (CRS) on the placement of vehicles in the travel lane of two-lane, undivided roadways and (2) determine the minimum shoulder width required for drivers to correct errant vehicle trajectories once alerted by passing over SRS. Field studies indicated that CRS on two-lane, undivided roadways with lane widths as narrow as 10 ft do not adversely impact the lateral placement of the vehicle in the travel lane. In fact, at locations with smaller shoulder widths (1 to 2 ft) drivers positioned the center of their vehicles closer to the center of the lane. Similar effects were found at locations with both edgeline rumble strips (ERS) and CRS. The impact of SRS located within 7 to 9 inches of the edgeline on the lateral placement of vehicles in the travel lane was less clear. However, it does appear that SRS located near the edgeline may shift vehicle travel paths closer to the centerline. In contrast, SRS located 35 inches from the edgeline did not seem to impact the lateral placement of vehicles in the travel lane. In addition, lateral offsets that position the center of 16-inch SRS in the middle of the shoulders at least 4-ft wide should provide enough remaining shoulder width for the 85th percentile distracted driver to correct their errant vehicle trajectory before leaving the paved roadway surface. Additional findings from all of the studies and detailed recommendations are discussed in the report.

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STUDIES TO DETERMINE THE OPERATIONAL EFFECTS OF SHOULDER AND CENTERLINE RUMBLE STRIPS ON TWO-LANE UNDIVIDED ROADWAYS

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Melisa D. Finley, P.E. (TX-90937).

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STATEMENT OF THE PROBLEM

From 1999 to 2001, there were approximately 26,100 serious (KAB – killed and incapacitating injury) crashes on two-lane, undivided roadways in Texas. Single vehicle run-off-road (ROR) crashes accounted for 48 percent of these crashes. In addition, 8 percent of the serious crashes were head-on and opposing-direction sideswipe crashes. Thus, these three types of crashes combined accounted for 56 percent of the serious crashes.

Recently, several volumes of National Cooperative Highway Research Program (NCHRP) Report 500 (*1*,*2*,*3*) listed continuous shoulder rumble strips (SRS) and centerline rumble strips (CRS) as countermeasures for ROR crashes and head-on and opposing-direction sideswipe crashes, respectively. Rumble strips are raised or depressed patterns on the roadway that produce audible and vibratory warnings when a vehicle's tires pass over them, thereby alerting drivers who may inadvertently encroach onto the shoulder or cross the centerline.

SRS placed near or on the edgeline provide warning to errant drivers as soon as they leave the travel lane and thus provide the largest amount of recovery area for the errant driver. While a small offset (distance from the outside edge of the edgeline to the inside edge of the rumble strip) may promote better lane keeping by reducing the frequency of inadvertent encroachments onto the shoulder, a small offset may also shift the lateral placement of vehicles in the travel lane toward the centerline (especially where travel lane widths are narrower than 12 ft). This could increase the potential for head-on and opposing-direction sideswipe crashes. SRS installed farther from the edgeline (i.e., a larger offset) could reduce any potential negative effect on vehicle lateral placement; however, at some maximum distance, it is likely that SRS will no longer warn drivers in time for them to correct their errant vehicle trajectory before leaving the paved roadway surface.

CRS provide warning to errant drivers who may be veering into oncoming traffic. However, there is concern that the lateral placement of vehicles in the travel lane may shift excessively toward the shoulder where CRS are used, especially where lane widths are less than 12 ft, and increase the potential for ROR crashes.

Research was needed to investigate the impact of SRS and CRS on the lateral placement of vehicles in the travel lane of two-lane, undivided roadways. Research was also needed to determine how much recovery time (and the related distance traveled) is required by drivers to correct their errant vehicle trajectory once they are alerted by SRS. This report describes the efforts and results of a research project that examined both of these issues.

BACKGROUND

Safety Impacts

SRS alert drivers that they are leaving the travel lane and entering the shoulder, while CRS warn drivers that they are entering the opposing travel lane. Therefore, SRS and CRS are used to reduce ROR crashes and head-on and opposing-direction sideswipe crashes, respectively. Since SRS and CRS on two-lane, undivided roadways are relatively new countermeasures, to date researchers have conducted very few crash studies, and those that have been completed have only focused on those crashes for which a safety benefit is expected. The available crash study findings are discussed below. Researchers also use surrogate safety measures, such as vehicle lateral placement in the travel lane, to evaluate the effectiveness of rumble strips. The findings from these studies are discussed later.

Shoulder Rumble Strips

Research findings have clearly shown that continuous SRS along the shoulder of freeways yield significant benefits – between 15 and 80 percent reductions in ROR crashes (*2,3,4,5*). Recently, a study in Mississippi (*6*) showed that edgeline rumble strips (ERS) on a two-lane, undivided roadway reduced right side ROR crashes by 25 percent. ERS are a form of SRS that are placed directly on the edgeline.

A Minnesota study used an Empirical-Bayes before-and-after study (*7*) to evaluate the safety-effectiveness of SRS at 23 treatment sites along approximately 183 miles of rural two-lane roadways. The installation of SRS reduced all single-vehicle ROR crashes by 13 percent and injury-producing single-vehicle ROR crashes by 18 percent.

Centerline Rumble Strips

One of the first installations of CRS systematically evaluated was in Delaware in passing zones of a rural section of a two-lane, undivided roadway. The main reason for the installation of CRS was head-on crashes. Researchers used a before-and-after study (*8*) that compared average yearly crash rates during the three years prior to installation to those during the six years after installation to assess the effectiveness of CRS. Although total annual crashes declined only 3 percent, average annual head-on crashes decreased 90 percent and crashes caused by drivers crossing the centerline decreased 60 percent. The crash severity was also reduced; despite an increase in the rate of injury crashes, fatal crashes were eliminated in the after period (even with a 30 percent increase in traffic).

The Colorado Department of Transportation (CDOT) also conducted an evaluation of CRS, installing them in no-passing zones along a 17-mile section of a two-lane, undivided mountain highway (*9*). Crash data from similar 44-month periods before and after installation showed a 22 percent reduction in head-on crashes and a 25 percent reduction in opposing-direction sideswipe crashes in spite of an 18 percent increase in the average annual daily traffic.

In the summer of 2003, the Missouri Department of Transportation (MODOT) installed CRS on a two-lane, undivided roadway. A two-year before-and-after study (*10*) showed that while the total number of crossover centerline crashes was low, the number of total crossover centerline crashes as well as severe crossover centerline crashes experienced significant reduction (60 percent and 84 percent, respectively).

It should be noted that all three of these CRS studies were based on before-and-after studies at high-crash sites. Due to the “regression to the mean” bias, the estimates of effectiveness are probably inflated to some degree.

In 2003, the Insurance Institute for Highway Safety (IIHS) conducted a more thorough investigation, analyzing crash data for 98 treatment sites along approximately 210 miles of rural two-lane roadways in seven states before and after installation of CRS (*11*). Average daily traffic (ADT) volumes at the treatment sites ranged from 5000 to 22,000 vehicles per day. Rather than conducting a simple before-and-after review, IIHS calculated the Empirical-Bayes estimate of expected crashes in the after periods of each installation and compared the estimate with the actual number of crashes to obtain the percent reduction. This analysis technique accounts for the effect of regression to the mean. The installation of CRS reduced all injury crashes by 15 percent, head-on and opposing-direction sideswipe injury crashes by 25 percent, and head-on and opposing-direction sideswipe collisions of all severities by 21 percent.

Another recent study in Massachusetts (*12*) evaluated the safety effects of CRS on three undivided roadways (number of lanes unknown). Researchers considered both targeted (head-on, angle collisions, and ROR) and total crashes at the study sites and selected comparison sites. The statistical analysis of the crash data was similar to that used in the IIHS study. The results showed no significant change in crash frequencies before and after the installation of centerline rumble strips. However, no fatal crashes occurred at two of the sites after the installation of CRS, suggesting that CRS are potentially effective at reducing the severity of crashes.

Operational Impacts

While research has shown that SRS and CRS on two-lane, undivided roadways significantly reduce targeted crashes, there are still questions about the operational impacts of these applications and their potential safety implications. Table 1 contains the key operational issues that need to be considered when developing guidelines for the placement of SRS and CRS on two-lane, undivided roadways. Below is an overview of these key issues and their interactions. The sections immediately following the overview contain a more in-depth discussion of each issue, including a review of previous research findings.

Table 1. Key Operational Issues.

Operational Issues	SRS	CRS
Impact on lateral placement of vehicles in a travel lane (especially where lane widths are less than 12 ft)	X	X
Impact on errant vehicle corrections and distracted driver reactions	X	X
Impact on certain types of vehicles (e.g., bicycles, motorcycles, wide loads, vehicles with trailers, mail carriers, and/or farm equipment)	X	X
Impact on surrounding environment (i.e., noise pollution)	X	X
Impact on shoulder usage under circumstances that induce encroachment	X	
Impact on passing maneuvers		X

In order for SRS and CRS on two-lane roadways to be effective, drivers must be alerted in enough time to correct their vehicles' trajectory once they realize they are veering outside their travel lane. SRS placed near or on the edgeline provide warning to errant drivers as soon as they leave the travel lane and thus provide the largest amount of recovery area for the errant driver. In addition, a small offset allows the remainder of the shoulder to be utilized by other users, such as bicyclists, and provides them with the maximum clear shoulder. A small offset may also promote better lane keeping by reducing the frequency of inadvertent encroachments onto the shoulder. However, a small offset may shift the lateral placement of vehicles in the travel lane toward the centerline, especially where travel lane widths are narrower than 12 ft, and thus potentially increase head-on and opposing-direction sideswipe crashes. A small offset may also cause increases in the frequency of hits on the rumble strip and thus increase the noise in the surrounding community. In addition, a small offset may adversely affect wide loads, vehicles towing trailers, and shoulder usage under circumstances that induce encroachment (e.g., during the presence of emergency vehicles, occurrence of dangerous actions by other drivers that require evasive maneuvers, vehicles using the shoulder to let faster vehicles pass, vehicles using the shoulder during hurricane evacuations, and the need to avoid turning vehicles).

Moving SRS further from the marked edgeline (i.e., a larger offset) may reduce the frequency of hits on the rumble strips by wide loads and vehicles towing trailers and thus reduce ambient noise. In addition, it would allow bicyclists to travel freely between the travel lane and the shoulder without traversing over the rumble strip. With sufficient offset and shoulder width, it would also allow vehicles to straddle the rumble strip when driving on the shoulder (e.g., vehicles using the shoulder to let faster vehicles pass, vehicles using the shoulder during hurricane evacuations, and slow-moving vehicles and equipment). However, a larger offset reduces the amount of recovery area available for drivers to correct their errant vehicles' trajectory before leaving the paved roadway surface. Previous research (*13*,*14*) has shown that for every foot the rumble strip is offset from the edge of the travel lane, there is an additional 0.03 second delay in warning.

Similar to SRS, CRS may adversely affect certain types of vehicles (e.g., wide loads, vehicles towing trailers, and motorcycles) and increase the noise in the surrounding community, especially if used in passing zones. In addition, CRS in passing zones may inhibit passing maneuvers (due to the noise and vibrations experienced when passing over them). CRS may also excessively shift the lateral placement of vehicles in the travel lane toward the shoulder, which could increase the potential for ROR crashes and vehicle-bicycle collisions (drivers may crowd bicyclists rather than move left across the CRS when passing the bicyclists). There is also concern that drivers accustomed to right-side SRS will "jerk" the steering wheel to the left when encountering CRS.

Impact of SRS and CRS on the Lateral Placement of Vehicles in a Travel Lane

In a recent Texas Transportation Institute (TTI) study (*15*), researchers evaluated the effect of milled ERS on the lateral placement of vehicles on a rural, undivided, two-lane roadway with 11-ft travel lanes and approximately 9-ft shoulders. Researchers found that ERS significantly decreased shoulder encroachments caused by natural lane shifting, wide loads, swaying trailers, and driver inattention by approximately 47 percent. The largest total decrease occurred in encroachments when only the right tires contacted the rumble strips (i.e., minor shoulder encroachments). Straddling maneuvers decreased for two-axle vehicles but increased for vehicles with three or more axles. Researchers hypothesized that the drivers of wide loads and trailers wished to avoid constant contact with ERS. There was a statistically significant decrease in mean lateral position, corresponding to vehicle positions farther onto the shoulder. Researchers attributed this to the proportionately smaller reductions in more major encroachments.

In the same study (*15*), TTI researchers also investigated whether CRS impacted vehicle lateral placement in a travel lane at four sites. Two of these sites were undivided, two-lane roadways, while the other two sites were undivided, four-lane roadways. Only one of the two-lane sites had shoulders. In addition, some of the sites were located on curves, while other sites were located in tangent sections. Researchers evaluated two raised CRS designs. One design used yellow pavement buttons placed every 4 ft adjacent to the outside edges of the centerline markings. The other design consisted of black pavement buttons staggered every 4 ft along the inside edges of the centerline markings. Frequency of inadvertent contact with the centerline decreased with the installation of CRS. The majority of drivers shifted their vehicles' lateral position farther from the centerline pavement markings after the installation of raised CRS, resulting in an increase in vehicle separation (i.e., the lateral distance between opposing traffic streams). Yellow pavement buttons placed in the travel lanes adjacent to the outside edge of the centerline markings appeared to have a greater impact on lateral position than staggered black pavement buttons.

A Pennsylvania Department of Transportation (PennDOT)-sponsored study (*16*) looked at lateral placement of vehicles from the standpoint that quantifying the operational characteristics of rumble strips may be a potential indicator of safety. The premise was that vehicle paths located near the center of the travel lane may result in a higher level of safety, and that a reduction in the variance of lateral placement may lead to lower crash rates (*17*). Thus, if rumble strips help drivers maintain proper lateral placement, crashes would decline and safety would improve. The results of the field data collection and subsequent analysis suggested that the presence of milled CRS on undivided, two-lane roadways affected both the mean and variance of lateral vehicle placement for both 12-ft and 11-ft lanes. Before rumble strip installation, the mean lateral placements were about 2 inches and 6 inches to the right of a centered vehicle path for 12-ft and 11-ft lanes, respectively. After the installation of rumble strips, the mean lateral placements of the vehicle paths were about 7.5 and 9 inches to the right of a centered vehicle path. Thus, the mean lateral placement shifted 5.5 inches and 3 inches away from the centerline after the CRS were applied for 12-ft and 11-ft lanes, respectively. However, the variance of the lateral placement decreased significantly after the installation of CRS for both lane widths.

Impact of SRS and CRS on Vehicle Corrections and Driver Reactions

Correcting the Vehicle into the Oncoming Lane. A common concern with the use of CRS is whether drivers who have been conditioned to adjust their vehicle to the left when crossing SRS will do the same when crossing CRS, which would send them further into the oncoming lane. Researchers at the University of Massachusetts-Amherst, conducting a research study for the Massachusetts Highway Department, utilized a full-scale driving simulator to evaluate the behavior and reaction of 60 drivers as they encountered rumble strips on a rural two-lane roadway (*12*). A review of the driving trajectory data showed that approximately 27 percent of drivers initially corrected left (versus right) after encountering CRS.

As a comparison, an evaluation was completed on the SRS encounters to determine how many drivers corrected right instead of in the desired left direction. From review of the observations and simulator data, the results showed that no drivers initially corrected right when encountering SRS. Further, drivers appeared more comfortable when they encountered SRS, whereas they were alarmed when they encountered CRS. The researchers concluded that although the result could have been due to conditions inherent in simulator studies, the possibility exists that drivers may correct left instead of right with CRS because of previous a priori expectancies and should be further studied. It should be noted that in this study the subjects were first exposed to right SRS and then to CRS.

In the TTI study previously discussed (*15*) researchers also investigated erratic maneuvers (i.e., hard braking, swerving, rapid alignment or lane shifting, correcting trajectory in the wrong direction, and loss of vehicle control) for both CRS and ERS. While it was originally intended to count the number of erratic maneuvers by type that occurred before and after the installation of CRS and ERS, researchers observed no erratic maneuvers after reviewing approximately 170 hours of video (50 hours for CRS and 120 hours for ERS). Hence, neither type of rumble strip induced erratic maneuvers. Furthermore, researchers did not detect any drivers initially correcting left when contacting CRS prior to returning to the original travel lane, and every vehicle encroachment onto the ERS consisted of a smooth transition.

Minimum Lateral Space for Vehicle Correction. As previously discussed, the lateral offset of SRS from the travel way affects the amount of recovery area available for the errant driver. In order to determine the minimum shoulder width needed for drivers to perceive the SRS warning and correct their errant vehicle trajectory, several factors including departure angle, driver reaction times to auditory and vibratory stimuli, and how drivers physically react to auditory and vibratory stimuli (i.e., steering, braking, etc.) are needed.

Vehicle departure angle is a function of the steering angle and the curvature of the roadway. Along a tangent section, a vehicle follows a certain path as it exits the travel lane. If this same vehicle path occurs on a horizontal curve, the resulting departure angle will be larger. As the vehicle departure angle increases, the exposure time to stimuli generated by SRS and the available recovery distance decreases. Previous studies (*18*,*19*,*20*) have indicated that the average departure angle for ROR crashes ranges between 3 and 8 degrees. However, it is not clear whether these analyses included crashes in tangent sections, at horizontal curves, or both. Regardless, the research results indicate that ROR crashes typically occur at shallow departure angles.

Driver reaction times differ based on the cognitive state of the driver. Intuitively, inattentive drivers have quicker reaction times than drivers who have fallen asleep. In the University of Massachusetts-Amherst study previously discussed (*12*) researchers also determined the amount of time it took the participants to return to their travel lane once they encountered rumble strips. When encountering SRS and CRS, participants took on average 1.94 seconds and 1.67 seconds, respectively, to return to their travel lane. Thus, participants took approximately 250 milliseconds more time to return to the travel lane after encountering SRS compared to encountering CRS. Researchers observed that the participants appeared more comfortable when they encountered SRS, which might explain the significantly longer time to return to the travel lane. A comparison between the times to return to the travel lane when CRS were or were not present implied that the geometry of the road (curved or straight) has an effect on the time to return to the travel lane when CRS are present.

In a more recent European driver simulator study (*21*), researchers induced drowsiness-related lane departures to assess visual reaction time and overall reaction time to an auditory warning. The auditory warning used was a simulated rumble strip noise. Overall reaction time was defined as the time gap between the beginning of the auditory warning and the first change in the steering angle passing a threshold of 1 degree. Researchers used a 1-degree threshold to exclude involuntary movements of the steering wheel. The visual reaction time was defined as the time gap between the opening of the eyes for at least 25 percent of the iris and the instant of the steering reaction of the driver. Figure 1 shows both reaction times. Researchers also collected lateral offset and steering wheel angle data, but these data were not analyzed.

Researchers found that the average reaction time to the simulated rumble strip noise was 0.44 second with a standard deviation of 0.17 second. Researchers also found that the steering reactions are too fast to be initiated by the visual impression of the driving scene alone. Thus, in addition to acting as a wake-up call, auditory warnings can influence human actions.

Impact of SRS and CRS on Certain Types of Vehicles

The installation of SRS and CRS on undivided, two-lane roads may be perceived by some users to adversely affect certain types of vehicles. To date, one of the biggest concerns regarding SRS has been bicycles. However, motorcycles, wide loads, vehicles with trailers, and mail carriers may also be adversely impacted.

Bicycles. As previously discussed, SRS placed near the edgeline generate the maximum clear shoulder for bicycles. Furthermore, they place a warning between errant vehicles and bicyclists. However, this small offset can force bicyclists to travel on the outside (right) portion of the shoulder, which may contain debris. Garder (*22*) and Moeur (*23*) both acknowledged that the air turbulence from passing vehicles pushes debris from the travel lane onto the shoulder. For this reason, bicyclists prefer to travel on the portion of the shoulder nearest to traffic since this area is typically relatively clear of such debris. SRS placed further from the marked edgeline allow bicyclists to travel freely between the travel lane and the shoulder when they need to avoid debris, make turns, or avoid other shoulder users.

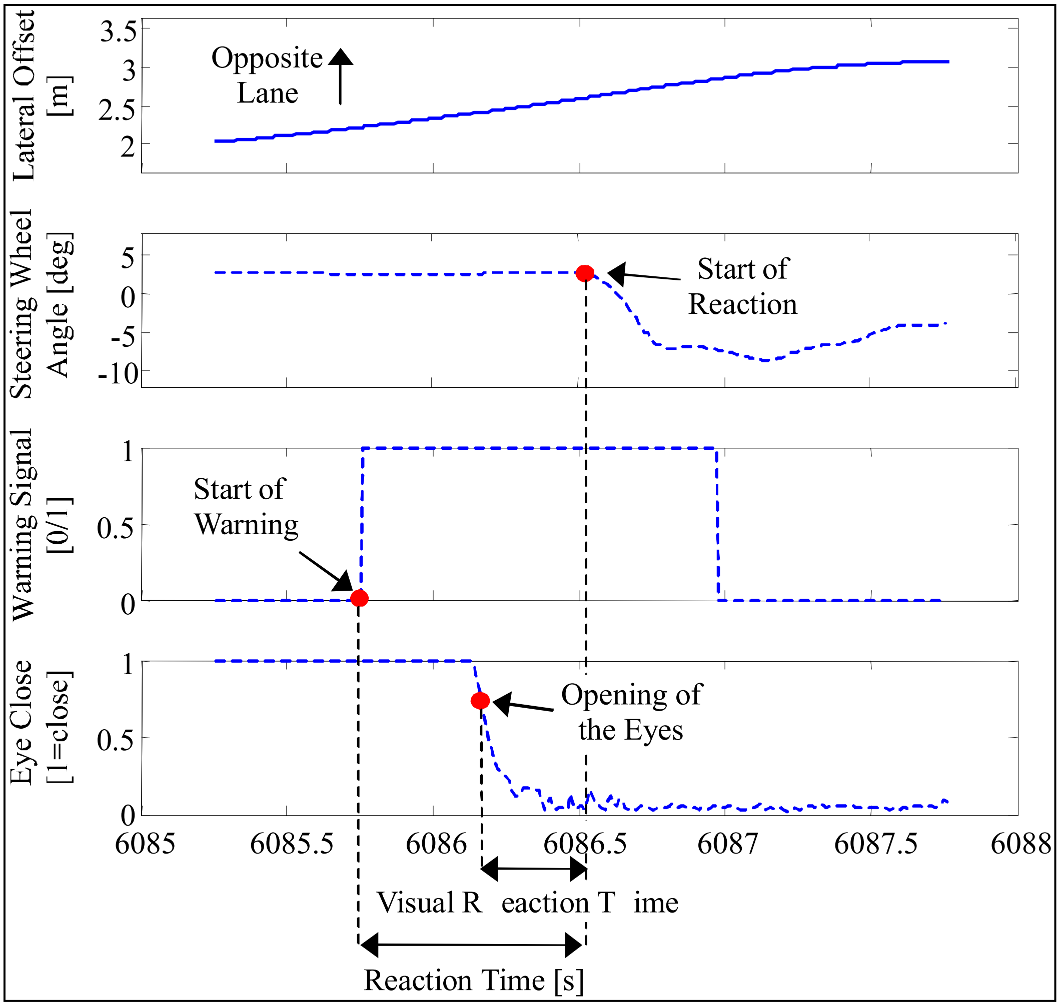


Figure 1. Example Lane Departure Warning Situation Showing Overall Reaction Time and Visual Reaction Time (*21*).

To date, several studies (*22,23,24,25,26,27*) have investigated the incompatibilities between SRS and bicycles. Most of these studies have focused on developing a "bicycle-tolerable" rumble strip pattern instead of examining the optimal lateral placement of SRS.

In 2000, 28 bicyclists evaluated various SRS sections with intermittent breaks (i.e., no rumble strips) to determine acceptable patterns (*23*). Researchers determined that 12-ft breaks in milled-in SRS would acceptably permit bicyclists to cross at high speeds (assumed to be between 23 and 28 mph), and either 40-ft or 60-ft cycles for the break pattern were acceptable.

A similar study by Torbic et al. (*24*) developed new SRS configurations for PennDOT that decrease the level of vibration experienced by bicyclists while providing adequate amount of stimulus to alert inattentive or drowsy drivers. Researchers utilized simulation and field evaluations to assess six configurations. The researchers recommended the adoption of two "bicycle-tolerable" rumble strip configurations, one for non-freeway facilities operating near 55 mph and the other for those operating at 45 mph. Both configurations have a transverse width of 16 inches (measured perpendicular to the travel direction), a groove width of 5 inches (measured parallel to the travel direction), and a depth of 0.39 inch. The flat portion between each groove was 7 inches and 6 inches, respectively.

In 2001, the California Department of Transportation (Caltrans) performed a study of various SRS designs (*25*) based on the work done by Torbic et al. The recommendation of the study was to replace the existing rolled SRS design with a milled SRS design that is 1 ft in transverse width and 0.3125 ± 0.0625 inch in depth on shoulders that are at least 5 ft wide. For shoulders less than this width, the installation of raised/inverted profile thermoplastic was recommended.

Another study in 2001 compared various styles of SRS in Colorado (*26*). The study included input from 29 bicyclists as well as vibration and auditory data collected in four different types of vehicles. The SRS that provided the most noticeable vibration and auditory stimuli to the vehicle were rated worst by bicyclists. The study recommended milled SRS with a depth of 0.375 ± 0.125 inch (3/8 inch ± 1/8 inch) on 12-inch centers in a pattern of 48 ft of SRS followed by 12 ft of gap (i.e., no SRS present in gap).

One study conducted in 2001 by Elefteriadou et al. (*27*) examined the lateral offset of SRS and its impact on bicyclists. In this study, researchers developed conceptual designs for rumble strips placed on roads with narrow or non-existent shoulders so that 1) their installation does not compromise the integrity of the pavement, 2) their location and/or type are acceptable to bicyclists, and 3) they can alert inattentive drivers. Researchers also created two methods for determining the optimum placement of rumble strips within the roadway cross-section. The first method was based upon the concept that for rumble strips to fulfill their intended purpose, the clear zone should be greater than the steering adjustment area. The clear zone was defined as the lateral distance between the edgeline and the nearest fixed object located in the roadside. To estimate the steering adjustment area, researchers calculated the diagonal distance traversed by the errant vehicle. Using this diagonal distance and the departure angle, the lateral distance or steering adjustment area was computed.

The decision tree developed by researchers stated that if the required steering adjustment area is larger than the clear zone, then rumble strips installed along the edgeline or on the shoulder will not be effective. If the steering adjustment area equals the clear zone and the shoulder width is greater than or equal to 4 ft, then install rumble strips on the marked edgeline. If the steering adjustment area equals the clear zone and the shoulder width is less than 4 ft and the width of the travel lane is less than 10 ft, do not install rumble strips on the marked edgeline because there will not be sufficient room to accommodate bicyclists. If the steering adjustment area is less than the clear zone and the shoulder width is less than 4 ft, install rumble strips on the shoulder at a distance from the marked edgeline such that the steering adjustment area does not extend beyond the clear zone boundary. If the steering adjustment area is less than the clear zone and the shoulder width is between 4 and 6 ft, install rumble strips close to or on the marked edgeline so that at least 4 ft to the right of the rumble strip is provided for bicyclists.

The second method uses the roadside hazard rating system to determine the optimum placement of rumble strips within the roadway cross-section. If the roadside hazard rating is 5 or higher (site has the potential for more severe crashes), rumble strips should be centered along the center of the edgeline. If the roadside hazard rating is 4 or lower (site has lower potential for severe crashes), the rumble strips should be placed on the outside (right) portion of the shoulder to provide an unobstructed area for bicyclists along the edge of the travel way. Such a placement also allows bicyclists to move between the travel lane and shoulder without traversing the rumble strip.

The American Association of State Highway and Transportation Officials (AASHTO) *Guide for the Development of Bicycle Facilities* (*28*) states that rumble strips or raised pavement markers are not recommended where shoulders are used by bicyclists unless there is a minimum clear path of 1 ft from the rumble strip to the travel way, 4 ft from the rumble strip to the outside edge of the paved shoulder, or 5 ft to adjacent guardrail, curb, or other obstacle. In addition, this document states that the accepted useable shoulder width required for a bicycle to travel is 4 ft.

In a 2001 technical advisory (*29*), the Federal Highway Administration (FHWA) supported these statements by recommending that SRS should not normally be used when the installation of SRS leaves a clear shoulder less than 4 ft wide. The FHWA also recommended that a modified design be used along shoulders 6 or 8 ft wide when the remaining available clear shoulder width is less than 6 ft and the road can be used by bicyclists. The recommended treatment for roadways with 10-ft shoulders is standard milled rumble strips, installed as close to the marked edgeline as practical, as long as an 8-ft clear shoulder width remains available after the installation of the rumble strip.

Other Types of Vehicles. In addition to bicycles, there is also the possibility of adverse effects on motorcycles. There is concern that motorcycle wheels may get caught in a rumble strip, thereby interfering with the steering of the bike, and potentially result in a crash. This could be more problematic if CRS are used in passing zones. However, investigations in Pennsylvania (*1*) and Massachusetts (*22*) with motorcycle groups have indicated no maneuverability problems and no major concerns by the groups. Even so, some states (e.g., Utah and Idaho) install warning signs to notify drivers that the roadway has CRS.

SRS and CRS on undivided, two-lane roadways may also negatively affect wide loads, vehicles with trailers, and mail carriers. As discussed previously, a recent TTI study (*15*) found that ERS increased the number of three or more axle vehicles that straddle the edgeline by 71 percent. Presumably, these were drivers of wide loads and trailers that could not keep their vehicles positioned entirely within the lanes and wished to avoid constant contact with ERS. To date, the effect on mail carriers that travel at slower speeds along wide shoulders has not been investigated.

Impact of SRS and CRS on Surrounding Environment

Several studies (*30*,*31*,*32*) have measured the noise created when a vehicle travels over SRS and found that the increase in ambient noise ranges from 2 to 19 decibels (dB), yielding ambient noise levels between 77 and 94 dB. However, none of these studies assessed the frequency of hits or the duration of the hits based on lateral offset, shoulder width, and adjacent lane width.

A Utah study (*33*) looked at noise pollution and complaints resulting from CRS; researchers found concerns similar to those with SRS. One of the greatest concerns of CRS was the side effects of noise to roadside residences and businesses, but researchers found no previous research attempting to maintain the effective sound levels of CRS while responding to the excess noise concerns of nearby residents or businesses. They found that the approach to remediation of noise pollution varied dramatically between states. The options given by various states included:

- avoid placement of rumble strips in populated locations unless crash data show a high potential for crash reduction in that specific area;
- build sound-wall construction;
- use shallower installation depths;
- use CRS in no-passing zones;
- inform residents prior to installation, but no efforts made to reduce noise; and
- run CRS continuously past driveways as safety devices, that is, impose no restrictions.

The Utah study concluded that avoiding the placement of rumble strips in populated areas was the only way to eliminate noise. Using sound-walls, reducing the rumble strip depth, and limiting installations to no-passing zones are methods of limiting the excess noise generated by rumble strips.

The Transportation Association of Canada (TAC), in its Synthesis of Best Practices (*34*), discussed noise generated by SRS and CRS. According to TAC, studies show that rumble strips terminated 656 ft away from residential or urban areas produce tolerable noise impacts on residences. At an offset of 1640 ft, the noise from rumble strips is negligible.

Impact of SRS on Shoulder Usage under Circumstances that Induce Encroachment

Under some circumstances, such as the presence of emergency vehicles, the need to complete evasive maneuvers, and the need to avoid left-turning vehicles, it is acceptable to encroach onto the shoulder. In addition, in Texas it is common practice for slower moving vehicles to pull onto the shoulder to let faster vehicles pass.

The recent TTI study (*15*) previously discussed also investigated the effect of ERS on shoulder usage under circumstances that induce encroachment on a two-lane roadway with 11-ft travel lanes in both directions and approximately 9-ft shoulders. Researchers found that the frequencies of shoulder encroachment for emergency and passing situations were not significantly affected by the installation of ERS. In other words, the installation of ERS did not discourage drivers from pulling onto the shoulder to allow emergency vehicles to pass, to complete evasive maneuvers, or to allow faster moving vehicles to pass. Researchers did find a significant decrease in turning encroachment volumes (i.e., drivers using the shoulder to pass left-turning vehicles) after the installation of ERS. However, this decrease might have been caused by a proportionate decrease in turn-conflict frequencies, not the influence of ERS on driver behavior.

In addition, researchers looked at the lateral position of vehicles during shoulder usage. Lateral position was defined as the distance away from the paved outside edge of the shoulder, with a position of zero on the paved outside edge and the maximum position on the inside edge of the edgeline. The lateral position of vehicles during emergency and turning situations was not significantly affected by the installation of ERS. In passing situations, drivers of two-axle vehicles were more likely to pull completely onto the shoulder when allowing a faster vehicle to pass (56 percent increase) after the installation of ERS. The effect of ERS on passing maneuvers by vehicles with three or more axles was neutral.

Impact of CRS on Passing Maneuvers

Some have speculated that the use of CRS in passing zones might have some negative operational effects by inhibiting passing maneuvers (i.e., driver may not want to experience the noise and vibration caused by crossing over the CRS). However, several states currently using CRS have not reported such problems (*1*).

Researchers at TTI also investigated the impact of CRS on passing operations in a recent Texas Department of Transportation (TxDOT)-sponsored project (*15*). One design of CRS was milled continuously in no-passing and passing zones along the centerline of a rural, undivided, two-lane highway between the cities of Comanche and Dublin in north-central Texas. Researchers found that the number of centerline encroachments by a passing vehicle prior to starting a pass did not significantly change after the installation of CRS, nor did the percentage of vehicles passing significantly change with the installation of CRS. Thus, the application of CRS in passing zones does not appear to hinder passing maneuvers.

Maintenance Impacts

One of the maintenance concerns related to rumble strips is the impact on pavement durability. States that have installed SRS and CRS on undivided, two-lane roadways have not reported any additional maintenance requirements as long as the rumble strips are placed on pavement that is in good condition (*1*). According to the FHWA**,** there appears to be little early deterioration of milled shoulder rumble strips on either cement concrete or asphalt pavements. There are also no apparent problems with installation or faster deterioration of rumble strips on open-graded pavements (*35*). Even so, most states do not install depressed CRS on bridge decks, concrete bridge approaches, and existing concrete pavement with overlay less than 2.5 inches in depth (*36*).

There are also concerns about ice and snow buildup in the grooves as well as cleaning the accumulations of debris in the grooves. Field tests refute concerns about the effects of the freeze-thaw cycle as water collects in the grooves. These tests show that vibration and the action of wheels passing over the rumble strips in fact knock debris, ice, and water out of the grooves. Of course, snow removal does play havoc with raised rumble strips. Snowplow blades passing over raised rumble strips tend to scrape them off the road surface, which is why raised rumble strips are usually restricted to use in areas that do not contend with snow removal (like most of Texas) (*35*).

One potential maintenance advantage of rumble stripes (where traditional pavement markings are applied on top of rumble strips) is longer pavement marking service life since drivers may be less likely to hit the rumble strips and thus the pavement markings applied on top of them. In addition, researchers have found that rumble stripes increase wet-night visibility when rainfall reaches an average rate or greater (*37*). However, SRS placed near or on the edgeline may be filled in when travel lane pavement maintenance such as a seal coat or an overlay occurs. On the contrary, SRS placed further from the edgeline would not be impacted unless the shoulder was also being maintained.

SUMMARY

Before installing SRS or CRS on two-lane, undivided roadways one must consider the potential safety, operational, and maintenance impacts. The discussion above summarized previous research efforts that explored these potential impacts. Below is a summary of the findings.

- Safety Impacts – SRS and CRS significantly reduce targeted crashes (i.e., ROR crashes and head-on and opposing-direction sideswipe crashes, respectively).
- Impact on Lateral Placement of Vehicles in Travel Lane – ERS significantly decrease minor shoulder encroachments (i.e., right tire contact). The installation of CRS on roadways with 11 ft and 12 ft lanes shifted the mean lateral placement of vehicle paths further to the right of a centered vehicle path. However, the variance of the lateral placement decreased significantly after the installation of CRS for both lane widths.
- Impact on Vehicle Corrections and Driver Reactions – Field studies did not detect any drivers initially correcting left prior to returning to the original travel lane when contacting CRS, and contact with ERS resulted in smooth transitions back into the travel lane. Driver reaction times to rumble strips have only been studied in driver simulators.
- Impact on Certain Types of Vehicles – Various “bicycle-tolerable” SRS configurations have been developed. Where shoulders are used by bicyclists, SRS should not normally be used when the installation of SRS leaves a clear shoulder less than 4 ft wide. Motorcycle groups have indicated no maneuverability problems when encountering CRS. Even so, some states install warning signs to notify drivers that the roadway has CRS. Field studies showed that ERS increase the number of three or more axle vehicles that straddle the edgeline, presumably to avoid contact with ERS.
- Impact on Surrounding Environment – Noise generated by SRS and CRS is an issue, especially in more populated areas. Remediation approaches vary dramatically between states.
- Impact on Shoulder Usage – Frequency of shoulder usage under circumstances that induce encroachment (i.e., emergency and passing situations) was not significantly affected by the installation of ERS.

- Impact on Passing Maneuvers – CRS in passing zones do not appear to hinder passing maneuvers.
- Maintenance Impacts – There are concerns related to pavement durability and ice and snow buildup in the depressions. While no apparent problems have been verified to date, most states do not install depressed rumble strips on bridge decks, concrete bridge approaches, and on pavements less than a specified thickness. Rumble stripes (traditional pavement markings applied on top of rumble strips) increase wet-night visibility. However, SRS placed near or on the edgeline may be filled in when travel lane pavement maintenance such as a seal coat or an overlay occurs.

While a few studies have investigated the impact of SRS or CRS on the lateral placement of vehicles in the travel lane of two-lane, undivided roadways, research was needed to assess the impacts across a range of travel lane widths, shoulder widths, and SRS lateral offsets. In addition, actual in-vehicle research was needed to determine how much recovery time (and the related distance traveled) is required by drivers to correct their errant vehicle trajectory once they are alerted by SRS.

CONTENTS OF THIS REPORT

This report describes the methodology and results of analyses conducted to 1) evaluate the impacts of SRS and CRS on the placement of vehicles in the travel lane of two-lane, undivided roadways and 2) determine the minimum shoulder width required for distracted drivers to correct errant vehicle trajectories once alerted by passing over SRS. Based on the findings, researchers made recommendations regarding the use of SRS and CRS on two-lane, undivided roadways based on shoulder width and adjacent lane width, as well as the optimal placement of SRS on the shoulder.

CHAPTER 2:
STATE-OF-THE-PRACTICE

INTRODUCTION

In order to determine the state-of-the-practice of SRS and CRS on two-lane, undivided roadways, in 2006 TTI researchers reviewed previous syntheses and other surveys conducted on nationwide practices, searched the websites of all 49 state departments of transportation (DOTs) for information on rumble strip installation practices, particularly as they pertained to two-lane, undivided roadways, and corresponded with state agency personnel in states known to be evaluating the use of SRS and CRS on two-lane roadways. TTI researchers also conducted telephone interviews with 33 TxDOT personnel. At least one person from each TxDOT district was interviewed. Topics discussed included the following:

- whether or not the district has installed or plans to install SRS or CRS on two-lane, undivided roadways;
- specific locations where SRS and CRS are installed or planned to be installed;
- characteristics of the roadway (e.g., average daily traffic, lane width, shoulder width, posted speed limit, etc.);
- characteristics of SRS and CRS (e.g., type, width, length, spacing, offset from edgeline marking, etc.);
- input with regard to the design of SRS and CRS (e.g., offset from edgeline, minimum lane and shoulder width, etc.); and
- concerns regarding the use of SRS and CRS on two-lane, undivided roadways.

NATIONWIDE IMPLEMENTATION

Figure 2 shows the nationwide status of SRS installations on two-lane, undivided roadways. The research team obtained information about SRS from 42 of the 49 states outside of Texas (86 percent). Of these states, 60 percent install SRS on two-lane, undivided roadways. Conversely, 19 percent do not allow SRS to be installed on two-lane, undivided roadways. The other 21 percent did not specify the roadway types on which SRS can be installed. Information from states currently installing SRS on two-lane, undivided roadways showed that most states (76 percent) are following the practice of installing SRS 0 to 12 inches from the outside edge of the edgeline, but some states (8 percent) allow SRS to be placed on the edgeline or offset SRS by more than 12 inches (12 percent). In fact, one state allows an SRS offset up to 26 inches. In addition, most state agencies (36 percent) specify that rumble strips may not be installed on shoulders less than 4 ft in width. However, minimum paved shoulder width requirements range from 2 to 8 ft. In the majority of the states, depressed SRS on two-lane roads are 0.5 to 0.625 inch deep, 7 inches long (measured parallel to the travel way), 16 inches wide (measured perpendicular to the travel way), and spaced 5 inches apart (distance between back edge of one rumble strip to front edge of next rumble strip).

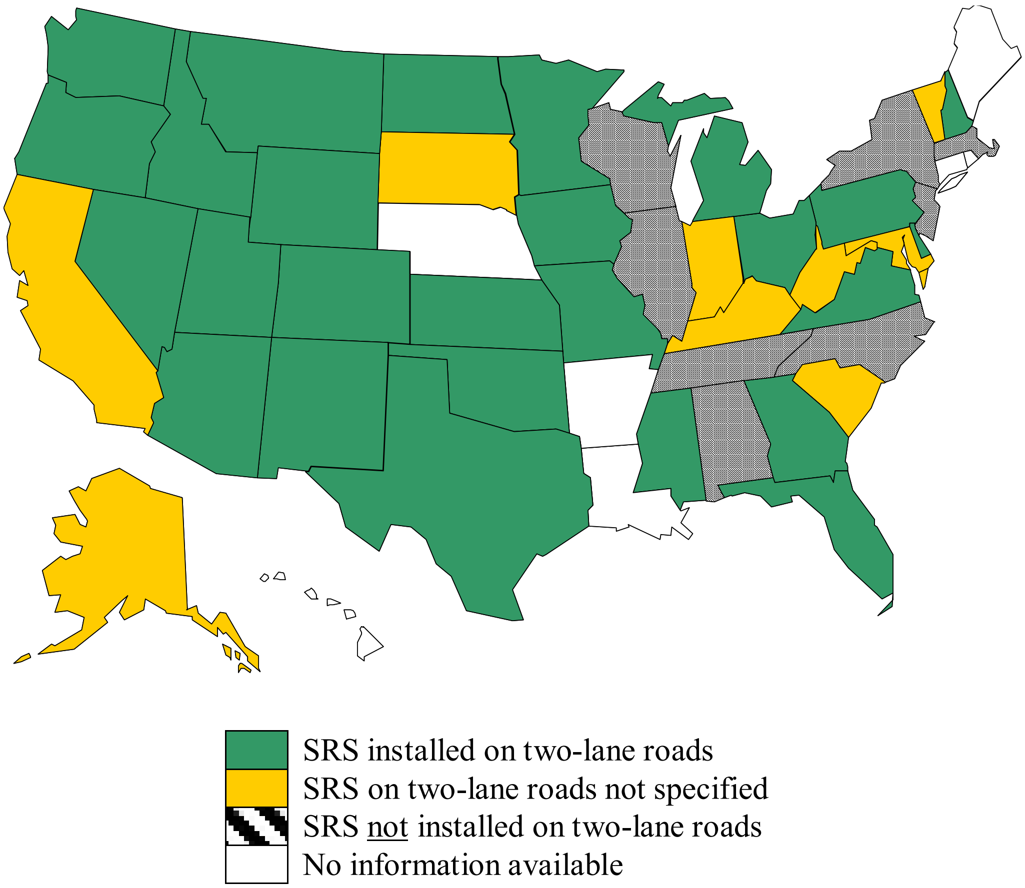


Figure 2. Nationwide SRS Installation on Two-Lane, Undivided Roadways.

Researchers only identified 12 states besides Texas (24 percent) that install CRS on two-lane, undivided roadways. However, based on other sources (*12,36*) it appears that 31 out of the other 49 state DOTs (63 percent) have installed CRS on over 1000 miles of roadway. Figure 3 shows the nationwide status of CRS installations on two-lane, undivided roadways. The typical dimensions (depth, length, width, and spacing) of CRS on two-lane, undivided roads are the same as those described above for SRS. Researchers only obtained information regarding the minimum shoulder width required before CRS could be installed from five states. These states all had different minimum values, ranging from 2 to 10 ft. Previous research (*36*) identified 14 states that use continuous CRS, three states that only use CRS in specific sections, two states that only use CRS in no-passing zones, and two states that only use CRS in curves.

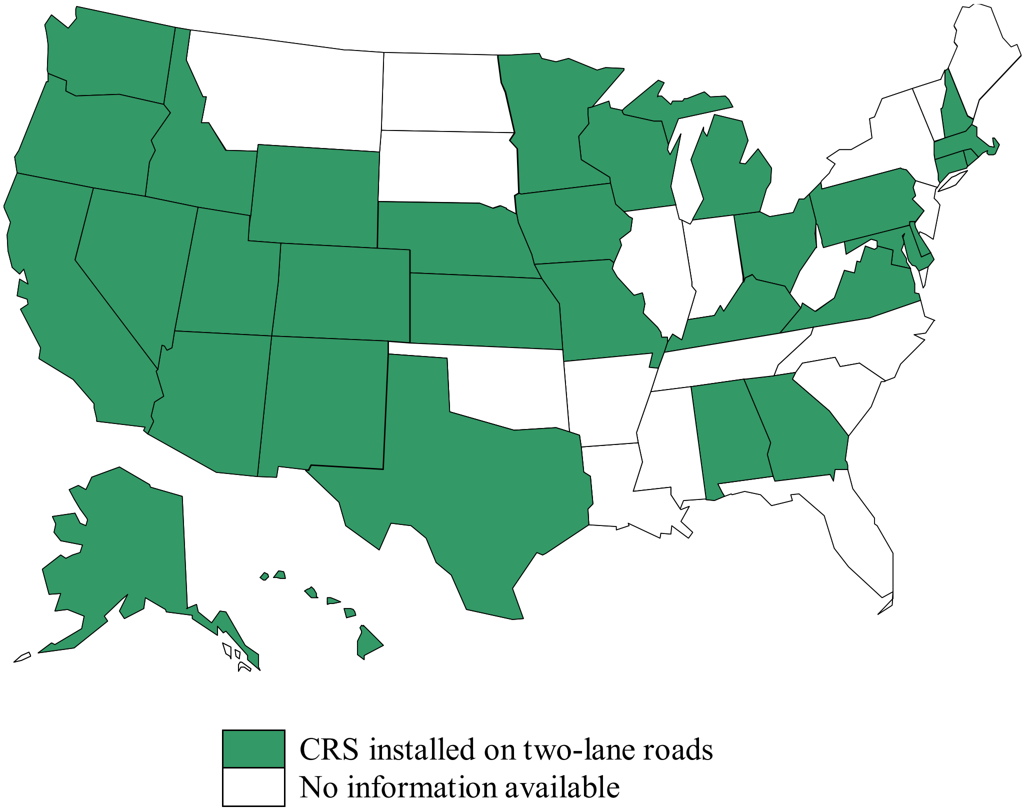


Figure 3. Nationwide CRS Installation on Two-Lane, Two-Way Roadways.

TEXAS IMPLEMENTATION

Standards

In April 2006, TxDOT released revised standards for SRS and CRS (*38*). These standards allow for both raised and depressed rumble strips. The depressed SRS and CRS shall be cut to a minimum 0.5-inch depth, 7-inch length, and a 16-inch width. However, an 8-inch wide SRS shall be used if the shoulder is less than 4 ft in width. A minimum depth of 0.375 inch may be considered where CRS and ERS are installed near residential areas, schools, churches, etc. The spacing (measured from leading edge to leading edge of adjacent rumble strips) for depressed SRS and CRS is 12 inches and 24 inches, respectively.

For depressed SRS, two options with respect to lateral offset are shown. The first option shows a 4-inch minimum and 12-inch maximum offset from the outside edge of the marked edgeline. A note states that the minimum offset should be used if the shoulder is less than 8 ft wide. A 6-ft minimum width between the outside edge of the rumble strip and the edge of the pavement is also shown for outside shoulders; however, a note states that this distance may be reduced in special situations as directed by the engineer. The second option shows the use of ERS. ERS should not be used when the adjacent lane width is less than 12 ft. ERS may be used when the shoulder is greater than 18 inches wide. Again, an 8-inch wide depressed rumble stripe shall be used when the shoulder is less than 4 ft wide; otherwise a 16-inch wide rumble strip shall be used.

Locations

In the fall of 2006, members of the research team surveyed representatives in all 25 TxDOT districts to gather information on the current state-of-the-practice within the state of Texas. At that time 32 percent (8 districts) had installed SRS, CRS, or both types of rumble strips on two-lane, undivided roadways. In addition, 16 percent (4 districts) were planning to install these types of rumble strips on two-lane, undivided roadways in the near future.

Based on conversations with TxDOT personnel and site visits, researchers identified over 200 miles of two-lane, undivided roadways in 9 districts where rumble strips were installed. Table 2 through Table 4 contain descriptions of the sites where SRS, CRS, and both ERS and CRS were installed. Researchers identified 19 sites (approximately 124 miles) of two-lane, undivided roads with SRS, 9 sites (approximately 80 miles) with CRS, and 4 sites (approximately 9 miles) with both ERS and CRS. Over 90 percent of the sites had depressed rumble strips; the other sites used raised rumble strips. Across all sites, the majority of roads had 12-ft lanes and shoulder widths greater than or equal to 8 ft. Researchers only identified shoulder widths less than or equal to 4 ft at sites with CRS or both ERS and CRS. At the SRS sites, the rumble strip offset from the edgeline varied from 4 to 35 inches.

Researchers also obtained TxDOT personnel's concerns and opinions regarding the use of SRS and CRS on two-lane, undivided roadways. As shown in Figure 4, 69 percent of the respondents thought that rumble strips should not be installed on two-lane, undivided roadways with lane widths less than 12 ft. Figure 5 shows that 79 percent of the respondents also believed that rumble strips should not be installed on two-lane, undivided roadways with shoulder widths less than 4 ft. Thus, the majority of those interviewed recommended that rumble strips be installed on two-lane, undivided roadways when the surface width (measured from edge of pavement to edge of pavement) is greater than or equal to 32 ft. With respect to the location of rumble strips on the shoulder, Figure 6 shows that 58 percent of the respondents agreed with the current allowable offset (4 to 12 inches). However, 26 percent believed that offsets larger than 12 inches should be used.

SUMMARY

In 2006, researchers identified over 200 miles of two-lane, undivided Texas roadways where rumble strips were installed. The majority of these miles had SRS; however, researchers also found roadways with CRS and roadways with both ERS and CRS. Typically, the rumble strip installations were located on roads with 12-ft lanes and shoulder widths greater than or equal to 8 ft. In addition, the SRS were usually offset from the edgeline between 4 to 12 inches; however, one district was utilizing offsets larger than 12 inches. These findings are not surprising based on TxDOT personnel's opinions and current TxDOT standards. Overall, the implementation of SRS and CRS on two-lane, undivided roadways in Texas is very similar to application of these types of rumble strips in other states.

Table 2. SRS Locations on Two-Lane, Undivided Roadways.

District	Site Number	Road	Location	Speed Limit (mph)	Lane Width (ft) [a]	Shoulder Width (ft) [b]	Approx. Length of Section (miles)	Type of RS	SRS Offset [c] (in)
Bryan	BRY2	SH 30	Grimes Co. between Roans Prairie & Walker Co. line	60	12	6	8	Milled	8
Childress	CHS2	US 83	Childress Co. north of Childress	70	12	8-10	16	Milled	10
Houston	HOU1	SH 105	Montgomery Co. from Grimes Co. line to Montgomery	60	12	11	7	Milled	7
	HOU2	SH 105	Montgomery Co. from San Jacinto Co. line (Peach Creek) to Liberty Co. line	60	11	11	4	Milled	6
	HOU3	FM 1942	East Harris Co. between US 90 in Barrett to Chambers Co. line	60	11	9	8	Milled	8
	HOU4	FM 2100	East Harris Co. north of FM 1960	55	12	7	4	Milled	4
	HOU5	FM 2100	East Harris Co. south of FM 1960 to Crosby	55	12	7	6	Milled	4
	HOU6	SH 36	Fort Bend Co. from US ALT 90 to Austin Co. line (Orchard to Rosenberg)	65	12	10	8	Milled	6
	HOU7	Spur 10	Fort Bend Co. from SH 36 to US 59	60	12	12	4	Milled	7
	HOU8	SH 36	Fort Bend Co. from S of Needville to Brazoria Co. line	65	11	10	7	Milled	5
	HOU9	FM 1301	Brazoria Co. west of SH 36 for 5 or 6 miles	65	12	9	6	Milled	7
	HOU10	FM 521	Brazoria Co. between SH 288B & FM 1462	60	12	11	4	Milled	6
	HOU11	FM 1994	Fort Bend Co. from FM 361 to FM 762	65	12	6	4	Milled	9
	HOU12	FM 359	Fort Bend Co. from FM 1093 to FM 723	55	12	9	5	Milled	7
	HOU13	FM 1093	Fort Bend Co. from FM 359 to Fulshear	--	12	9	3	Milled	6
Lubbock	LBB1	US 380	Lynn and Garza Co. between Tahoka & Post	70	12	10	--	Milled	12
Yoakum	YKM1	ALT US 77 US 183	Dewitt Co. S of Cuero, from FM 2718 to Goliad Co. line	70	12	11	11	Rolled	29
	YKM2	US 77	Fayette Co. N of La Grange to Lee Co. line	70	11	8	8	Rolled	12
	YKM3	US 77	Fayette Co. S of Schulenburg to Lavaca Co. line	70	12	9	11	Rolled	35

SH = State Highway; US = United States; FM = Farm-to-Market; ALT = Alternate; RS = Rumble Strip; -- = Unknown

[a] Measured from the outside edge of the centerline to the inside edge of the edgeline.

[b] Measured from the inside edge of the edgeline to the edge of pavement (i.e., includes edgeline).

[c] Measured from the outside edge of the edgeline to the inside edge of the rumble strip.

Table 3. CRS Locations on Two-Lane, Undivided Roadways.

District	Site Number	Road	Location	Speed Limit (mph)	Lane Width (ft) [a]	Shoulder Width (ft) [b]	Approx. Length of Section (miles)	Type of RS
Amarillo	AMA1	US 54	Dallam and Hartley Co. between New Mexico & Dalhart	70	12	10-12	20	Milled
Austin	AUS2	RM 12	Hayes Co. N of 290 (Dripping Springs) to RM 3238	60	12	1	7	Milled
	AUS3	RM 3238	Hayes Co. between Bee Cave & Wimberly	55	10	2	6	Milled
	AUS4	FM 969	Travis Co. from Taylor Lane to Decker	65	11	None	6	Raised
Beaumont	BMT1	SH 321	Liberty Co. south of SH 105 to Dayton	65	12	10	2	Milled
	BMT2	SH 105	Hardin Co. between Sour Lake & Jefferson Co. line	65	12	10	7	Milled
	BMT3	SH 146	Liberty Co. between Dayton & Chambers Co. line	70	12	10	10	Milled
Brownwood	BWD1	US 67	Comanche Co. between Comanche & Dublin	70	12	8	15	Milled
Childress	CHS1	SH 256	Childress Co. from Hall Co. line 6 miles E toward US 83 (5 to 6 miles)	70	12	4	7	Milled

US = United States; RM = Ranch-to-Market; FM = Farm-to-Market; SH = State Highway; RS = Rumble Strip

[a] Measured from the outside edge of the centerline to the inside edge of the edgeline.

[b] Measured from the inside edge of the edgeline to the edge of pavement (i.e., includes edgeline).

Table 4. Locations on Two-Lane, Undivided Roadways with Both ERS and CRS.

District	Site Number	Road	Location	Speed Limit (mph)	Lane Width (ft) [a]	Shoulder Width (ft) [b]	Approx. Length of Section (miles)	Type of RS
Austin	AUS1	RM 32	Hayes Co. from RM 12 to Comal Co. line	60	11	3	4	Milled
	AUS5	SH 195	Williamson Co., Curve 1.9 miles south of FM 970	65	12	10	0.14	Raised
	AUS6	SH 195	Williamson Co., Curve 5.7 miles south of FM 970	65	12	10	0.16	Raised
Bryan	BRY1	SH 6	Robertson Co. between Hearne & Calvert	70	12	9	5	Milled

RM = Ranch-to-Market; SH = State Highway; RS = Rumble Strip

[a] Measured from the outside edge of the centerline to the inside edge of the edgeline.

[b] Measured from the inside edge of the edgeline to the edge of pavement (i.e., includes edgeline).

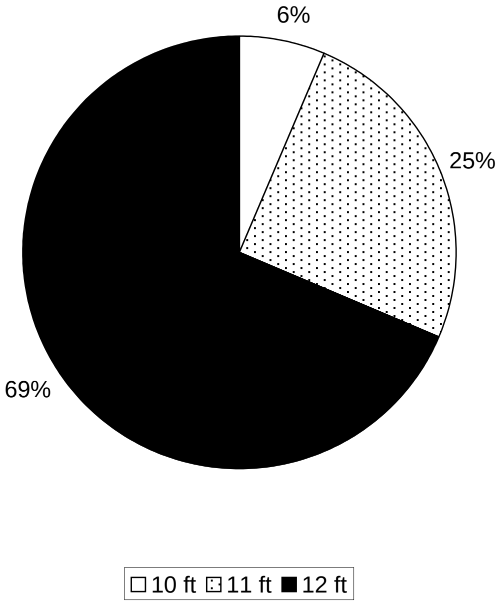


Figure 4. Minimum Lane Width Preferred by Survey Respondents (n=16).

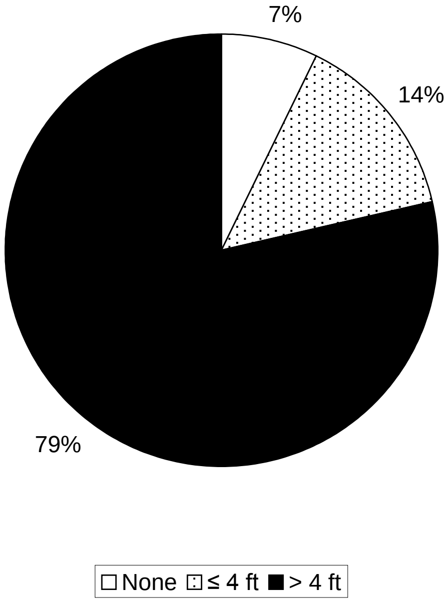


Figure 5. Minimum Shoulder Width Preferred by Survey Respondents (n=14).

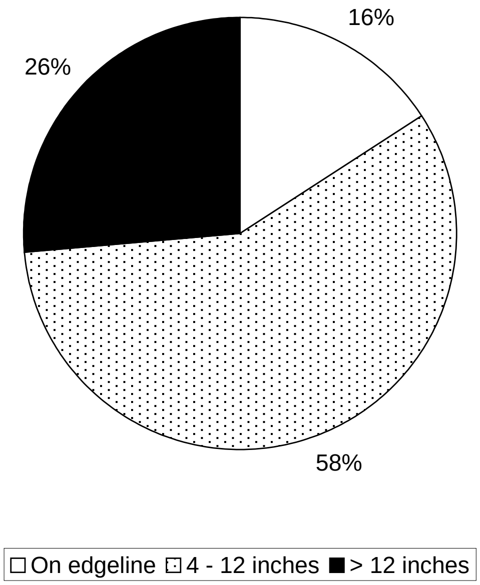


Figure 6. SRS Offset Preferred by Survey Respondents (n=19).

CHAPTER 3:
FIELD STUDIES

INTRODUCTION

SRS placed near or on the edgeline of two-lane, undivided roadways provide warning to errant drivers as soon as they leave the travel lane and thus provide the largest amount of recovery area for the errant driver. While a small offset may promote better lane keeping by reducing the frequency of inadvertent encroachments onto the shoulder, a small offset may also shift the lateral placement of vehicles in the travel lane toward the centerline (especially where travel lane widths are narrower than 12 ft.) This could increase the potential for head-on and opposing-direction sideswipe crashes. With CRS, there is concern that the lateral placement of vehicles in the travel lane may shift toward the shoulder (again especially where lane widths are less than 12 ft) and thus increase the potential for ROR crashes. As part of this research project, TTI researchers designed and conducted field studies on two-lane, undivided roadways to evaluate the impacts of depressed SRS and CRS on the placement of vehicles in the travel lane.

STUDY LOCATIONS

Researchers wanted to assess the effects of depressed rumble strips on two-lane, undivided roadways with the following characteristics:

- SRS, CRS, and both SRS and CRS;
- 10 ft, 11 ft, and 12 ft lane widths;
- 1 to 4 ft, 6 to 9 ft, and ≥10 ft shoulder widths; and
- SRS on edgeline (-4 inches), 0 to 12 inches from edgeline, and ≥24 inches from the edgeline.

Due to this desire to include multiple variables and budget limitations, researchers could not conduct a before-and-after study. Instead, researchers collected data at sites with existing rumble strip installations and comparison sites (similar roadways without rumble strips). The comparison sites provided baseline lateral placement values (i.e., an estimate of how drivers typically position their vehicles on two-lane roadways with various cross-sections).

Using the site data obtained from the TxDOT personnel interviews and data collected through site visits, researchers identified tangent sections at least 0.5 mile long on two-lane, undivided roadways with existing rumble strips where vehicle lateral placement data could be collected. In addition, researchers found roadways with similar cross-section characteristics without rumble strips. Table 5 shows the site characteristics of the locations where researchers collected data. As discussed in Chapter 2, only a limited number of the existing sites had lane widths less than 12 ft. Unfortunately, site visits revealed that some of these sites had other constraints that made it difficult to collect the desired data (e.g., limited tangent sections, large number of access points, etc.). In addition, researchers only identified shoulder widths less than or equal to 4 ft at sites with CRS or both ERS and CRS. Thus, the investigation of the impact of rumble strips across a range of travel lane widths and shoulder widths was not as robust as initially planned.

Table 5. Data Collection Site Characteristics.

Site Number	Roadway	Rumble Strip Location	Lane Width [a] (ft)	Shoulder Width [b] (ft)	Surface Width [c] (ft)
BRY2	SH 30	SRS	12	6	36
HOU11	FM 1994	SRS	12	6	36
HOU12	FM 359	SRS	12	9	42
YKM3	US 77	SRS	12	9	42
HOU1	SH 105	SRS	12	11	46
AUS3	RM 3238	CRS	10	2	24
AUS2	RM 12	CRS	12	1	26
BMT1	SH 321	CRS	12	10	44
AUS1	RM 32	ERS & CRS	11	3	28
BRY1	SH 6	ERS & CRS	12	9	42
1C	FM 244	None	11, 10 [d]	3	27
2C	SH 21	None	12	9	42
3C	SH 30	None	12	11	46
4C	FM 974	None	10	1	22
5C	FM 3403	None	12, 11 [e]	3	29

SH = State Highway; RM = Ranch-to-Market; FM = Farm-to-Market; US = United States;
SRS = Shoulder Rumble Strips; CRS = Centerline Rumble Strips;
ERS = Edgeline Rumble Strips; C = Comparison

[a] Measured from the outside edge of the centerline to the inside edge of the edgeline.

[b] Measured from the inside edge of edgeline to the edge of pavement (i.e., includes edgeline).

[c] Measured from edge of pavement to edge of pavement.

[d] Lane width was 11 ft and 10 ft in the northbound and southbound directions, respectively.

[e] Lane width was 12 ft and 11 ft in the northbound and southbound directions, respectively.

Table 6 contains a description of the rumble strips. Researchers collected data at five sites with SRS, three sites with CRS, and two sites with both ERS and CRS. The dimensions of the rumble strips were fairly consistent with current TxDOT standards. Deviations are most likely due to the rumble strips being installed prior to the release of the current standards in April of 2006.

Table 6. Rumble Strip Characteristics.

Site Number	Rumble Strips	Type of Rumble Strip	Length [a] (in)	Width [b] (in)	Spacing [c] (in)	SRS Offset [d] (in)
BRY2	SRS	Milled	6	16	12	8
HOU11	SRS	Milled	6	16	12	9
HOU12	SRS	Milled	7.5	16	13	7
YKM3	SRS	Rolled	2	21	9.5	35
HOU1	SRS	Milled	7	16	12	7
AUS3	CRS	Milled	9	16	24	NA
AUS2	CRS	Milled	8	16	23	NA
BMT1	CRS	Milled	5	16	23	NA
AUS1	ERS	Milled	6.5	7.5	24	On edgeline
	CRS	Milled	6.5	16	24	NA
BRY1	ERS	Milled	8	12	12	On edgeline
	CRS	Milled	8	12	12	NA

NA = Not Applicable

[a] Measured parallel to the direction of travel.

[b] Measured perpendicular to the direction of travel.

[c] Measured from the leading edge of one rumble strip to the leading edge of the following rumble strip in the direction of travel.

[d] Measured from the outside edge of the edgeline to the inside edge of the rumble strip.

DATA COLLECTION

Researchers collected vehicle lateral placement data at all 15 sites from May 2007 to October 2007. At each site, researchers used traffic classifiers and piezoelectric sensors in a Z-configuration to collect speed, volume, and lateral position data in each direction of travel. Figure 7 shows an example of this configuration, while Table 7 contains the configuration's dimensions. The data collection period varied from two to four days at each site depending on the traffic volume.

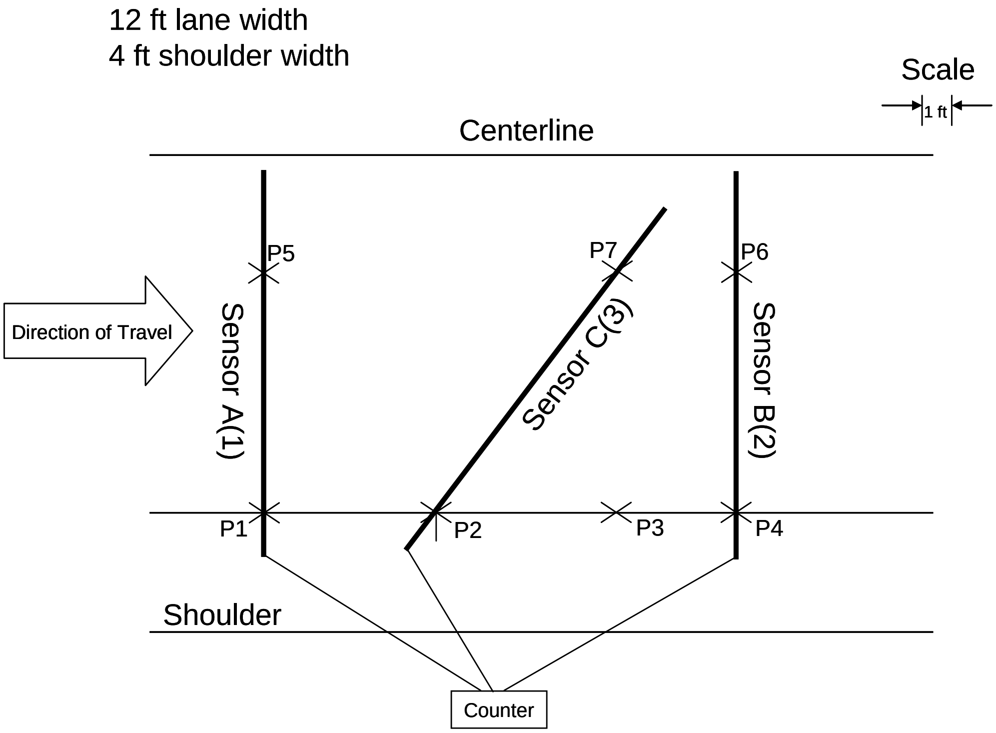


Figure 7. Example of Z-Configuration.

Table 7. Z-Configuration Dimensions.

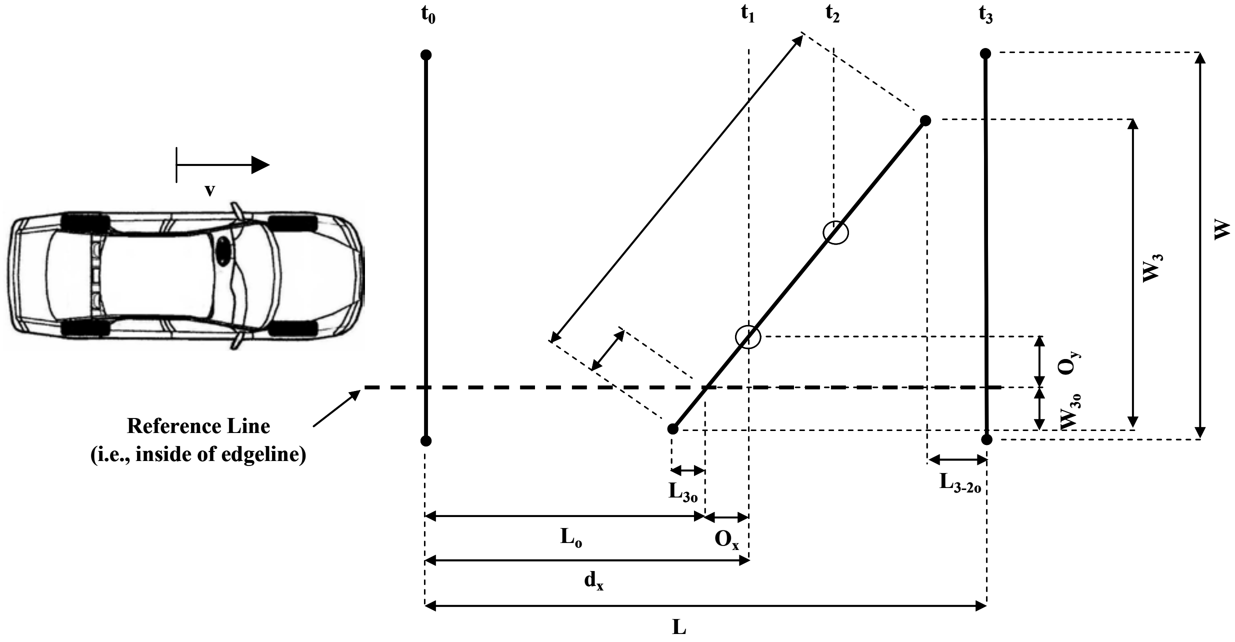
Dimension Description	Length (ft)
Distance between P1 and P2	6
Distance between P1 and P3	12
Distance between P5 and P7	
Distance between P1 and P4	16
Distance between P5 and P6	
Distance between P1 and P5	8
Distance between P3 and P7	
Distance between P4 and P6	
Distance between P2 and P5	10
Distance between P2 and P7	

DATA REDUCTION AND ANALYSIS

First, researchers output the raw data into a spreadsheet. Each line of raw data contained the sensor number activated, the date and time the sensor was activated, and a time stamp denoting the cumulative time from the start of data collection until the sensor was activated. Researchers developed algorithms within the spreadsheet to identify a "vehicle" from the lines of raw data based on axle spacing and headway. The algorithm then calculated the speed of each vehicle and the location of each vehicle's right tire from the inside edge of the edgeline as shown in Figure 8. Due to equipment malfunctions, data at comparison site 1 in the northbound direction could not be used.

The TxDOT project panel members wanted to know whether the impacts of depressed SRS and CRS on the placement of vehicles in the travel lane were affected by whether or not the vehicle encountered oncoming traffic. Thus, researchers used another algorithm to divide the vehicles into two categories: isolated vehicles and vehicles encountering oncoming traffic. Previous research (*39*,*40*,*41*,*42*,*43*,*44*) indicates a propensity of drivers encountering an approaching vehicle to increase the lateral distance between the two vehicles beginning about 10 seconds before meeting up to 2 seconds after the vehicles have passed. Thus, researchers used this window of influence to determine which vehicles encountered oncoming traffic.

Next researchers removed "blank" data (i.e., speed and/or lateral position that could not be calculated) and unrealistic data. For each site, unrealistic lateral placement data were found by comparing the computed lateral placement to the range of realistic lateral placement values based on the sensor layout and roadway cross-section. With respect to the speed data, researchers removed all negative values, zero values, and values over 100 mph. At each site, researchers then computed the minimum speed, maximum speed, mean speed, standard deviation, and 95 percent confidence intervals. The largest confidence interval across all sites was then identified, and all speed data outside this range were discarded. Researchers used this process to reduce the data set since they did not have confidence in the higher speed values on two-lane, undivided roads and they did not want to include lower speeds, which could be an indication of a driver slowing down to turn (which could affect their lateral position in the roadway, especially if the road had larger shoulders). Researchers further reduced the data set by removing all data that did not occur under dry pavement conditions (i.e., during rain events).



L = Length over entire trap (inches)
L_o = Length of offset from Sensor 1 to where Sensor 3 intersects the Reference Line (inches)
W = Width measured perpendicular to direction of traffic of Sensor 2 (inches)
d_x = Distance covered by an axle that has traversed from Sensor 1 to Sensor 3 (inches)
O_x = Offset distance of the first tire contact in the direction of travel (inches)
O_y = Offset distance of the first tire contact perpendicular to the direction of travel (inches)
t_i = Time at point *i* (seconds)
v = velocity (inches per second)

$$v = \frac{L}{t_3 - t_0}$$
Eq. 1

$$d_x = v(t_1 - t_0)$$
Eq. 2

$$O_x = d_x - L_0$$
Eq. 3

$$O_y = \frac{8}{6} O_x$$
Eq. 4a

$$O_y = \frac{8}{6}\left(\left(\frac{L}{t_3 - t_0}\right)(t_1 - t_0) - L_o\right)$$
Eq. 4b

Figure 8. Speed and Lateral Placement Calculations.

Next, for each site researchers computed the following descriptive statistics for isolated vehicles, vehicles encountering oncoming traffic, and all vehicles: sample size, mean lateral position, variance, standard deviation, the percent of vehicles hitting edgeline pavement markings, and percent of vehicles hitting centerline pavement markings. The Appendix contains these descriptive statistics.

Assuming a typical vehicle track width of 6 ft (distance from outside edge of tire to outside edge of tire), researchers then converted the mean lateral position data so that it referred to the distance of the vehicle centroid from center of lane (also shown in the Appendix). This allowed researchers to determine how drivers position their vehicle about the center of the travel lane. Similar to the PennDOT study discussed previously (*16*), TTI researchers assumed that vehicle paths located near the center of the travel lane may result in a higher level of safety.

Researchers did not use statistical analysis to assess whether the differences in the mean lateral position were significant since very small changes in the lateral position would have been considered statistically significant based on the large sample sizes. Instead, based on engineering judgment and previous research (*4*), researchers utilized a practically significant minimum difference in mean lateral placement between comparison sites and rumble strip sites of 6 inches.

RESULTS

Type of Vehicle

Figure 9 shows the mean distance of the vehicle centroid from the center of the lane for isolated vehicles and vehicles encountering oncoming traffic at the comparison sites. Negative numbers are to the left of the center of the lane (i.e., closer to the centerline) and positive numbers are to the right of the center of the lane (i.e., closer to the edgeline). A review of these data confirmed expectations that, independent of the cross-section of the roadway, isolated vehicles tend to position themselves closer to the centerline than those vehicles that encounter oncoming traffic. On average, vehicles encountering oncoming traffic centered themselves 3 inches further to the right (i.e., toward the edgeline). In addition, at most of the sites the difference in the mean lateral position between the two types of vehicles was not practically significant (i.e., less than 6 inches). These same trends were evident at the sites with rumble strips; thus, researchers decided to combine the data for the two types of vehicles for further analysis.

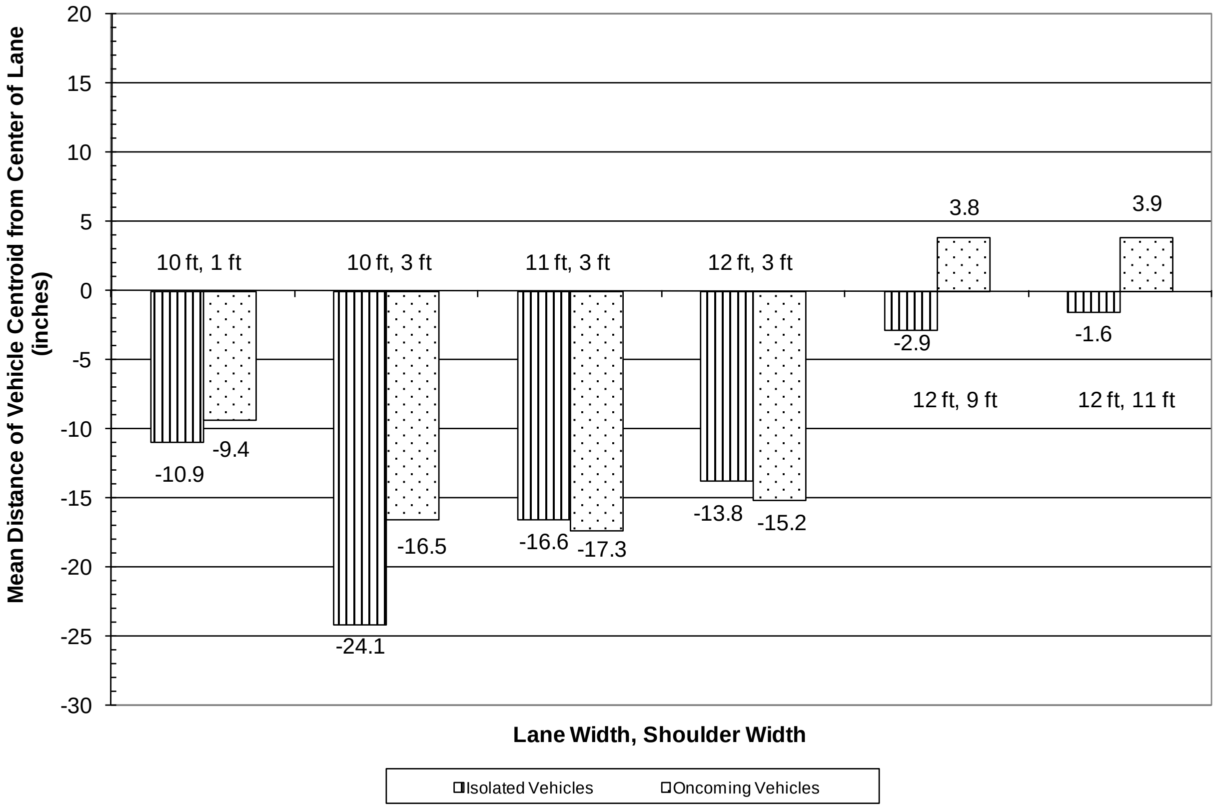


Figure 9. Comparison Site Mean Distance of Vehicle Centroid from Center of Lane by Vehicle Type.

Comparison Sites

Researchers reviewed the data from the comparison sites to gain insight into how drivers typically position their vehicle in the travel lane on two-lane roadways with various lane and shoulder widths. Figure 10 shows the mean distance of the vehicle centroid from the center of the lane for all vehicles at the comparison sites. Again, negative numbers are to the left of the center of the lane (i.e., closer to the centerline) and positive numbers are to the right of the center of the lane (i.e., closer to the edgeline). For small shoulder widths (1 to 3 ft), drivers tend to center their vehicle between 10.4 and 20.5 inches to the left of the center of the lane (i.e., closer to the centerline). At the sites with 3-ft shoulders, the mean distance of the vehicle centroid from the center of the lane for sites with 10-ft and 12-ft lanes was 20.5 inches and 13.9 inches, respectively. Thus at the site with the largest lane width, drivers positioned the center of their vehicle 6.6 inches closer to the center of the lane. At the sites with 12-ft lanes, drivers tended to center their vehicle near the center of the lane (approximately 2 inches to the right) when the shoulder was at least 9 ft wide. In contrast, when the shoulder width was 3 ft or less, the mean distance of the vehicle centroid from the center of the lane was approximately 14 inches to the left (i.e., toward the centerline). Thus, drivers travel closer to the centerline on roads with smaller shoulders and closer to the center of the lane on roads with larger shoulders.

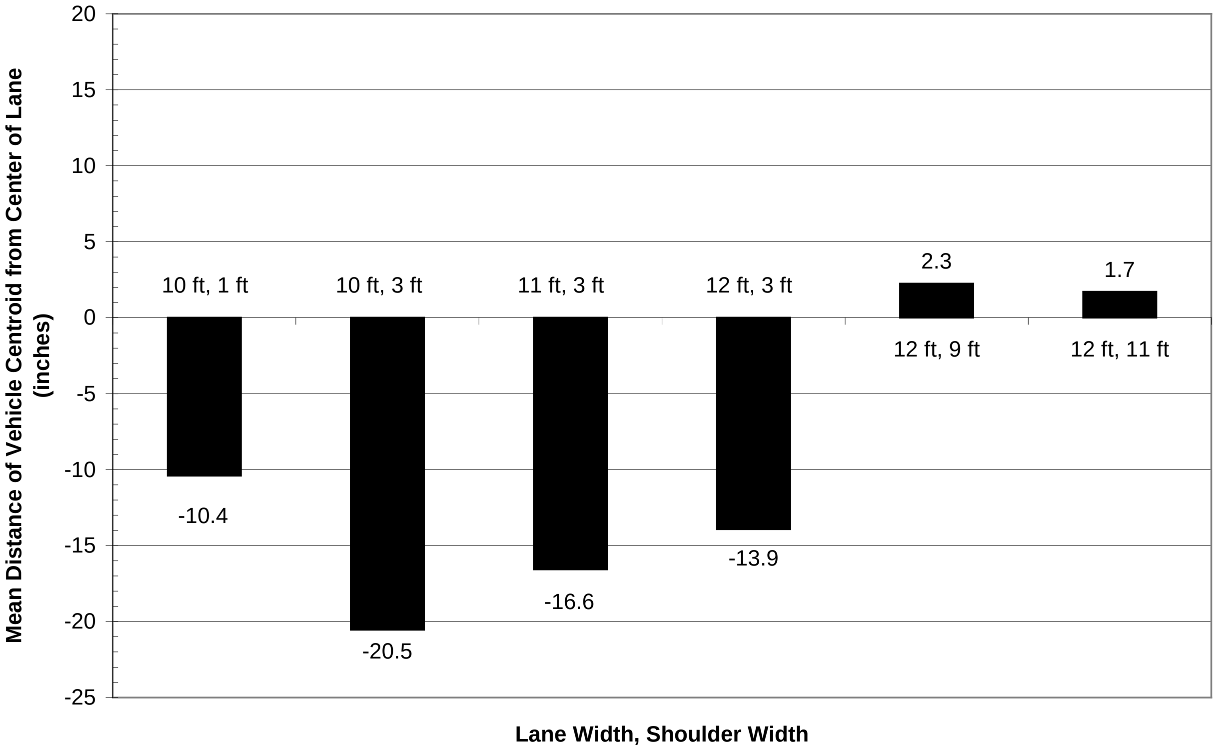


Figure 10. Comparison Site Mean Distance of Vehicle Centroid from Center of Lane.

At all of the comparison sites, the percent of vehicles hitting the edgeline marking was less than or equal to 2 percent. In contrast, the percent of vehicles hitting the centerline markings ranged from less than 1 percent to 25 percent. The largest percentages (8 and 25 percent) occurred at sites with 10-ft lanes and small shoulders (1 to 3 ft, respectively). Approximately

5 percent of the vehicles still hit the centerline at sites with small shoulders but larger lane widths (11 or 12 ft). Less than 2 percent of the vehicles hit the centerline at sites with 12-ft lanes and shoulders greater than or equal to 9 ft.

CRS Sites

Figure 11 compares the lateral placement data at the comparison sites and sites with CRS. Similar to the comparison sites, at sites with CRS and small shoulder widths (1 to 2 ft), drivers tend to center their vehicle to the left of the center of the lane (i.e., closer to the centerline). However, at the CRS sites, the centroid of the vehicle was 4.4 and 6.3 inches to the left of the center of the lane compared to 20.5 and 13.9, respectively, at the comparison sites. Thus at sites with CRS and small shoulder widths (1 to 2 ft), drivers positioned the center of their vehicle 7.6 to 16.1 inches closer to the center of the lane. In addition, the percent of vehicles hitting the centerline markings at these sites was 3 percent or less, and there was no apparent increase in the number of vehicles hitting the edgeline.

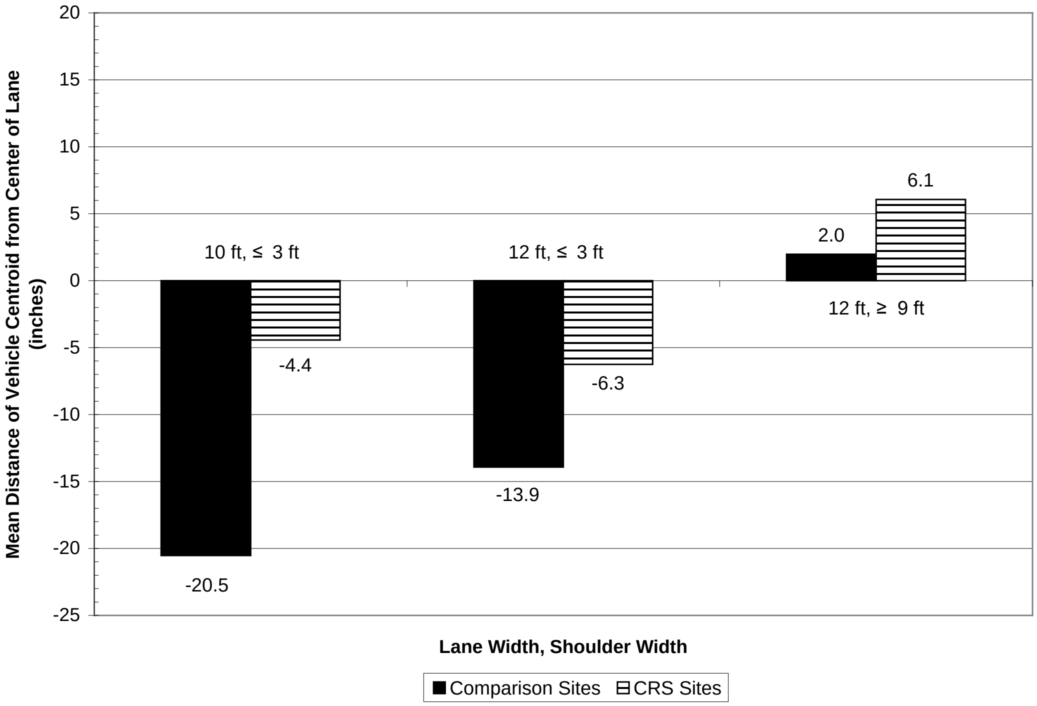


Figure 11. Comparison of Mean Distance of Vehicle Centroid from Center of Lane – Comparison Sites vs. CRS Sites.

At the CRS site with a larger shoulder width (≥9 ft) drivers tended to center their vehicle to the right of the center of the lane (i.e., closer to the edgeline). This trend is similar to that found at the comparison sites; however, at the CRS site drivers centered their vehicle approximately 4 inches further to the right of the center of the lane. Even though drivers were traveling closer to the shoulder, researchers did not consider this shift to be practically significant since it was less than 6 inches. There was also no practical difference in the percent of vehicles hitting the centerline or edgeline.

SRS Sites

Figure 12 compares the lateral placement data at the comparison sites and sites with SRS. Unfortunately, researchers were not able to collect data at SRS sites with lane widths less than 12 ft and a comparison site with 12-ft lanes and a 6-ft shoulder. At the sites with small offsets (7 to 9 inches), the effect of SRS on the lateral placement of vehicles in the travel lane was highly variable. At three of the sites, drivers positioned the center of their vehicle between 2.1 and 9.8 inches to the left of the center of the lane (i.e., closer to the centerline). However, the mean distance of the vehicle centroid from the center of the lane at one site was 6.4 inches to the right of the center of the lane (i.e., closer to the edgeline). In other words, while the shoulder width did vary across these sites, there does not seem to be a logical correlation. The percent of vehicles hitting the edgeline and centerline at all of these sites was less than 1 percent and approximately 3 percent, respectively.

At the site with a 35-inch offset, drivers centered their vehicle approximately 3 inches further to the right of the center of the lane than at the comparison site. Even though drivers were traveling closer to the shoulder, researchers did not consider this shift to be practically significant since it was less than 6 inches. There was also no practical difference in the percent of vehicles hitting the centerline or edgeline. Based on these data, it appears that SRS offsets further away from the edgeline have less of an impact on the lateral placement of vehicles in the travel lane.

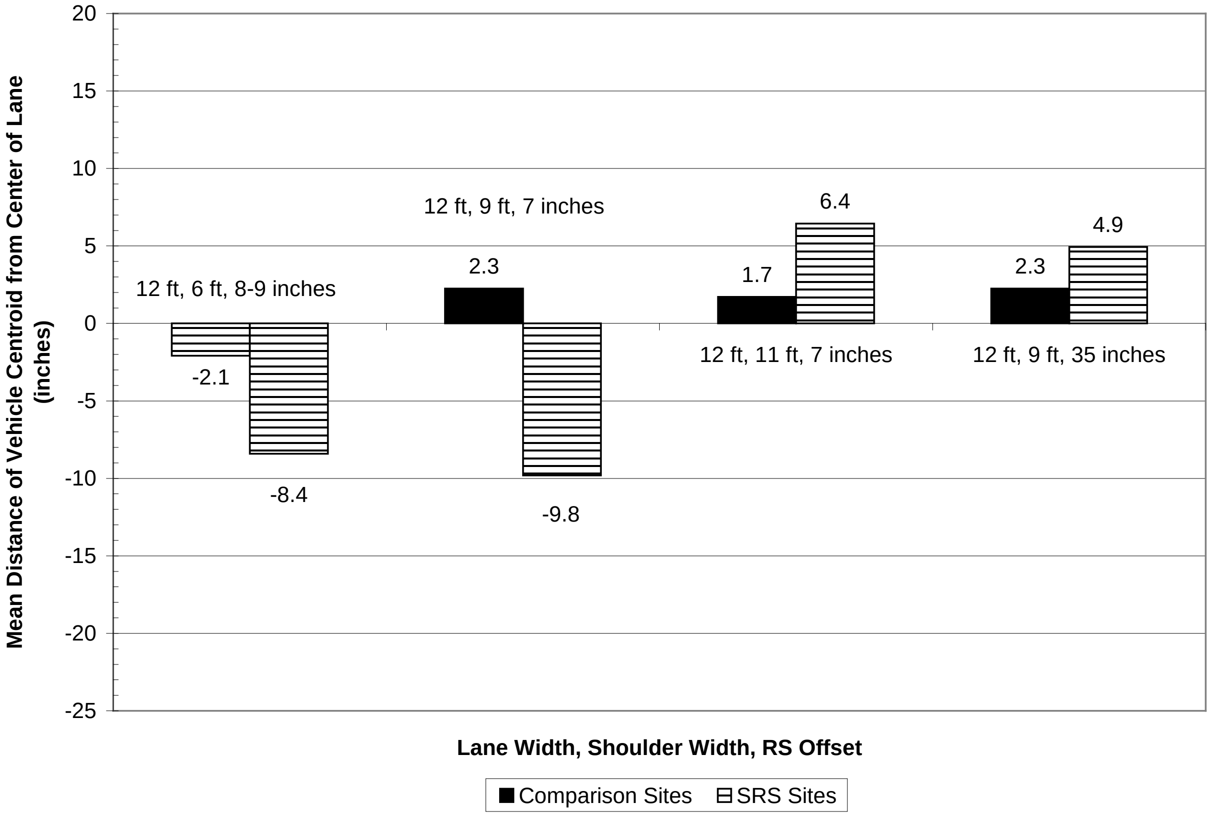


Figure 12. Comparison of Mean Distance of Vehicle Centroid from Center of Lane – Comparison Sites vs. SRS Sites.

Sites with Both CRS and ERS

Figure 13 compares the lateral placement data at the comparison sites and sites with both types of rumble strips (i.e., CRS and ERS). At all sites, the SRS were actually ERS since the location of the leading edge of the rumble strip was the same as the leading edge of the edgeline pavement marking. At the site with a smaller shoulder width (3 ft), the center of the vehicle was 7 inches to the left of the center of the lane compared to 16.6 inches at the comparison site. Thus, drivers centered their vehicle approximately 10 inches closer to the center of the lane at the site with both types of rumble strips. While the percent of vehicles hitting the centerline at this site (8 percent) was slightly higher than that experienced at the comparison site (5 percent), there was no practical difference in the percent of vehicles hitting the edgeline.

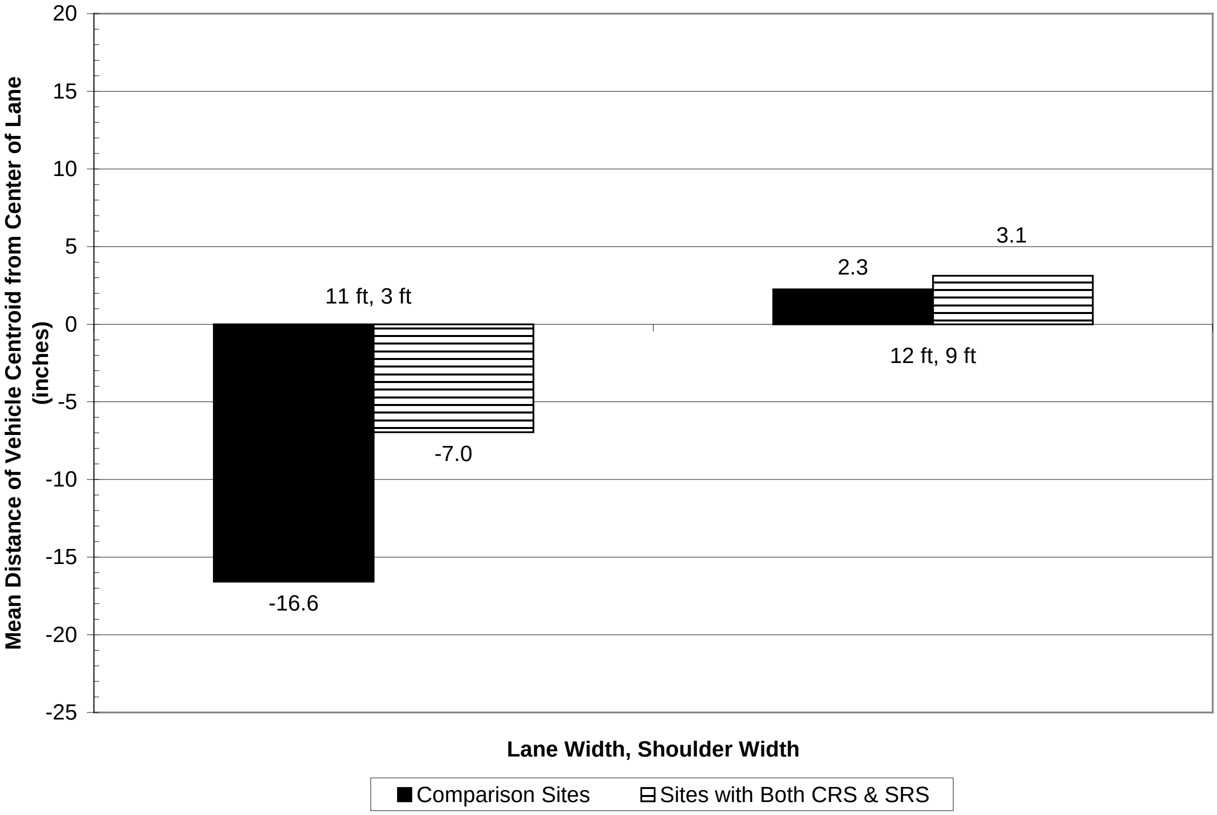


Figure 13. Comparison of Mean Distance of Vehicle Centroid from Center of Lane – Comparison Sites vs. Sites with Both Types of Rumble Strips.

For the larger shoulder width (9 ft), there was no practical difference between the mean position of the centroid of the vehicle between the comparison site and the site with both types of rumble strips. While there was a slight increase (approximately 2 percent) in the number of vehicles hitting the edgeline compared to the site without rumble strips, there was a negligible change in the percent of vehicles hitting the centerline.

The findings at the sites with both types of rumbles strips are similar to those found at sites with only CRS. Even though the results for roadways with 12-ft lanes and large shoulders (≥9 ft) were not practically significant, it appears that the combination of ERS and CRS resulted in drivers centering their vehicle more closely to the center of the travel lane. However, this trend is not apparent at the sites with smaller shoulders (3 ft).

Compared to the sites with only SRS, it also seems that the combination of ERS and CRS on roadways with 12-ft lanes and large shoulders (≥9 ft) resulted in drivers positioning the center of their vehicles closer to the center of the travel lane. However, one must remember that these data are only from two sites and the findings at all of the SRS sites with small offsets (7 to 9 inches) were highly variable. Unfortunately, researchers were not able to make inferences regarding the impacts of SRS and the combination of ERS and CRS for roadways with smaller shoulder widths (≤3 ft).

SUMMARY

At CRS-only sites and sites with both CRS and ERS on narrow shoulders (1 to 3 ft), drivers tend to position the center of their vehicle closer to the center of the travel lane than if the rumble strips were not there, thus potentially resulting in a higher level of safety. In contrast, on roadways with shoulder widths greater than or equal to 9 ft, neither CRS nor the combination of CRS and ERS appears to practically affect the lateral position of vehicles in the travel lane.

The effect of SRS located within 7 to 9 inches of the edgeline on the lateral position of vehicles in the travel lane was highly variable; thus, their impact was not as clear. Nevertheless, it does appear that SRS located near the edgeline may cause drivers to center their vehicles to the left of the center of the lane (i.e., closer to the centerline) in some cases. Researchers did find that SRS located further from the edgeline (35 inches) did not practically affect the lateral position of vehicles in the travel lane. Furthermore, it seems that the detrimental effect of SRS close to the edgeline on vehicle lateral placement can be mitigated by including CRS.

CHAPTER 4:
CLOSED-COURSE STUDIES

INTRODUCTION

While the findings in Chapter 3 showed that SRS installed further from the edgeline (i.e., a larger offset) did not practically affect the lateral position of vehicles in the travel lane, at some maximum offset, it is likely that SRS will no longer warn drivers in time for them to correct their errant vehicle trajectory before leaving the paved roadway surface. As part of this research project, TTI researchers designed and conducted a closed-course study to determine the minimum distance required for drivers to correct errant vehicle trajectories once alerted by SRS. Using an instrumented vehicle, researchers were able to observe how drivers exited the travel lane, corrected their errant vehicle trajectory, and returned to the travel lane.

EXPERIMENTAL DESIGN

Development of Driving Course

Researchers conducted the closed-course study at the Texas A&M University Riverside Campus, a 2000-acre complex of research and training facilities situated 10 miles northwest of the university's main campus. For a previous demonstration, TTI colleagues applied pavement markings on one of the runways to simulate a tolling zone for managed lanes. The simulated roadway consisted of 3200 ft of two-lane road with white edgelines and a double white centerline. The section widened to four lanes, with white hash marks in the gore, for approximately 500 ft. The transition in and out of this section covered 1600 ft. The lane width was 11 ft. The slight discontinuities at the transition points provided a moderately challenging lane tracking task for drivers, and when paired with an in-vehicle secondary task (discussed in further detail later), produced lane departures in these areas. To further encourage lane departures, in the southbound direction where the course originally widened to two lanes, researchers altered the pavement markings to form only one lane and added delineator posts to narrow the travel lane. The distance prior to the simulated roadway from both directions was approximately 1800 ft.

Researchers were not able to permanently alter the pavement at the Texas A&M University Riverside Campus, so they considered several approaches to replicate the sound and vibration created by milled rumble strips. Ultimately, researchers chose to use a commercial extruded bar-shaped rumble strip (Figure 14). This raised rumble strip was 10 inches long, 4 inches wide, 0.75 inch high, and had a beveled edge on one end.

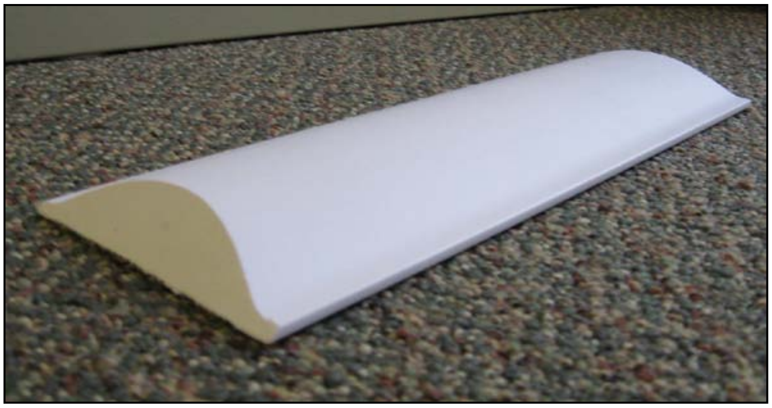


Figure 14. Bar-Shaped Extruded Plastic Rumble Strip.

Researchers ordered one thousand of these rumble strips and installed them on the course at strategic locations around the track to further increase the likelihood of rumble strip hits. These locations are denoted with the letters A through E in Figure 15. Researchers installed the rumble strips with the beveled edge directly on the inside edge of the edgeline (see Figure 16) to increase the likelihood of rumble strip hits by the participants. Figure 17 contains a view of the simulated driving course in the southbound direction.

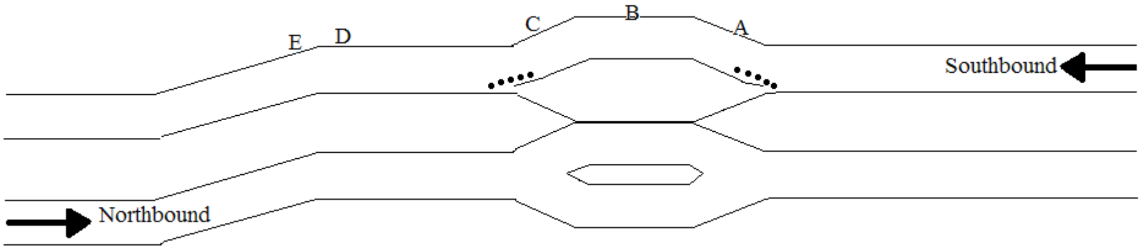


Figure 15. Driving Course with Rumble Strip Sections Labeled.

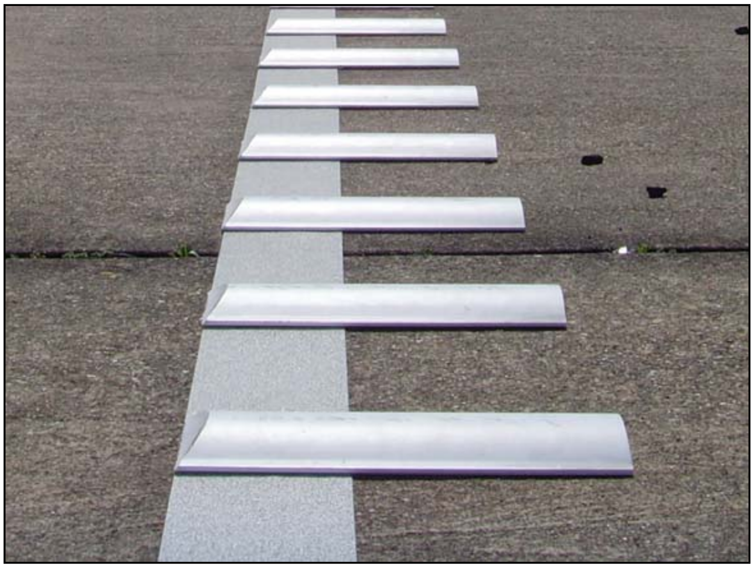


Figure 16. Close-up of Rumble Strips Positioned on the Edgeline.

Figure 17. Simulated Driving Course Facing Southbound.

Instrumented Vehicle

The TTI instrumented vehicle is a 2006 Toyota Highlander that is equipped with multiple integrated systems to record various data relating the driver's behaviors, the external driving situation, and the dynamic vehicle performance. The principal system within the instrumented vehicle was the Dewetron DEWE5000. Essentially a large portable computer, the DEWE5000 served as the data acquisition device for all the peripheral systems in the vehicle. The DEWE5000 is capable of sampling at 5000 Hz; however, for this experiment data were collected at 100 Hz.

A Trimble DSM232 Global Positioning System (GPS) tracked the position of the vehicle around the course. It employed a Differential GPS antenna mounted on the roof of the vehicle directly over the driver's seat. The GPS sampled data at 10 Hz, a critical feature not available on most GPS systems.

An Assistware SafeTRAC measured the lateral lane position of the vehicle as well as the lane width and the lateral velocity. This is accomplished through the combination of a forward-looking video camera and sophisticated image processing software. The SafeTRAC outputs lateral lane position, lateral velocity, and lane width at 10 Hz.

Three potentiometers collected data on the position of the brake pedal, the gas pedal, and the steering wheel. A Crossbow Piezoresistive Accelerometer collected acceleration data for three axes (i.e., roll, pitch, and yaw rates) at a sensitivity of 0.6218 mV/g.

The following three video cameras also collected data during the experiment: one facing the participant, one facing forward to obtain the driver's view, and one mounted over the front right wheel. The last camera was positioned in order to provide video of exactly when and from what direction the rumble strips were contacted by the leading tire. Figure 18 shows a picture of this camera on the side of the instrumented vehicle.

In-Vehicle Secondary Task

As mentioned previously, researchers used an in-vehicle secondary task to draw the participant's attention away from the travel path and thus encourage rumble strip hits. Researchers chose a data entry task as it provided distraction in both the visual and psychomotor channels. A keyboard mounted near the glove box of the vehicle forced participants to move their upper body in a way that would further encourage rumble strip hits. Figure 19 shows the location of the keyboard in the instrumented vehicle. Participants entered strings of numbers and symbols into the keyboard as they drove. Initially, all participants began with a short list of data entry strings and the standard keyboard. On subsequent runs, the study administrator tailored the difficulty level specifically to each participant's ability to accomplish the secondary task and yet still drive just poorly enough to deviate from the travel lane and hit the rumble strips.

Figure 18. Camera Mounted over Front Right Wheel.

Figure 19. Keyboard Used as Input Device in Distracter Task.

Protocol

Participant check-in and briefing took place at the TTI facility at the Texas A&M Riverside Campus. Upon arrival to the study location, participants were provided an explanation of the study and their driving task and were asked to read and sign the informed consent document. They were given a standard static visual acuity test (Snellen) prior to initiating the driving portion of the study. Each participant was compensated $40.00.

As described previously, the study was conducted in a state-owned passenger vehicle that has been instrumented with equipment that records various data relating the driver's behaviors, the external driving situation, and the dynamic vehicle performance. The participant drove the study vehicle on the closed-course at 55 and 70 mph. The study administrator accompanied the participant at all times, provided verbal directions to the participant, and recorded the participant's responses.

Once on the closed-course the study administrator briefed the participant on the procedure and showed him or her how to operate the cruise control. The participant then drove the course once in the northbound direction so that he or she could become familiar with the course and setting the cruise control. Once the participant was comfortable with the vehicle, the study administrator showed the participant the keyboard mounted on the glove box and explained the secondary task.

The study administrator then told the participant the speed at which he or she was to drive (either 55 or 70 mph). The participant would then accelerate to the requested speed and set the cruise control. The cruise control ensured that the speed was maintained during the performance of the secondary task. After entering the simulated driving course, the study administrator presented the participant with the list of strings of numbers and symbols for the secondary task. The list was placed on the passenger seat angled towards the driver. Participants were instructed to try to completely enter the strings of information as quickly as possible. The study administrator used additional lists as necessary during each run to encourage lane departures.

Participants repeated this process multiple times at both speeds. The total number of runs for each participant was based on multiple factors, including the total driving time available (around 1.5 hours) and the likelihood that more passes would elicit more rumble strip hits. After multiple rumble strips hits, some participants became more resistant to performing the secondary task in areas where lane departures would result in rumble strip hits. Conversely, some participants became so adept at the secondary task that they could easily complete the most difficult tasks at 70 mph without leaving their lane.

Participants

Researchers recruited a total of 36 participants from the Bryan-College Station area to participate in the study. The participants were required to have a current valid driver's license. The sample was composed of 19 females and 17 males. Researchers divided the participants into two age groups: less than 50 years old and over 50 years old. The over-50 age group contained 22 participants and the average age was 68. The less-than-50 age group contained 14 participants and the average age was 27.

DATA ANALYSIS

In order to determine the minimum distance required for drivers to correct errant vehicle trajectories once alerted by SRS several factors including departure angle and driver reaction times to stimuli (in this case SRS) were needed. Researchers were also interested in how drivers physically react to SRS.

Researchers divided lane departures into two categories: rumble strip hit and non-rumble strip hit. The most accurate method for determining when the rumble strips were hit was to review the output from the accelerometer for the lateral axis of the vehicle. Initially, researchers used the video data to identify the time when the tires first contacted the rumble strips. Then the largest spike in the accelerometer prior to this point in time was identified as the rumble strip hit. In cases where the participant exited the lane and did not hit the rumble strips, researchers marked the time at which they exited the lane. This time was defined as the point when half of the edgeline was covered by the right front tire in the over-wheel video.

Researchers used lane position data to determine the departure angles. In order to determine reaction times, researchers identified the time when the steering wheel was first corrected back in the opposite direction after hitting the rumble strips or just exiting the lane. The steering wheel reaction was coded from the output of the potentiometer connected to the steering wheel. Last, researchers determined the lateral distance traveled after exiting the travel lane to the point when the steering wheel was first corrected back in the opposite direction.

Unfortunately, due to time limitations researchers were unable to compute the departure angle and reaction times for the lane departures with non-rumble strip hits. Researchers did review the data to assess whether speed (i.e., 55 and 70 mph) or "first rumble hit" influenced driver reactions to the SRS; however, neither of these conditions was found to affect driver reactions.

RESULTS

Figure 20 shows the cumulative distribution of the departure angle data for those lane departures where rumble strips were hit. The average departure angle was 1.04 degrees, with a 0.82 degree standard deviation and a 95 percent confidence interval between 0.88 and 1.2 degrees. The 85th percentile departure angle was 1.94 degrees; however, 81 percent of the departure angles were less than 1.5 degrees. The maximum departure angle was 4.56 degrees. As expected, these findings indicate that distracted drivers typically exit the travel lane at very shallow angles.

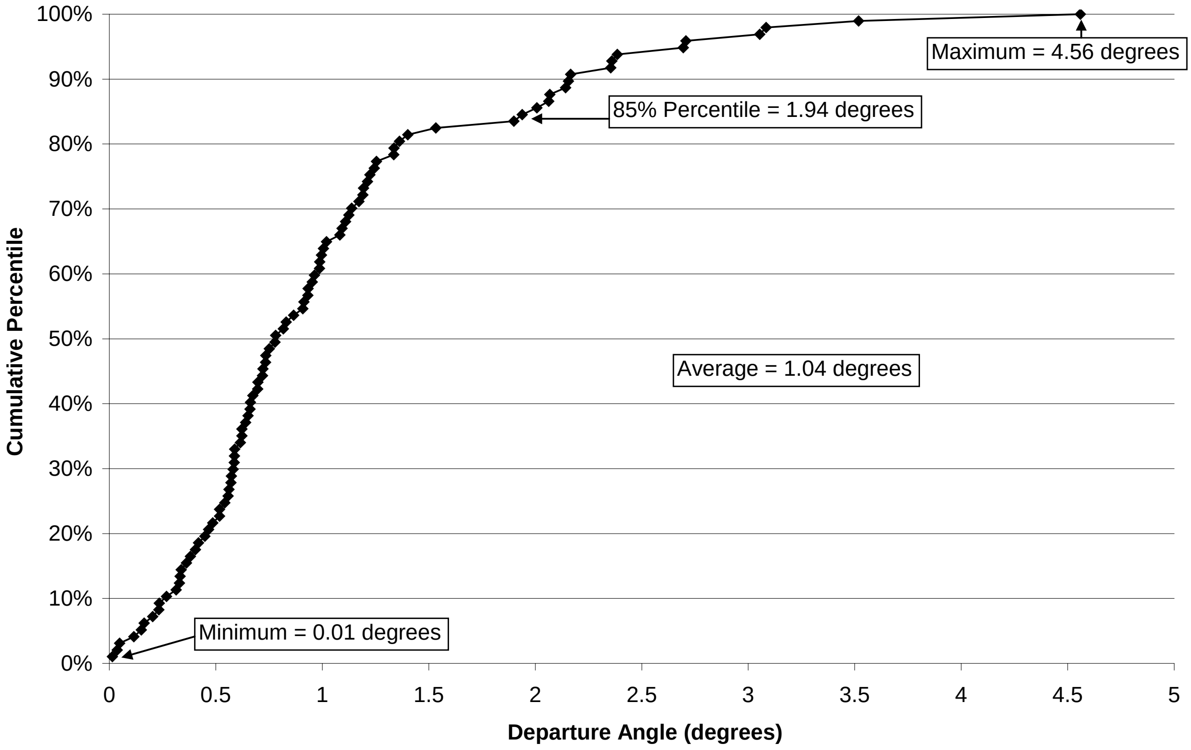


Figure 20. Cumulative Departure Angle Distribution (n=97).

Overall reaction time was defined as the time gap between the beginning of the rumble strip auditory warning and the first change in the steering angle back in the opposite direction. Figure 21 shows the cumulative distribution of the reaction time data. The average reaction time was 0.4 second, with a 0.24 second standard deviation and a 95 percent confidence interval between 0.35 and 0.45 second. These findings are similar to those found in the recent European driver simulator study (*21*). The 85th percentile reaction time was 0.6 second, while the maximum reaction time was 1.25 seconds.

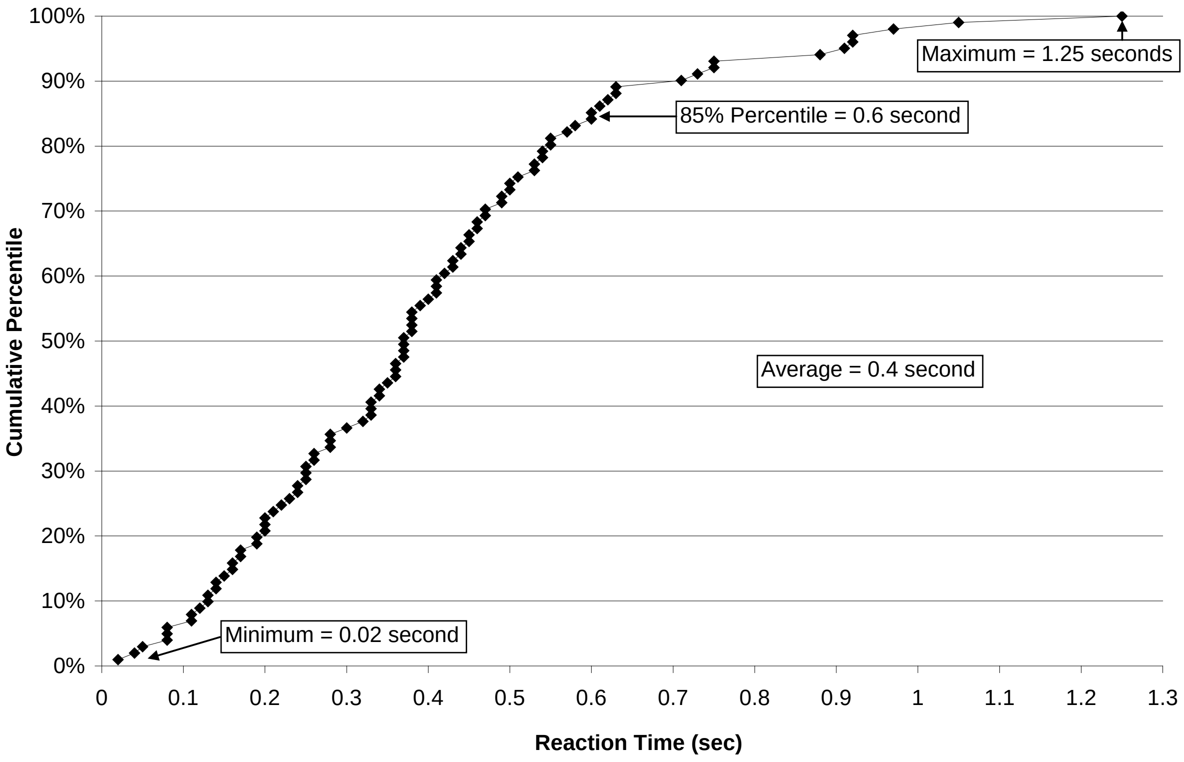


Figure 21. Cumulative Reaction Time Distribution (n=101).

The primary objective of the closed-course study was to determine the minimum distance required for drivers to correct errant vehicle trajectories once alerted by passing over SRS. Figure 22 shows the cumulative distribution of the lateral distance traveled after hitting the rumble strips to the point when the steering wheel was first corrected back in the opposite direction. The average lateral distance for drivers to correct their errant trajectory after hitting the SRS was 7.73 inches, with an 8-inch standard deviation and a 95 percent confidence interval between 5.67 and 9.79 inches. The 85th percentile distance was 13.24 inches (a little more than 1 ft); however, 83 percent of the lateral distances traveled were less than 1 ft. The maximum distance was 42.31 inches (approximately 3.5 ft).

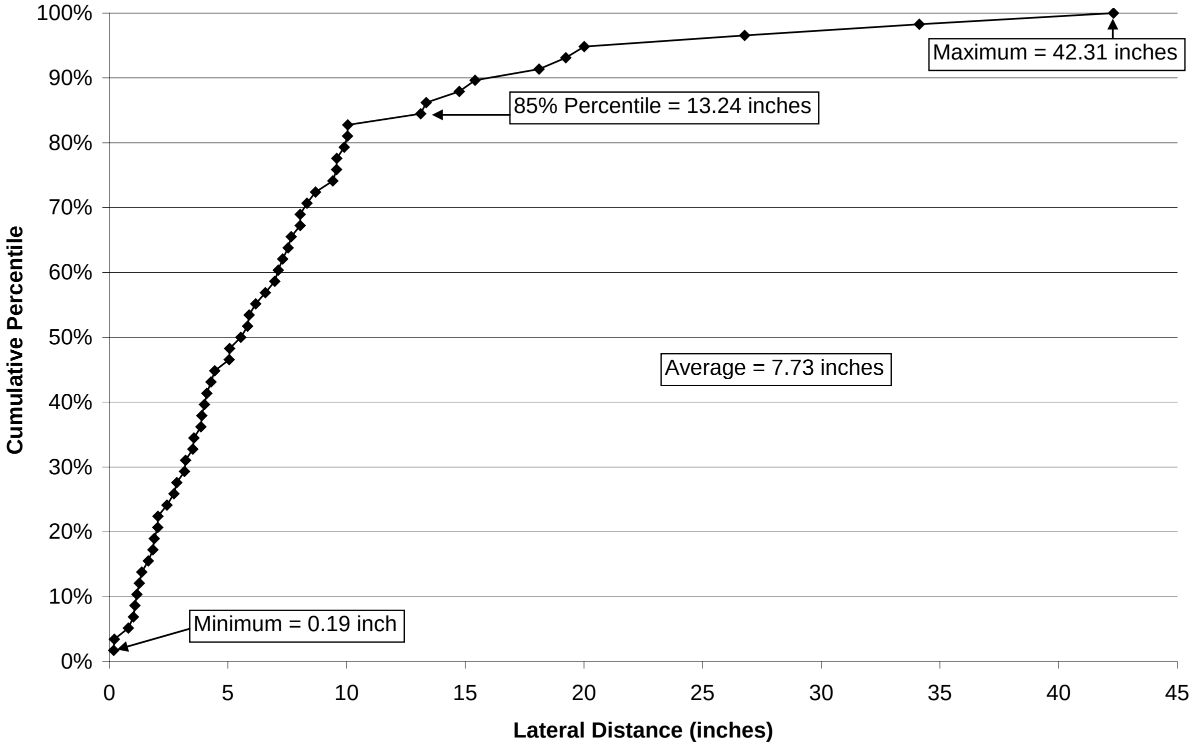


Figure 22. Cumulative Lateral Distance Distribution (n=58).

Researchers investigated the lateral velocity when participants exited the lane and returned to the lane to assess driver reaction to hitting the rumble strips. Researchers also reviewed the non-rumble strip hit data to gain insights into the difference between hitting rumble strips and not hitting rumble strips. Table 8 contains the lateral velocity descriptive statistics for departing the lane, returning to the lane after contacting SRS, and returning to the lane without contacting the SRS. As expected, both of the average return to lane lateral velocities (hitting rumble strip and not hitting rumble strip) are slightly higher than the average exiting lane lateral velocity. However, the range of values and 95 percent confidence interval for the return to lane without hitting the rumble strips lateral velocities are larger than those that hit the rumble strips.

Table 8. Lateral Velocity Descriptive Statistics.

Descriptive Statistic	Lateral Velocity		
	Exiting Lane	**Returning to Lane Hit Rumble Strip**	**Returning to Lane Did Not Hit Rumble Strip**
Average	1.16 mph	1.35 mph	1.36 mph
Standard deviation	0.56 mph	0.54 mph	0.75 mph
Sample size	143	75	46
95% confidence interval	1.07 to 1.25 mph	1.23 mph to 1.47 mph	1.15 to 1.58 mph
Maximum	3.27 mph	3.13 mph	4.38 mph
Minimum	0.18 mph	0.27 mph	0.40 mph

During the study, researchers observed that participants who hit the rumble strips (and thus received an auditory and vibratory warning) returned to the lane more gradually than those that did not hit the rumble strips (and thus did not receive any warning that they were exiting the travel lane). To further investigate this trend researchers computed the difference between the exit lateral velocity and the return lateral velocity for each run. Figure 23 shows the cumulative distribution of the lateral velocity differences for those participants that did and did not hit the SRS. Those participants that hit the rumble strips changed their lateral velocity less than those that did not hit the rumble strips, indicating a less severe change in direction. Researchers attributed this to the fact that participants who hit the rumble strips did not travel as far out of the lane as those participants that did not hit the rumble strips, and thus did not need to correct their errant vehicle trajectory as much as those participants that traveled further out of the lane before realizing (on their own) that they had left the travel lane.

FURTHER ANALYSIS

Using the 85th percentile driver data from the closed-course study researchers determined the remaining paved shoulder width available after a driver exits the travel lane, is alerted by SRS, and begins to correct his or her errant vehicle trajectory for a range of shoulder widths and SRS offsets. First, they calculated the distance from the inside edge of the SRS to the edge of pavement for various shoulder width and SRS lateral offset combinations. This is the maximum distance a vehicle can travel after encountering the SRS before exiting the paved surface. Using this maximum horizontal distance and a 2-degree departure angle, researchers computed the corresponding maximum distance along the vehicle path (i.e., diagonal distance from inside edge of SRS to the edge of the pavement). Next, the distance traveled during a 0.6 second driver's perception and reaction time (hereafter referred to as driver reaction time) was calculated. It is important to note that researchers did not use the 85th percentile value from the closed-course study (13.24 inches); instead this distance was calculated based on the speed of the roadway (70 mph) and departure angle. This was a more conservative analysis that yielded a larger margin of safety. Researchers then subtracted the reaction distance from the maximum diagonal distance the vehicle could travel before exiting the paved surface. Using this distance and the departure angle, the lateral width of the remaining available paved shoulder was calculated (Table 9). Based on the findings in Table 9, lateral offsets that position the center of 16-inch-wide SRS in the middle of shoulders at least 4 ft wide should provide enough remaining shoulder width for the 85th percentile distracted drivers to correct their errant vehicle trajectory before leaving the paved roadway surface.

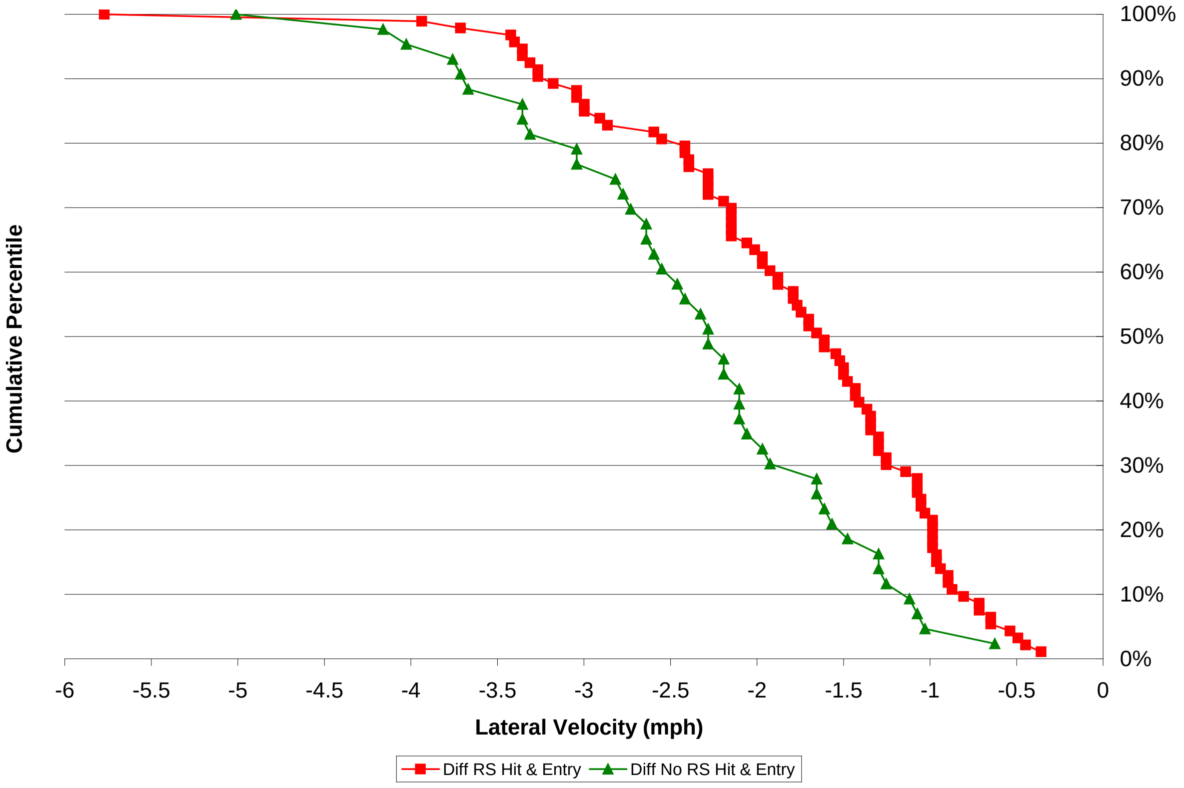


Figure 23. Cumulative Distribution of Lateral Velocity Differences.

Table 9. Remaining Shoulder Width (DA=2 degrees, RT=0.6 second, SL=70 mph).

Shoulder Width [a] (ft)	SRS Lateral Offset (in) [b]							
	-4	0	4	8	12	24	36	48
4	1.9 ft	1.5 ft	1.2 ft	0.9 ft	0.5 ft [c]	NA	NA	NA
6	3.9 ft	3.5 ft	3.2 ft	2.9 ft	2.5 ft	1.5 ft [c]	NA	NA
8	5.9 ft	5.5 ft	5.2 ft	4.9 ft	4.5 ft	NA	2.5 ft [c]	NA
10	7.9 ft	7.5 ft	7.2 ft	6.9 ft	6.5 ft	NA	NA	3.5 ft [c]

DA = Departure Angle; RT = Reaction Time; SL = Speed Limit; NA = Not Applicable

[a] Measured from the inside edge of edgeline to the edge of pavement (i.e., includes 4-inch edgeline).

[b] Measured from the outside edge of the edgeline to the inside edge of the rumble strip.

[c] This offset positions the center of a 16-inch-wide rumble strip in the middle of the shoulder, assuming a 4-inch edgeline.

SUMMARY

Using an instrumented vehicle on a closed-course study TTI researchers were able to observe how distracted drivers exit the travel lane, react to SRS, and correct their errant vehicle trajectory once alerted by SRS. As expected, distracted drivers typically exited the travel lane at very shallow angles (less than 2 degrees). In addition, drivers reacted very quickly to the auditory and vibratory warnings produced by SRS (on average less than 0.5 second). During this reaction time, most drivers (83 percent) travel laterally less than 1 ft before starting to correct their errant vehicle trajectory back in the opposite direction (i.e., toward the travel lane). Compared to drivers that did not hit the SRS, drivers who contacted the SRS did not change their lateral velocity as much, indicating a less severe change in direction and potential safety benefit. Further analysis showed that lateral offsets that position the center of 16-inch-wide SRS in the middle of shoulders at least 4 ft wide should provide enough remaining shoulder width for the 85th percentile distracted drivers to correct their errant vehicle trajectory before leaving the paved roadway surface.

CHAPTER 5:
CONCLUSIONS AND RECOMMENDATIONS

Rumble strips are raised or depressed patterns on the roadway that produce audible and vibratory warnings when a vehicle's tires pass over them, thereby alerting drivers who may inadvertently encroach onto the shoulder or across the centerline. While previous research has shown that SRS and CRS on two-lane, undivided roadways significantly reduce the targeted crashes (i.e., ROR and head-on and opposing-direction sideswipe crashes, respectively), it is not known how these rumble strip applications affect other types of crashes (i.e., influence of SRS on head-on and opposing-direction sideswipe crashes or influence of CRS on ROR crashes). In addition, there are still questions about the operational impacts of these applications and their potential safety implications. In this project, researchers investigated the impacts of depressed SRS and CRS on the lateral placement of vehicles in the travel lane of two-lane, undivided roadways as a potential indicator of safety. Researchers assumed that vehicle paths located near the center of the travel lane would decrease the likelihood of crashes and thus improve safety. Based on the results of the field and closed-course studies presented in this report, researchers made the following conclusions and recommendations regarding continuous depressed rumble strips:

- It appears that CRS on two-lane, undivided roadways with lane widths as narrow as 10 ft do not adversely impact the lateral placement of vehicles in the travel lane. In fact, at locations with CRS and smaller shoulder widths (1 to 2 ft) drivers positioned the center of their vehicle closer to the center of the lane, thus potentially improving safety. Therefore, researchers recommend that CRS may be used on two-lane, undivided roadways with lane widths as narrow as 10 ft.
- It also seems that the combination of ERS and CRS on two-lane, undivided roadways with lane widths as narrow as 11 ft do not adversely impact the lateral placement of vehicles in the travel lane. In fact, a similar benefit of drivers positioning the center of their vehicles closer to the center of the lane was experienced at locations with smaller shoulder widths (3 ft), again potentially improving safety. Thus, researchers recommend that the combination of ERS and CRS may be used on two-lane, undivided roadways with lane widths as narrow as 11 ft.

- The effect of SRS located within 7 to 9 inches of the edgeline on the lateral placement of vehicles in the travel lane is highly variable on two-lane, undivided roadways with 12-ft lanes. Nevertheless, it does appear that the potential exists for SRS located within 7 to 9 inches of the edgeline to shift vehicle travel paths closer to the centerline, which may increase the likelihood for head-on and opposing-direction sideswipe crashes and thus negatively impact safety. Even though researchers did not evaluate the impacts of ERS without CRS, they expect that ERS may also shift the lateral placement of vehicles in the travel lane toward the centerline. However, it does seem that the application of CRS in conjunction with ERS may counteract this tendency since drivers tended to position their vehicles closer to the center of the lane. In addition, it appears that depressed SRS located 35 inches from the edgeline do not adversely impact the lateral placement of vehicles in the travel lane on two-lane, undivided roadways with 12-ft lanes. Thus as shown in Figure 24, researchers recommend that CRS be installed in conjunction with SRS that are placed on the edgeline (i.e., ERS) or within 9 inches of the edgeline. In addition, the use of CRS should be considered when SRS are located more than 9 inches but less than 35 inches from the edgeline. Researchers do not believe that CRS are needed when SRS are placed 35 inches or more from the edgeline.
- Lateral offsets that position the center of 16-inch-wide SRS in the middle of shoulders at least 4 ft wide should provide enough remaining shoulder width for the 85th percentile distracted driver to correct his or her errant vehicle trajectory before leaving the paved roadway surface. Thus, on shoulders 4 ft or greater in width researchers recommend the maximum allowable lateral offsets shown in Table 10 for depressed SRS.

Researchers also recommend that a crash study be conducted to assess the actual safety implications of SRS and CRS installed on two-lane, undivided roadways. Unlike previous research, the study should assess the impacts of SRS and CRS on all types of crashes, not just those for which a safety benefit is expected.

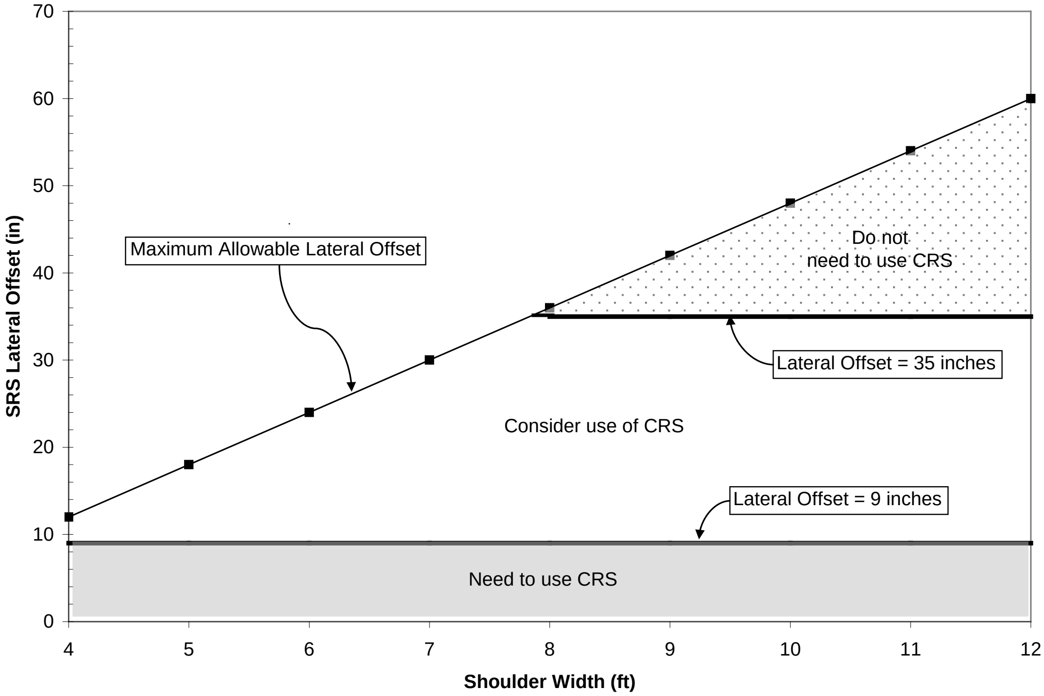


Figure 24. Recommendations for the Use of CRS in Conjunction with SRS.

Table 10. Maximum Allowable Lateral Offset for Depressed SRS on Shoulders 4 ft or Greater in Width.

Shoulder Width (ft) [a]	Maximum Lateral Offset (in) [b]
4	12
5	18
6	24
7	30
8	36
9	42
10	48
11	54
12	60

[a] Measured from the inside edge of edgeline to the edge of pavement (i.e., includes edgeline).

[b] Measured from the outside edge of the edgeline to the inside edge of the rumble strip. Assuming a 4-inch edgeline, this offset positions the center of a 16-inch-wide rumble strip in the middle of the shoulder.

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APPENDIX:
FIELD STUDY DETAILED RESULTS

Table A1. Descriptive Statistics for Comparison Sections.

Site No.	Lane Width (ft)	Shoulder Width (ft)	Type of Vehicle	Sample Size [a] (n)	Mean Lateral Position [b] (Measured) (in)	Variance (in^2)	Standard Deviation (in)	Mean Lateral Position [c] (Computed) (in)	% of Vehicles Hitting Edgeline	% of Vehicles Hitting Centerline
4C	10	1	Isolated	1679	34.9	139.7	11.8	-10.9	0	7.1
			Oncoming	807	33.4	136.2	11.7	-9.4	0	8.3
			All	2498	34.4	139.0	11.8	-10.4	0	7.9
1C(SB)	10	3	Isolated	598	48.1	147.4	12.1	-24.1	0.2	31.3
			Oncoming	545	40.5	223.2	14.9	-16.5	0.2	17.6
			All	1144	44.5	199.1	14.1	-20.5	0.2	24.8
5C(SB)	11	3	Isolated	545	46.6	150.8	12.3	-16.6	0	4.6
			Oncoming	46	47.3	238.4	15.4	-17.3	0	6.5
			All	600	46.6	157.5	12.6	-16.6	0	4.7
5C(NB)	12	3	Isolated	499	49.8	143.8	12.0	-13.8	0	4.2
			Oncoming	65	51.2	140.7	11.9	-15.2	0	6.2
			All	564	49.9	143.3	12.0	-13.9	0	4.4
2C	12	9	Isolated	1840	38.9	218.4	14.8	-2.9	0.7	1.3
			Oncoming	5960	32.2	239.0	15.5	3.8	2.5	0.7
			All	7802	33.8	242.1	15.6	2.3	2.1	0.8
3C	12	11	Isolated	3195	37.6	188.0	13.7	-1.6	0.3	1.9
			Oncoming	4808	32.1	189.1	13.8	3.9	0.5	1.3
			All	8004	34.3	195.7	14.0	1.7	0.4	1.6

[a] The "all" sample size does not necessarily equal the sum of the "isolated" and "oncoming" sample sizes since some vehicles could not be sorted into the two vehicle type categories but could be used when all data were combined (i.e., category did not matter).

[b] Measured from the inside edge of the edgeline to the vehicle's right tire.

[c] Computed distance from center of the lane to the vehicle centroid. Assumed vehicle track width of 6 ft. Negative numbers are to the left of the center of the lane and positive numbers are to the right of the center of the lane.

Table A2. Descriptive Statistics for CRS Sites.

Site No.	Lane Width (ft)	Shoulder Width (ft)	Type of Vehicle	Sample Size [a] (n)	Mean Lateral Position [b] (Measured) (in)	Variance (in^2)	Standard Deviation (in)	Mean Lateral Position [c] (Computed) (in)	% of Vehicles Hitting Edgeline	% of Vehicles Hitting Centerline
AUS3	10	2	Isolated	3172	29.6	105.9	10.3	-5.6	0.03	3.8
			Oncoming	6649	27.9	96.4	9.8	-3.9	0.1	2.9
			All	9821	28.4	100.0	10.0	-4.4	0.04	3.2
AUS2	12	1	Isolated	3141	46.3	127.5	11.3	-10.3	0.2	1.5
			Oncoming	7529	40.6	142.6	11.9	-4.6	0.1	1.2
			All	10671	42.3	145.0	12.0	-6.3	0.2	1.3
BMT1	12	10	Isolated	4827	32.7	194.9	14.0	3.3	1.0	1.0
			Oncoming	7320	28.1	207.9	14.4	7.9	2.2	0.7
			All	12147	29.9	207.7	14.4	6.1	1.7	0.8

[a] The “all” sample size does not necessarily equal the sum of the “isolated” and “oncoming” sample sizes since some vehicles could not be sorted into the two vehicle type categories but could be used when all data were combined (i.e., category did not matter).

[b] Measured from the inside edge of the edgeline to the vehicle’s right tire.

[c] Computed distance from center of the lane to the vehicle centroid. Assumed vehicle track width of 6 ft. Negative numbers are to the left of the center of the lane and positive numbers are to the right of the center of the lane.

Table A3. Descriptive Statistics for SRS Sites.

Site No.	Lane Width (ft)	Shoulder Width (ft)	Type of Vehicle	Sample Size [a] (n)	Mean Lateral Position [b] (Measured) (in)	Variance (in^2)	Standard Deviation (in)	Mean Lateral Position [c] (Computed) (in)	% of Vehicles Hitting Edgeline	% of Vehicles Hitting Centerline
BRY2	12	6	Isolated	3606	47.7	147.4	12.1	-11.7	0	3.8
			Oncoming	5769	42.4	148.6	12.2	-6.4	0.1	1.3
			All	9375	44.4	154.8	12.4	-8.4	0.04	2.3
HOU11	12	6	Isolated	2756	39.9	242.7	15.6	-3.9	0.1	3.3
			Oncoming	1187	33.8	218.7	14.8	2.2	0.3	1.5
			All	3944	38.1	243.4	15.6	-2.1	0.2	2.8
HOU12	12	9	Isolated	4146	48.5	175.8	13.3	-12.5	0.1	3.4
			Oncoming	6934	44.2	185.8	13.6	-8.2	0.1	2.3
			All	11082	45.8	186.3	13.7	-9.8	0.1	2.7
YKM3	12	9	Isolated	3061	31.0	184.7	136.	5.0	1.8	1.0
			Oncoming	4359	31.1	196.6	14.0	4.9	2.1	0.8
			All	7420	31.1	191.5	13.8.	4.9	2.0	0.9
HOU1	12	11	Isolated	6397	30.1	196.0	14.0	5.9	0.5	0.7
			Oncoming	22412	29.4	178.8	13.4	6.6	0.6	0.6
			All	28815	29.6	182.5	13.5	6.4	0.6	0.6

[a] The “all” sample size does not necessarily equal the sum of the “isolated” and “oncoming” sample sizes since some vehicles could not be sorted into the two vehicle type categories but could be used when all data were combined (i.e., category did not matter).

[b] Measured from the inside edge of the edgeline to the vehicle’s right tire.

[c] Computed distance from center of the lane to the vehicle centroid. Assumed vehicle track width of 6 ft. Negative numbers are to the left of the center of the lane and positive numbers are to the right of the center of the lane.

Table A4. Descriptive Statistics for Sites with Both CRS and ERS.

Site No.	Lane Width (ft)	Shoulder Width (ft)	Type of Vehicle	Sample Size [a] (n)	Mean Lateral Position [b] (Measured) (in)	Variance (in^2)	Standard Deviation (in)	Mean Lateral Position [c] (Computed) (in)	% of Vehicles Hitting Edgeline	% of Vehicles Hitting Centerline
AUS1	11	3	Isolated	3831	37.9	168.0	13.0	-7.9	0.03	8.9
			Oncoming	4181	36.1	179.8	13.4	-6.1	0.1	7.8
			All	8012	37.0	175.0	13.2	-7.0	0.04	8.3
BRY1	12	9	Isolated	4964	35.6	215.2	14.7	0.4	0.4	2.5
			Oncoming	16236	32.1	208.8	14.5	3.9	0.5	1.5
			All	21204	32.9	212.6	14.6	3.1	0.5	1.7

[a] The “all” sample size does not necessarily equal the sum of the “isolated” and “oncoming” sample sizes since some vehicles could not be sorted into the two vehicle type categories but could be used when all data were combined (i.e., category did not matter).

[b] Measured from the inside edge of the edgeline to the vehicle’s right tire.

[c] Computed distance from center of the lane to the vehicle centroid. Assumed vehicle track width of 6 ft. Negative numbers are to the left of the center of the lane and positive numbers are to the right of the center of the lane.