GEORGIA DOT RESEARCH PROJECT 23-07

Final Report

INVESTIGATE THE IMPACT OF RUMBLE STRIPS ON MOTORCYCLISTS

GDOT
Georgia Department of Transportation

Office of Performance-based Management and Research
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16. Abstract:
This research project evaluates how rumble strip design and placement affect motorcycle safety and comfort, with the goal of developing recommendations for the Georgia Department of Transportation (GDOT) to improve roadway design practices. Rumble strips are a proven countermeasure for roadway departure crashes; however, their vibration and geometry can pose stability concerns for motorcyclists, particularly during braking or leaning maneuvers. The study included a review of existing literature, analysis of Georgia crash data, and a statewide survey of motorcyclists to assess perceived safety and comfort related to different rumble strip configurations. Additionally, a simulation framework was developed to model motorcycle vibration and wheel response under varying rumble strip geometries, speeds, and surface conditions. Survey findings indicated that more than 70 % of respondents experienced discomfort or instability when crossing traditional milled rumble strips, especially along centerlines and shoulders. Simulation results showed that sinusoidal and shallower designs produce smoother vibration patterns and reduced vertical acceleration, suggesting improved stability and rider control. Sinusoidal rumble strips reduced peak vertical acceleration by approximately 50% compared to conventional milled designs. This was confirmed through interviews with affected motorcyclists. Based on these results, the study recommends implementation of sinusoidal rumble strips in Georgia, as well as updated installation guidance emphasizing context-sensitive design, and regular maintenance to ensure rider safety. These efforts will enhance GDOT's ability to balance roadway departure crash reduction with the safety needs of vulnerable road users.

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Final Report

INVESTIGATE THE IMPACT OF RUMBLE STRIPS ON MOTORCYCLISTS

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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EXECUTIVE SUMMARY

To improve roadway safety and reduce motorcycle-related crash severity across Georgia's transportation network, the Georgia Department of Transportation (GDOT) initiated Research Project RP 23-07, Investigate the Impact of Rumble Strips on Motorcyclists. While rumble strips have long proven effective in reducing run-off-the-road and head-on collisions for passenger vehicles, their effects on motorcycles remain unclear. GDOT seeks to develop a data-driven framework to improve rumble strip design and placement that enhances motorcyclist safety without reducing overall roadway safety benefits.

This research addresses a significant gap in current transportation safety studies. Few studies have examined the suitability of different rumble strip types for motorcyclists. Early screening of GDOT crash data revealed limited cases where rumble strips contributed to crashes. However, due to potential underreporting, the true extent of these incidents remains uncertain. To address these limitations, this study combines literature review, community outreach, and experimental design to form a comprehensive understanding of the issue. The objectives of this research are to inform GDOT's design standards, installation practices, and maintenance policies for rumble strips to better accommodate motorcyclist safety while preserving roadway departure crash reduction benefits.

To accomplish these objectives, several key tasks were undertaken. First, a literature review synthesized findings from previous studies, revealing that while centerline rumble strips are generally considered safe, there is a significant gap in the current literature. Second, a survey of Georgia motorcyclists, conducted in collaboration with the Georgia Department of Driver Services, collected responses from 84 riders statewide. Results indicated that edge-line rumble strips generated the greatest concern (reported by 63.9% of participants), followed by centerline and in-lane strips, with riders frequently citing vibration intensity and rumble strips on curves as primary

hazards. Third, a simulation study employed a physics-based Python model to analyze motorcycle interactions with different rumble strip profiles, showing that sinusoidal and shallower milled designs significantly reduce vertical acceleration amplitudes, thereby improving stability. Finally, the policy implications of these findings will guide GDOT in refining rumble strip standards, updating signage guidelines, and potentially incorporating rumble strip awareness and navigation into the state's motorcycle safety training curriculum.

Based on these findings, several implementation measures are recommended to enhance motorcyclist safety while maintaining the effectiveness of rumble strips for other road users. The findings suggest consideration be given to limiting rumble strip installation in designated passing zones where motorcyclists are more likely to cross the centerline. Wherever feasible, GDOT may consider incorporating sinusoidal rumble strip profiles, on sharp horizontal curves, installation may be limited to tangent sections, with the addition of motorcycle-safe guardrails where rumble strips are present to reduce run-off-road crash severity. Raised plastic rumble strips may also merit consideration as an alternative for certain passing zones or temporary conditions, as their flexible material produces less intense vibration while maintaining sufficient tactile and auditory alert. Finally, GDOT could continue proactive community outreach to motorcyclists through the Georgia Department of Driver Services (DDS) to increase awareness of new design practices and promote safe roadway behavior

CHAPTER 1. INTRODUCTION

BACKGROUND AND MOTIVATION

This report investigates the impact of various types of rumble strips on motorcyclists and assesses their safety effectiveness. Rumble strips are a proven safety countermeasure shown to reduce crash rates. However, there is limited research on their effects on motorcyclists. The study synthesizes findings from past research, including documented studies from the Minnesota Department of Transportation and European Auto Transport. Few studies have examined how suitable rumble strips are for motorcyclists on curves or how different rumble strip designs impact them. Preliminary crash data analysis from the Georgia Department of Transportation was inconclusive, however, this could be potentially due to underreporting of ROTR (run off the road) crashes. Therefore, motorcyclists were surveyed to get community input. In addition, simulation was conducted to see how rumble strips affect motorcyclists mechanistically.

RESEARCH OBJECTIVES AND SCOPE

The objective of this research is to develop a structured set of guidelines and specifications for rumble strips in the state of Georgia with respect to motorcyclist. To accomplish the goals and the objectives of this research project, the following tasks were performed:

- **Literature Review Task:** Perform a literature review to synthesize different research findings from national and international research efforts on the safety impact of rumble strips on motorcycles.

- **Interview and Survey Task:** Conduct interviews and surveys with motorcycle communities to understand their opinions and concerns on the impact of rumble strips on motorcycle safety.
- **Crash Analysis and Field Test Task:** Conduct motorcycle crash analysis and field tests on locations with rumble strips installed to investigate the impact of rumble strips on motorcycle safety.
- **Outreach Program Task:** Propose an outreach program and develop outreach education materials to promote communication between transportation engineers and motorcycle communities on rumble strips' impacts on riding safety.
- **Final Report Task:** Prepare a draft final report by summarizing the research outcomes and completing the final report.

CHAPTER 2. LITERATURE REVIEW

This chapter provides an overview of the various types of rumble strips and their significance. It also examines current national practices, including those implemented by state Departments of Transportation (DOTs). Additionally, it reviews relevant studies, summarizes existing practices, and identifies key gaps in the literature.

RUMBLE STRIP LOCATION

Rumble strips are an important safety feature used in road design to alert drivers through auditory and vibratory stimuli that they are straying from the driving lane. These strips can be categorized based on their placement relative to the lane of travel, each serving distinct purposes and contexts. The classification includes in lane / traverse rumble strips, edge line rumble strips, centerline rumble strips, and shoulder rumble strips. A summary can be found below in table 1.

Table 1. Locations Of Rumble Strips

Type of Rumble Strip	Description
In Lane Rumble Strips	Used at stop signs or signalized intersections to alert drivers to slow down.
Shoulder Rumble Strips	Installed on highways to prevent vehicles from veering off the road.
Edge Line Rumble Strips	Provide early warning to drivers as they begin to leave the driving lane.
Centerline Rumble Strips	Prevent head-on collisions and lane departures on undivided highways

In Lane Rumble Strips

In lane rumble strips are placed perpendicular to the direction of travel, usually at stop signs or signalized intersections. This strategic placement serves as an effective tactile and auditory warning to alert drivers to slow down. By creating vibrations and noise as vehicles pass over them, these rumble strips enhance road safety by ensuring drivers are aware of critical stopping points or changes in traffic conditions ahead (1). Their use at intersections is instrumental in reducing the incidence of crashes by promoting heightened driver attentiveness and compliance with traffic signals (1, 2).

Figure 1. Photo. In Lane Rumble Strips (2)

Shoulder Rumble Strip

Rumble strips installed on the shoulders of roads are a common safety measure, especially on highways and rural roads. They are designed to alert drivers when their vehicles begin to veer off the driving lane (3). By emitting a distinct vibratory and auditory warning, these rumble strips help in capturing the driver's attention, thereby preventing potential off-road crashes. Their effectiveness is particularly crucial in areas where drivers are more likely to encounter long stretches of monotonous roads, helping to combat driver fatigue and inattention (3).

Figure 2. Photo. Shoulder Rumble Strips (4)

Edge Line Rumble Strip

Edge line rumble strips, like shoulder rumble strips, are designed to enhance roadway safety by alerting drivers when they begin to deviate from their lane. However, while both types are used to prevent vehicles from leaving the roadway, their placement differs significantly. Edge line rumble strips are installed directly on the edge line of the roadway, marking the boundary between the driving lane and the shoulder. This placement is particularly effective in alerting drivers immediately as they begin to cross into the shoulder area (5). In contrast, shoulder rumble strips are located further out on the shoulder itself, serving as a last line of alert before a vehicle leaves the roadway entirely. Both types are critical in reducing run-off-road collisions, but edge line strips provide an earlier warning, potentially allowing drivers more time to correct their path (6).

Figure 3. Photo. Edge line Rumble Strips (6)

Centerline Rumble Strips

Centerline rumble strips are strategically placed along the centerline of undivided highways to enhance road safety by preventing head-on collisions and lane departures. These strips serve a critical role by providing both tactile and auditory warnings to drivers who might inadvertently cross into oncoming traffic or stray from their designated lane (7). Their presence is particularly vital on undivided highways where the risk of such crashes is heightened due to opposing traffic lanes being in proximity. By alerting drivers to correct their vehicle's trajectory before a potentially dangerous situation occurs, centerline rumble strips significantly contribute to reducing the likelihood of serious crashes (8).

Figure 4. Photo. Centerline Rumble Strips (8)

TYPES OF RUMBLE STRIPS

Rumble strips can be categorized into different types based on their physical design and how they interact with vehicle tires. The two main types are raised and indented rumble strips.

Raised strips are elevated above the road surface. They are created by adding material to the roadway surface to form bumps or raised bars. When a vehicle drives over these strips, the tires experience a sudden bump, generating audible noise and vibration. This type is often used where it is not feasible to modify the existing road surface by cutting or milling, such as on bridge decks or certain types of pavements that could be damaged by more invasive procedures (9).

Indented rumble strips are the most common type of rumble strips. They are created by removing material from the road surface, usually through a milling process, to form grooves or indents. When vehicles pass over these grooves, the air compression in the tire treads along with the physical interaction between the tire and the edges of the grooves produces a strong vibratory and auditory response. Indented rumble strips are highly effective and can be installed in a variety of patterns to maximize their alerting impact on drivers (10).

Both types serve the primary purpose of alerting inattentive drivers through audible and tactile feedback, thereby reducing crashes. However, the choice between raised and indented rumble strips can depend on several factors, including road type, climatic conditions, road safety objectives, and installation cost considerations (10).

RAISED RUMBLE STRIPS

Plastic Rumble Strips

Material and Installation: Constructed from pre-formed durable lightweight plastics, these strips are attached to the road surface using adhesives or mechanical fasteners. They are adaptable to various environmental and traffic conditions.

Effect on Drivers: These strips deliver noticeable tactile and auditory alerts. Their flexible nature makes them less disruptive, suitable for areas where mild alerts are sufficient (11).

Figure 5. Photo. Plastic Raised Rumble Strip (11)

Rubber Rumble Strips

Material and Installation: These strips are made from recycled rubber or synthetic materials and are either glued or bolted to the road surface. Rubber is particularly versatile and suitable for various installation contexts.

Effect on Drivers: Rubber strips generate softer auditory and vibratory feedback compared to metal and thermoplastic, which can be beneficial in noise-sensitive areas. They still effectively alert drivers while being gentler on vehicles (12).

Figure 6. Photo. Transverse Rubber Rumble Strip (13)

Rumble Strip Tape

Material and Installation: Rumble strip tape is a quick and easy-to-install alternative, made from durable, textured adhesive materials that can be applied directly to the road surface. This type of strip is ideal for temporary applications or areas where changes in road configuration are frequent (14). It should be noted that these are also often called rumble stripes by some DOTs.

Effect on Drivers: Although less durable than permanent rumble strips, the tape provides sufficient vibratory and auditory feedback to alert drivers to potential hazards or road layout changes. It is particularly useful for construction zones or temporary diversion routes (9).

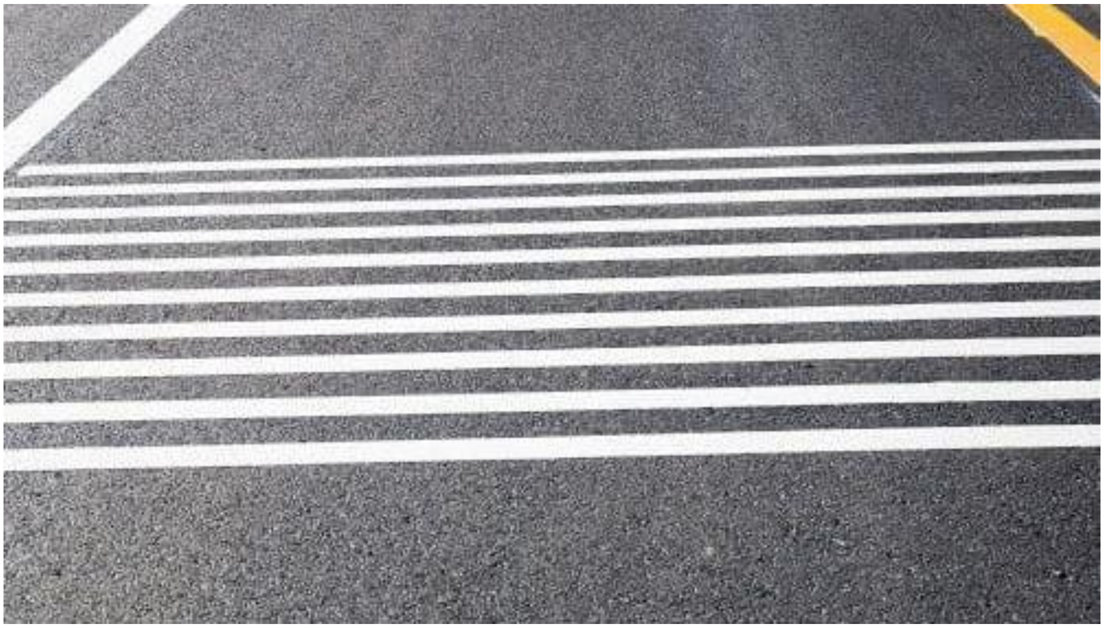


Figure 7. Photo. Rumble Strip Tape (14)

INDENTED RUMBLE STRIPS

Continuous Milled Rumble Strips

Material and Installation: These are formed by milling continuous lines directly into the pavement across the full width or targeted areas of a lane. The process involves specialized equipment that grinds the pavement to create uniform grooves.

Effect on Drivers: Continuous milled rumble strips provide a consistent auditory and tactile warning as drivers stray from their lane. They are particularly effective on long stretches of highways where driver's attention may wane (15).

Figure 8. Photo. Continuous Rumble Strip (15)

Alternated (Segmented) Milled Rumble Strips

Material and Installation: Similar to continuous strips, these are milled into the pavement but in segmented patterns, with gaps between the milled sections. This design can reduce noise both inside and outside the vehicle, making it more community friendly. It should be noted that some DOTs refer to these as segmented rumble strips while some refer to them as segmented.

Effect on Drivers: Segmented strips still provide significant tactile feedback to alert drivers, but with reduced noise output. This makes them ideal for areas close to residential zones where noise pollution is a concern (15).

Figure 9. Photo. Alternating (Segmented) Rumble Strip (15)

Sinusoidal (Sine Wave) Rumble Strips

Material and Installation: These rumble strips are milled into a sinusoidal wave pattern, rather than the typical rectangular or square groove. The rolling pattern of the sine wave creates less noise compared to traditional designs.

Effect on Drivers: Sinusoidal rumble strips reduce exterior noise pollution while still providing effective lane departure warnings. They offer smoother interaction with the vehicle, which can be less damaging to tires and suspension systems (16).

Figure 10. Photo. Sinusoidal Rumble Strip (16)

SUMMARY OF RUMBLE STRIP TYPES

To summarize the different types identified in this study, a table is provided below.

Table 2. Types of Rumble Strips

Type of Rumble Strip	Material	Installation Method	Effect on Drivers	Ideal Use Case
Plastic	Pre-formed plastic	Adhesives/fasteners	Noticeable tactile and auditory alerts	Various environmental and traffic conditions
Rubber	Recycled rubber	Glued/bolted	Softer feedback, less disruptive	Noise-sensitive areas
Rumble Strip Tape	Textured adhesive	Applied directly	Quick, temporary feedback	Construction zones, temporary routes
Continuous Milled	Pavement grooves	Milled into pavement	Consistent warning	Highways
Segmented Milled	Pavement grooves	Milled into pavement	Reduced noise, significant feedback	Residential areas
Sinusoidal	Pavement grooves	Milled in sine wave	Smoother interaction, less noise	Areas sensitive to noise pollution

SUMMARY OF DOMESTIC AND INTERNATIONAL STUDIES

Various studies have proven that the centerline rumble strips are an effective way to increase road safety for drivers. A study done by the Minnesota Department of Transportation titled "Effects of Centerline Rumble Strips on Motorcycles" investigated the effectiveness and safety of centerline rumble strips on motorcyclists. Over a seven-year span from 1999 to 2006, 9,845 motorcycle accidents were analyzed, and only 29 were found to be related to rumble strips. Even these, which were related to rumble strips, were not caused by them. The study also showed that the rumble strips did not cause any changes in driver behavior, including steering or braking. The study recommended the further investigation of motorist warning signs and training.

Another study, conducted by the European Transportation Review: “Effectiveness and acceptability of milled rumble strips on rural two-lane roads in Sweden”, investigated rumble strips in rural areas of Sweden. Unlike the Minnesota study, this study sought to understand motorists' opinions of the rumble strips. The study used quantitative crash data and roadside interviews. The study used crash data from 2003 to 2012 and found that milled rumble strips reduced 27% of single vehicle crashes, and reduced fatalities and serious injuries by 20%.

In the interviews conducted, 90% of respondents agreed that the addition of rumble strips was a good idea. A study conducted in Massachusetts, “Safety Evaluation of Centerline Rumble Strips: Crash and Driver Behavior Analysis” published in the Transportation Research Record (TRR), found that the addition of centerline rumble strips did not play any part in reducing crashes, however, it did find that no deaths had occurred on two of the three study corridors after their implementation. The study consisted of driving simulators, and tested driver responses to shoulder and centerline rumble strips and showed that 27% of drivers corrected their trajectory when they encountered these rumble strips.

A 30-month long study by the Texas Department of Transportation, “Traffic Operational Impacts of Transverse, Centerline, and Edge-line Rumble Strips”, aimed to investigate the effects of the installation of in-lane, called transverse in this study, edge line, and centerline rumble strips. The study investigated the erratic behaviors of drivers when they met each type of rumble strip. It found that the addition of rumble strips was not a factor for increased crashes, and that drivers were able to correct their trajectory safely in these conditions.

Research Gaps and Limitations in Current Literature

While these studies have provided plenty of evidence that centerline rumble strips are effective in reducing crash frequency and fatality, the data regarding motorcycles and in-lane rumble strips was underrepresented. There is also no study done on the effects on motorcyclists of these rumble strips on curved roads, where they could potentially pose a more severe hazard to motorcyclists than in other types of terrain. Although some studies find that they do not pose a hazard to motorists, they do not acknowledge that they may feel unsafe if they lose control of their vehicles in these conditions.

To address the identified gap in literature and determine what issues there are with rumble strip and to what extent we conducted a survey. In the survey conducted on Georgia motorists, many complain that different weather conditions such as rain can make these more dangerous. This is potentially another area that needs to be studied further. In the same survey, the motorists were asked how many years of experience they had driving motorcycles to see if there is any correlation between experience and control issues in these conditions. This raises the question can experience affect a motorcyclist's response and control level when encountering a rumble strip? If so, can these problems be mitigated with more thorough training, or enhanced signage and warnings. The concern with rainy conditions making the rumble strips with thermoplastic paint slick and slippery is also important to be considered in future research. Is there any alternative to this type of marking that can reduce the concern? The survey aims to answer these questions on a smaller, more detailed scale to better understand how motorcyclists feel about rumble strips.

CHAPTER 3. CRASH SCREENING AND SURVEY OF MOTORCYCLIST

CRASH SCREENING

As an initial measure, crashes in GDOT's crash database were screened to crash reports which contained the word "rumble". Each police report was reviewed for relevance as there are many cases such as collisions on "Rumble Road" which were irrelevant. Reviewing the police reports, it became evident that rumble strips can cause discomfort to motorcyclists and potentially contribute to crashes. However, it was unclear to the extent. There were less than twelve total recorded crashes where rumble strips were indicated to be an issue over the eleven-year period from 2013 to 2023. The most relevant crashes are listed in this report. These twelve crashes can be found in the appendix. Out of the twelve crashes there were three where rumble strips were indicated as playing a direct role. In the remaining nine it was unclear whether the motorcyclist would have lost control or crashed anyway due to other factors such as speeding or alcohol use. The three most relevant crashes are discussed in detail.

Below is the crash narrative directly quoted from a police report which indicated rumble strip as a potential issue for discomfort. The ID for this report is 5663642. The listed vehicle for this crash was a motorcycle. In the case described below, it is unclear whether the initial discomfort caused by the rumble strip led to the subsequent roadway departure, or whether the rumble strip located on the curve directly contributed to the crash. However, it is worth noting as it aligns with many complaints motorcyclists have on sharp curves.

"Vehicle #1 was traveling west on Maynards Mill Road approaching the stop sign at Ga 42. As Vehicle #1 approached the stop sign he ran over the rumble strip in the road causing pain in his back. Driver #1 stated he then went to reposition on the seat and was unable to lean into the curve causing him to run off the road and lose control of the motorcycle. Both witnesses stated they saw the driver reposition on the motorcycle and run off the road."

Below is a crash narrative from a police report that references rumble strips as a potential contributing factor. The vehicle listed in this incident was a motorcycle. According to the report, the motorcycle was traveling west on GA 520 when it departed the roadway after contacting the rumble strips along the shoulder. The rider lost control, entered the median, and overturned. While it is not entirely clear whether the rumble strips directly caused the loss of control or if other factors played a role, this case is noteworthy as it reflects ongoing concerns among motorcyclists regarding the placement and design of rumble strips along roadway edges.

"Vehicle #1 was traveling west on GA 520 in the left lane. Vehicle #1 traveled onto the south shoulder of GA 520 and the driver lost control. Vehicle #1 traveled into median and overturned removing the driver. The driver of Vehicle #1 stated that he lost control when he ran over the rumble strips on the edge of the roadway. Note: This crash investigation was digitally recorded"

This crash below highlights potential safety concerns for motorcyclists when rumble strips are placed along or near the centerline. In this case, contact with the centerline rumble strip during a turning maneuver appeared to contribute to a loss of control. The incident illustrates how rumble strips, while beneficial for alerting drivers, may pose stability challenges for motorcyclists, particularly during lane changes or turning movements.

"Vehicle #1 was traveling south on State Route #3. Vehicle #1 turned right onto State Route #30. The driver of vehicle #1 failed to maintain her lane of travel by striking the center divider line which is a rumble strip. Witness #1 stated once vehicle #1 struck the center line rumble strip the driver lost control. The driver of vehicle #1 was thrown from the vehicle into the middle of State Route #30. The passenger of vehicle #1 attempted to stop vehicle #1 but then jumped from the vehicle and landed on the north shoulder. Vehicle #1 rolled onto the north shoulder and lightly struck an embankment coming to rest. The driver of vehicle #1 stated when she turned, she struck the centerline rumble strip which caused her to be thrown off the motorcycle. Note: This crash was audio and video recorded on USB in car #382/perm #2270."

Based on the available crash data, there is approximately one motorcycle crash per year in which rumble strips were identified as a contributing factor. Over the eleven-year period analyzed (2013-2023), three of these crashes resulted in fatal or serious injuries (FSI). While the overall number of rumble strip-related motorcycle crashes is low and unlikely to yield statistically significant findings (which is supported by the research), the severity of outcomes in these cases is notable. However, during the same timeframe, more than 400,000 roadway departure crashes occurred statewide, resulting in nearly 6,000 fatalities and over 17,000 serious injuries. These figures underscore the importance of balancing the proven safety benefits of rumble strips for the broader driving population with the potential risks they may pose to motorcyclists. Continued efforts to refine rumble strip placement and design could help retain their benefits while minimizing adverse effects for all road users.

MOTORCYCLIST SURVEY SUMMARY

Since many runoffs the road crashes go unreported, motorcyclists in Georgia were surveyed regarding concerns about rumble strips due to increasing complaints about their safety. These complaints primarily focused on the risk of slipping as a wheel loses contact with the ground, which is particularly dangerous for motorcycles. With only two wheels, any loss of contact can lead to wheel lock-up and potential crashes upon landing. To evaluate whether this concern was widespread, we distributed a survey to motorcyclists across Georgia with the help of the Department of Driver Services (DDS). The survey aimed to gather insights about concern levels related to specific rumble strip types and scenarios. The survey questions can be found in the appendix.

Rumble strips are categorized into four types: in-lane, center line, edge line, and shoulder rumble strips. Respondents were asked to rate their level of concern for each type on a scale of 1 (no concern) to 4 (high concern). This approach helped us identify which rumble strip type caused the most distress and potential trends. In addition to quantitative ratings, we solicited open-ended feedback about specific concerns and suggestions for improvements. This qualitative data was critical to confirm whether the complaints stemmed from genuine safety issues or mere inconvenience. By analyzing this feedback, we also hoped to uncover common solutions, facilitating smoother experiment design and implementation. Based on the literature review summarized in the previous section we created a hypothesis on what the potential issues could be found below.

Table 3. Rumble Strip Dimensions

Description	Visual	Dimensions (inches)
Center Line **Purpose**: Prevent Head On Crashes **Potential Concern**: Could cause motorcycles to fall while passing		Depth: 0.5 Width: 16 Length: 7 Max Radius: 12 Spacing: 12
Edge Line **Purpose**: Prevent ROTR Crashes **Potential Concern**: Could cause motorcycles to ROTR if leaning when they cross them		Depth: 0.5 Width: 6 Length: 7 Max Radius:12 Spacing: 5
Shoulder **Purpose**: Prevent ROTR Crashes **Potential Concern**: Deep Grooves could cause motorcycles to fall		Depth: 0.5 Width: 6 Length: 7 Max Radius:12 Spacing: 5
In Lane (Transverse) **Purpose**: Alert Drivers of Stop Sign **Potential Concern**: Could cause motorcyclist discomfort and/or safety issues while braking		"Each pad consists of fifteen parallel 4-inch grooves cut at 1-foot intervals and extend nearly across the full width of the lane of travel." (Ohio DOT)

Additionally, the survey assessed concerns about riding over rumble strips in curves. During wide turns, motorcycle wheels make reduced contact with the ground, leaving little margin for error. Motorcycle crash data (2013-2022) from the Survive the Ride Association of NSW highlights that "80% of single-vehicle motorcycle crashes happen on corners." This demonstrates the inherent challenges of cornering, particularly when rumble strips are involved. Complaints submitted to GDOT suggested that riders avoid proper wide turns to evade rumble strips, potentially increasing risk. The survey sought to validate these concerns and inform experimental designs to test the actual danger of rumble strips in curves.

SURVEY ANALYSIS

The survey received responses from 84 motorcyclists, all of whom had experience with at least one rumble strip type. The distribution of concern levels can be found below. It should be noted that approximately 70% of respondents have been motorcyclists for 10+ years.

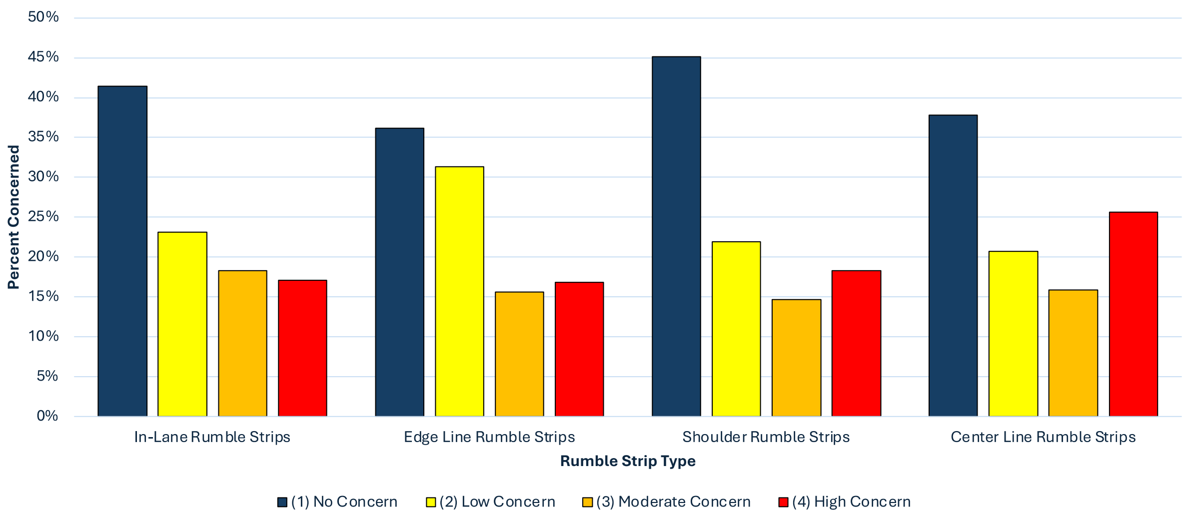


Figure 11. Graph. Concern for Rumble Strip Types

Anecdote, suggestions and further analysis for each type of rumble strip is below.

In-Lane Rumble Strips

58.5% of respondents expressed concern about in-lane rumble strips. While they are typically placed before stop signs and expected to pose minimal safety risks due to lower speeds, their unavoidable nature makes it critical to study. Several motorcyclists reported that painted surfaces on these strips can become slippery, particularly during wet conditions or extreme heat. One participant shared, "In my car... I love them. On my motorcycle, the vibration seems to be more pronounced. I wonder if it would affect my grip of the road if it were slippery and/or I had to make a quick stop." Another noted, "They become slippery when wet or when riding on them." Riders widely suggested experiments with alternative materials or designs for in-lane rumble strips to mitigate these issues.

Edge Line Rumble Strips

Edge line rumble strips elicited concern from 63.9% of respondents, the highest among all four types. These strips were described to be particularly problematic when motorcyclists are navigating wide or sharp turns, as the bike's lean angle reduces wheel contact with the ground. This can cause instability, as illustrated by one participant who stated, "If a motorcycle is leaned over, he would need a small amount when it hits one of those the operator could lose control." Riders on three-wheeled motorcycles also reported unique challenges, with one sharing, "I ride a 3-wheel Can-Am which has 2 wheels in the front. If one wheel hits the strips, it can cause the bike to pull violently to the side. It also plays havoc with the stability of the computer." Importantly, 77% of participants who expressed issues with edge line rumble strips suggested that alternative designs could help alleviate the safety risks.

Shoulder Rumble Strips

Shoulder rumble strips were the least concerning overall, with 54.9% of respondents expressing some level of concern. However, visibility and water accumulation on the strips during heavy rain were highlighted as significant issues. One rider explained, "Only an issue when getting onto the shoulder from the freeway either because of a mechanical issue or to assist a fellow rider. These also fill with a significant amount of water during heavy rain, creating a traction hazard at higher speeds, like those experienced when exiting traffic on a freeway." While these strips are less likely to be driven over, participants still recommended signage to further reduce potential hazards in emergency situations which is already currently used in many areas.

Center Line Rumble Strips

62.2% of respondents expressed concern about center line rumble strips. A notable 25% of riders reported high concern, exceeding the percentages for moderate (15%) and low concern (20%). Center line rumble strips are particularly hazardous when riders attempt to pass other vehicles or brake on these strips. One participant recounted a severe incident: "When a tractor trailer pushed a friend out of his lane with improper lane changing, he naturally braked. This design of cut-away pavement has the front wheel airborne half the time. The front wheel locked from the moderate braking. The bike went down at 65 mph into a guard rail. He paid a very high price with injuries for reacting with some braking—when front wheels lock the unit will go down!" Riders suggested that shallower rumble strip designs could help keep motorcycle tires, especially the front wheel, in consistent contact with the ground. This design adjustment could significantly mitigate the risks associated with braking or lane changes on center line rumble strips. In addition, many motorcyclists stated that removing them in passing zones could be beneficial.

Limitations due to Survey Sample

Approximately **69%** of respondents had 10+ years of experience, with only 15% in the 5-10 years range.

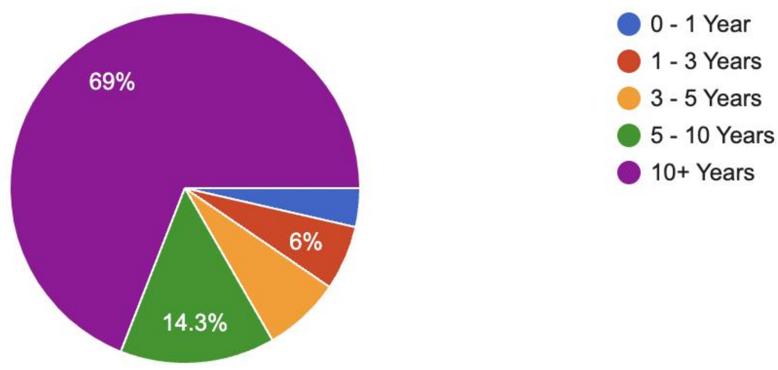


Figure 12. Pie Chart. Experience of Survey Participants

Survey Participants Years of Experience Distribution

This lack of diversity limits the analysis of inexperienced riders. Many seasoned riders voiced concern for novice motorcyclists, introducing potential bias:

- *"Rumble strips can cause a cornering issue for a moderately skilled rider. As a trained professional rider, [I] find them just a bit uncomfortable."*

Future surveys could target younger, less experienced riders.

Rumble Strips Along Curves

Approximately 54.1% of riders with experience on curves reported encountering issues with rumble strips located around curves. This is a notably high proportion, suggesting that more than half of experienced motorcyclists perceive rumble strips in these areas as a significant safety or comfort concern. Such a high rate indicates that the placement and design of rumble strips on curved sections of road may not adequately account for the unique handling dynamics and lean angles required by motorcycles, which differ substantially from those of cars or trucks. These findings highlight the importance of re-evaluating rumble strip installation practices, particularly in areas where lateral forces and balance play a larger role in rider stability.

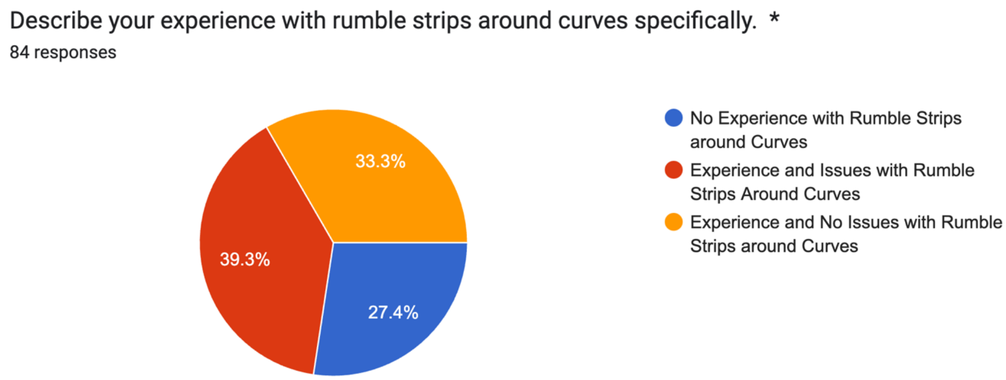


Figure 13. Pie Chart. Survey Participants Experience Around Curves

Key concerns highlighted by respondents include:

- **Signage**:
    - Approximately **30%** requested more signage to alleviate concerns, especially on shoulder rumble strips.
    - *"When the rumble strips are not marked with paint, it could catch [them] by surprise especially at night."*
- **Extreme Weather**:
    - Respondents identified slippery conditions due to wet or icy painted surfaces:
        - *"Painted lines and the raised surface during rain or snow could cause tires to lose traction when braking."*
- **Design Issues**:
    - Over 77% of riders suggested alternative designs to improve safety.

- Complaints included the depth of rumble strips and their impact on tire traction:
    - *"The tire contact is screwed up because of the ridges and valleys of the cut-away pavement."*
- Suggestions included reducing depth or altering spacing:
    - *"This design of cut-away pavement has the front wheel airborne half the time… The front wheel locked… causing a crash at 65 mph into a guard rail."*

CHAPTER 4. SIMULATION AND CURVE ANALYSIS

The survey results provided valuable qualitative insight into the specific conditions under which motorcyclists perceive rumble strips as hazardous, particularly in curved roadway segments and adverse weather. However, the reported frequency of crashes involving rumble strips within Georgia's crash database remains comparatively low, suggesting that while the perceived risk among riders is significant, the actual rate of crash occurrence is far lower. To better understand these discrepancies and to objectively quantify the mechanical effects of rumble strip design on motorcycle dynamics, a simulation-based analysis was developed. This next phase of the study applies physics-based modeling and geometric analysis to evaluate how different rumble strip profiles affect vertical acceleration, lean angle stability, and tire-road contact under varying operational conditions. The results of this simulation and subsequent field validation provide a more comprehensive understanding of how design modifications, particularly sinusoidal or shallow milled profiles can enhance motorcycle stability without compromising the safety benefits of rumble strips for other roadway users. Importantly, it compares the newer sinusoidal design for rumble strips with the conventional design.

The dynamic modeling approach and parameter selection in this study were guided primarily by Motorcycle Dynamics by Vittore Cossalter (2nd Edition, Lulu Press, 2012), which is the most widely recognized reference for the theoretical and experimental foundations of motorcycle behavior. The book provides validated parameter ranges for suspension stiffness, damping coefficients, tire compliance, and mass distribution, all of which informed the baseline assumptions used in this simulation.

SIMULATION MODEL PARAMETERS

To represent the dynamic interaction between a motorcycle and the rumble strip surface, a simplified two-degree-of-freedom (2-DOF) vertical dynamic model was developed. In mechanical modeling, a degree of freedom (DOF) refers to an independent direction or mode in which a system can move. A two-degree-of-freedom (2-DOF) model therefore has two independent vertical motions that can occur simultaneously and interact with each other.

This model includes both a sprung mass, representing the motorcycle frame and rider, and an unsprang mass, representing the front wheel and fork assembly representing how a motorcycle travels in real life. The parameters used in this model are grounded in typical motorcycle design and reflect realistic response characteristics rather than any single make or model. The purpose of the simulation is to compare relative vibration and contact behaviors between rumble strip designs under equivalent conditions, rather than to predict absolute accelerations for a specific vehicle.

The sprung mass ($m_{frame} = 200$ kg) represents the motorcycle and rider weight supported by the suspension of each wheel representing a motorcycle and rider together riding 400 kg which is typical (18). This value approximates a mid-size motorcycle’s front section and provides appropriate inertia for vertical motion modeling. The unsprang mass ($m_{wheel} = 12$ kg) represents the wheel, tire, brake, and lower fork assembly, which are not isolated by the suspension. Including an unsprang mass allows the model to capture realistic wheel hop and contact loss behavior, phenomena that would be missed in a single-mass approximation.

The wheel radius ($R_{wheel} = 0.43$ m) corresponds to a 17-inch motorcycle tire, which is common for on-road motorcycles (20). This provides geometric context for the tire's contact point relative to the road. The static suspension length ($L_0 = 0.12$ m) defines the equilibrium spacing between the frame and wheel center, effectively representing suspension sag under rider weight. Gravity ($g = 9.81$ m/s^2) is included in establishing a realistic static load balance between spring forces and the weight of the components.

Suspension behavior is characterized by spring stiffness ($k_{susp} = 30{,}000$ N/m) and a damping coefficient ($c_{susp} = 1{,}200$ N·s/m) (21). These parameters approximate typical motorcycle fork properties, producing a sprung natural frequency of approximately 1.8-2.0 Hz, consistent with experimental ride data (21). The damping term prevents unbounded oscillations and, importantly, introduces realistic speed dependence, since vibration intensity scales with vertical velocity across the damper.

The tire stiffness ($k_{tire} = 350{,}000$ N/m) represents the effective vertical stiffness of a pneumatic motorcycle tire inflated to roughly 36 psi which is common among motorcycles. This parameter determines how much the tire compresses as it rolls over the rumble strip and is a primary contributor to the sharpness of vertical impulses. The tire damping term ($c_{tire} = 4{,}000$ N·s/m) accounts for energy dissipation due to internal hysteresis of the rubber and the dynamic compression of air within the tire cavity (21). These parameters jointly govern how quickly impacts are transmitted to the suspension and how much vibration energy is absorbed before reaching the rider. Together, these parameters produce two dominant vibration modes, an unsprang natural frequency around 8.0-10.0 Hz, associated with the wheel's motion over short-wavelength features, and a sprung natural frequency around 2.0 Hz, associated with the rider's body response. To help visualize how motorcycle suspension separates the motion of the sprung and unsprang masses, a clear explanation is provided in the video *"Motorcycle Suspension | How Does It Work?"* by Mike on Bikes (2020). The video effectively demonstrates how the frame and wheel exhibit distinct natural frequencies and how damping influences each response (22).

Although the exact numerical values of these parameters may differ among motorcycle makes and models, the ratios between stiffness, damping, and mass are what primarily determine the shape and timing of the acceleration response. Therefore, while the absolute G-levels may vary in the field, the comparative trends between different rumble strip geometries should be held valid.

DYNAMIC FORCE AND MOTION SIMULATION

Using the parameters defined earlier, the motorcycle's vertical response was simulated in Glow Script 3.2 VPython to represent the dynamic interaction between the wheel, suspension, and the rumble strip surface. This section explains how the simulation updates the system state over time and illustrates the resulting force and motion responses. For further analysis, the code is available for review.

The simulation proceeds incrementally in small time steps of size dt = 0.0005 s, where each time step represents an instantaneous update in the forces, accelerations, and displacements acting on the system. This method is known as time stepping or numerical integration, where the state of the system at time $t + dt$ is computed based on the current conditions at time t.

As described earlier, the model is structured as a two-degree-of-freedom (2-DOF) vertical system, representing the unsprang mass (wheel) and the sprung mass (motorcycle frame and rider). The wheel follows the rumble strip surface geometry defined by the function which calculates the local height and slope of the rumble strip profile (conventional and sinusoidal).

The term δ_t (tire deflection) represents the instantaneous vertical compression of the tire as it rolls over the rumble strip surface. Physically, it measures how much the tire is deformed between the road contact point and the wheel center. Mathematically, it is defined as

$$\delta_t = (R_{\text{wheel}} + y_{\text{ground}}) - y_w$$

Figure 14. Equation. Tire Deflection

where R_{wheel} is the unloaded tire radius, y_{ground} is the local vertical height of the rumble strip surface and y_w is the vertical position of the wheel center. When the wheel moves downward toward the ground, δ_t increases, indicating tire compression and generating an upward restoring force. When δ_t reaches zero, the tire just touches the surface, and any further upward motion of the wheel center implies loss of ground contact (the tire becomes unloaded). This variable is essential for capturing realistic tire behavior, as it governs when contact is maintained, when impacts occur, and how vertical loads are transmitted from the rumble strip into the suspension system.

At each time step, the simulation evaluates the tire force, the suspension force, and the gravitational force, each representing a key component of the motorcycle's vertical dynamics. The tire force models the interaction between the wheel and the rumble strip surface, the suspension force governs the exchange of energy between the wheel and the motorcycle frame, and the gravitational force provides the constant downward load that establishes static equilibrium and affects the overall motion response:

- **Tire Force ($\boldsymbol{F_{tire}}$)**

  The tire acts as a linear spring damping element between the ground and the wheel. This term models the compression of the tire and the damping effect from the tire's internal hysteresis and air pressure. Where $\dot{y}_{\text{ground}}$ is the vertical velocity of the rumble strip surface, and $\dot{y}_w$ is the vertical velocity of the wheel center. The tire force is defined as:

$$F_{\text{tire}} = k_{\text{tire}}\,(\delta_t) + c_{\text{tire}}\,(\dot{y}_{\text{ground}} - \dot{y}_w)$$

Figure 15. Equation. Tire Force

- **Suspension Force ($\boldsymbol{F_{susp}}$)**

  This represents the restoring and dissipative forces acting through the shock absorber and spring. In the equation below y_f *is the* vertical position of the frame and $\dot{y}_f$ is its respective velocity. Likewise, y_w *is the* vertical position of the wheel and $\dot{y}_w$ is its respective velocity. L_0 is the static equilibrium length of the suspension (the nominal separation under static load). The suspension connects the sprung and unsprang masses, modeled as:

$$F_{\text{susp}} = -k_{\text{susp}}(y_f - y_w - L_0) - c_{\text{susp}}(\dot{y}_f - \dot{y}_w)$$

Figure 16. Equation. Suspension Force

- **Gravitational Force ($\boldsymbol{g}$)**

  Both masses experience their respective weight, which acts downward and balances the system under static conditions.

The resulting accelerations of the frame (a_f) and wheel (a_w) are determined using Newton's Second Law:

$$a_f = \frac{F_{\text{susp}} - m_{\text{frame}}g}{m_{\text{frame}}}, a_w = \frac{-F_{\text{susp}} + F_{\text{tire}} - m_{\text{wheel}}g}{m_{\text{wheel}}}$$

Figure 17. Equation. Frame and Wheel Accelerations

These accelerations are integrated over time to update velocities and displacements, producing a continuous record of the motorcycle's vertical motion as it traverses each groove. The model outputs the peak G-value and contact loss count (number of times the tire loses contact with the ground).

SIMULATED EXPEIREMENTS

Three simulation runs were performed at speeds of 25 mph, 50 mph, and 75 mph to examine how the motorcycle's vertical dynamics vary with speed. For the conventional rumble strips, the tests used a cylindrical groove profile corresponding to the conventional rumble strip geometry (7 in width, and 5 in gap) at three different depths 3/8, 1/2, and 5/8 inch. The resulting groove profile used in the simulation is shown below. Note that both the x- and y-axes are in inches, but they are plotted at different scales for visual clarity.

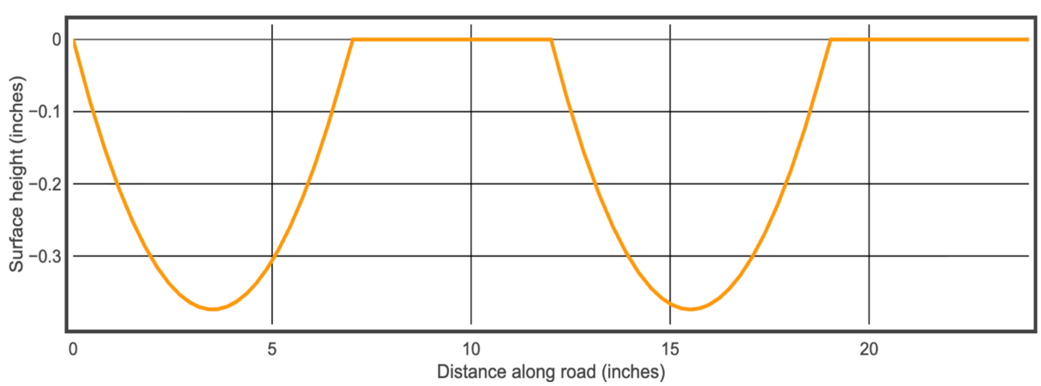


Figure 18. Graph. Conventional Rumble Strip Side Profile

Similarly, for the sinusoidal rumble strips, the groove geometry was modeled using a smooth, continuous sinusoidal surface rather than a cylindrical cut to reflect the design specification. The surface height varied periodically along the direction of travel, with the crest corresponding to the flat roadway surface and the trough reaching the maximum groove depth. The mathematical representation defined the height and local slope of the surface as functions of the longitudinal position, ensuring a realistic sinusoidal shape over each groove spacing. The resulting sinusoidal groove profile used in the simulations is shown in Figure below. As before, both axes are in inches, though plotted at different scales for clarity. This plot illustrates how the sinusoidal design produces a gradual, wave-like surface variation, unlike the sharp transitions seen in conventional rumble strips.

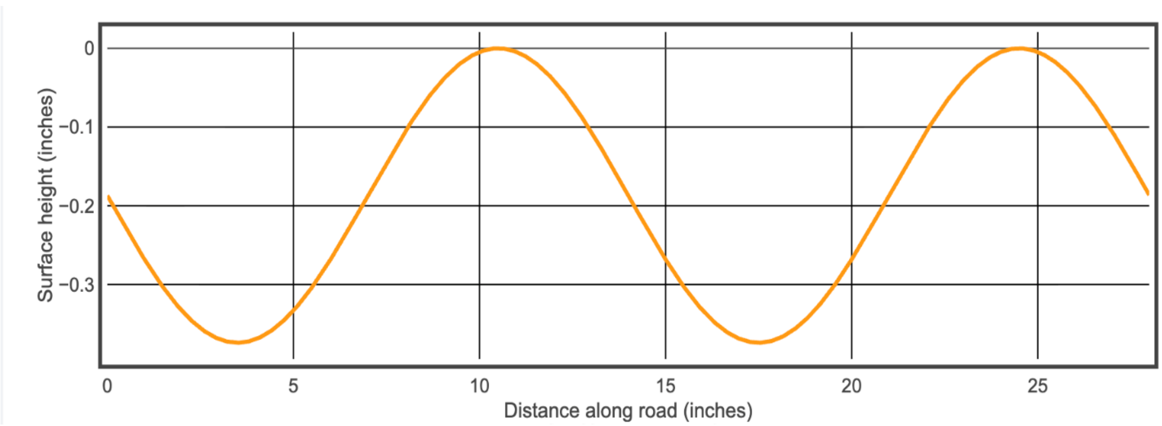


Figure 19. Graph. Sinusoidal Rumble Strip Side Profile

The simulations were run for 3 speeds (25 mph, 50 mph, and 75mph) for both conventional and sinusoidal rumble strips, at 3 depths (3/8-inch, 1/2 inch and 5/8 inch) for a total of 18 runs.

The peak acceleration represents the maximum instantaneous vertical acceleration experienced by the motorcycle during its passage over the rumble strip. It captures the single highest "spike" in acceleration that occurs as the tire interacts with the groove, indicating the severity of the impact or vibration transmitted to the vehicle and rider. Higher peak values generally correspond to a sharper or harsher response. The root mean square (RMS) acceleration, on the other hand, provides a measure of the overall vibration intensity over the entire rumble strip encounter. It reflects the average energy content of the acceleration signal rather than just the maximum value, making it a more representative indicator of ride comfort and sustained vibration exposure.

It was observed that the sinusoidal rumble strips produced significantly lower acceleration values under all test conditions, except for the peak acceleration at 25 mph and a depth of 3/8 inch. The corresponding results are shown in the figure below. However, at higher speeds the sinusoidal rumble strips showed approximately half the peak force.

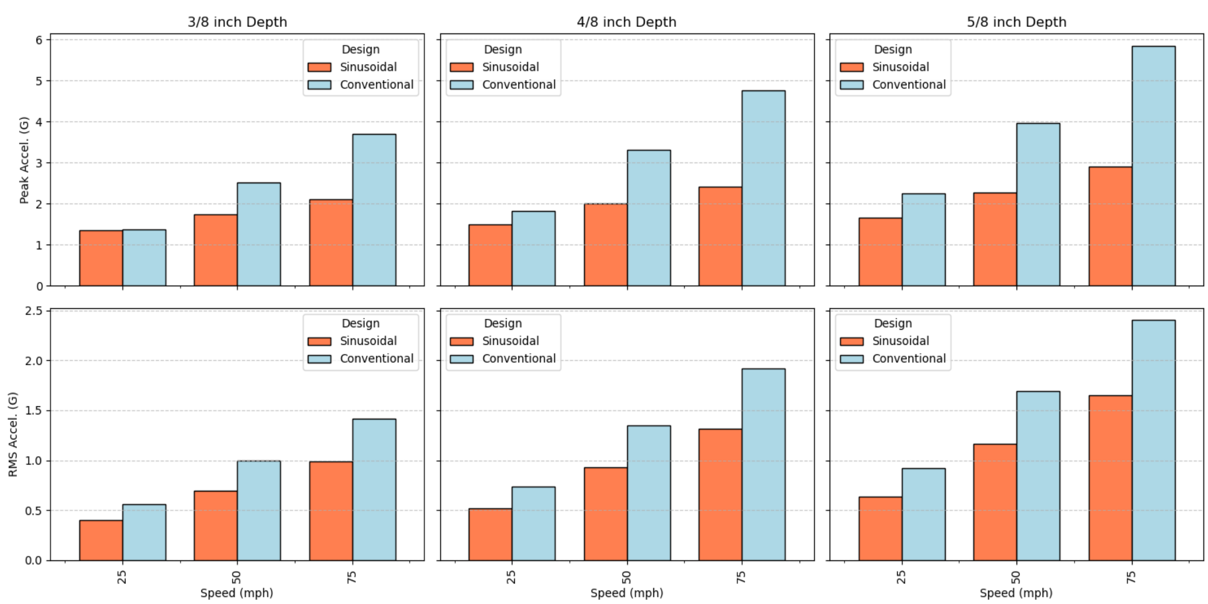


Figure 20. Graph. Simulation Results Peak Force and Root Mean Square Force

The plot below shows the vertical acceleration response of the motorcycle when traveling over the conventional rumble strip at a speed of 25 mph. The x-axis represents time (in seconds), while the y-axis shows the corresponding vertical acceleration, measured in units of G (acceleration relative to gravity). It can be observed that the signal exhibits two distinct oscillation patterns. This occurs because the motorcycle model includes two primary degrees of freedom (DOF), one associated with the unsprang mass (wheel and suspension), and the other with the sprung mass (main body). The higher-frequency oscillations correspond to the wheel’s rapid response to the rumble strip grooves, while the lower-frequency component represents the slower motion of the motorcycle body reacting to the road input.

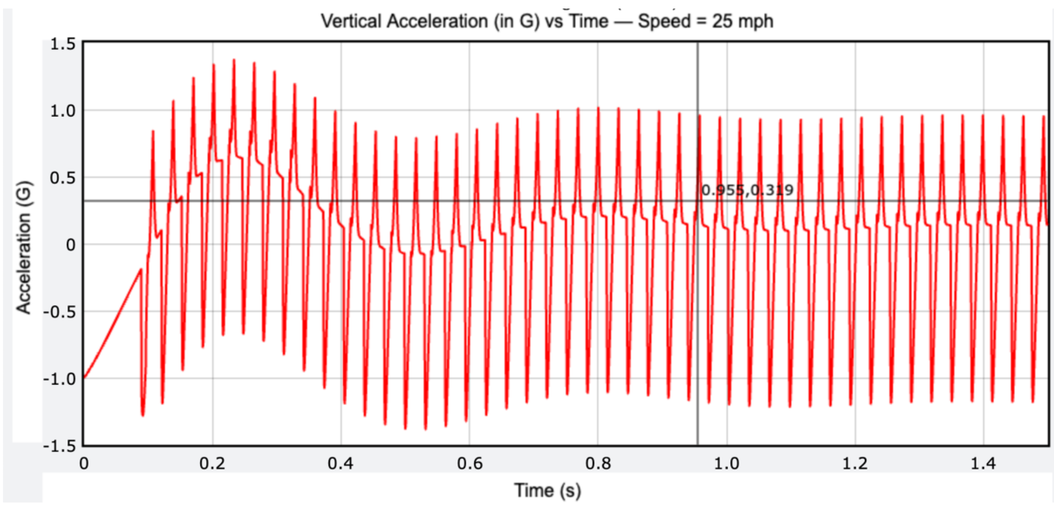


Figure 21. Graph. Conventional Rumble Strip Acceleration Profile 3/8-inch 25 mph

The plot below shows the vertical acceleration response for the sinusoidal rumble strip at the same speed. Compared to the conventional design, the sinusoidal profile produces longer-period oscillations, meaning the vibrations occur more gradually. As a result, the root mean square (RMS) acceleration is lower, indicating a reduction in overall vibration of energy transmitted to the motorcycle. The acceleration signal also appears smoother due to the continuous, wave-like geometry of the sinusoidal groove. Unlike the sharp edges of the conventional rumble strip, the sinusoidal surface causes more progressive changes in tire contact, reducing abrupt impacts and high frequency.

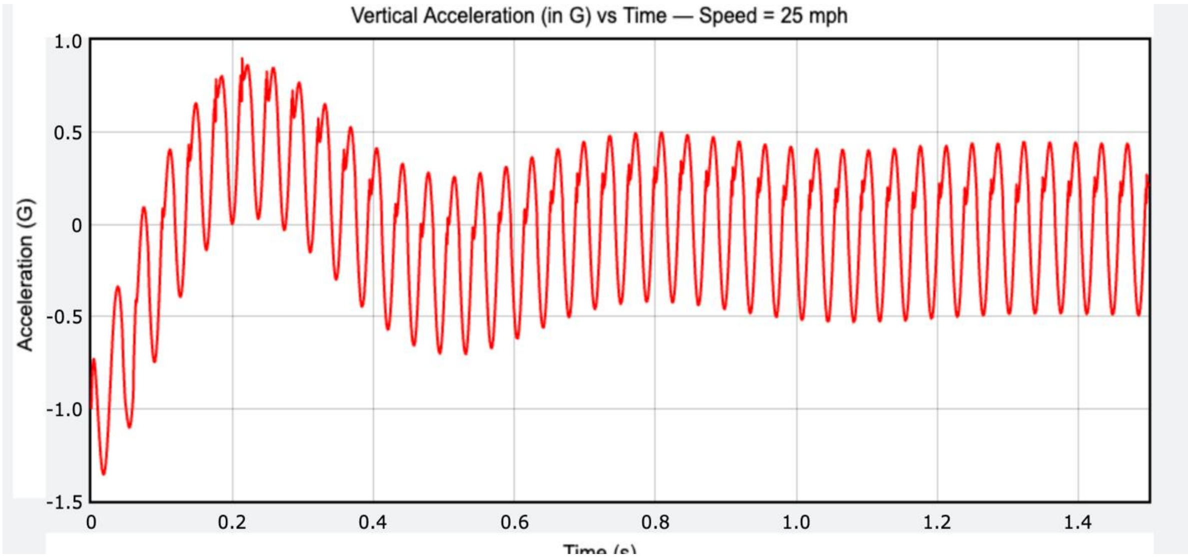


Figure 22. Graph. Sinusoidal Rumble Strip Acceleration Profile 3/8-inch 25 mph

These results are consistent with practical experience and help explain why sinusoidal rumble strips are sometimes referred to as “mumble strips.” The characteristic sound produced when a vehicle drives over rumble strips comes from the tire rapidly impacting the groove edges. Because the sinusoidal profile has a smooth, wave-like surface rather than sharp edges, the tire transitions more gradually. As a result, the generated sound is quieter and lower in pitch more of a continuous “mumble” rather than the sharp, pulsing “rumble” typical of conventional rumble strips. This smoother interaction not only reduces noise but also contributes to improved ride comfort and lower vibration levels, which can be seen through the graphs and personal experience.

CURVE ANALYSIS

In addition to examining rumble strip geometry, the relationship between roadway curve radius and motorcycle lean angle was analyzed to better understand the limits of safe cornering. The ability of a motorcycle to navigate a curve safely depends on the balance between centrifugal force and gravitational force. As speed increases or curve radius decreases, the motorcycle must lean at a greater angle to maintain equilibrium and prevent sliding or loss of traction.

The lean angle was determined using the fundamental relationship between speed, gravitational acceleration, and curve radius, expressed by the following equation:

$$\tan(\theta) = \frac{v^2}{gR}$$

Figure 23. Equation. Motorcycle Lean Angle

where:

- θ= lean angle (radians)
- v= vehicle speed (ft/s)
- g= acceleration due to gravity (32.174 ft/s^2)
- R= curve radius (ft)

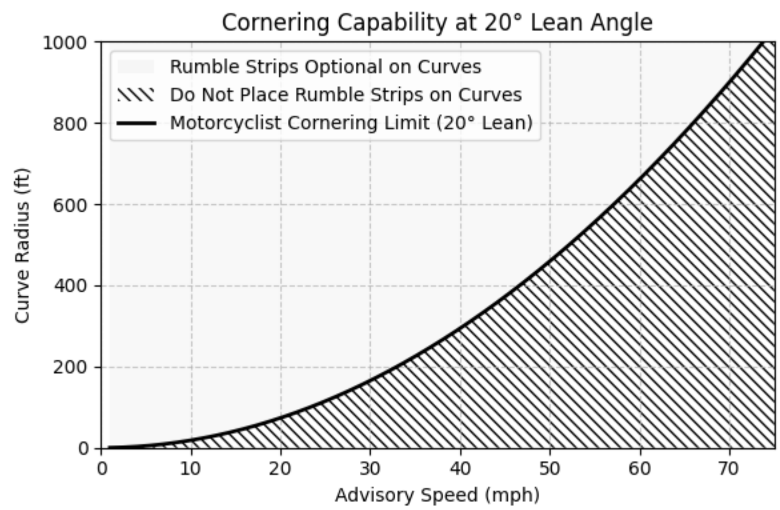
Rearranging the equation gives the radius required for a given lean angle and speed:

$$R = \frac{v^2}{g\tan(\theta)}$$

Figure 24. Equation. Required Curve Radius for a Given Lean Angle

The figure below illustrates the relationship between curve radius and motorcycle speed for a lean angle of 20 degrees. The curve represents the theoretical boundary at which a motorcyclist can maintain stable cornering without exceeding the traction limits required to balance centrifugal and gravitational forces. Curves that fall below this line would require a lean angle greater than 20°, increasing the risk of tire slip or instability, particularly when additional disturbances such as rumble strips are present. During normal everyday riding, motorcycles typically lean around 20 degrees, which represents a comfortable and stable angle for most riders (23).

To aid in interpretation, the plot is shaded into two regions. The red region below the curve indicates areas where rumble strip installation is not recommended due to the sharpness of the curve and the higher lean demands placed on riders. Conversely, the green region above the curve represents roadway conditions where rumble strips may be safely installed without exceeding typical rider comfort or handling limits. The table for each 5-mph cutoff can be seen in the appendix.



Note: For locations where rumble strips cannot be installed due to sharp curvature, installation of motorcycle-safe guardrails is recommended.

Figure 25. Graph. Minimum Radius for Edge Line Rumble Strips

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

Ton the simulation results, crash report analysis, literature review, and feedback collected through the motorcyclist survey and interviews, several conclusions and recommendations have been developed to improve motorcyclist safety while maintaining the proven effectiveness of rumble strips for other road users. The findings of this study reaffirm that sinusoidal rumble strips, when designed in accordance with GDOT specification standards, provide a safer and more comfortable alternative to conventional milled rumble strips. Simulation data demonstrated that the sinusoidal profile substantially reduces both the peak and root mean square (RMS) acceleration experienced by motorcycles, resulting in smoother vibrations and improved traction. These results imply that such designs could maintain tactile and audible feedback for passenger vehicles while minimizing discomfort and handling instability for motorcyclists.

The analysis also highlights that the location and context of rumble strip installation are critical to ensuring safety. Findings suggest that rumble strips may be less suitable in designated passing zones, where motorcyclists are more likely to cross the centerline to overtake slower vehicles. In contrast, in-lane rumble strips placed before stop-controlled intersections or stop signs appeared to present minimal safety concerns for riders based on available data and survey feedback.

On sharp horizontal curves, the analysis suggests that rumble strips may be less appropriate along curved segments where the required lean angle approaches or exceeds the comfort and safety threshold for typical motorcyclists. The design table developed as part of this study provides a reference radius threshold for a 20-degree lean angle, representing the upper limit of comfortable, everyday cornering under dry pavement conditions (see Table

5). In locations with curves sharper than this threshold, findings indicate that limiting rumble strip placement to the tangent sections before and after the curve could improve safety by reducing lean demands on motorcyclists. When rumble strips are omitted or removed for safety reasons, additional roadside protection such as motorcycle-safe guardrails can be considered to help reduce the severity of run-off-road crashes.

In addition to design and installation practices, continued education and outreach are vital. GDOT may consider collaborating with the Georgia Department of Driver Services (DDS), motorcycle advocacy organizations, and rider training programs to promote awareness of updated rumble strip designs and installation policies. Informing the riding community about these safety improvements can help build public support, ensure compliance, and reduce misperceptions regarding rumble strip performance and intent. Ongoing monitoring of crash data, field inspections, and rider feedback is also recommended to evaluate the long-term effectiveness of sinusoidal rumble strips and refine installation criteria as needed. By implementing these measures, GDOT can improve roadway safety for all users while reducing the negative impacts that traditional rumble strip designs have on motorcyclists.

FUTURE RESEARCH AND FIELD EVALUATION

Additional research could further validate simulation findings and confirm the safety benefits of modified rumble strip designs under real-world conditions. Controlled field studies using instrumented motorcycles equipped with IMU and GPS sensors to collect data on vibration, lean angle, and acceleration for different rumble strip geometries and operating speeds could measure the real-world forces.

Expanding survey outreach to include a wider range of riders, especially those with less experience, may also offer broader insights into comfort and safety perceptions. Collaboration with other state DOTs and the Federal Highway Administration (FHWA) could also help the adoption of nationally consistent guidelines for motorcycle-safe rumble strips.

APPENDIX A. SUPPORTING CRASH NARRATIVES AND DESIGN TABLES

Table 4. Recorded Crashes

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Vehicle #1 was traveling south on State Route #3. Vehicle #1 turned right onto State Route #30. The driver of vehicle #1 failed to maintain her lane of travel by striking the center divider line which is a rumble strip. Witness #1 stated once vehicle #1 struck the center line rumble strip the driver lost control. The driver of vehicle #1 was thrown from the vehicle into the middle of State Route #30. The passenger of vehicle #1 attempted to stop vehicle #1 but then jumped from the vehicle and landed on the north shoulder. Vehicle #1 rolled onto the north shoulder and lightly struck an embankment coming to rest. The driver of vehicle #1 stated when she turned she struck the centerline rumble strip which caused her to be thrown off the motorcycle. Note: This crash was audio and video recorded on USB in car #382/perm #2270.	(A) Suspected Serious Injury	2023	32.085017	-84.240508

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Vehicle 1 (motorcycle) was traveling west on GA 16. While traveling west driver 1 lost control of vehicle 1 as he negotiated a left curve. Vehicle 1 traveled off the right shoulder striking several construction barrels. After striking the construction barrels driver 1 was thrown from vehicle 1. Vehicle 1 and driver 1 continued west in the ditch off the right shoulder of GA 16. Area of impacts occurred off the right shoulder of GA 16. Driver 1 stated he hit the rumble strips in the middle of the road and he began to lose control. He stated he traveled towards the right shoulder. He stated after he hit the barrels he was thrown from vehicle 1. Witness stated the motorcycle was traveling very fast as he passed traffic. He stated when he was passing traffic at a high speed the driver lost control when he traveled over the rumble strips between the west and east lanes on GA 16. The witness left before I was able to obtain his information. Crash investigation was digitally recorded. Perm #1724	(B) Suspected Minor/Visible Injury	2023	33.244788	-84.429447

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Vehicle #1 was traveling northbound on GA 101 just south of GA 6. Driver #1 who was found to be under the influence of alcohol stated that he went over some rumble strips and lost control. Witness #1 stated that he was not sure what happened but he saw driver #1 leave the roadway and travel down an embankment. Driver #1 operated his vehicle while under the influence of alcohol which caused him to fail to maintain his lane and leave the east side of the of the roadway. Driver #1 then traveled down an embankment and overturned his vehicle onto its left side. This crash investigation was audio and video recorded.	(B) Suspected Minor/Visible Injury	2023	33.963762	-84.994507

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
On 06/26/2022 at 1953 hours officers were dispatched to the 5400 block of Deans Bridge Road in reference to a single vehicle accident with injuries.Officer's investigation Vehicle 1 was traveling north in the left lane of 5400 block Deans Bridge Road and negotiating a curve. Witness 1 [REDACTED] and Witness 2 [REDACTED] were both traveling north in the 5400 block of Deans Bridge Road. Witness 1 was in the left lane and Witness 2 was in the right lane. Witness 1 stated he observed Vehicle 1 approaching him from behind in the left lane so he changed lanes (left lane to right lane). Witness 1 further stated the observed Vehicle 1 wobbling and enter the center median crashing in the median.Witness 2 stated Vehicle 1 passed him at a high rate of speed and after Vehicle 1 negotiated the curve Vehicle 1 hit the right shoulder and then the left shoulder entering the median. Witness 2 further stated once Vehicle 1 enter the median Vehicle 1 crashed in the median.Officer's investigation revealed Vehicle 1 traveling north in the left lane and then negotiating the curve. Upon exiting the curve Vehicle 1 hit the rumble strips on the right shoulder and over corrected entering the left should. Vehicle 1 then entered the median. Once in the median Vehicle 1 barrel rolled several times and the rider was ejected from the vehicle. Vehicle 1 came to a final rest in the southbound lanes of 5400 block Deans Bridge Road and the rider came to a final rest in the median. The rider of Vehicle 1 was found at fault for failure to maintain lane.Deputy	(K) Fatal Injury	2022	33.300099	-82.251265

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Coroner Ashley Thigpen (Car 49) arrived on scene and pronounced the deceased at 2100 hours of 06/26/2022.Post crash video available. The claim check for Vehicle 1 is maintained by Officer in the case file.				

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Vehicle 1 was traveling south on Georgia Hwy 23. The driver of vehicle 1 was attempting to pass another vehicle that was also traveling south. The driver of vehicle 1 traveled back into his lane when he observed on coming traffic. While crossing back over the centerline the driver of vehicle 1 lost control and laid the motorcycle down. The driver of vehicle 1 was totally ejected from the vehicle. Vehicle 1 continued to travel approximately 246 feet before coming to a final rest. The driver stated he was trying to pass a vehicle. He stated that he saw a vehicle coming in the north lane and that he could not complete his pass. He stated he lost control when his motorcycle hit the rumble strips as he was attempting to travel back into his lane.The witness was traveling north on Highway 23. He stated he observed the motorcycle attempting to pass another vehicle. He stated the driver lost control when he attempted to travel back into the south lane. Width of roadway is approximately 26 feetThis investigation was not recorded	(A) Suspected Serious Injury	2022	32.126593	-82.120684

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Vehicle #1 was traveling west on GA 520 in the left lane. Vehicle #1 traveled onto the south shoulder of GA 520 and the driver lost control. Vehicle #1 traveled into median and overturned removing the driver. The driver of Vehicle #1 stated that he lost control when he ran over the rumble strips on the edge of the roadway. Note: This crash investigation was digitally recorded	(C) Possible Injury / Complaint	2021	31.734795	-84.382742
Vehicle 1 was traveling east in the left lane on I-20 near mile marker 168. Driver 1 failed to maintain his lane to the left and traveled on the rumble strip. Driver 1 lost control of the vehicle and laid it down on its left side. Vehicle 1 came to an uncontrolled final rest on its left side in the grass median. Driver 1 stated that he lost control of the vehicle after he hit the rumble strip.The area of impact was on I-20 near mile marker 168.This investigation was recorded digitally on 4RE GSP 307.	(C) Possible Injury / Complaint	2020	33.503684	-82.571975

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Vehicle 1 was traveling southbound on GA 11 approximately 0.2 miles north of Truelove Road. Driver 1 traveled onto the rumble strip on the west shoulder and lost control of vehicle 1. Vehicle 1 overturned onto its right side. The witness stated he was traveling behind vehicle 1. The witness stated vehicle 1 traveled into the center left turn lane and then overturned after traveling onto the west shoulder.The crash investigation was recorded on Watch Guard Digital Video.	(C) Possible Injury / Complaint	2020	34.567375	-83.763322
Added :Sep 1 2019 3:25PMDriver [REDACTED] Todd stated that he was traveling southbound on I985 at Mile Marker 19 when he tried to avoid hitting a bird. Todd advised that he was in the inside lane when he swerved for the animal causing him to leave the roadway and hitting the rumble strips on the shoulder of the road. Todd stated that he couldn`t get the Motorcycle back on the road causing him to wreck the Motorcycle.	(B) Suspected Minor/Visible Injury	2019	34.247253	-83.83386

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
On December 1 2019 at 1432 hours I responded to I-95 NB about 500 feet away from mile marker 109 to investigate a motorcycle accident with injuries.Driving up to the scene I was able to identify the driver of unit #1 [REDACTED] [REDACTED] and passenger [REDACTED] [REDACTED] were laying on the ground with the witnesses holding c-spine. EMS arrived on scene immediately started to take over the medical care and to prepare for transport.I spoke with the friend of the driver [REDACTED] [REDACTED] and he was the driver of the other motorcycle and witness #1 of the accident. He stated that they were coming from Jacksonville Florida and headed to Camp Lejune North Carolina because they are both Marines. [REDACTED] [REDACTED] stated that he was driving about 100 feet behind [REDACTED] [REDACTED] and they were in the left lane. Then a car came over in [REDACTED][REDACTED]s lane and [REDACTED] [REDACTED] said that [REDACTED] [REDACTED] yanked his handle bars and that put him driving over the rumble sticks causing him to loose control. [REDACTED] [REDACTED] stated that his motorcycle slid for about 10 feet and then throwing the [REDACTED] [REDACTED] and [REDACTED] [REDACTED] on the grass area of the median. Witness #2 [REDACTED] [REDACTED] was the driver behind both of the motorcycles and witnessed the accident and pulled over to ensure	(B) Suspected Minor/Visible Injury	2019	32.191696	-81.194187

Table 4. Recorded Crashes (Continued)

Narrative	**KABCO Severity**	**Crash Year**	**Latitude**	**Longitude**
that help was on the way. He stated that he saw the unit #1 [REDACTED] [REDACTED] driving with the passenger and saw the bike immediately go towards the left off the road and slamming on brakes. He was not able to verify what cause the [REDACTED] Dealmedia to slam on brakes. [REDACTED] [REDACTED] and [REDACTED] [REDACTED] was thrown from the bike onto the median grass area. [REDACTED] [REDACTED] stopped and dialed 911 as he was directing traffic until help arrived on scene. Unit #1 contained extensive damage to the fuel tank area the driver mirror and other major cosmetic damage. The unit #1 was towed by Sapp's Wrecker Services with their 2 black helmets. Unknown if the bike is in driveable condition. The investigation found that the driver of unit #1 with a contributing factor "FALLING TOO CLOSE AND DRIVER LOST CONTROL. The investigation was based on the witnesses statements which was supported by the location of the driver and passenger and the damage to the unit. No citation were issued. On December 4 2019 at approximately 0720 hours I spoke with the unit #1 driver [REDACTED] [REDACTED] after he was released from the hospital. He informed me on how the accident took place to his knowledge. He stated that he and the passenger [REDACTED] [REDACTED] were riding and the car in front of him had no brake lights he approached the car much sooner than anticipated and he slammed on the brakes. While slamming on the brakes his				

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
motorcycle hit the rumble sticks on the side of the road and it caused him to lose control then slide a few feet before they both hit the ground. Immediately he was greeted by his friend [REDACTED] [REDACTED] the other motorcycle rider and he recalled that himself and the passenger [REDACTED] [REDACTED] laid on the ground until EMS arrived on scene.				

Table 4. Recorded Crashes (Continued)

Narrative	KABCO Severity	Crash Year	Latitude	Longitude
Added: Nov 29 2015 10:18PMDue to his injuries Driver 1 was not able to give his side of the story.The incident was observed first hand by Witness 1. She stated:Driver 1 was traveling on I-20 East weaving in and out of traffic in the #1 and #2 lanes. As Driver 1 approached Six Flags Dr. he began "splitting lanes" (riding down the middle of two lanes). After he passed several cars Driver 1 merged back into the #1 lane. As he came back into the #1 lane. Driver 1 appeared to lose control and rode off the roadway and into the rumble strip (the rough treads located on both sides of the road designed to alert the driver that he\/she has drifted off the roadway).As Driver 1 hit the rumble strip he lost control of his motorcycle and fell to the ground where he received several injuries.Driver 1 was taken to Grady Memorial Hospital to receive medical treatment.An arrest warrant was later obtained for Driver 1 for several traffic charges. Such charges are: Reckless Driving Driving While License Suspended No Proof of Insurance and Suspended Registration.	(B) Suspected Minor/Visible Injury	2015	33.774081	-84.564526

Table 5. Minimum Radius for Edgeline Rumble Strips

Advisory Speed (mph)	Radius (ft) @ 20°
20	73.5
25	114.8
30	165.3
35	225
40	293.9
45	372
50	459.2
55	555.7
60	661.3
65	776.1
70	900.1

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