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SAFETY EVALUATION OF CENTERLINE RUMBLE STRIPS

MASS HIGHWAY

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10. Abstract

A study of centerline rumble strips was undertaken as part of the Massachusetts Highway Department (MassHighway) Research Program. The objective of this research was to evaluate the effectiveness of centerline rumble strips in reducing crossover crashes and improving the safety of undivided roadways. The research was divided into three distinct phases. The objective of Phase I was to identify the current use of centerline rumble strips in the U.S. and around the world. Phase I also included a review of the current state-of-the-knowledge related to centerline rumble strips. The objective of Phase II was to evaluate the safety effects of the current installations of centerline rumble strips in Massachusetts on State Routes (Route) 2, 20, and 88. Finally, the objective of Phase III was to determine driver's reaction to centerline rumble strips by evaluating behavior in a full-scale driving simulator. The experiment was conducted during the summer and fall of 2001 and spring and summer of 2002.

Phase I results found that 20 of the 50 state Departments of Transportation, along with several provinces in Canada, are using centerline rumble strips. Several more states plan to use centerline rumble strips in the future. Massachusetts continues to be a leader in the use of centerline rumble strips as a safety measure. States who do not plan to use centerline rumble strips had concerns with noise, pavement deterioration, pooling and freezing water in the rumble strips, and the safety of motorcyclists and bicyclists.

The results of the crash analysis found that Route 2 experienced a slight decrease in the annual frequency of targeted crashes while Routes 20 and 88 remained relatively consistent. An analysis of fatal crashes at the study locations found no fatal crashes on Routes 2 and 88 in the study area since the installation of the centerline rumble strips. Route 20 experienced fatal crashes in 1997 and 1998, all after the installation of centerline rumble strips. No fatal crashes were experienced on Route 20 in 1999 and 2000. This study found no significant change in crash frequencies before and after the installation of centerline rumble strips. There was no evidence found to suggest that the installation of the centerline rumble strips significantly reduced crash rates.

Phase III considered the human factors elements of rumble strips and evaluated drivers reaction to encounters with centerline rumble strips. The results found that drivers took more time to return to the travel lane when centerline rumble strips were present. Approximately 27 percent of the drivers made an initial leftward vehicle correction when encountering centerline rumble strips. No improper corrections were experienced with shoulder rumble strip scenarios.

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SAFETY EVALUATION OF CENTERLINE RUMBLE STRIPS

Final Project Report

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EXECUTIVE SUMMARY

A study of centerline rumble strips was undertaken as part of the Massachusetts Highway Department (MassHighway) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to MassHighway.

The overall objective of this research was to evaluate the effectiveness of centerline rumble strips in reducing cross-over-the-centerline crashes and improving the safety of undivided roadways. Three research phases were completed. The objective of Phase I was to identify the current use of centerline rumble strips in the United States and around the world. A survey of all state Departments of Transportation was completed along with surveys of Canadian Provinces and several other countries. Phase I also incorporated the current state-of-the-knowledge related to centerline rumble strips and included a review of safety data found in the literature and through transportation agencies. Phase II evaluated the safety effects of the centerline rumble strips installed on State Routes (Route) 2, 20, and 88 in Massachusetts. Before and after statistical procedures were used to complete this analysis. Both targeted crashes (those involving a vehicle crossing over the centerline) and total crashes were considered at the study sites and selected comparison sites. Study sites represented the roadway segments containing centerline rumble strips. Comparison sites were selected roadway segments of similar geometry and characteristics located near each study site. Comparison sites provided an opportunity to evaluate safety trends unrelated to the installation of centerline rumble strips during the same time period. Phase III evaluated driver reaction to centerline rumble strips using a full-scale driving simulator. Sixty drivers (30 male and 30 female) ranging in age from 18 to 70 completed the study and drove scenarios with several different shoulder and centerline rumble strip encounters. Driver's reaction to each rumble strip encounter and the associated vehicle trajectory was recorded and evaluated.

Phase I results found that 20 of the 50 state Departments of Transportation, along with several provinces in Canada, are using centerline rumble strips. Several more states plan to use centerline rumble strips in the future. Massachusetts is clearly a national leader in the proactive use of centerline rumble strips as a safety measure. States who do not plan to use centerline rumble strips had concerns with noise, pavement deterioration, pooling of water in the rumble strips and freezing in winter, and the safety of motorcyclists and bicyclists. Several states have completed research on the effectiveness and safety benefits of centerline rumble strips and have identified positive results. Most of the state officials noted a reduction in crashes where centerline rumble strips were installed.

A detailed analysis of crashes on Routes 2, 20, and 88, before and after the installation of centerline rumble strips, was completed in Phase II. Figure E1 provides a map showing the location of three centerline rumble strip locations in Massachusetts. Tables E1 and E2 present the study and comparison site targeted crash frequencies. Route 2 experienced a slight decrease in the annual frequency of targeted crashes while Route 20 and Route 88 remained relatively consistent. Crash frequency was defined as the total number of targeted crashes per unit of time. Several of the comparison sites, specifically Route 18 and Route 131, witnessed significant increases in targeted crash types.

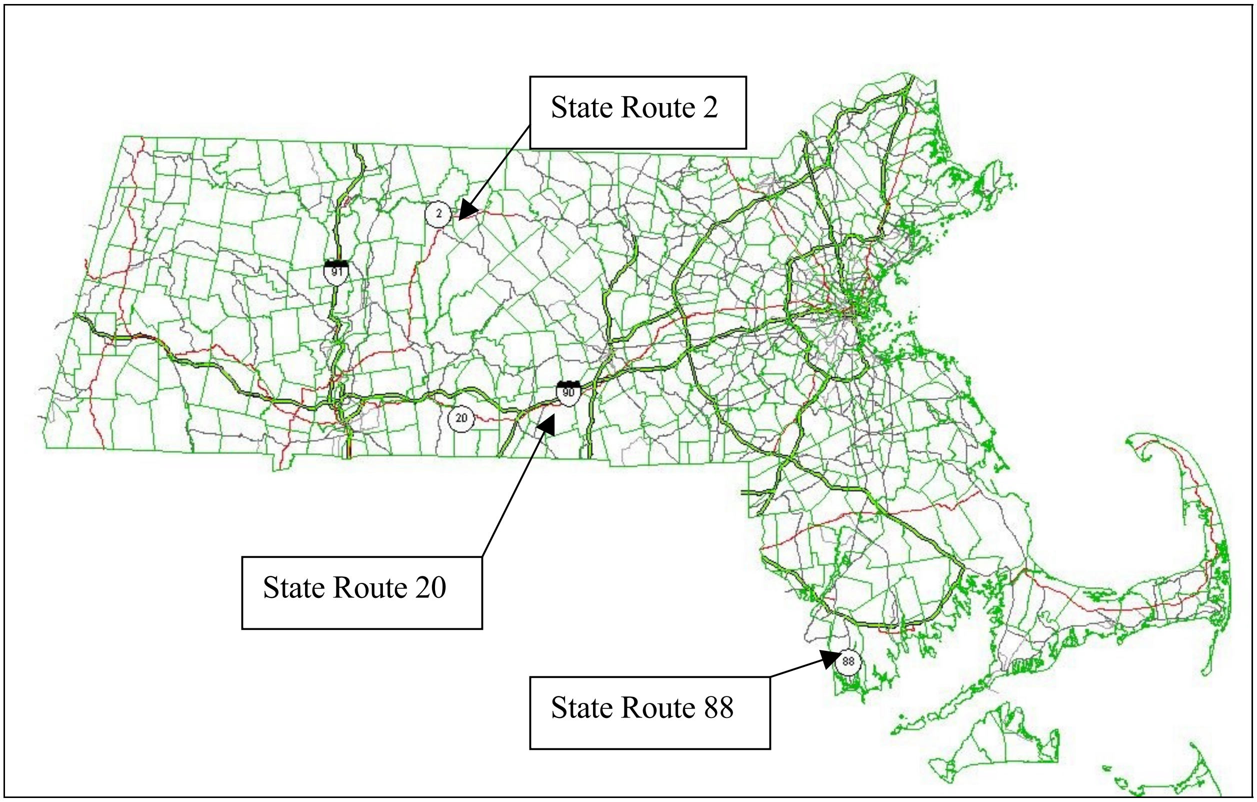

FIGURE E1. Centerline Rumble Strip Locations in Massachusetts.

TABLE E1. Targeted Crash Frequency Data for Study Sites

Route\Year	1995	1996	1997	1998	1999	2000
Route 2	7	8	7	4 (before); 1 (after)	6	5
Route 20	6	7 (before); 2 (after)	5	6	5	6
Route 88	0	0	1	0 (before); 0 (after)	1	1

TABLE E2. Targeted Crash Frequency Data for Comparison Sites

Route\Year	1995	1996	1997	1998	1999	2000
Route 2A	11	4	7	2	6	8
Route 202	2	3	3	4	3	2
Route 31	1	4	0	1	2	1
Route 49	1	1	0	1	1	2
Route 131	7	14	10	6	6	16
Route 177	0	0	3	1	2	7
Route 18	16	19	30	37	34	36

An analysis of fatal crashes at the study locations, during the study period, provides more insight into the effectiveness of centerline rumble strips. No fatal crashes were experienced on Routes 2 and 88 in the analysis area since the installation of the centerline rumble strips. Route 20 experienced two fatal crashes in 1997 and one in 1998, all after the installation of centerline rumble strips. No fatal crashes were experienced in 1999 and 2000. Both fatal crashes in 1997 occurred at nearly the same location, approximately 200 feet east of the Charlton/Oxford Town Line near mile marker 104.1. This location is adjacent to an 819-foot radius horizontal curve. The fatal crash in 1998 was also close to the location of the 1997 fatal crashes, taking place approximately 300 feet west of the Charlton/Oxford Town Line near mile marker 103.9. MassHighway currently has a construction contract ongoing that will make improvements to this corridor and address any potential safety issues.

The before and after crash data were analyzed in a number of different ways. In the first analysis, targeted crashes were considered at both the study and comparison sites. Using statistical procedures that predict roadway safety in the after period if centerline rumble strips had not been applied, crash frequencies based on historical and comparison site trends were computed along with safety estimates of the centerline rumble strip section in the after period. The results showed that the overall number of predicted crashes increased by approximately 3 crashes/year. This result was not statistically significant. The number of actual crashes on Route 2 was approximately 1 crash per year lower than predicted. Route 20 data showed that actual crashes were approximately 2.2 crashes/year greater than predicted. Route 88 data showed that actual crashes were approximately 1 crash per year higher than predicted. None of these results were statistically significant.

The effect of traffic volume was considered using the same comparison sites. Increases in traffic volume change exposure and can affect both crash rates and frequencies. Results were consistent with the previous analysis. Overall, approximately 3 more crashes occurred than predicted, with a standard deviation of approximately 6. Each of the roadways showed no statistically significant difference in crash frequencies before and after the centerline rumble strip installation.

An analysis was completed considering only injury crashes in the before and after conditions. Expected injury crashes were approximately one crash/year higher on Routes 2 and 88 than actual injury crashes. Neither result was statistically significant. Route 20 experienced a 2.6 crash/year increase in injury crashes (standard deviation 2.5) showing a statistically significant increase in this crash type.

Additional evaluations considering all crashes before and after the installation of centerline rumble strips as well as different combinations of comparison sites were completed. Results were consistent with the previous analysis.

The results of the crash data analysis in Phase II showed no significant change in crash frequencies before and after the installation of centerline rumble strips. There were no significant trends in the comparison sites that would lead to the conclusion that the stability of the crash frequencies at the study locations were a function of the environment. This study found no evidence to suggest that the installation of the centerline rumble strips significantly reduced crash rates. Some positive reductions in injury crashes were observed on Routes 2 and 88, although the results were not significant. No fatal crashes have occurred on Routes 2 and 88 since the installation of centerline rumble strips which can be attributed to the benefits of centerline rumble strips; however, three cross-over-the-centerline fatal crashes did occur on Route 20 after the centerline rumble strips were installed.

Phase III considered the human factors elements of rumble strips and evaluated drivers reaction to encounters with centerline rumble strips. The results found that drivers took more time to return to the travel lane when centerline rumble strips were present as compared to when centerline rumble strips were not present. This result was probably due to the unexpected nature of the centerline rumble strip encounter and the corresponding violation of driver's expectations. Considering all scenarios, the difference in the average time to return to the travel lane was significantly higher during the first encounter, but decreased with experience.

Drivers were found to react and correct the vehicle trajectory more quickly with shoulder rumble strip encounters than with centerline rumbles strip encounters. Familiarity with shoulder rumble strips is likely the reason for this result.

The initial corrective movement when centerline rumble strips were encountered was surprising. Approximately 27 percent of the drivers made an initial leftward correction of the vehicle when encountering centerline rumble strips. Results varied from approximately 20 percent of drivers on straight roadway segments to 37 percent of drivers on curved roadway segments of sufficient radius to require no passing zones. One can argue that this high percentage of drivers correcting left is due to the laboratory conditions, lack of opposing vehicles in the simulation, the experimental nature of this research, or less than normal driving conditions. Additionally, the increase in the percentage of left corrections on horizontal curves may be due simply to the uniqueness of the simulated driving environment. Nevertheless, it is difficult to deny the fact that there is some probability of a driver becoming confused and reacting improperly. Considering a drowsy or inattentive driver who is unaware of their roadway position, this result is potentially concerning. Yet centerline rumble strips were effective at gaining driver's attention, and although a slight correction into the opposing lane is not ideal, the attentiveness gained by the centerline rumble strips may still prevent a crash or result in a far less severe incident than a complete head-on collision with a drowsy driver. The majority of drivers made proper corrections when encountering centerline rumble strips demonstrating their value at improving safety on the Massachusetts roadway system. Furthermore, no improper (rightward) corrections were experienced with shoulder rumble strip scenarios.

Considering the cumulative results from the three Phases presented, centerline rumble strips are an effective traffic control device and safety countermeasure in areas were a history of cross-over-the-centerline fatal and injury crashes occur. The results show beneficial trends in fatal and injury crash reductions; however, a statistically significant decrease in all crashes was not observed. The fatal crashes on Route 20 after the installation of centerline rumble strips demonstrate the fact that centerline rumble strips can only warn but not prevent drivers from crossing over the roadway centerline.

The results of this research, supported by the findings in other states, show that centerline rumble strips are a recommended countermeasure in areas where cross-over-the-centerline crashes occur. The researchers recommend that additional analysis be completed that considers additional years of before and after crash data. A wider time frame may show more positive trends in crash frequency. Additionally, further study is recommended pertaining to the human factors elements of centerline rumble strips. Some consideration should be given to an alternate configuration or intermittent layout of centerline rumble strips to produce a different tone and message to the driver than what is experienced with continuous shoulder rumble strips.

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CHAPTER 1
CENTERLINE RUMBLE STRIPS

A study of centerline rumble strips was undertaken as part of the Massachusetts Highway Department (MassHighway) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to MassHighway.

INTRODUCTION

Safety on our nation's roadway system continues to be a concern for those responsible for its operation. In 2001, more than 6.25 million vehicle crashes took place resulting in 37,795 fatalities (1). In total, 42,116 people were killed in transportation related incidents. The Commonwealth of Massachusetts experienced 410 fatal crashes resulting in 433 traffic fatalities in 2000, approximately 1.0 percent of the nation's total (2). Drivers and passengers in motor vehicles accounted for 338 of the 433 fatalities. Over 91,450 people were injured in Massachusetts crashes.

Transportation safety has taken a more significant role in recent years as travel in the United States increases and the world's transportation system rapidly develops. Human factors play an important role in safety; therefore, any provision to improve the safety of transportation system should take human factors into account. For example, fatigue, drowsiness, or inattentiveness is often the cause of many run-off-the-road crashes, head-on collisions, rear-end collisions, and collisions with parked vehicles or other stationary objects.

One of the most common roadway crash in the United States is a *run-off-the-road* incident in which a vehicle leaves the roadway and either turns over or hits a fixed object. Run-off-the-road crashes account for one-third of all traffic fatalities, and two-thirds of traffic fatalities on rural roadways (1, 3). In an effort to reduce run-off-the-road crashes and other crash types caused from vehicles deviating from their designated lane, traffic engineers have looked to traffic control devices to aid in their safety mission. Many state transportation agencies have installed shoulder rumble strips along the travel lanes of primary roadways (functional classification of freeway or principal arterial) as a traffic control device countermeasure to lane deviation.

Shoulder rumble strips are a linear series of grooves cut or rolled into the pavement shoulder designed to warn drivers that they are leaving the roadway. The use of shoulder rumble strips has increased significantly in the last few years fueled by AASHTO's recommendation to install shoulder rumble strips as part of the strategic highway safety plan (3). Some transportation agencies also place rumble strips on the inside shoulders of divided highways. When a vehicle tire passes over the rumble strips, it causes the vehicle to vibrate and produces a *rumble* sound. The audible warning and physical vibration produced is intended to stimulate an inattentive or drowsy driver and gain their attention. Research has shown that the use of shoulder rumble strips can reduce the frequency of run-off-the-road crashes (4).

PROBLEM STATEMENT

The effectiveness of shoulder rumble strips has led several transportation agencies to consider the use of centerline rumble strips. In areas where a history of head-on and cross-over-the-centerline crashes exist, centerline rumble strips can be effective in warning the driver of a potential incursion into opposing traffic right-of-way. Centerline rumble strips are constructed in a similar manner as shoulder rumble strips, with a linear series of grooves carved into the pavement. As the tire of a vehicle moves over the centerline rumble strip, the ensuing vibration produces a startling sound in an effort to capture the attention of a potentially drowsy or inattentive driver.

One of the concerns with the use of centerline rumble strips (and inside shoulder rumble strips) is driver's *ad hoc* and *a priori* expectancies derived from previous experiences with shoulder rumble strips. Shoulder rumble strips were first installed on the New Jersey Garden State Parkway in 1955 and many states started using them in the 1960's. Therefore, most drivers are familiar with shoulder rumble strips and aware of their presence on the outside shoulder of freeways and many principal arterial roadways. Because of this awareness (i.e., expectancy), driver's subconscious reaction to a sudden encounter with shoulder rumble strips is to correct the trajectory of the vehicle by turning left, away from the outside edge of roadway.

This expectancy and associated vehicle maneuver can be problematic with the use of centerline rumble strips. Drivers who encounter a centerline rumble strip, and are unaware of their current lane position, may assume that they are experiencing a shoulder rumble strip. The common reaction to the rumble strip encounter is to turn the steering wheel to the left, which may be detrimental to the potential safety benefits of centerline rumble strips. A question remains as to the driver's ability to distinguish between centerline and shoulder rumble strips. Prior to this research effort, a comprehensive study of centerline rumble strips, including an analysis of driver reaction, the potential safety benefits, and frequency of use has not been completed.

RESEARCH OBJECTIVES

The overall objective of this research was to evaluate the effectiveness of centerline rumble strips in reducing cross-over-the-centerline crashes and improving the safety of undivided roadways. The research plan was developed in three phases. The objective of Phase I was to identify the current use of centerline rumble strips in the United States and around the world. Phase I also incorporated the current state-of-the-knowledge related to centerline rumble strips and included a review of safety data found in the literature and through transportation agencies. The objective of Phase II was to evaluate the safety effects of centerline rumble strips installed on State Routes (Route) 2, 20, and 88 in Massachusetts. The objective of Phase III was to evaluate driver reaction to centerline rumble strips using a full-scale driving simulator.

SCOPE

The scope of this project was limited to identifying current practices of centerline rumble strips and the safety evaluation of centerline rumble strips installed on Massachusetts Routes 2, 20, and 88. Evaluation of different sounds caused by varied rumble strip spacings and intermittent placement was not part of this study. Various construction methods, including the length, width, and depth of each rumble strip, was not considered in this study. The evaluation of driver reaction to centerline rumble strips was limited to the driving simulator.

REPORT OUTLINE

This report consists of seven chapters. The first chapter introduces rumble strips as a traffic control device used to improve safety, and states the research problem, research objectives, and scope of the research. Chapter 2 presents a review of the existing literature on rumble strips and other relevant issues. Chapter 3 explains the experimental design used to achieve the outlined research objectives.

The results of the state Department of Transportation surveys concerning current use of centerline rumble strips is presented in Chapter 4. Chapter 5 presents the *Before* and *After* crash analysis to evaluate the safety of the centerline rumble strips installed on Routes 2, 20 and 88 in Massachusetts. Chapter 6 presents the evaluation of human behavior and interaction with centerline rumble strips using the fixed-base full-scale driving simulator at the University of Massachusetts. The conclusions and recommendations of the research study are presented in Chapter 7. Other relevant tables, graphs, and data are presented in the Appendices.

CHAPTER 2
LITERATURE ON RUMBLE STRIPS

Rumble strips are raised or grooved patterns usually constructed in the shoulders of pavements. Rumble strips can also be placed across the pavement surface upstream of roadway changes such as toll plazas, lane changes for a work zone, horizontal curves, stop for a traffic signal, or unexpected roadway alignments. Rumble strips are designed to alert drivers to a departure from the roadway, most often due to drowsiness, fatigue, or inattentiveness, or to an approaching roadway zone that requires a high level of awareness. The texture of rumble strips is different from the road surface. When a vehicle passes over the rumble strip, a sudden *rumbling* sound is caused due to the vibration of the vehicle. Rumble strips act as a surrogate alarm system by causing vibrations and loud noise levels within the vehicle's passenger compartment.

The intent of rumble strips is to warn drivers to maneuver appropriately in avoidance of a potential conflict or crash situation. Moreover, rumble strips can act as a roadway guide for drivers in areas where rain, fog, snow, and dust obscure pavement edges, and in situations where highway hypnosis, caused by monotonous stretches of straight highways, mesmerize drivers and decrease their concentration levels. Research has shown that an effective countermeasure to lane deviation effects of highway hypnosis is the use of rumble strips (5).

Rumble strips can be used under any roadway condition but are primarily used on freeways, interstate highways, and parkways. In some states, rumble strips are installed on two-lane rural roads that have high numbers of single-vehicle crashes (5).

This chapter presents information on the types of rumble strips used in the United States. Shoulder rumble strips and the safety effectiveness of rumble strips are discussed along with the burgeoning use of centerline rumble strips. This chapter concludes with background information on full-scale driving simulators and their ability to evaluate traffic control devices such as rumble strips.

TYPES OF LONGITUDINAL RUMBLE STRIPS

Rolled and milled rumble strips are the two most common types used in the United States and Canada. The other two types of rumbles strips that are used are formed rumble strips and raised rumble strips (6). Each of these rumble strip types is described in the following sections.

Rolled-In Rumble Strips

Rolled-in rumble strips are placed during new construction activities that include asphalt shoulders. A steel-wheel roller with steel pipes welded to the wheel drum makes these strips by traveling along the pavement surface. The steel pipes make depressions as the roller pass over the hot asphalt pavement. Each groove is approximately 1.5 inches wide, 16 inches long, and 1 inch deep, and can be either rounded or V-shaped, but can vary depending on the shape and size of the pipe used. A vehicle tire will drop approximately 0.03 inches into each pavement groove; creating the rumble effect (6). Similar rumble strips can be formed into concrete shoulder using one of several concrete finishing devices. Figure 1 shows a rolled in rumble strip in asphalt pavement.

Formed Rumble Strips

Formed rumble strips in asphalt pavements are simply another name for rolled-in rumble strips (6). States that use the *formed* rumble strips terminology specify similar groove size (approximately 1.5 inches wide, 16 inches long, and 1 inch deep rounded or V-shaped) and construction methods (pressed into hot asphalt pavements and shoulders with steel wheel rollers). The term *formed* is also used for rumble strips installed in Portland Cement Concrete (PCC) shoulders. Metal forms, most often with rumble strip size and spacing consistent with rolled-in rumble strips in asphalt shoulders, are pressed into the wet PCC shoulder creating the rumble strip pattern.

Milled-In Rumble Strips

Milled-in rumble strips are applications that are cut into existing pavement edges, in lieu of rolled-in or formed rumble strips completed during new construction (6). Many transportation agencies prefer to use milled rumble strips because they are considered easy to implement. Milled rumble strips can be cut as part of new construction or can be constructed on existing asphalt and PCC concrete pavements and shoulders. These rumble strips have been found to have an insignificant effect on the integrity of the pavement structure. Figure 2 depicts a typical milled rumble strip application.

FIGURE 1. Typical Rolled Rumble Strip in Asphalt Pavement.

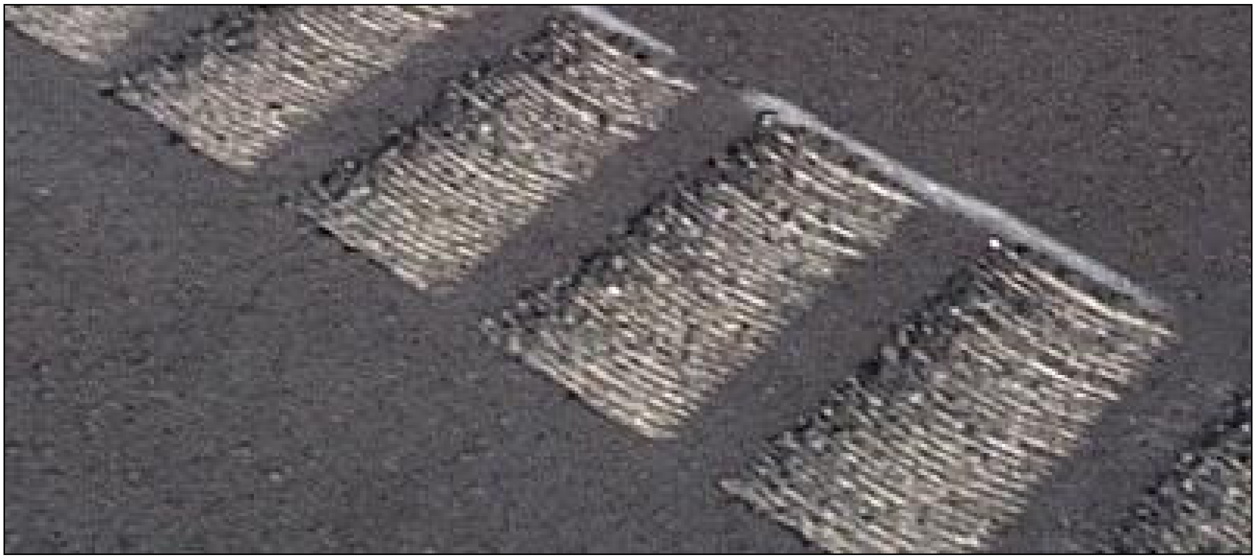

FIGURE 2. Typical Milled Rumble Strip.

Most milled rumble strips have a longitudinal width of approximately 7 inches and a transverse length of 16 inches. The offset from the edge of the travel lane is typically 12 to 16 inches. A machine-driven rotary cutting head is used to cut each grove, generally with 12 inch radius cuts. Rotary cutting creates a smooth uniform and consistent groove of approximately 0.5 inches in depth, allowing vehicle tires to drop to the bottom of the groove. A recent study has estimated that milled rumble strips are 12.6 times rougher and 3.4 times louder than rolled in rumble strips (6).

Raised Rumble Strips

Raised rumble strips are typically a series of 2 to 12 inches wide rounded or rectangular markers or strips, placed by adhering to new or existing pavements. The height of raised rumble strips can vary from 0.25 to 0.5 inches; therefore, its use is usually restricted to states in warmer climates that do not use plows for snow removal (6). Figures 3 and 4 show several types of raised markers often used as rumble strips.

FIGURE 3. Typical Raised Marker Rumble Strips.

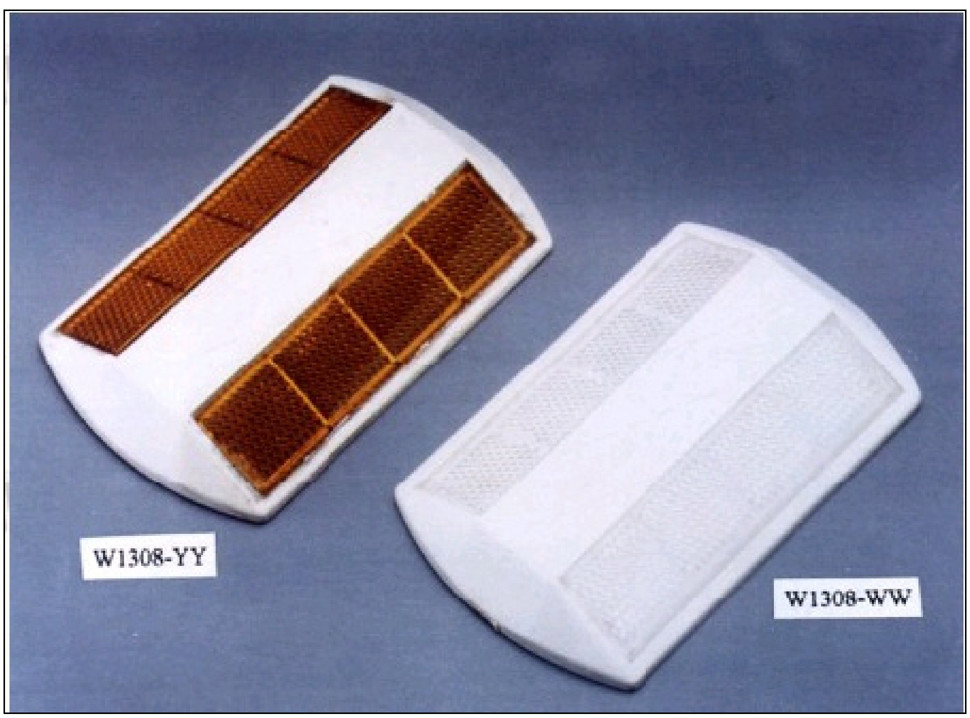

FIGURE 4. Raised Marker Rumble Strips.

SHOULDER RUMBLE STRIPS

The 2001 statistics from the Fatality Analysis Reporting System (FARS) and the National Highway Traffic Safety Administration (NHTSA) show that 37,795 fatal crashes occurred of which almost 14,000 involved single vehicle run-off-the-road vehicle crashes (1, 7). Run-off-the-road crashes involve vehicles in which the first harmful event takes place off of the roadway, most often a rollover or fixed-object collision. One of the primary causes of run-off-the-road crashes is driver error, often due to drowsiness, fatigue, or inattentiveness. It is estimated that 56,000 crashes, 71,000 injuries, and 1,500 deaths each year in the United States are due to drowsy drivers (1, 7). The University of Maine conducted a study in 1999 that surveyed 205 drivers, finding that 31 percent of drivers have dozed off at least once while driving in the past 12 months (8). Further, it was found that 15 (eight percent) of the surveyed drivers had a collision due to dozing off. The survey showed that younger people are more likely to doze off than older drivers and men are twice as likely as women to doze off.

The percentage of run-off-the-road crashes taking place has remained consistent over the last few years and represent one third of all fatalities. Rumble strips have been recommended as one the devices that can provide a countermeasure to help reduce the high number of run-off-the-road crash types. Shoulder rumble strips on long tangents and monotonous sections of rural highways are recommended by FHWA through Notice N7560.0 (4). Figure 5 shows a picture of a typical shoulder rumble strip application.

There are many reports on the safety benefits of shoulder rumble strips, some of which are discussed in the following paragraphs.

FIGURE 5. Linear Milled Shoulder Rumble Strips.

The Wyoming Division of FHWA published a report on shoulder rumble strip effectiveness and current practice. A five-year review from 1992 to 1996 found that a significant percentage of total crashes are run-off-the-road crashes (4). The results of this review are presented in Table 1. Fatigue and drowsiness were found to be the primary reasons for run-off-the-road crashes. Alcohol and drugs may also contribute to speed, fatigue, and drowsiness.

The effectiveness of shoulder rumble strips was evaluated by considering crash reduction in various states. A summary of studies of the effectiveness of shoulder rumble strips is presented in Table 2 (4). Pennsylvania found a 70 percent reduction of single vehicle run-off-the-road crashes along rural segments of the Pennsylvania Turnpike with the introduction of shoulder rumble strips. New York observed a 72 percent reduction of single-vehicle run-off-the-road crashes after installing shoulder rumble strips on rural Interstate highway segments. Massachusetts found that single-vehicle run-off-the-road crashes were reduced by 42 percent after installing shoulder rumble strips on the rural segments of the Massachusetts Turnpike. Washington State installed rumble strips at six Interstate highway locations and found a single-vehicle run-off-the-road crash reduction of 18 percent. FHWA's study on shoulder rumble strips in California, Arizona, Mississippi, Nevada, and North Carolina found a 20 percent reduction in single-vehicle run-off-the-road crashes.

Griffith conducted a study of shoulder rumble strips placed in Illinois and California, using data from the Highway Safety Information System (HSIS) (9). This study also provided an excellent overview of the literature on shoulder rumble strips, including the 1993 NCHRP Synthesis Report describing the state of the practice (10). Considering crashes before and after the installation of shoulder rumble strips, Griffith found that single-vehicle run-off-the-road crashes on Illinois freeways were reduced by 18.3 percent after installing shoulder rumble strips. The reduction in run-off-the-road crashes increased to 21 percent when considering only rural freeways. The study also looked at the cost of shoulder rumble strips, concluding that the benefit/cost ratio is extremely large due to the cost savings in crash reduction and the relatively small expense of installing shoulder rumble strips. Finally, Griffith pointed out the need to conduct video studies of drivers who encounter shoulder rumble strips to better understand how drivers react.

TABLE 1. Wyoming Report on Run-Off-The-Road Traffic Crashes

	Run-Off-The-Road Crashes		
	Rural	**Overturn**	
Year	**Percent of Fatal Crashes**	**Percent of Fatal Crashes**	**Percent of Injury Crashes**
1996	81.0	38.8	21.1
1995	84.8	45.7	20.4
1994	82.3	41.5	20.3
1993	74.0	35.0	21.9
1992	85.4	37.4	22.1

TABLE 2. Run-Off-The-Road Crash Reduction After Shoulder Rumble Strips

State/Date	Highway Type	Percent Single Vehicle Run-Off-The-Road Crash Reduction
Pennsylvania /1994	Interstate - Pennsylvania Turnpike – rural	70
New Jersey /1995	Interstate - New Jersey Turnpike – rural	34
New York /1994	Interstate Highway – rural	72
Massachusetts /1997	Interstate - Massachusetts Turnpike – rural	42
Washington /1991	Interstate Highway – rural	18
California /1985	Interstate Highway – rural	49
Kansas /1991	Interstate Highway – rural	34
Federal Highway Administration /1985	Interstate Highway – rural (California, Arizona, Mississippi, Nevada, and North Carolina)	20

FHWA released a Technical Advisory on using shoulder rumble strips in December of 2001 (11). Information on placing shoulder rumble strips is provided along with references to the current available literature on the topic. Much of this information is also provided on a comprehensive web site that summarizes recent research studies and looks at current status of State Department of Transportation (DOT) practices and policies (12).

Recent reports show that 85 percent of state transportation agencies incorporate shoulder rumble strips in their highway improvement programs (4). While shoulder rumble strips are effective in mitigating run-off-the-road crashes, they may be hazardous to motorcycles and bicyclists. At locations where shoulder rumble strips are installed, bicyclists may not be able to enter or exit the shoulder area safely (5).

Some traffic engineers have hypothesized that shoulder rumble strips may reduce crashes in the area of installation but may not reduce the overall number of crashes. Instead, crashes may simply be moved to downstream segments of roadway that do not contain shoulder rumble strips. This hypothesis, call *crash migration*, may occur when a driver is temporarily protected by a safety improvement, but crashes downstream or some other point in the network where the safety improvement is not installed (13). Due to crash migration, downstream locations may have an increase in the number of crashes after shoulder rumble strip installation. No evaluation of this aspect of crash migration, associated with the installation of shoulder rumble strips, was found in the literature.

CENTERLINE RUMBLE STRIPS

The safety benefits found with shoulder rumble strips have prompted transportation engineers to use rumble strips along the centerline of undivided roadways. Centerline rumble strips have been installed in an attempt to reduce the number of crashes caused by vehicles crossing over the centerline into opposing traffic. Figures 6 and 7 show centerline rumble strip installations in Massachusetts.

In 2000, there were 5,233 fatal head-on collisions in the United States as reported in *Traffic Safety Facts 2000*, published by the National Highway Traffic Safety Administration (NHTSA) (1). NHTSA also reports that a substantial number of fatalities each year are due to drivers crossing the lane or driving in the wrong direction and drowsiness, fatigue, illness, and blackout. Traffic engineers believe that centerline rumble strips may be effective in reducing the number of cross-over-the-centerline crash types and associated fatalities and injuries.

FIGURE 6. Centerline Rumble Strip on State Route 20 in Massachusetts.

FIGURE 7. Centerline Rumble Strip on State Route 88 in Massachusetts.

Currently, centerline rumble strips are used only on a small number of roadways across the country. A 1999 survey of transportation agencies found eight states and Alberta, Canada using centerline rumble strips. Nevertheless, a growing interest in the perceived potential for safety benefits and use of centerline rumble strips exists. Since drivers are familiar with shoulder rumble strips and may react the same way when they encounter a centerline rumble strip (i.e., turn vehicle towards the left), there is some concern that drivers may incorrectly react in centerline rumble strip applications leading to additional and more serious crashes.

Effectiveness of Centerline Rumble Strips

The Colorado Department of Transportation recently completed research on the safety benefits of centerline rumble strips (14). A before and after crash analysis was done for the 17 miles of centerline rumble strips installation on State Highway 119. Figure 8 shows a photograph of the Highway 119 application. The Colorado study found a statistically significant reduction in the number of cross-over-the-centerline type crashes, including a 34 percent reduction in head-on collisions and a 37 percent reduction in cross-over sideswipe crashes. Researchers hypothesized that greater benefits may be found if an 18 percent increase in average daily traffic (ADT) is considered. Other research findings showed no apparent change in the effectiveness of the centerline rumble strips due to the accumulation of debris inside the grooves. Rumble strips did not appear to have any detrimental effect on the life of the pavement. Colorado did find that the yellow centerline pavement marking wore off quicker than at other non-rumble strip locations. The researchers also expressed concern over the potential dangers to motorcyclists and bicyclists.

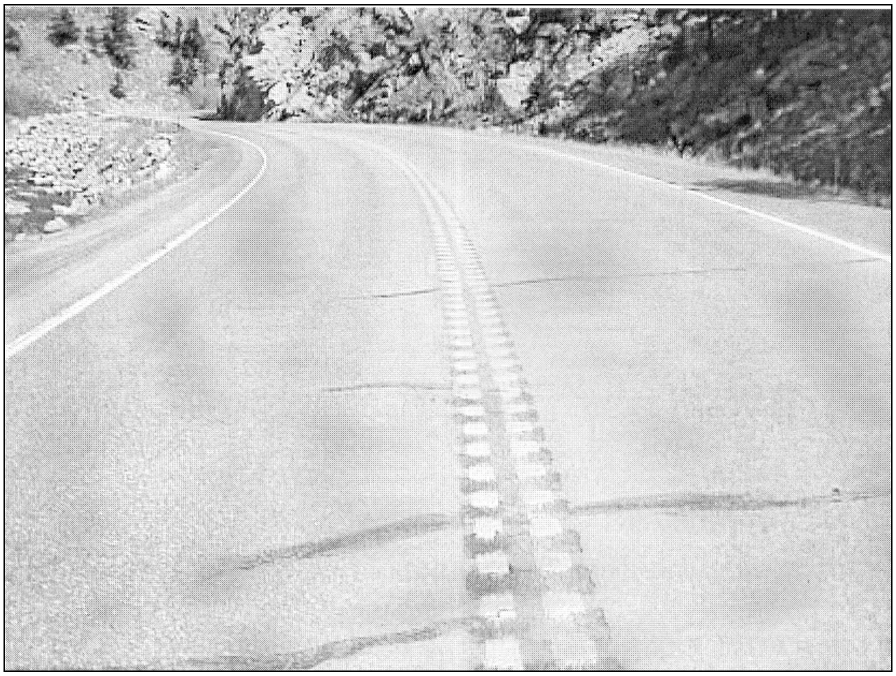

FIGURE 8. Centerline Rumble Strips in Colorado.

The Delaware Department of Transportation conducted research on the safety benefits of centerline rumble strips (15). Before and after crash analysis was done for the centerline rumble strip installation on Route US 301. The before and after crash analysis results are shown in Table 3.

TABLE 3. Delaware Centerline Rumble Strip Crash Data Analysis

Before and After Crash Summary for US 301			
	Average Number of Crashes per Year		
Accident Type	**Before Period (8/91 - 7/94) 3 years**	**After Period (12/94 - 11/00) 6 years**	**Percent Change**
Head on	2/year	0.2/year	-90%
Drove Left of Center	2/year	0.8/year	-60%
Property Damage	6.3/year	6.8/year	8%
Injury	4.7/year	5.8/year	23%
Fatal	2/year	0/year	-100%
Total	12.6/year	13/year	3%
Average Daily Traffic (Year)	16,500 (1994)	21,700 (2000)	5% yearly

The Delaware study indicates that the average number of head-on collisions decreased by 90 percent after the installation of centerline rumble strips. Crashes caused by drivers crossing over the centerline rumble strips decreased by 60 percent. The study determined that the benefit/cost ratio for centerline rumble strip installations was approximately 110. Researchers report that there was no observable deterioration in the pavement, and the centerline rumble strips were easy to maintain. Researchers also alluded to the possibility of inducing crash migration (i.e., increased crash frequencies upstream and downstream of the centerline rumble strip location) due to the installation of centerline rumble strips. No data were provided to evaluate this effect.

California tested the effects of centerline rumble strips in no-passing zones (16). A review of 36 months of before and after crash data found that crashes were reduced by 11 percent and fatalities reduced by 77 percent. Minnesota installed centerline rumble strips at two sites on rural roads with 55 mph speed limits (16). A review of three years of before and after data found no reduction in head-on crashes. Similarly, the Transportation Association of Canada created a "Best Practices" report on the use of shoulder and centerline rumble strips (16). Centerline rumble strips have been installed in Alberta, but no safety data has been produced.

Kansas conducted a study of centerline rumble strips in the Fall of 1999 and Spring of 2000 (17 – 19). The Kansas study focused on how states were constructing and placing milled centerline rumble strips, and the associated noise and vibration produced by different rumble strip patterns. Table 4 summarizes the results of milled centerline rumble strips used on two-lane undivided roadways.

TABLE 4. Milled Centerline Rumble Strips Reported in 1999

State	Width (inches)	Length (inches)	Depth (inches)	Spacing Between Strips (inches)	Location
CA	6.5	16	0.5	24	No Pass Zones
WA	6.5	16	0.5	12	No Pass Zones
	6.5	16	0.5	24	No Pass Zones
OR	7	16	0.63	12	No Pass Zones
AZ	6.5	12	0.5	12	All Zones
	6.5	8	0.5	12	All Zones
	6.5	5	0.5	12	All Zones
MA	6.5	18	0.5	12	No Pass Zones
PA	6.5	30	0.5	Alternating 24/48	No Pass Zones
	6.5	16	0.5	Alternating 24/48	No Pass Zones
	6.5	16	0.5	Alternating 24/48	No Pass Zones
	6.5	18	0.5	Alternating 24/48	No Pass Zones
	6.5	10	0.5	Alternating 24/48	No Pass Zones
	6.5	12	0.5	Alternating 24/48	No Pass Zones
CO	6.5	12	0.5	12	All Zones
CN	6.5	16	0.5	12	No Pass Zones
Alberta	6.5	12	0.5	12	All Zones

Kansas also evaluated the noise level produced by the rumble strip/vehicle tire interaction (17). The results of this study indicated that continuously 12-inch on center spaced rumble strips produced the highest decibel levels, ranging between 80 and 94 dB at 60 mph, depending on vehicle type.

The results of the literature review show that a limited amount of information is available on the effectiveness of centerline rumble strips. Additionally, no information was found pertaining to driver behavior or driver comprehension of centerline rumble strips. Furthermore, no literature was found which evaluates and compares driver reaction to both centerline and shoulder rumble strips.

DRIVING SIMULATOR

To evaluate the safety benefits of centerline rumble strips, research into the operation of the complex driver-vehicle-environment system is necessary. Among these elements, the driver is unique because the driver is non-deterministic, i.e., driver behavior defies prediction by means of common physical laws (20, 21). The only means of studying driver behavior is by direct observation. It may not be possible to study driver behavior in real life situations without exposing the driver to considerable physical danger. Therefore, full-scale driving simulators can provide tremendous research benefits.

A driving simulator is a virtual reality simulation of the environment. By modifying the vehicle to suit this virtual environment, researchers can study driver behavior without exposing the driver to physical danger. A driving simulator consists of a vehicle, projectors and screens for visualization, speakers to produce audio cues, and a computer that controls the entire simulation. Figure 9 shows the driving simulator at the University of Massachusetts at Amherst (UMass).

The UMass driving simulator is a mid-level Real Drive simulator (22). The vehicle cab is an actual 1995 Saturn sedan. Drivers operate the driving simulator vehicle just as they would do in a real vehicle on the open road. The visual world is displayed on three screens, one in front of the car and two on each side. Each screen subtends 60 degrees in the horizontal direction and 30 degrees in the vertical direction.

When the driver turns the wheel, brakes, or accelerates, the roadway that is visible to the driver changes appropriately. The images themselves are updated 60 times a second using state-of-the-art Silicon Graphics computers (a Silicon Graphics Infinite Reality Engine, an O2 and two Indy). The sound system for the simulator consists of four speakers, two located on the left and right sides of the car and two sub-woofers located in front of the car. The system provides realistic road, wind, and other vehicle noises with appropriate direction, intensity, and Doppler shift. The drivers' position in the visual database is recorded 60 times a second.

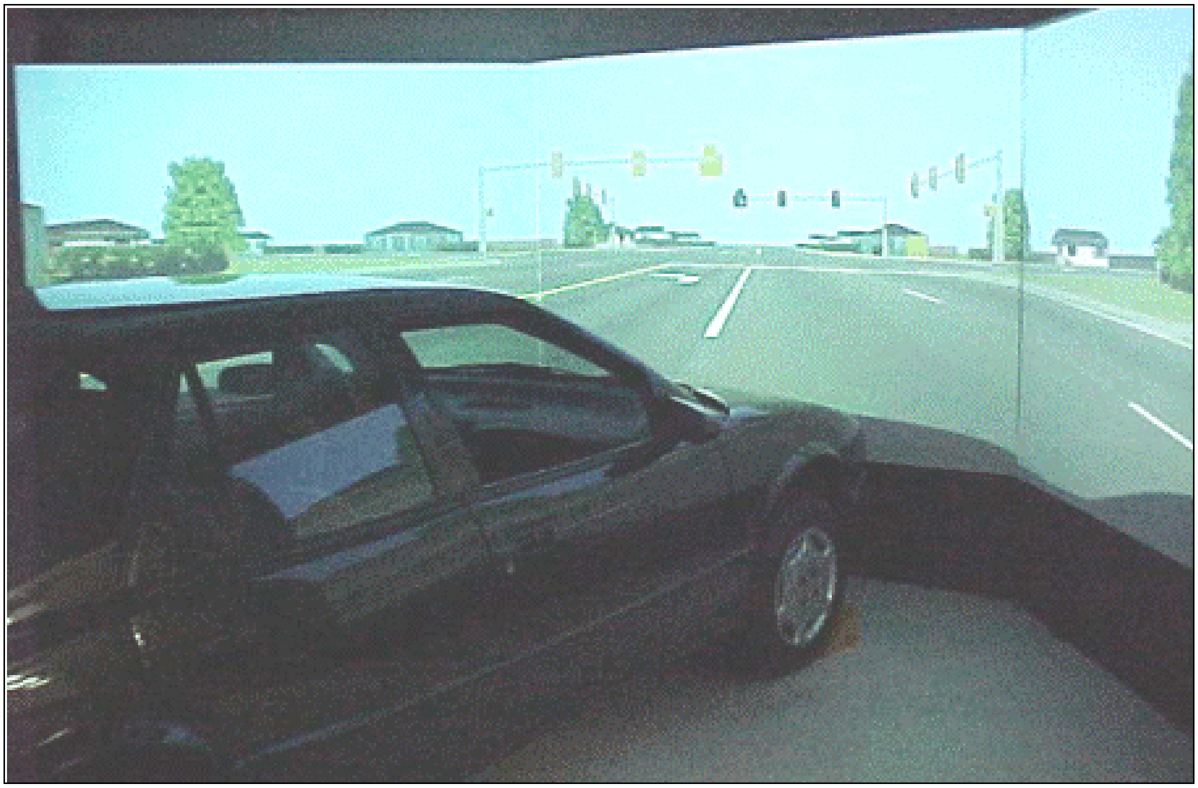

FIGURE 9. Driving Simulator at the University of Massachusetts.

Simulator Sickness

Simulator sickness is a potential concern when using a driving simulator. Simulator sickness is usually associated with virtual reality interfaces and refers to a wide range of symptoms including nausea, dizziness, eyestrain, and headaches (23). Simulator sickness is very similar to the more common motion sickness.

According to the standard "sensory rearrangement theory," motion sickness arises from conflicting motion cues, either between different sensory channels or between expected and experienced stimuli (23). In a simulator, for instance, we often have visual cues indicating that we are moving, but not inertial motion cues. Motion sickness arises even if the simulation was a perfect representation of the environment.

Interface sickness is the symptom that arises due to limitation of the simulator to accurately simulate an environment. This is caused by problems in the visual display such as poor resolution or inter-ocular distance arrangement. Interface sickness is also caused by time lags, scale changes, and position sensing inaccuracies in the simulator support system. We can expect that simulator sickness due to interface sickness will decrease with technology improvement.

Experience with driving simulators has shown that only a small percentage of drivers (study subjects) are affected by simulator sickness. Therefore, the effect of simulator sickness on driving simulator experiments has been minimal.

CHAPTER 3
EXPERIMENTAL DESIGN

RESEARCH PROCEDURE

Three research phases were developed to meet the project objectives. Each phase and associated tasks are presented in Figure 10. The first phase identified the current use of centerline rumble strips across the United States. The use of centerline rumble strips in Canada and other countries was also explored. Phase II was designed to evaluate the safety benefits of centerline rumble strips installed on Massachusetts Routes 2, 20, and 88. Phase III was designed to evaluate driver behavior towards centerline rumble strips, using a full-scale driving simulator. Each of the phases is described in detail in the following sections.

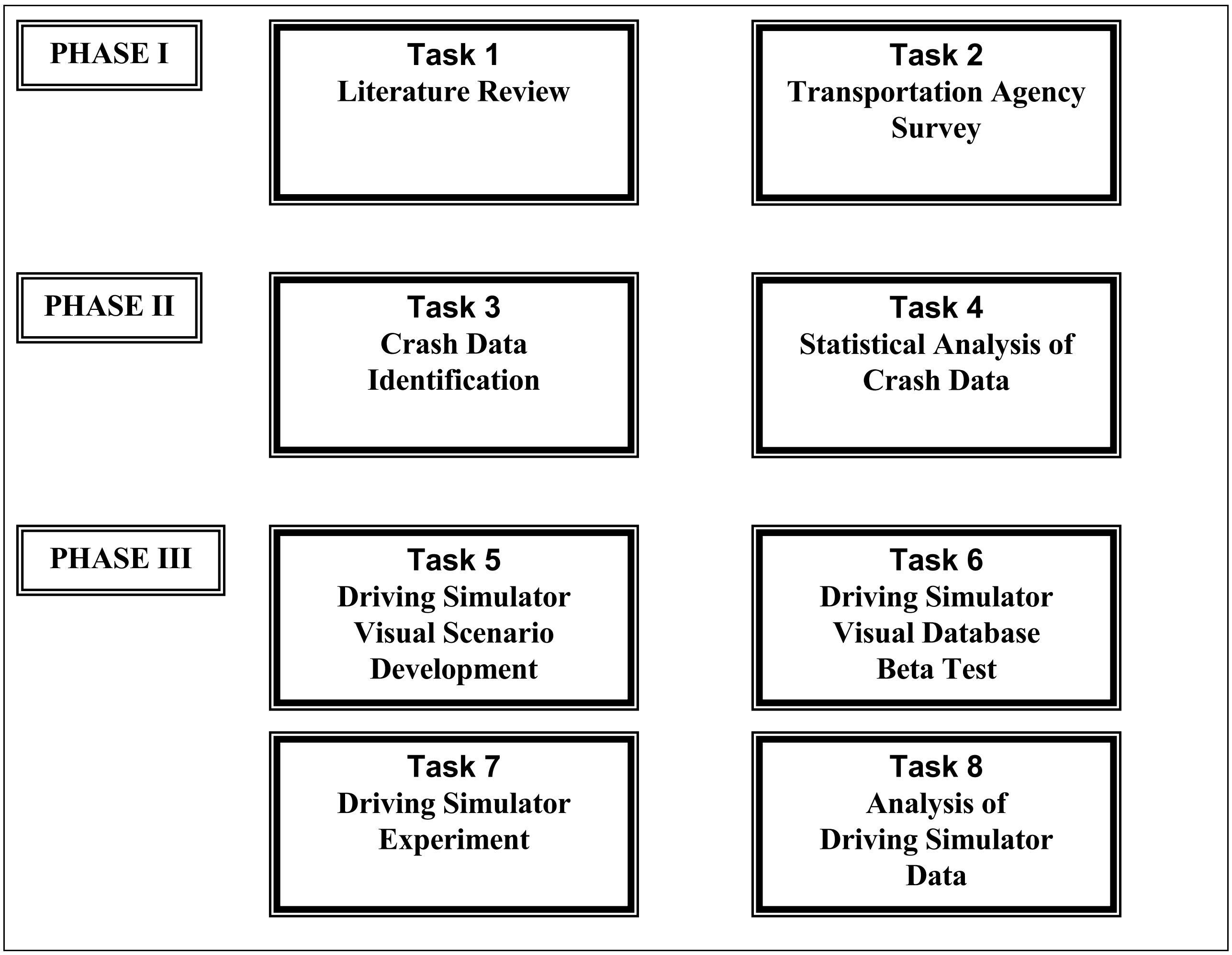

FIGURE 10. Project Flow Chart.

PHASE I

Phase I was divided into two tasks. Task 1 was designed to review and evaluate published and unpublished literature and current practices relevant to the use of centerline rumble strips. Literature sources pertaining to the effectiveness of shoulder rumble strips were also considered. Information from the United States, international locations, and various literature databases were searched. Unpublished information from state transportation agencies and other sources were investigated. The literature review was presented in the Chapter 2 of this report.

Task 2 included developing and conducting a survey of transportation agencies with the objective of determining their use, policies, and specifications related to centerline rumble strips. A survey document was created and placed on a web site for easy access. An e-mail message was sent to the state research engineer in all 50 states, asking him or her to complete the online survey. Since the desired number of respondents was low (< 60), this type of survey allowed manageable written and verbal follow-up to maximize response rates. Researchers called state engineers to obtain unreturned surveys and to follow-up on questions and comments. Using web technology to conduct the survey made it quite easy for respondents to complete. Responses were received from all 50 states. A copy of the survey is included in Appendix A.

The survey included both freestyle and multiple-choice response. Freestyle survey format provided no structure to the survey response and was very successful at soliciting unscripted comments on use and effectiveness of centerline rumble strips. Assimilation and analysis of freestyle comments were difficult as well as time consuming, but very informative. Multiple-choice responses provided a specific set of possible responses. Extreme care was taken to ensure that the multiple-choice survey questions were not biased in any way that could direct responses to a particular selection.

The agency survey was designed to explore a number of topics. First, information about the respondent was requested. Next, several questions were presented to explore the use of centerline rumble strips in the respondent's jurisdiction. In most cases, the jurisdiction was statewide. For those respondents who indicated that they did use centerline rumble strips, information was gathered on the number, length, and type of rumble strips used. Reasons for installing centerline rumble strips were explored, along with performance and evaluation criteria. A request for specific information related to study data, policies, and/or specifications currently used was made. Finally, those respondents who indicated that they did not use centerline rumble strips were asked why they were not using them, and then asked if they planned to use them anytime soon.

To ensure that the survey was of sufficient quality and suitable for distribution, the survey was beta tested with several transportation agencies. No changes were made to the survey after the beta test.

PHASE II

Phase II began with Task 3, which was designed to collect and analyze crash data for the segments of Massachusetts Routes 2, 20, and 88 containing centerline rumble strips. At the time of this study, only three segments of centerline rumble strips, all on two-lane roadways, had been installed in Massachusetts. Data were obtained from MassHighway's Accident Record System and also from the Massachusetts Traffic Safety Research Program (MassSAFE) database for a minimum of two years before and two years after the installation of centerline rumble strips, through the year 2000. The first step in the analysis was to identify the target crashes. Since the purpose of centerline rumble strips is to alert drivers who are leaving their travel lane and entering opposing traffic, target crashes were those reported that involved:

- Head-on collisions;
- Angle collisions (consistent with head-on); and
- Run-off-the-road crashes (crossing the centerline).

Identifying these crashes in the crash database proved to be anything but trivial. Since specific crash reports on each crash were not available, some interpretation of which crashes were included and eliminated was required. Every effort was made to objectively select only crashes that were associated with traversing the centerline of the roadway. The statistical process provided a means of quantifying the effects of the crash selection.

The next step in the analysis was to identify suitable comparison sites for each study site. Comparison sites were selected considering geometry, cross-section, travel speeds, traffic volumes, the influence of traffic flow on crashes, and climatic conditions. Ideally, comparison sites were similar in all aspects to the study sites except for not having centerline rumble strips. Based on these requirements, Routes 2A and 202 were identified as comparison sites for Route 2. Similarly, Routes 131, 31 and 49 were identified as comparison sites for Route 20, and Routes 177 and 18 were identified as comparison sites for Route 88. Traffic volume counts were obtained from all study and comparison sites to allow for the comparison of both crash frequencies and rates. Table 5 provides a summary of the relevant centerline rumble strip data. Figures 11 through 14 show the approximate location of the centerline rumble strip installations.

A statistical analysis of the crash data, using a *before* and *after* analysis (BAA) methodology, was completed in Task 4. Before and after analysis procedures involve the prediction of the number of crashes at each study site in the after period, if the centerline rumble strip had not been implemented (24). To estimate the safety benefits of the centerline rumble strips, the expected number of crashes in the after period was compared to the observed number of crashes after implementation of centerline rumble strips. If more crashes were predicted/expected than actually occurred, the centerline rumble strip is shown to be effective at reducing crash frequencies. Crash frequencies were defined at the total number of targeted crashes per unit of time.

TABLE 5. Centerline Rumble Strip Locations in Massachusetts

State Route	Town	Limits	Length	Date of Installation	ADT
2	Erving Wendell Orange Athol Phillipston	Near Exit 14 in Erving to Mile Marker 78 in Phillipston	9.12 miles	November, 1998	9,000
20	Sturbridge Charlton Oxford	Route 49 in Sturbridge to Route 12 in Oxford	10 miles*	November, 1996	8,600
88	Westport	Drift Road to Briggs Road	6.14 miles	November, 1998	7,000

* A 12,500 foot section of Route 20 from Depot Road to Richardson's Corner was under construction in 1999 (no rumble strips).

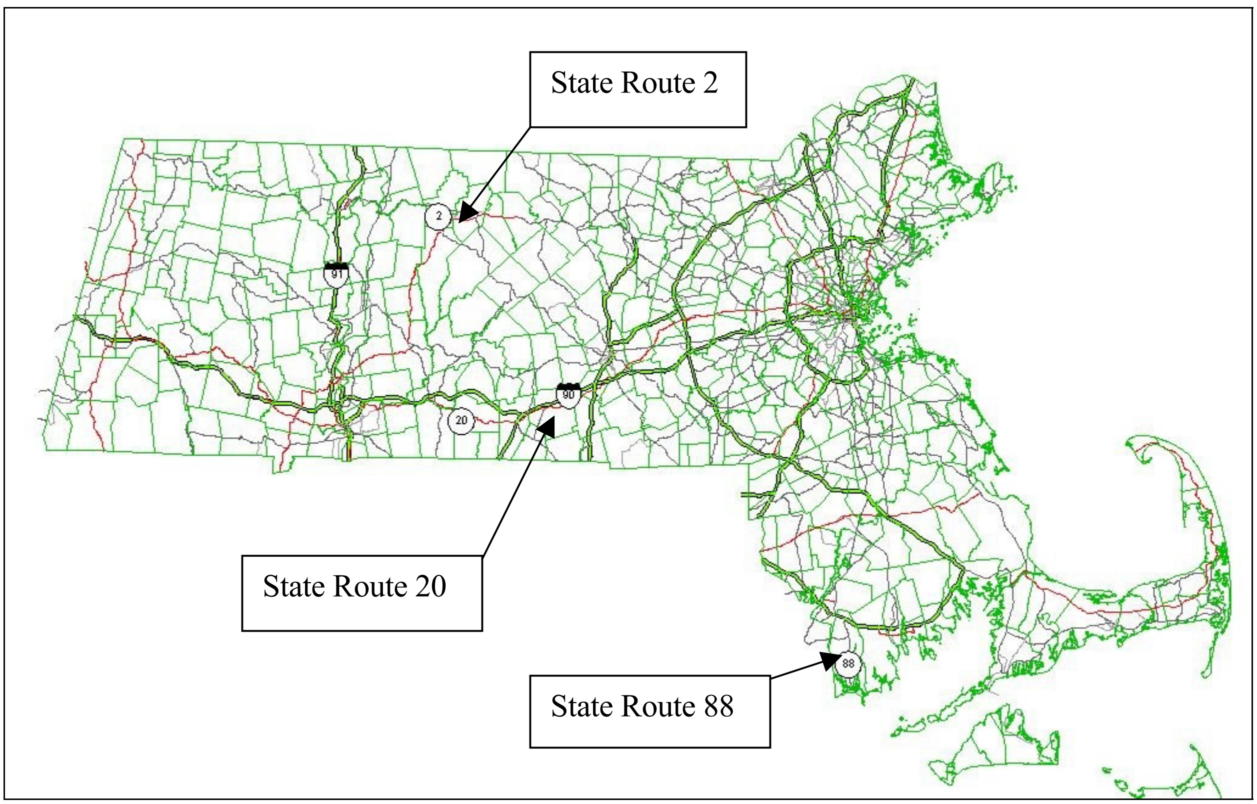

FIGURE 11. Centerline Rumble Strip Locations in Massachusetts.

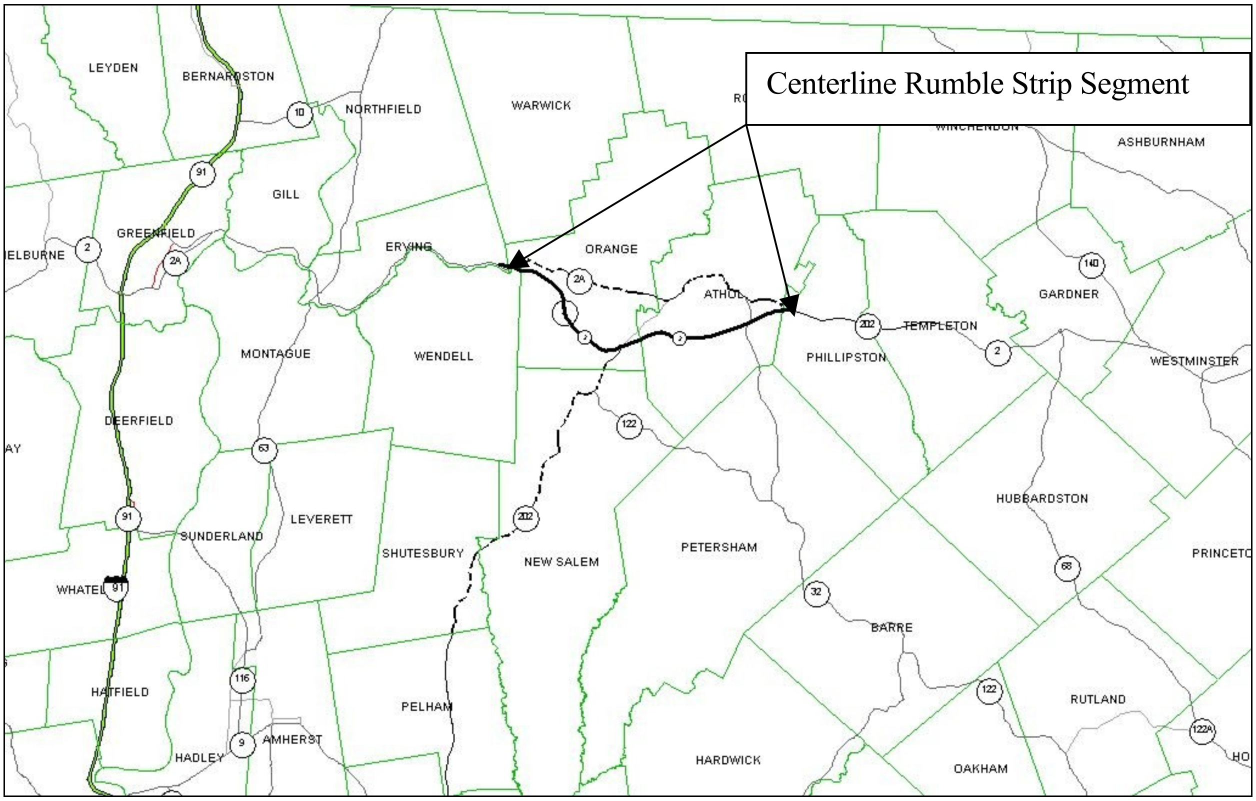

FIGURE 12. State Route 2 Centerline Rumble Strip Location.

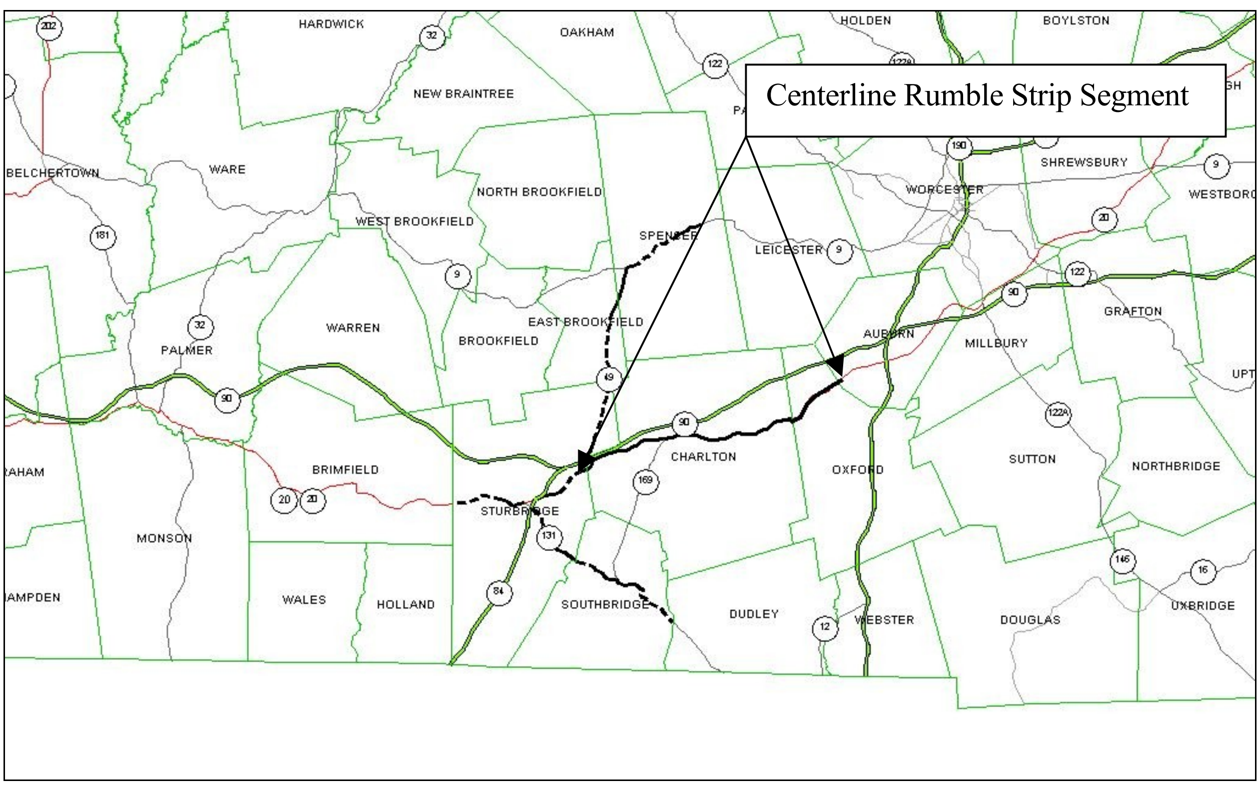

FIGURE 13. State Route 20 Centerline Rumble Strip Location.

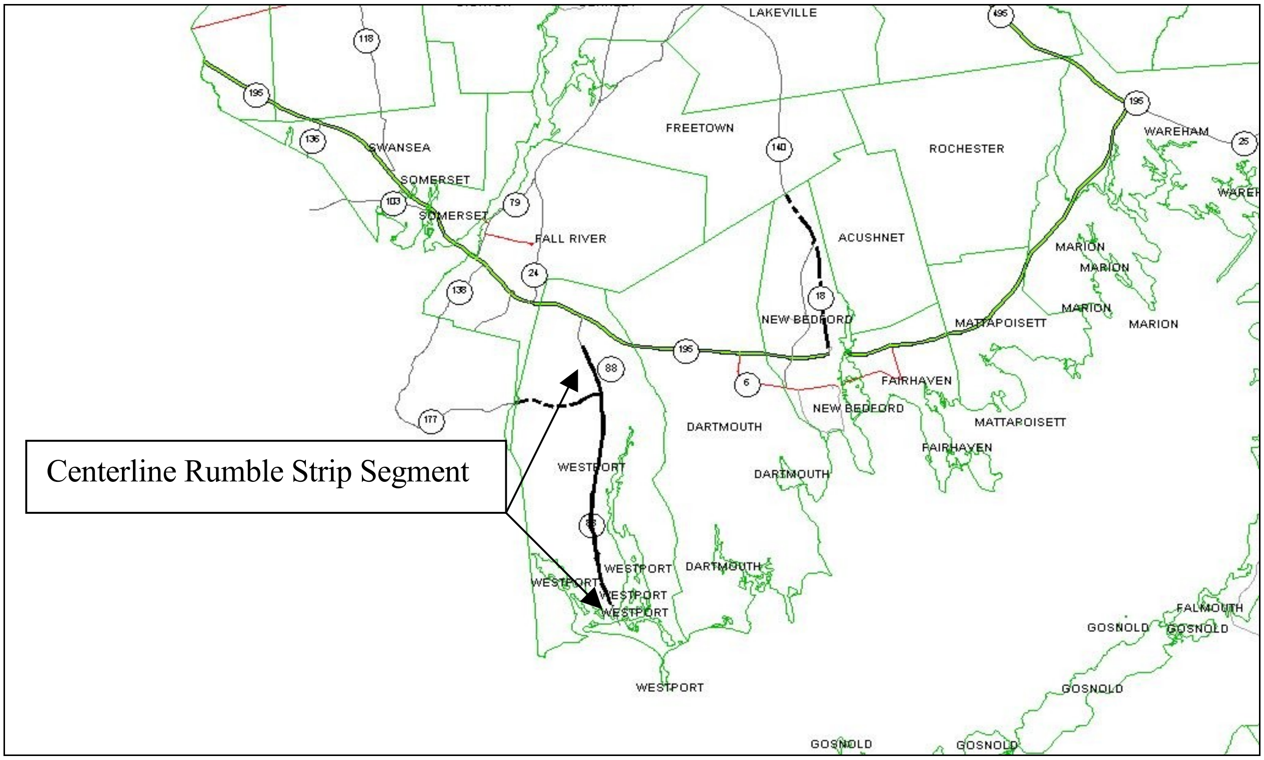

FIGURE 14. State Route 88 Centerline Rumble Strip Location.

BAA has traditionally been completed using various methodologies, some of which can lead to results that lack statistical correctness. To avoid this potential problem, a BAA with a comparison group methodology was used. In this methodology, suitable comparison sites were selected as previously mentioned. The comparison sites were used to estimate the change in number of crashes that would have occurred if the centerline rumble strips were not implemented in the study sites. Additionally, multiple years of data were considered to overcome any biases due to short-term fluctuations in the data.

The BAA analysis was completed using the targeted crashes presented in Appendix C with the statistical process described in Appendix D. Crash data two years before installation of centerline rumble strips and two years after the installation were used in the analysis. Several analyses were considered, including different combinations of comparison sites and traffic volumes.

PHASE III

The third phase of the research was designed to evaluate the safety and effectiveness of centerline rumble strips by evaluating driver behavior and reaction to encounters with rumble strips. The full-scale driving simulator at UMass was used to conduct this evaluation.

A number of roadway factors can influence drivers reaction to centerline rumble strips including the type of passing zone, the geometry and alignment, the number of lanes of travel, the posted and operating speed, the density of the traffic, and the type of signal generated by the rumble strip, among others. Currently, there is no information available to determine how effective centerline rumble strip applications would be under each of these potential scenarios. In addition, a number of other issues could affect driver behavior and reaction when centerline rumble strips are installed.

The first issue arises from the extensive use of shoulder rumble strips. When encountering a right shoulder rumble strip, corrective action requires that the vehicle direction be guided to the left to regain lane position. Unless the driver is using the shoulder for an emergency stop, shoulder rumble strips are not crossed and are discontinued at access points. Centerline rumble strips may require different driver behavior, especially if placed continually through passing and no passing zones. Centerline rumble strips in passing zones must be crossed to make a passing maneuver. Rumble strip encounters during passing may startle or confuse drivers, taking attention from the passing task at exactly the moment when driver workload is extremely high and maximum attention levels are required.

A second issue that may occur is drivers who are not paying full attention to the roadway may misinterpret centerline rumble strips. These drivers are exactly the persons for whom the rumble strips are intended. Since rumble strips have been placed on shoulder applications for many years, drivers have developed a level of expectancy for their presence. A driver who is inattentive and encountering a centerline rumble strip may quickly and subconsciously steer left, based on an a priori expectation, thus exacerbating an already risky situation. Beyond the human senses felt while encountering a rumble strip, there is currently no defined way for an inattentive driver to determine if he/she has encounter a shoulder or centerline rumble strip. Similar concerns have been raised with shoulder rumble strips, not considering the potential problems with centerline rumble strips. Some traffic engineers do not recommend the use of shoulder rumble strips on two-lane and four-lane undivided roadways on the premise that an errant driver, startled by the noise and vibration of the rumble strip, might swerve into traffic in the opposing direction (5).

A third issue pertains to the belief that even if centerline rumble strips are interpreted correctly, drivers may make a strong corrective swerve to the right because of the potentially startling nature of the alert. This maneuver could lead to a temporary loss of vehicle control and increase the potential for a run-off-the-road crash.

One method of effectively testing each of these issues presented is a field test that includes the many different traffic scenarios in which centerline rumble strips might be applied. However, field tests of this nature are expensive, potentially risky, and simply not practical to implement. A full-scale fixed-base high-fidelity driving simulator was used to overcome this problem and evaluate driver behavior related to rumble strip encounters.

Driving Simulator Visual Database and Scenarios

Task 5 involved the development of the simulator experiment. Drivers who participated in the driving simulator experiment sat in the vehicle and maneuvered through a virtual world, displayed on a screen in front of the vehicle, just as if operating their own vehicle. The "visual world" was created using the computer technology in the laboratory and Designers Workbench software. Two visual worlds (databases) were created, each contained a long stretch of roadway with both curved and straight alignments. Passing and no passing zones were also included.

Databases where further broken down into two modules. The only difference in these modules was the order in which the scenarios were presented. Each module consisted of a two-lane roadway segment using a rural cross-section, approximately eight miles in length. The primary objective of the experiment was to allow drivers to encounter rumble strips in an unexpected manner, and observe their reaction. How drivers reacted to encounters with both shoulder and centerline rumble strips provided the critical data for analysis.

To assure that each driver encountered rumble strips at the appropriate time in the simulation, several visual distracters were placed in each module that required drivers to temporarily take their eyes off of the road. During this time, small shifts in the travel lane (lane shifts) were programmed into the visual database. These lane shifts forced drivers into an opposing lane or shoulder incursion and an unexpected encounter with rumble strips. Lane shifts occurred at various locations within each module, some on tangent sections of roadway and some on curves. Note that lane curvature and lane shifts were independent; drivers were in the curve before a lane shift occurred. Therefore, the necessary corrective maneuvers were similar to those in tangent sections. The unexpected nature of this encounter necessitated that drivers did not see the lane shifts programmed into each module before they encounter them. Therefore, a nighttime environment in the visual database was made with foggy conditions, creating a visibility range of approximately six meters. Environmental conditions were created using the setting in the Real Drive Scenario Builder (RDSB) software. The RDSB software also recorded the position and the speed of the driver/vehicle 60 times each second.

Drivers were randomly divided between the two visual databases created; therefore, approximately 50 percent of the drivers participating in the experiment observed each visual database. This methodology counterbalanced the data collection to assure validity of results. The first three scenarios in each module had lane shifts to the left, forcing drivers to unexpectedly encounter shoulder rumble strips. This gave drivers an *ad hoc* experience with shoulder rumble strips. The next four scenarios had lane shifts to the right, leading drivers to cross over the centerline of the roadway. In two of these scenarios, centerline rumble strips were present to warn drivers of the opposing lane incursion. In the other two scenarios, no rumble strips were present and drivers were not warned.

The second module in the database consisted of the three shoulder rumble strip scenarios followed by the four centerline rumble strip scenarios. The two scenarios that did not have centerline rumble strips in the first module had centerline rumble strips, and vice versa.

As the driver traveled through the database, various sections of the roadway were used to capture the performance of drivers during lane incursion. The section in which the driver's performance was carefully monitored was considered to be a scenario. It took approximately 20 minutes to drive through each module. Thus, there was a potential lane shift (i.e., rumble strip encounter) about once every three minutes, infrequently enough so that drivers did not develop an expectation that such events will occur one right after the other.

The effects of different factors were evaluated in the driving simulator. Factors included roadway geometry (curved and straight), type of passing zone (passing allowed in both directions or passing prohibited in either direction), and presence of centerline rumble strip when a lane incursion occurs (centerline rumble strip either present or absent). For comparison purposes, driver's behavior on shoulder rumble strips was also evaluated.

Each visual database had two modules and each module had seven scenarios. The only difference between the modules in each database was the order in which the seven scenarios are encountered. The random scenario presentation is shown in Table 6. Each module had three scenarios of edge line incursions at the beginning so that drivers obtained ad hoc experience with shoulder rumble strips. Two of these scenarios were in a straight section of roadway and one was on a curved section. The remaining four scenarios had lane incursions along the centerline. Two of these incursions occurred in straight sections and two in curved sections. In the two scenarios that occurred in the straight section of the roadway, one occurred in a passing zone and the other in a no passing zone. Module 1 and 2 were identical except that if a centerline rumble strip was present in module 1, the same scenario in module 2 did not have a centerline rumble strip.

Procedure

At the beginning of each experiment, participants were told that the research team was interested in the effect of different billboard formats on the time that it takes a driver to find certain key information when driving in hazardous conditions such as fog or rain. Billboards were placed so that on average, once every ten seconds drivers needed to search for a target word or symbol in a billboard (spacing approximately 500 feet). The billboards contained three rows of three letters. Drivers were asked to indicate how many times the letter "V" appeared in each row of the billboard. Visibility was decreased to approximately six meters by creating foggy conditions in the database. Lane shifts/incursions were easy to create in the driving simulator without alerting the driver to the fact that such incursion had occurred by engaging the driver in a secondary activity (such as searching for a target on a billboard). The foggy conditions ensured that the driver did not have too much time to react, even if they observed the lane incursion. No opposing traffic was provided at each lane shift although random opposing vehicles were included in the simulation. A typical billboard layout is presented in Figure 15.

As mentioned, drivers were instructed to search for billboards and read out the number of times the letter "V" appears in each row of the billboard. Since the visibility was approximately six meters, drivers had very little time to read the billboards. Therefore, drivers were forced to take their eyes off of the road and concentrate on each the billboard. Drivers, paid $15 for their participation, were told that they would be paid $10, with up to $5 bonus money based on the number of correct responses to the billboard information. Although drivers were paid $15 regardless of their performance, this method provided additional incentive for drivers to focus on the billboard information. While searching for billboards, drivers were required to maintain a speed of approximately 30 mph.

TABLE 6. Simulator Experimental Scenarios

Database 1		
Scenario No	**Module 1**	**Module 2**
1	Straight, No passing, SRS	Straight, No passing, SRS
2	Straight, No passing, SRS	Straight, No passing, SRS
3	Curved, No passing, SRS	Curved, No passing, SRS
4	Curved, No passing, CRS	Straight, No passing, No CRS
5	Straight, Passing, No CRS	Curved, No passing, No CRS
6	Curved, Passing, No CRS	Straight, Passing, CRS
7	Straight, No passing, CRS	Curved, Passing, CRS
Database 2		
Scenario No	**Module 1**	**Module 2**
1	Straight, No passing, SRS	Straight, No passing, SRS
2	Straight, No passing, SRS	Straight, No passing, SRS
3	Curved, No passing, SRS	Curved, No passing, SRS
4	Curved, Passing, No CRS	Straight, Passing, CRS
5	Straight, No passing, CRS	Curved, No passing, No CRS
6	Curved, No passing, CRS	Straight, No passing, No CRS
7	Straight, Passing, No CRS	Curved, Passing, CRS

SRS – Shoulder rumble strips
CRS – Centerline rumble strips

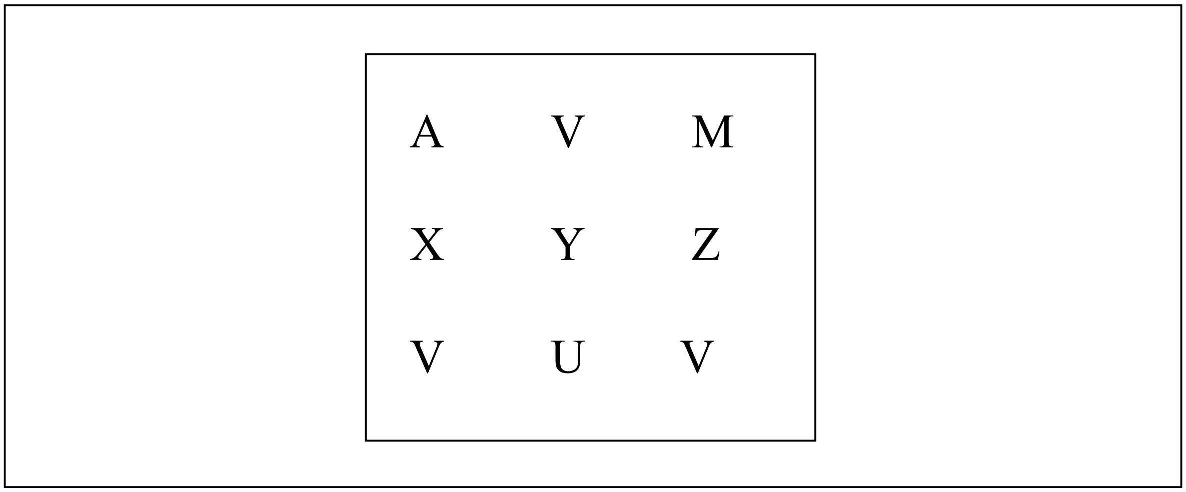

FIGURE 15. Typical Billboard in the Visual Database.

To assure that a lane incursion took place, lane markings on the pavement and pavement edges were shifted at billboard locations. Centerline markings were displaced approximately three feet. In nearly all cases, drivers did not detect these changes. When the driver returned attention to the road, he or she would notice that they had strayed over the lane line (centerline or edgeline). In some scenarios, drivers were notified of the lane incursion through rumble strips. In others scenarios, drivers were given no information and the researchers simply let the scenario unfold.

Tactile and Auditory Rumble

The *rumble* of the rumble strip was completed using a system designed by the research team. A series of five vibratory motors were placed in the driving simulator vehicle cab. Motors provided a 'physical' shaking of the simulator vehicle and passenger compartment at a frequency similar to an actual rumble strip encounter. The first vibrator motor was fixed to the left side of frame under the driver's seat. The second vibrator motor was similarly attached to the right side frame of the driver's seat. A third vibrator motor was fixed to the central console of the cab. The fourth and firth motor were fixed to the passenger seat of the vehicle in the same manner as the driver's seat. The general placement of the motors is shown in Figure 16.

The motors were manually turned on and off by a researcher stationed outside of the vehicle through a *Ready2Rumble* control device when the driver encountered a rumble strip. Motors under the driver's seat, along with the center console, were activated when centerline rumble strips were encountered. Motors under the passenger's seat, along with the center console, were activated when shoulder rumble strips were encountered. This methodology provided the directional realism of the rumble strips experienced in actual roadway conditions. Figure 17 show the motor control board used to activate the vibratory motors.

To further replicate a real rumble strip encounter, a comprehensive stereo system, including two subwoofers placed under the hood of the vehicle and tied to the frame, provide noise replication of a rumble strip. The volume of the rumble strip noise was measured and compared to observations obtained from actual rumble strip encounters.

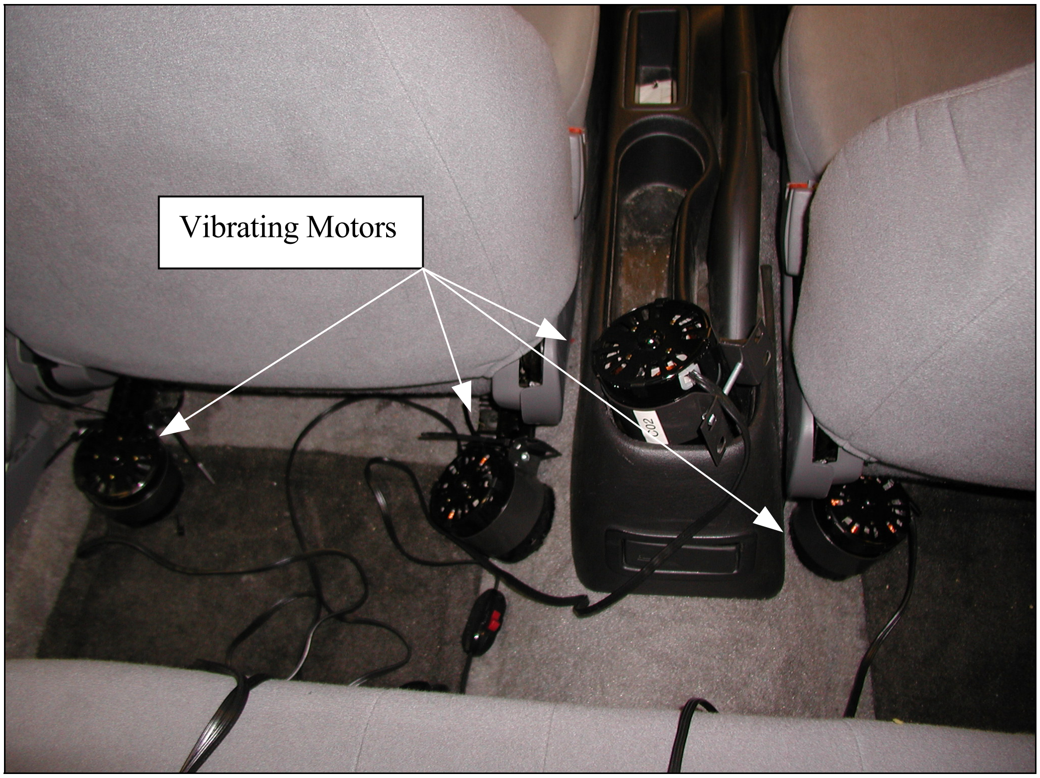

FIGURE 16. Installation of Vibratory Motors Inside Vehicle Cab.

FIGURE 17. *Ready2Rumble* Control Box to Activate the Vibratory Motors.

Data Collection

Task 6 involved the testing and analysis of the database. Five drivers were beta tested to ensure that the correct effects were being obtained. Additionally, the beta test provided the opportunity to search for any required modifications that only become apparent after administrating the driving simulation experiment. Following successful beta testing, Task 7 involved conducting the experiment. A total of 60 drivers were tested in the full experiment, 30 each on the two visual databases. Each driver began by driving a practice scenario, including billboard target searches. Then, drivers drove each of the modules encountering the different scenarios. A five-minute rest break was provided at the end of each module. Drivers were demographically divided by age. Twenty-five young (18-30), 23 middle aged (40-60) and 12 older (60+) drivers, all from the Amherst, MA area, participated. Half the drivers from each category were assigned to each database. As mentioned, drivers were compensation for their participation.

Data Analysis

Task 8, the final research task, involved the analysis of the simulator data. Driver's position in the visual database ('x', 'y', 'z' coordinates) was recorded during the critical roadway sections. Data recorded by the driving simulator were processed to obtain the data relevant to the research objectives. To identify the location of each scenario, a data mark was made in each RDSB file. A computer program was written to extract the data around the scenarios using the internal data mark. This program searched the entire database, extracting only the 'x' and 'y' coordinates of the vehicle in the scenario location, and the associated vehicle speed. Vehicle movements, including those in which the path of the vehicle did not encounter the rumble strips, were also recorded for comparison purposes.

The first step in the analysis was to plot the results of each scenario and compare these results to the "standard scenario", i.e., the baseline condition in which no rumble strip was encountered. Starting and ending points of the deviation due to the lane incursion were determined. The distance traveled between these two points was also determined by summing up the distances between subsequent points. From the velocity data, the average speed between each set of points was estimated. Using the distance traveled and average velocity data, an analysis was conducted to determine how long it took a driver to return to his or her lane after passing over the centerline or shoulder lane marking, both when a rumble strip was and was not included. These data were calculated for all scenarios and for all the drivers. The hypothesis that the time for a driver to return to his or her lane after crossing the centerline was shorter with a rumble strip than without a rumble strip was tested. Additionally, the path of the vehicle after crossing the center or right edge of the travel lane was determined. These data were used to identify whether the vehicle was initially corrected properly.

A statistical analysis was completed to check the hypothesis that drivers took more time to return when centerline rumble strips were present than when there were no centerline rumble strips. The first factor level selected was the time it took to return when there were no centerline rumble strips. The second factor level was the time it took to return when there were centerline rumble strips. Let 'Y_1' be the mean of the first factor level, 'Y_2' the mean of the second factor level, and 'D' be the difference in return times. The variable tested was:

$$D = Y_1 - Y_2 \quad (1)$$

In other words, a positive 'D' value would indicate that centerline rumble strips caused drivers to return to their travel lane quicker than if no rumble strips were present. If 'D' was 0, then no difference occurred. Therefore, the hypothesis that 'D' is zero was tested. Standard Analysis of Variance (ANOVA) statistical procedures were completed and the 'F' statistic determined for the data (25, 26). The confidence interval for the value of 'D' was estimated using traditional statistical procedures with 95 percent level of confidence. With the help of the interval estimated and the hypothesis tested, the influence of centerline rumble strips on the time it takes to return to the travel lane was determined.

The analysis described above was expanded to determine how drivers reacted to their first encounter with centerline rumble strips. This analysis provided information on driver's first/subconscious reaction to this type of traffic control. The effect of passing/no passing and curved/straight sections on the time it took to return to the travel lane was also evaluated. For this analysis, the difference between the time it took to react and successfully return to the travel lane when centerline rumble strips were present and the time it took when centerline rumble strips were not present was evaluated.

The final evaluation was focused on determining which direction drivers made their initial corrective maneuver when they encountered centerline rumble strips. The hypothesis that drivers may correct left instead of right with centerline rumble strips was tested. Again, the 'x-y' coordinate data provided the key information. By plotting the vehicle trajectory data in relation to the centerline rumble strip location, correction maneuvers could be visually observed. Coordinate data accounted for roadway curves to either the left or right and the associated lane incursions. Vehicle trajectories related to simple lane curvature and changes in trajectories due to lane shifts could be easily differentiated.

CHAPTER 4
AGENCY SURVEY RESULTS

The objective of the agency survey was to understand the current policy and use of centerline rumble strips across the United States and the experience of state DOT officials with centerline rumble strips. Surveys were obtained from all 50 states and several international locations. Responses to each of the survey questions from all 50 states are summarized in the following sections. Note that information was also obtained from Australia, Canada, and Spain, but not included in the U.S. data. A copy of the survey form is included in Appendix A. Detailed response information is included in Appendix B.

SECTION 1 – USE OF CENTERLINE RUMBLE STRIPS

The first question in the survey asked if the respondent's agency (i.e., DOT) had used centerline rumble strips. Twenty states indicated that they have installed centerline rumble strips. These states include Alaska, Arizona, California, Colorado, Connecticut, Delaware, Hawaii, Kentucky, Maryland, Massachusetts, Minnesota, Nevada, New Hampshire, New Mexico, Ohio, Oregon, Pennsylvania, Virginia, Washington, and Wyoming.

Question 2 pertained only to states indicating that they are not currently using centerline rumble strips. The question asked respondents to indicate their potential for using centerline rumble strips within the next three years. There were 30 responses to this question. Kansas was the only state that has definite plans to install centerline rumble strips. Twelve states said they were considering the use of centerline rumble strips. Four states said that they will probably install centerline rumble strips. Six states said that they will not use centerline rumble strips. Seven states said that their choice was none of the above, although six of these states indicated that they may experiment with centerline rumble strips or use if shown to be effective. Tennessee has some reservation about using centerline rumble strips because of weakening an already weak pavement area along the longitudinal joint. Florida had concerns over driver reaction to centerline rumble strips.

SECTION 2 – CENTERLINE RUMBLE STRIP INSTALLATIONS

Question 3 queried the number of separate installations of centerline rumble strips in each jurisdiction. There were 20 responses to this question. Fourteen states currently have only one to two installations while three states have three to four installations in their jurisdiction. Maryland and California have five to six installations and only Pennsylvania has more than eight installations in their jurisdiction.

Question 4 asked for numeric response pertaining to the approximate number of lane miles of centerline rumble strips installed. There were 20 responses to this question. Two states have installed less than a mile of centerline rumble strips; six states have installed between one to five lane miles of centerline rumble strips. Three states have installed five to ten miles and two states have installed between 15 to 20 miles. Seven states have installed more than 20 miles of centerline rumble strips.

Question 5 was used to obtain information about the type of centerline rumble strips used. There were 20 responses to this question. Fourteen states have continuous centerline rumble strips. New Mexico was the only state with intermittent centerline rumble of six feet length with six feet spacing. Maryland uses both continuous and in series with specific intervals. Arizona has a couple of experimental installations of centerline rumble strips. California, Kentucky, and Colorado did not respond to this question, but it is known that continuous rumble strips are used.

Question 6 asked respondents to identify the primary reason for installing centerline rumble strips. Twenty states responded to this question. The most common response, countermeasure to high crash location, was chosen by 10 states. Five states indicated that a general enhancement of road safety was the primary reason. No state is using centerline rumble strips exclusively as delineation in low visibility areas. Colorado has installed centerline rumble strips for a research study while New Mexico installed centerline rumble strips due to a combined effect of enhanced road safety, countermeasure to high crash locations, and cost. California and Kentucky did not provide detailed responses.

Question 7 asked respondents to evaluate the most significant criteria for installing centerline rumble strips among crash frequency/rate, roadway geometry, traffic volume, public/police request, meteorological conditions, and others. There were 20 responses to this question. Crash frequency/rate was ranked as the most significant criterion by 14 respondents. Public/police request was the most significant criterion in three states for installing centerline rumble strips. Roadway geometry was also considered significant for New Mexico to install centerline rumble strips. Maryland indicated that respond to a fatal crash was their most significant criteria.

Overall, roadway geometry was generally considered the second most significant criterion, followed by public/police request and traffic volumes. Meteorological condition was given the lowest overall ranking as a significant criterion for installing centerline rumble strips.

Question 8 asked if cost is a significant criterion given the most significant criteria in Question 7. There were 20 responses to this question. Six states considered cost to be significant when compared with the significant criteria of Question 7 while twelve states indicate that cost was not a significant criterion. California and Kentucky did not provide detailed responses.

Alaska mentioned that maintenance and operations cost have not been significant. Connecticut commented that although cost is important in the decision, a reduction in crash frequency is a higher priority. Washington is of the opinion that the answer should be both yes and no. Cost is a criterion. However, with crashes being the top priority, the small cost compared to the cost of a head on collision makes it unlikely to rule out centerline rumble strips due to cost criterion. Delaware calculated a benefit/cost ratio of 110, concluding that the benefits clearly outweighed any cost issues.

Question 9 asked respondents to indicate what benefit must exist to overcome the cost of centerline rumble strip installation. Twelve states responded to this question. Most of the states that responded said that benefits due to reduction in crashes were necessary to install centerline rumble strips. Hawaii said that cost is not an issue in installing centerline rumble strips. Arizona commented that it is hard to quantify the benefits that will be necessary.

Question 10 asked if centerline rumble strip installations have performed satisfactorily. Twenty states responded to this question. Eleven states indicated that the centerline rumble strips performed satisfactorily while four states said that they were not satisfied with centerline rumble strips. New Hampshire has been disappointed by the visibility of pavement markings on centerline rumble strips under nighttime conditions because snow, salt, sand, etc. collects in the 'grooves' of the rumble strips and blocks or deteriorates a portion of the pavement marking effectively reducing retroreflectivity. Connecticut and Wyoming responded 'no' because they did not have data yet to evaluate the results. Colorado, Delaware, Minnesota, and Washington have noticed reduction in crashes after the installation of centerline rumble strips. Delaware found a 90 percent reduction in head-on crashes over six years while traffic volumes increased from 12,000 to 21,000 AADT. Arizona, California, Hawaii, Kentucky, and New Mexico did not have data to report.

Question 11 asked if any unexpected problems were created by using centerline rumble strips (e.g., other safety problems, maintenance problems, noise problems, etc.). There were 17 responses to this question. Seven states said that they had problems while ten states did not have any problems with centerline rumble strips. Most of the states identified noise problems and pavement deterioration as the main issues with centerline rumble strips. Alaska, Connecticut, and Ohio had problems with noise complaints. Connecticut removed their centerline rumble strips because of this. Arizona had problems with pavement raveling. Colorado commented that there may be some concern about motorcycle and bicycle riders. Minnesota reported that the emergency vehicle operators were critical of centerline rumble strips. According to the emergency vehicle operators in Minnesota, the roadway is more difficult to patrol specifically during high-speed chases. Further, an ambulance driver complained that driving across the rumble strips with a patient on a cardiac monitoring device may cause the device to malfunction. Pennsylvania indicated that paint trucks needed carriage adjustments to paint on either side of the rumble strips.

Question 12 enquired about any formal evaluation that was done by the states on the safety effects of centerline rumble strips. Eighteen states responded to this question. Colorado, Delaware, New Mexico, Oregon, Pennsylvania, and Washington indicated that they are either conducting or have completed research on safety effects of centerline rumble strips. Colorado found that rumble strips significantly reduced crossover type crashes on winding two lane highways. Washington reported a significant reduction in crossover crashes in their first test section. Delaware found a benefit cost ratio of 110 (reported to FHWA).

Question 13 asked if respondent agencies had created specifications, warrants, policies, or guidelines for the use of centerline rumble strips. Of the 18 states responding, only Oregon and Pennsylvania reported that they have created specifications, warrants, policies or guidelines for the use of centerline rumble strips.

Question 14 asked respondents to estimate the cost of installing centerline rumble strips. Fourteen states responded to the question. Alaska, Maryland, Massachusetts, Nevada, Ohio, and Washington found the cost to be approximately $1,000 per mile. New Hampshire reported that the cost of installing centerline rumble strips is no different from that of the edge line rumble strips. Hawaii reported $16,000 per mile for installing centerline rumble strips and Virginia reported $11,000 per mile. Delaware, New Mexico, and Oregon report approximately $1,000 to $3,000 per mile for installing centerline rumble strips. Pennsylvania reported the cost to be $6,600 per mile for installing centerline rumble strips. The wide deviation of the cost in installing centerline rumble strips is likely due to different methods of installation.

SECTION 3 – GENERAL COMMENTS ON CENTERLINE RUMBLE STRIPS

Question 15 asked respondents to report on any positive or negative experience using centerline rumble strips and other general comments. There were 40 responses to this question. Eleven states indicated that they had either positive or negative experience with centerline rumble strips. Alaska reported that their centerline rumble strips were 12 inches wide and that it might be too wide. Colorado received several positive comments from the public in the area where centerline rumble strips were installed. Delaware received a 2001 National FHWA award for their project on centerline rumble strips.

Indiana was concerned that centerline rumble strips may become a trough for pooling water in the warm months and snow and ice in the winter months, thereby creating a crash potential for any motorist that might drive on the centerline rumble strips. Indiana permits 12-foot wide vehicles on their roadways; therefore, these vehicles often drive over the centerline and might have problems with centerline rumble strips.

A representative of the Minnesota DOT, District 6, suggested a few issues for consideration and future research. The issues are:

1. Do the rumble strips send a clear, easily understood message to the errant driver resulting in a definite and predictable driver reaction? Can the rumble strips result in an incorrect driver reaction or an over-reaction?
2. Should rumble strips be installed only in No Passing Zones, or instead, along the entire stretch of involved roadway-including passing zones? Does the use of rumble strips in both passing and no passing zones send a conflicting message?
3. What precedent is set by installing rumble strips? What criteria should be used to determine where centerline rumble strips should be installed? Will the public demand that rumble strips be constructed on other roadways, whether warranted or not?
4. Are the centerline rumble strips truly effective?
5. Does the existence of the rumble strips on the centerline affect the nighttime effectiveness of the centerline striping? Are more painting materials required with a resultant higher cost?
6. Is the pooling of water or compaction of snow in the rumble strips an issue?
7. What additional long-term pavement maintenance need is created due to grinding of the rumble strips? Are additional costs involved? Is the pavement life affected?
8. What maintenance issues for the rumble strips are created? Do the rumble strips need to be re-ground into the pavement every few years? Do certain maintenance practices tend to prolong or decrease rumble strip life?

New Hampshire commented that centerline rumble strips, like any other device, are reluctantly installed by an agency to appease local interest and the initial installations have encouraged others to request similar treatments. New Hampshire adds that though the primary function of centerline rumble strips is to warn drivers when they drift over the centerline, the public has requested centerline rumble strips to keep aggressive drivers from passing inappropriately.

Pennsylvania reported that their constituents like centerline rumble strips in winter. When the roads are snow covered, centerline rumble strips alert the drivers where the center of the road is located.

CENTERLINE RUMBLE STRIPS IN OTHER COUNTRIES

In an effort to determine the use of centerline rumble strips across the world, several officials of transportation agencies in various countries were contacted. Officials from Australia, Canada, and Spain responded. Spain is not currently using centerline rumble strips. Spain is not planning to use any centerline rumble strips in the near future. Australia does not have centerline rumble strips.

In Canada, recent work has been done on edge line and centerline rumble strips under the leadership of the Road Safety Standing Committee. The committee recently published a series of best practices in the design and application of edge line and centerline rumble strips based on Canadian and International experiences.

The province of Alberta in Canada is currently evaluating centerline rumble strips on provincial highways. In Ontario, centerline rumble strips use is under consideration. An older concept, referred to as a "singing median" (a flush serrated concrete median), is still used on some older segments of provincial highways. These medians have been largely abandoned due to winter maintenance issues.

CHAPTER 5
CRASH DATA ANALYSIS

The second phase of this research was to evaluate the safety benefits of centerline rumble strips installed in Massachusetts on Routes 2, 20 and 88. All crashes identified on each route and included in the crash databases, at least two years before and two years after the installation of the centerline rumble strips, were reviewed. Those crashes correlated to a cross-over-the-centerline type crash were selected for analysis. A *before* and *after* or BAA crash analysis was employed.

RESULTS

Target Crash Frequency

Tables 7 and 8 present the number of targeted/selected crashes reported on each of the study and comparison sites. Targeted crashes were those crashes involving head-on crashes or other cross-over-the-centerline events. Recall that the centerline rumble strips on Route 20 were installed in November of 1996, while the centerline rumble strips on Routes 2 and 88 were installed in November of 1998. Figure 18 presents a plot of the crash frequency for each year depicting the frequency trend at each study and comparison site.

TABLE 7. Targeted Crash Frequency Data for Study Sites

Route\Year	1995	1996	1997	1998	1999	2000
Route 2	7	8	7	4 (before); 1 (after)	6	5
Route 20	6	7 (before); 2 (after)	5	6	5	6
Route 88	0	0	1	0 (before); 0 (after)	1	1

TABLE 8. Targeted Crash Frequency Data for Comparison Sites

Route\Year	1995	1996	1997	1998	1999	2000
Route 2A	11	4	7	2	6	8
Route 202	2	3	3	4	3	2
Route 31	1	4	0	1	2	1
Route 49	1	1	0	1	1	2
Route 131	7	14	10	6	6	16
Route 177	0	0	3	1	2	7
Route 18	16	19	30	37	34	36

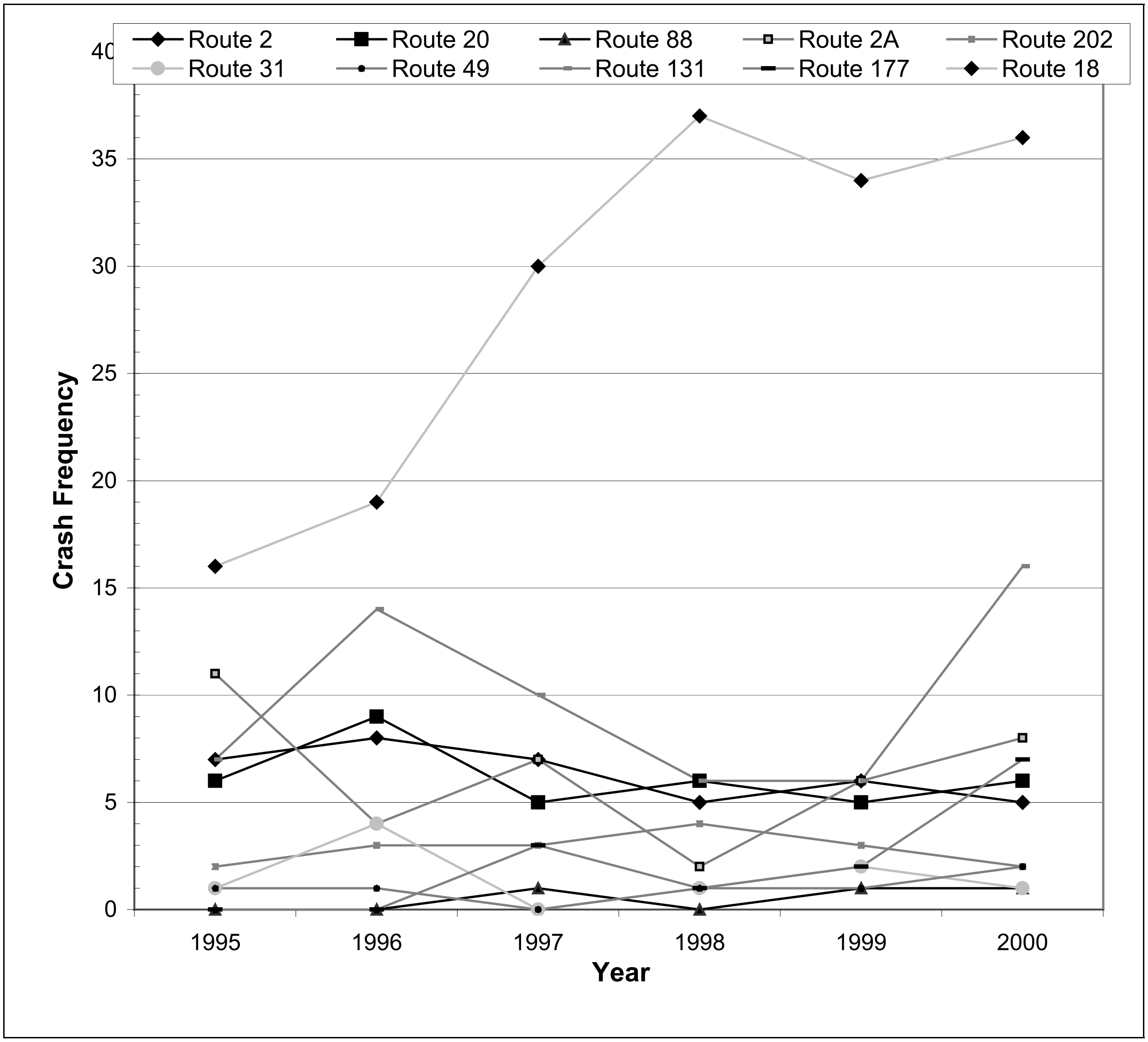

FIGURE 18. Crash Frequency for Study and Comparison Sites.

Table 7 and Figure 18 show that the frequency of centerline-related crashes per year at the study locations did not experience a dramatic decrease after the installation of centerline rumble strips. Route 2 experienced a slight decrease in the annual frequency of targeted crashes while Route 20 and Route 88 remained relatively consistent. Several of the comparison sites, specifically Route 18 and Route 131, witnessed significant increases in these crash types.

An analysis of fatal crashes at the study locations, during the analysis period, provides more insight into the use of centerline rumble strips. As presented in Table 9, no fatal crashes were experienced on Routes 2 or Route 88 in the analysis area since the installation of centerline rumble strips.

TABLE 9. Fatal Crashes at Study Sites

Route\Year	1995	1996	1997	1998	1999	2000
Route 2	0	0	3	3 (before); 0 (after)	0	0
Route 88	0	0	1	0 (before); 0 (after)	0	0
Route 20	0	1 (before); 0 (after)	2	1	0	0

Route 20 experienced fatal crashes in 1997 and 1998, all after the installation of the centerline rumble strips. No fatal crashes were experienced in 1999 and 2000. Both fatal crashes in 1997 occurred at nearly the same location, approximately 200 feet east of the Charlton/Oxford Town Line near mile marker 104.1. This location is adjacent to an 819-foot radius horizontal curve. The first fatal crash took place on March 14, 1997, at 4:45 PM. Road conditions were slippery due to freezing rain. The eastbound driver crossed over the centerline rumble strips and hit a westbound vehicle head-on. Police investigation determined that the driver was traveling at an improper speed for conditions. The second fatal crash in 1997 took place on November 1, at 6:56 PM. Road conditions were wet. The eastbound driver crossed over the centerline rumble strips and hit a westbound vehicle head-on. Police investigation determined that the driver was traveling at an improper speed for the conditions and was under the influence of alcohol. The operator of the westbound vehicle died as a result of the crash.

The fatal crash in 1998 was also near the location of the 1997 fatal crashes, taking place approximately 300 feet west of the Charlton/Oxford Town Line near mile marker 103.9. On October 8, at 9:40 PM, a westbound driver lost control of his vehicle during heavy rain, crossed over the centerline rumble strips, and struck an eastbound vehicle head-on. The westbound driver was killed. Police indicated that heavy rain and worn front tires contributed to the crash.

A fatal crash also took place in 1999 on Route 20 in Sturbridge. The location of this crash was outside of the centerline rumble strip area. This single vehicle crash involved an eastbound driver who apparently fell asleep, crossed over the centerline of the roadway, and struck a fixed object.

Statistical Analysis

Study site crash data were combined with various combinations of comparison site data to statistically compute changes in crash patterns after the installation of centerline rumble strips. Comparison sites were used as follows:

- Route 2A and 202 for Route 2;
- Route 31, 131 and 49 for Route 20; and
- Route 18 and 177 for Route 88.

A summary table of the Empirical Bayes approach for before and after statistical analysis procedures and calculations used in these analyses is presented in Appendix D.

In the first analysis, targeted crashes were considered at both the study and comparison sites. The results show that the overall number of predicted crashes increased by approximately 5 with a standard deviation of 9.8, meaning that approximately 3 more crashes/year occurred than predicted using before data and trend data from comparison sites. This results in an estimated 7 percent increase in crashes with a 41 percent standard deviation. Note that with the large standard deviations, the change in crash frequency before and after the installation of centerline rumble strips is not statistically significant. Considering only Route 2, the total number of actual crashes was approximately 1 crash/year lower than predicted, with a 3.8 crash standard deviation. This finding results in a small percent improvement; however, the large standard deviation indicates that the results are not statistically significant. Route 20 data shows that actual crashes were approximately 2.2 crashes/year greater than predicted, with a standard deviation of 2.9. This results in an estimated crash increase of 15 percent, with a standard deviation of 28 percent. Again, the results are not statistically significant. Route 88 data shows that actual crashes were approximately 1 crash/year higher than predicted. The results were not statistically significant.

In a second analysis, the effects of changes in traffic volumes at both the study and comparison sites were considered using the same comparison sites. It is common practice in safety engineering to consider changes in crash rates (such as crash frequency per vehicle mile) as a measure of safety. The use of crash rates is assumed to automatically account for changes in traffic flow. However, it has been shown that crash rates do not account for changes in traffic flow before and after safety treatments unless the expected crash frequency is proportional to traffic flow (24). This is often not the case. Therefore, changes in traffic volume are accounted for by using a proportionality function that relates traffic volumes before and after the installation of centerline rumble strips with crash frequencies. Again, a table summarizing the crash results is presented in Appendix D. The results are consistent with the previous analysis. Overall, approximately 3 more crashes occurred than predicted, with a standard deviation of approximately 6. Each of the individual roadways showed that there was no statistically significant difference in crash frequencies before and after the centerline rumble strip installation.

An analysis was completed considering only injury crashes in the before and after conditions. Expected injury crashes were approximately one crash/year higher on Routes 2 and 88 than actual injury crashes, indicating a small safety improvement. However, neither result was statistically significant. Route 20 experienced a 2.6 crash/year increase in injury crashes (standard deviation 2.5) showing a statistically significant increase in this crash type.

Three additional evaluations were completed to further validate the results. First, the hypothesis that the installation of centerline rumble strips may affect all crash types was explored. In other words, this analysis expanded upon the difficulty presented in identifying targeted crashes (cross-over-the-centerline) versus all crash types that may have been affected by the installation of the centerline rumble strips. Therefore, changes in all crash types before and after the installation of centerline rumble strips was considered. A summary of all crash types on the selected routes two years before and two years after the installation of centerline rumble strips is presented in Table 10. Figure 19 provides a plot of these data.

TABLE 10. Total Frequency of All Crash Types on Each State Route

Route\Year	1995	1996	1997	1998	1999	2000
Route 2 (study)	N/A	N/A	49	33	45	47
Route 20 (study)	103	123	88	95	N/A	N/A
Route 88 (study)	N/A	N/A	6	21	36	47
Route 2A	N/A	N/A	56	33	44	39
Route 202	N/A	N/A	24	15	17	14
Route 31	18	22	16	14	N/A	N/A
Route 49	5	5	3	8	N/A	N/A
Route 131	90	102	107	96	N/A	N/A
Route 177	N/A	N/A	16	13	14	18
Route 18	N/A	N/A	521	541	549	550

The results of this analysis show that crashes increased on Route 2 and Route 88 after the installation of centerline rumble strips. Crashes decreased on Route 20. Route 2 crashes increased by approximately 10 crashes per year while Route 20 crashes decreased by approximately 22 crashes per year. Neither results was statistically significant. Route 88 crashes increased by approximately 28 crashes per year with a 7 crash per year standard deviation. This result was statistically significant.

Second, an expanded comparison was made, considering targeted crashes with trends in all crash types at the comparison sites. Third, a more global comparison was made, considering targeted crashes with trends in surrounding areas/towns to each study site. This evaluation compared trends in targeted crashes to the trend in all crashes in one or more nearby areas. Table 11 shows total crashes in selected towns near the study sites. Figure 20 provides a plot of these data. Note that Figure 20 does not include New Bedford because of the magnitude of increase in crash frequency.

The results from both analyses were consistent and again show no significant change in crash frequencies before and after the installation of centerline rumble strips. There were no significant trends in the comparison sites to conclude that the stability of the crash frequencies at the study location were a function of the environment.

Considering all of the crash data discussed, there is no statistical evidence to suggest that the installation of the centerline rumble strips significantly reduced crash rates. However, no fatal crashes have occurred on Route 2 and Route 88 since the installation of centerline rumble strips. This finding suggests the centerline rumble strips were potentially effective in reducing the severity of crashes. Three cross-over-the-centerline crashes did occur on Route 20 after the centerline rumble strips were installed, all near the same horizontal curve.

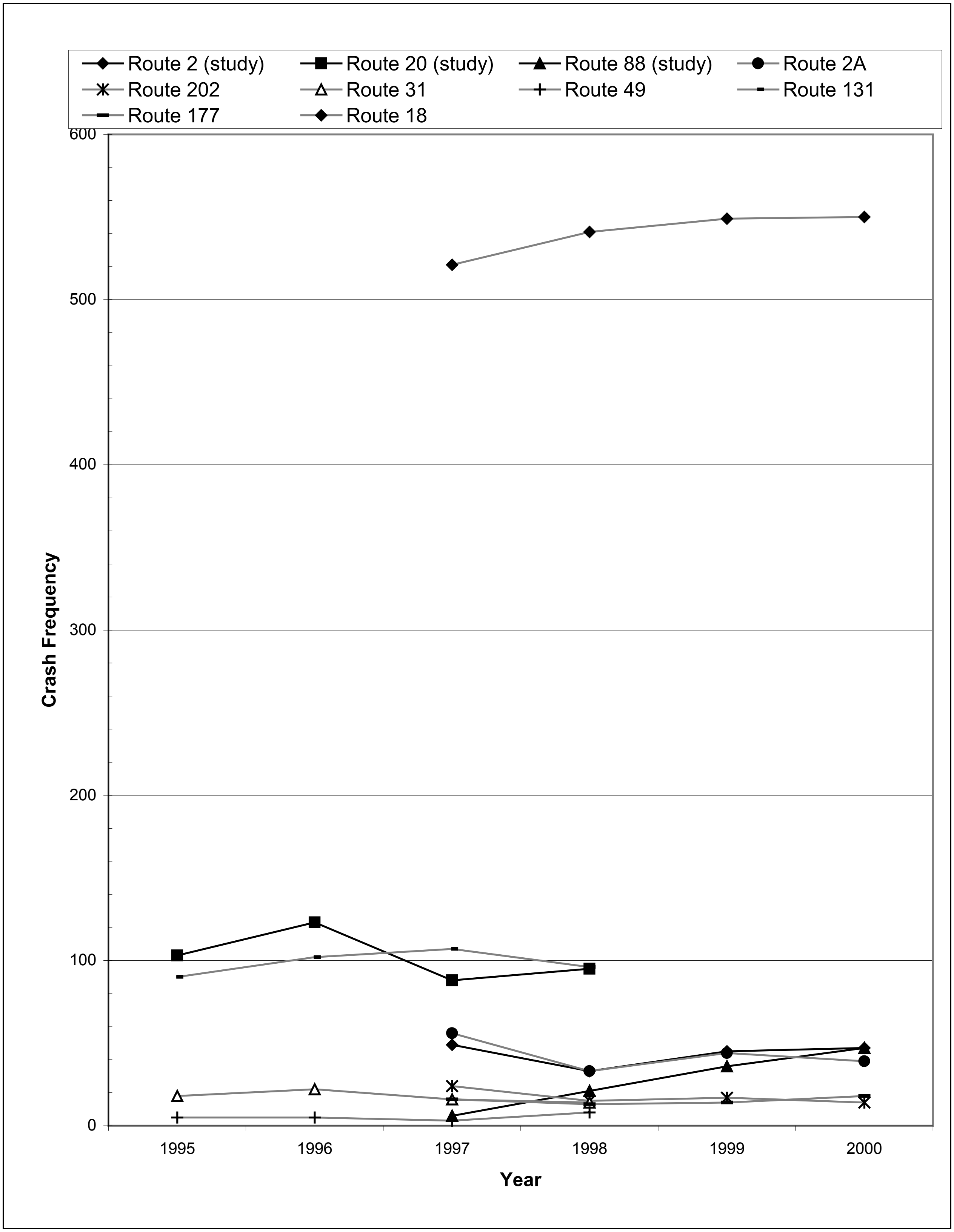

FIGURE 19. Trends in Crash Frequency of All Crash Types.

TABLE 11. Crash Frequency Data from Selected Towns

Town	Study Site	1995	1996	1997	1998	1999	2000
Orange	Route 2	172	197	189	122 (before); 26 (after)	161	175
Phillipston	Route 2	27	33	38	33 (before); 1 (after)	37	21
Shutesbury	Route 2	25	23	16	19 (before); 2 (after)	14	21
Spencer	Route 20	237	256 (before); 31 (after)	287	259	273	318
Sturbridge	Route 20	301	381 (before); 57 (after)	397	369	516	550
Southbridge	Route 20	237	228 (before); 23 (after)	242	226	235	252
Charlton	Route 20	436	351 (before); 55 (after)	391	383	469	463
Westport	Route 88	93	86	361	374 (before); 38 (after)	405	439
New Bedford	Route 88	3255	3296	3369	3169 (before); 69 (after)	3368	3697

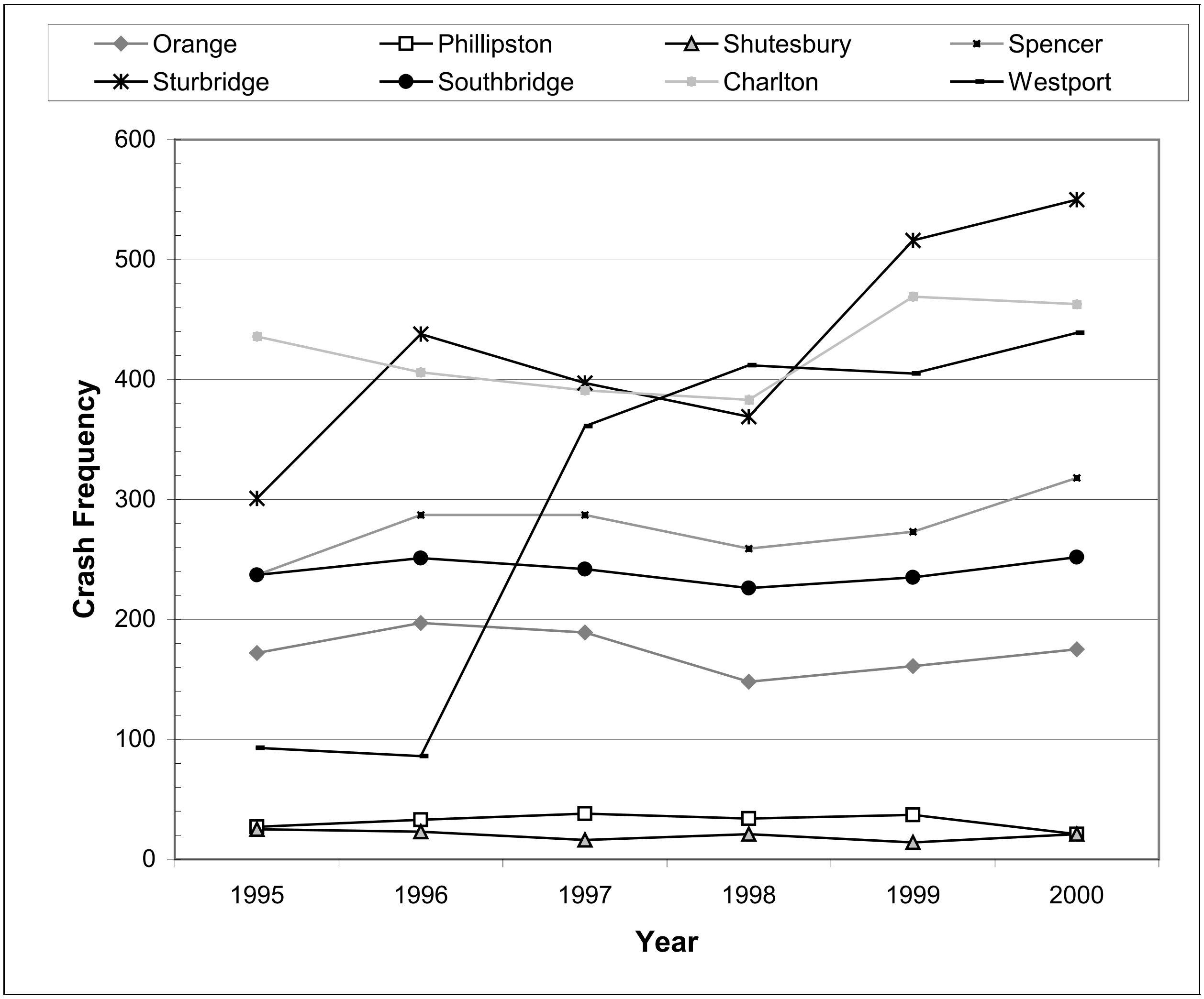

FIGURE 20. Trends in Crash Frequency in Nearby Towns.

CHAPTER 6
DRIVING SIMULATOR ANALYSIS

The objective of the final phase of the research was to evaluate the safety and effectiveness of centerline rumble strips by evaluating drivers' behavior and reaction to rumble strip encounters. A full-scale driving simulator was used to conduct this evaluation. The data analysis and results are summarized in the following sections.

DEMOGRAPHICS

The demographic distribution of the drivers who completed the experiment is presented in Table 12. A total of 60 drivers completed the experiment. Each database had 30 drivers, 15 male and 15 female. Twenty-six drivers were less than 40 years of age, 22 drivers were between 40 to 60 years of age, and 12 drivers were over 60 years old.

TABLE 12. Demographic Distribution of Simulator Drivers

Database 1					
Module 1, Module 2			**Module 2, Module 1**		
Age	**Male**	**Female**	**Age**	**Male**	**Female**
<20	0	1	<20	2	0
20 – 30	2	2	20 - 30	0	2
30 – 40	1	1	30 - 40	1	1
40 – 50	3	1	40 - 50	1	3
50 – 60	1	0	50 - 60	1	0
60+	1	2	60+	2	2
Total	8	7	Total	7	8
Database 2					
Module 1, Module 2			**Module 2, Module 1**		
Age	**Male**	**Female**	**Age**	**Male**	**Female**
<20	0	1	<20	1	1
20 - 30	4	2	20 - 30	1	1
30 - 40	0	1	30 - 40	1	0
40 - 50	2	1	40 - 50	1	3
50 - 60	0	2	50 - 60	2	1
60+	1	1	60+	2	1
Total	7	8	Total	8	7

RESULTS

To determine how drivers reacted to each centerline and shoulder rumble strip encounter (i.e., direction of vehicle trajectory), each vehicle path was plotted in 'x' and 'y' coordinates (each coordinate value is 1 meter = 3.28 feet) and compared to a linear map of the rumble strip location. These plots provided a simple graphical representation to visually observe how drivers responded in each of the scenarios presented. Typical 'x-y' plots for several of the driver-scenario combinations are presented in Figures 21 through 31. Note that on each plot, the solid black line shows the center/edge line location, with the sharp change in location representing the shift in center/edge line and the beginning of the rumble strip location. Recall that the roadway was experimentally shifted in the driving simulator while the driver was distracted to assure that the rumble strip was encountered. The curvature of the roadway (either left or right), reflected by the solid black line, allowed differentiation between vehicle trajectories and driver corrections due to roadway curvature and rumble strip incursions. Each of the thinner gray-shaded lines in the figure represents a vehicle path and its relation to the center/edge line. Lines that move in the positive 'y' direction and cross over the black centerline in scenarios that considered centerline rumble strips represent drivers who to some degree improperly correct (i.e., corrected left) when encountering the centerline rumble strip. These Figures were used to visually evaluate the lane incursions at each of the study scenarios locations. Note that Table 6 provides a summary of the database, module, and scenario for each Figure shown.

A review of the trajectory data shows that several drivers corrected improperly when encountering centerline rumble strips. Figure 21 provides an example of a shoulder rumble strip encounter. Notice that the trajectory pattern for all drivers is quite varied and demonstrates a 'relaxed' correction to the shoulder incursion. Figures 22, 24, 28, and 29 show examples of vehicle trajectories of centerline lane incursions with no centerline rumble strips. Note that the trajectories are quite condensed and show rather uniform corrections. Figures 23, 25, 26, 27, 30, and 31 show examples of vehicle trajectories of centerline incursions with centerline rumble strips present. Figures 23, 25, 26, and 31 represent centerline rumble strips on horizontal curves. Figures 27 and 30 show centerline rumble strips on tangent sections. Note the increased variability in trajectory as drivers react to the rumble strip encounter and determine the appropriate correction. The various lines on each Figure above the black line representing the centerline indicates drivers whose initial reaction was more of a left-hand than a right-hand correction (a right-hand correction is appropriate for the centerline rumble strip encounter). A numerical computation of the frequency of this occurrence is presented later in this chapter.

A statistical analysis was completed to compare the time to return to the lane with and without centerline rumble strips present. The result of the statistical analysis, for all scenarios, is shown in Table 13. The results show that the mean time to return the lane, when there are no centerline rumble strips, is about 20 milliseconds less than that of the time to return when there are centerline rumble strips. These results were not statistically significant ($p = 0.723$).

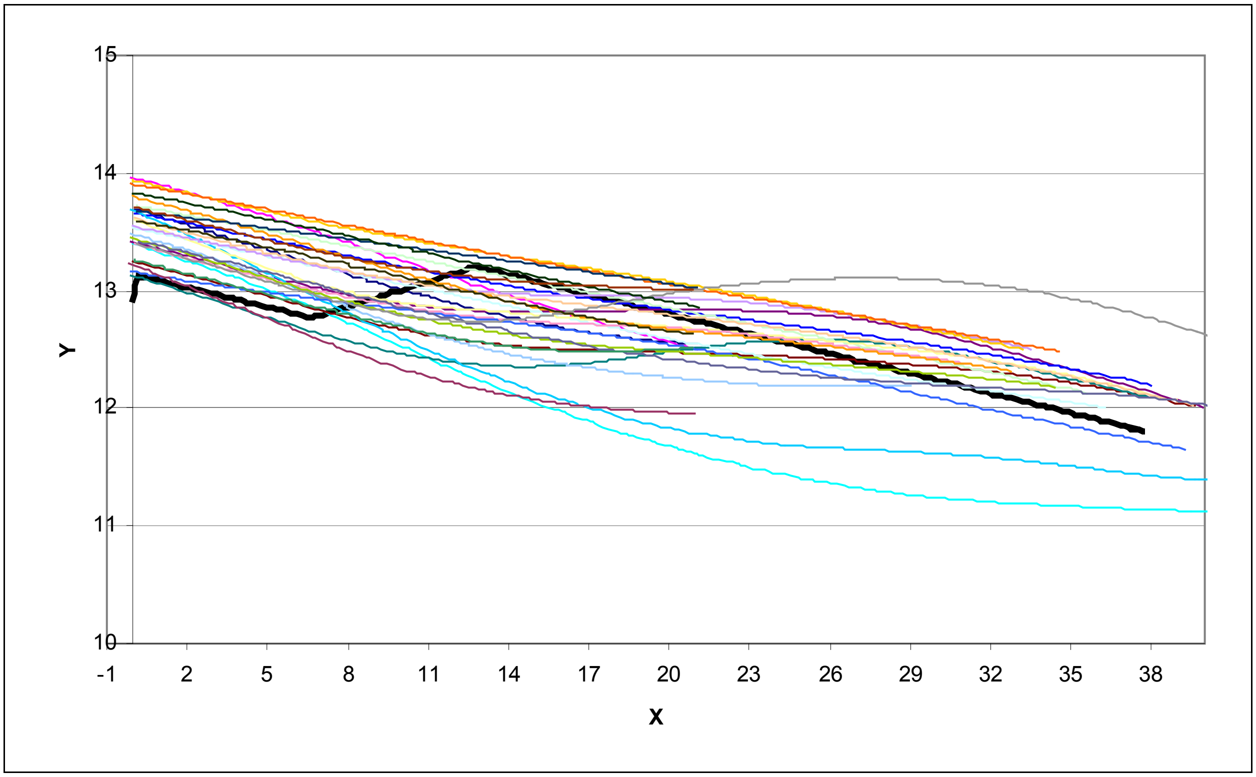

FIGURE 21. Vehicle Paths, Shoulder Rumble Strip, Database 1, Module 1, Scenario 1.

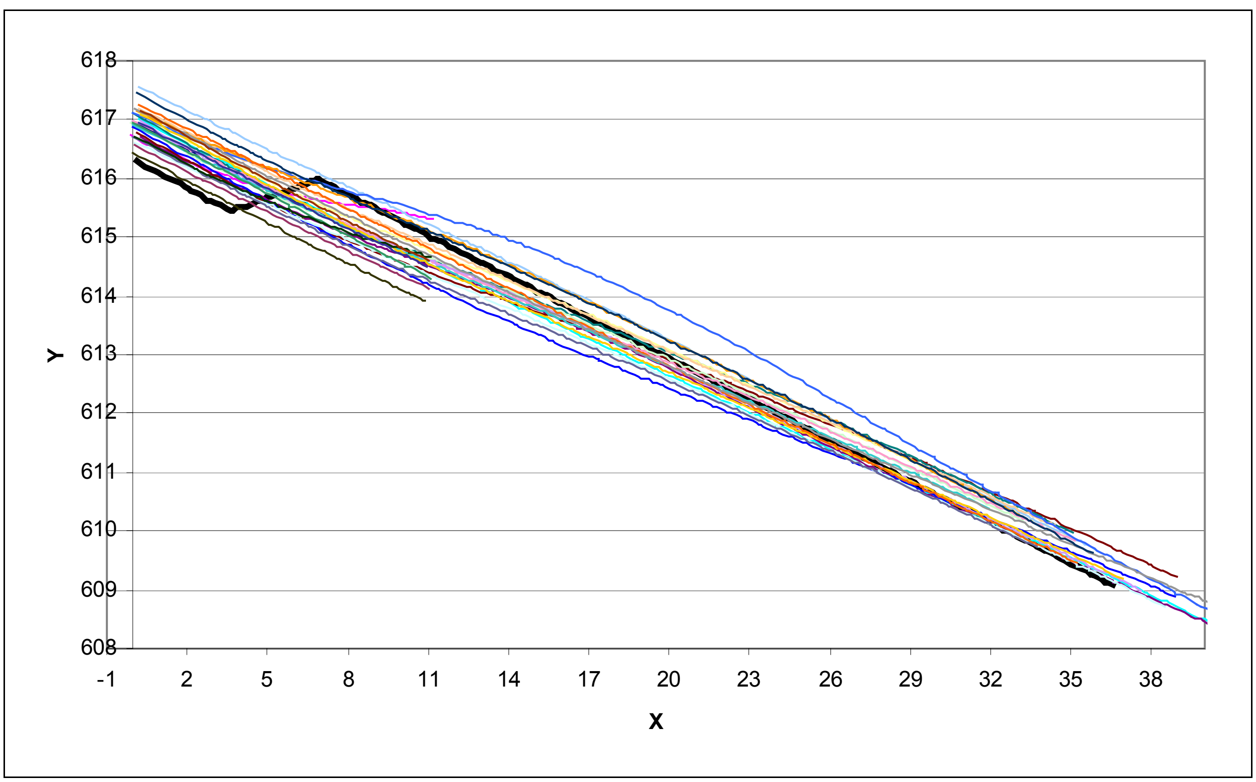

FIGURE 22. Vehicle Paths, No Centerline Rumble Strip, Database 1, Module 1, Scenario 5.

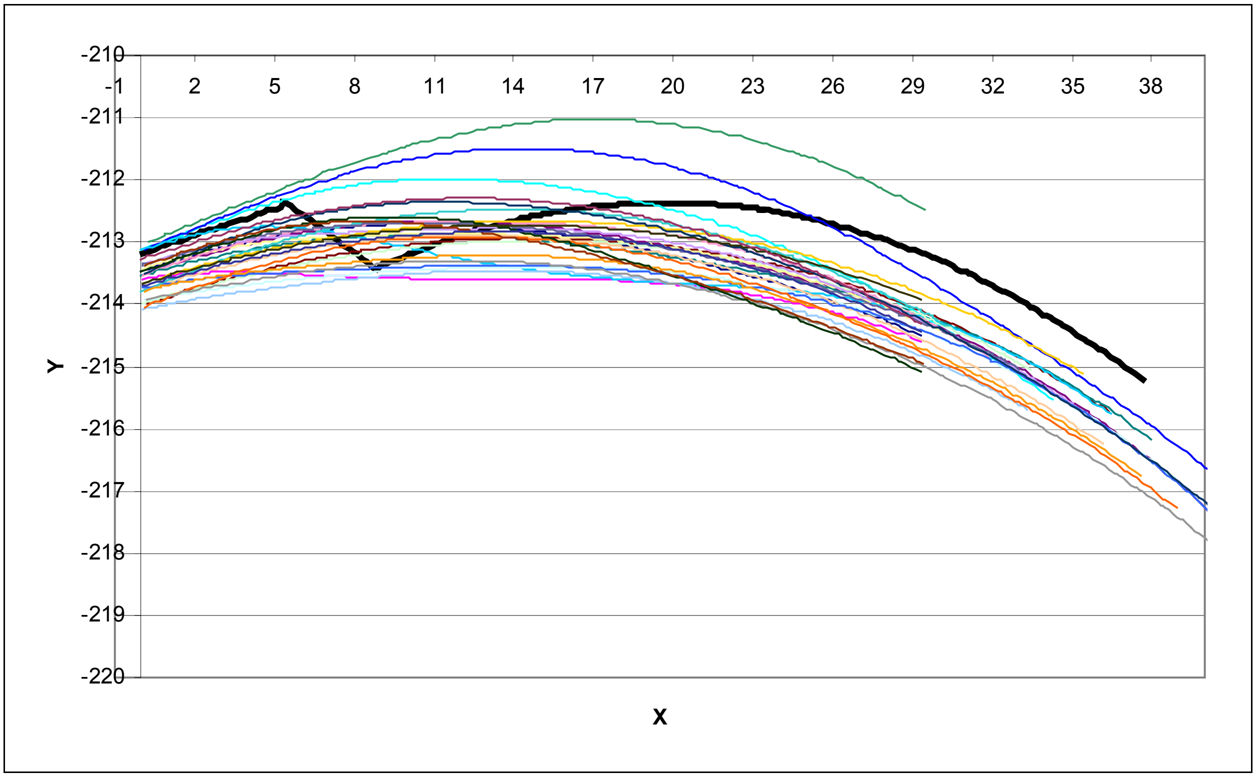

FIGURE 23. Vehicle Paths, Centerline Rumble Strip, Database 1, Module 1, Scenario 7.

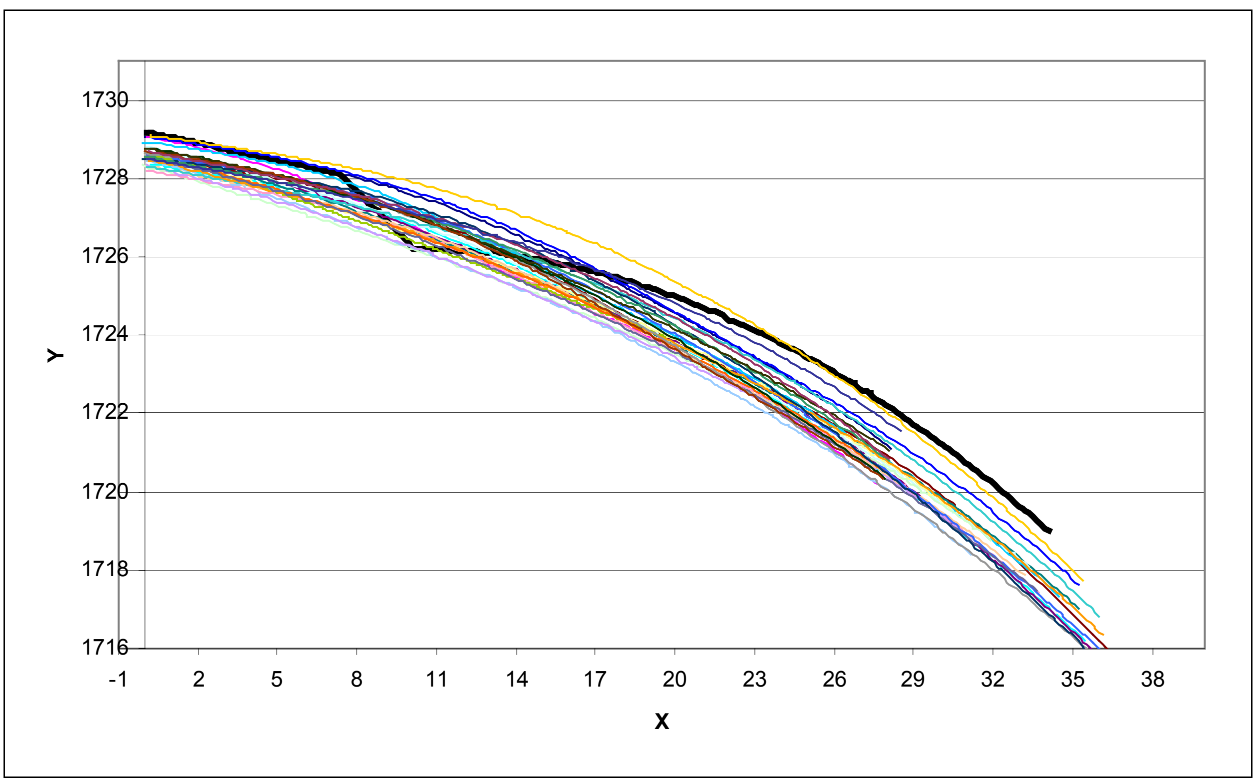

FIGURE 24. Vehicle Paths, No Centerline Rumble Strip, Database 1, Module 2, Scenario 5.

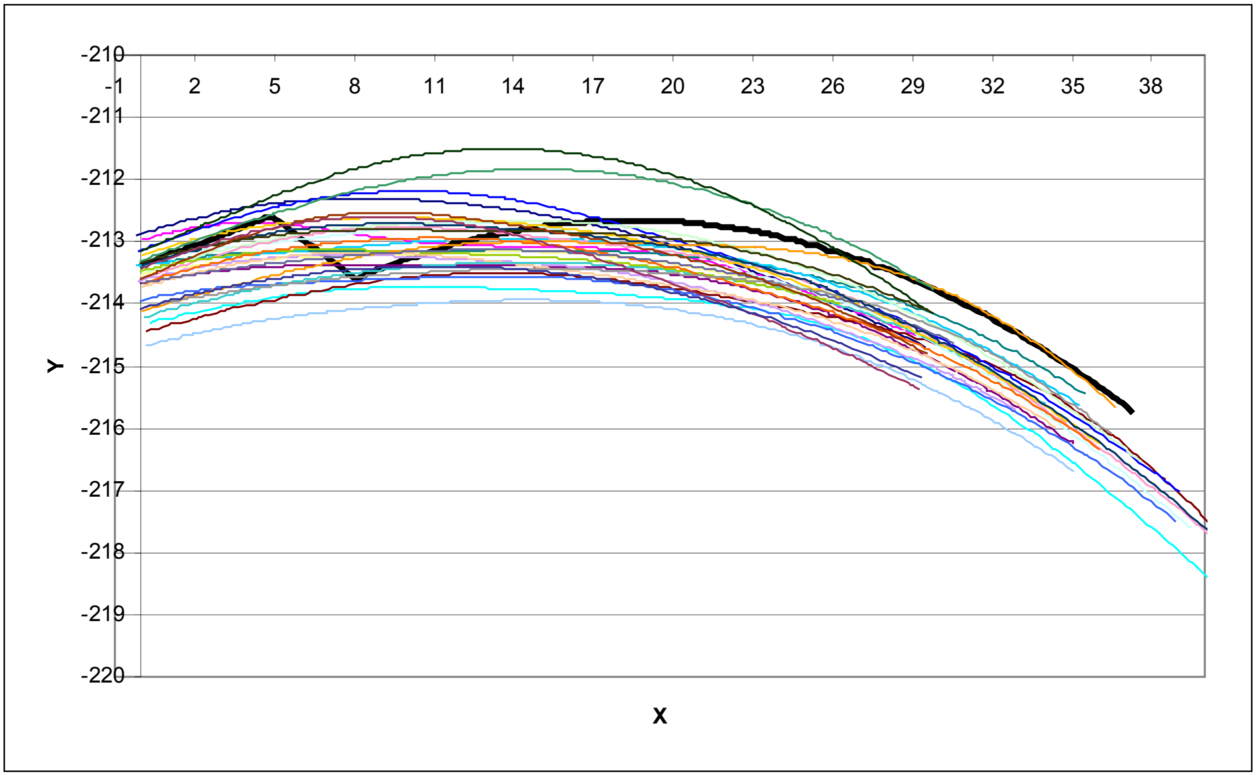

FIGURE 25. Vehicle Paths, Centerline Rumble Strip, Database 1, Module 2, Scenario 7.

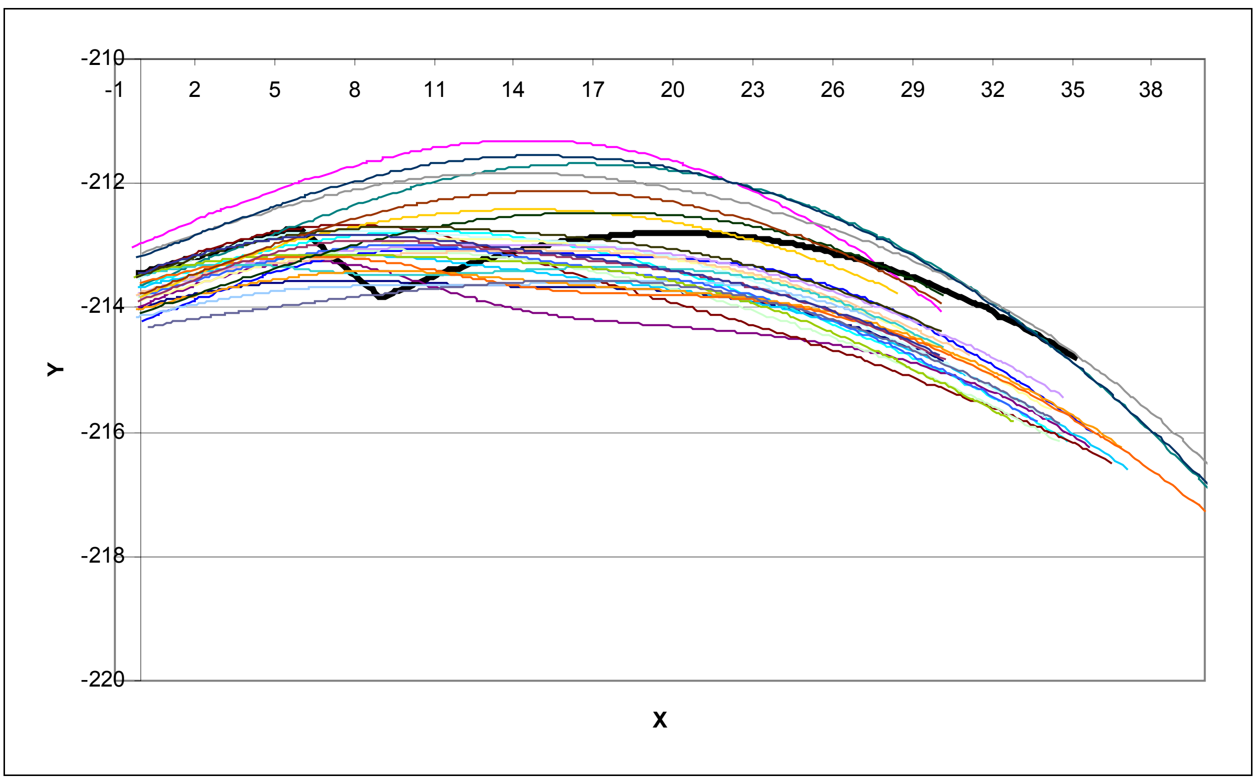

FIGURE 26. Vehicle Paths, Centerline Rumble Strip, Database 2, Module 1, Scenario 6.

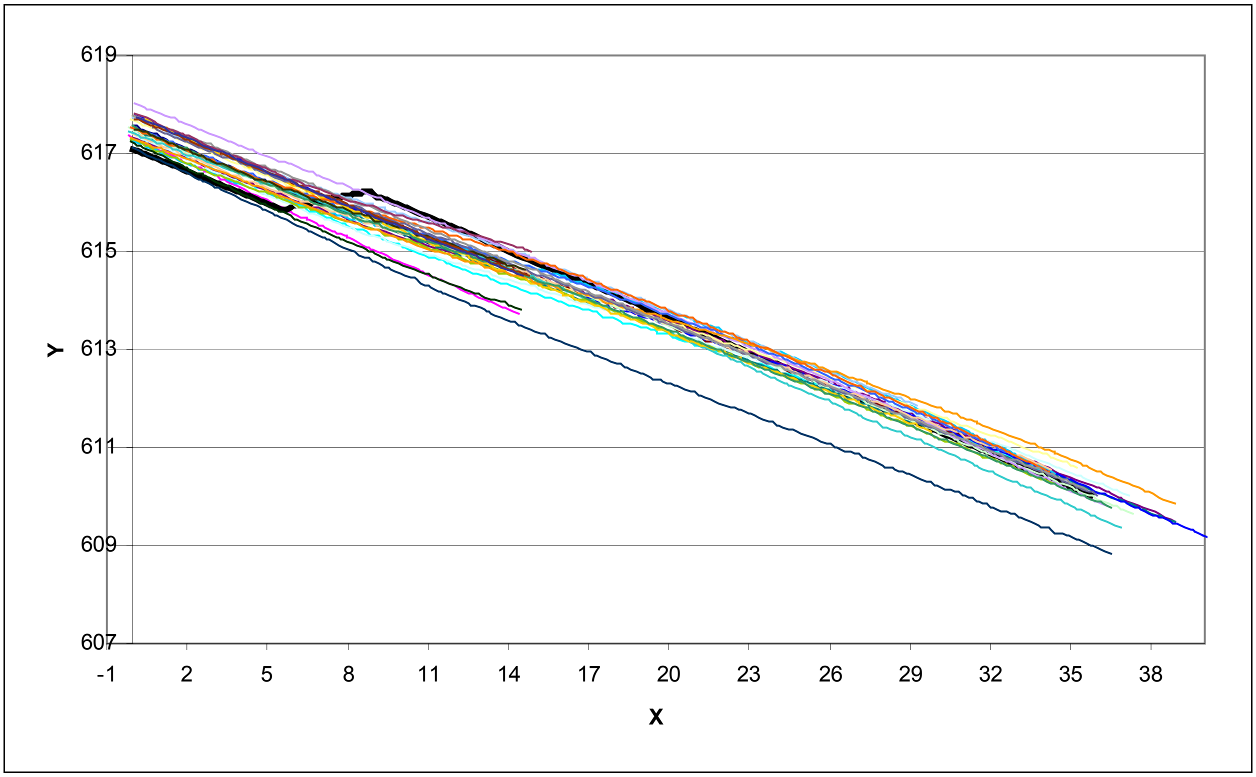

FIGURE 27. Vehicle Paths, Centerline Rumble Strip, Database 2, Module 1, Scenario 5.

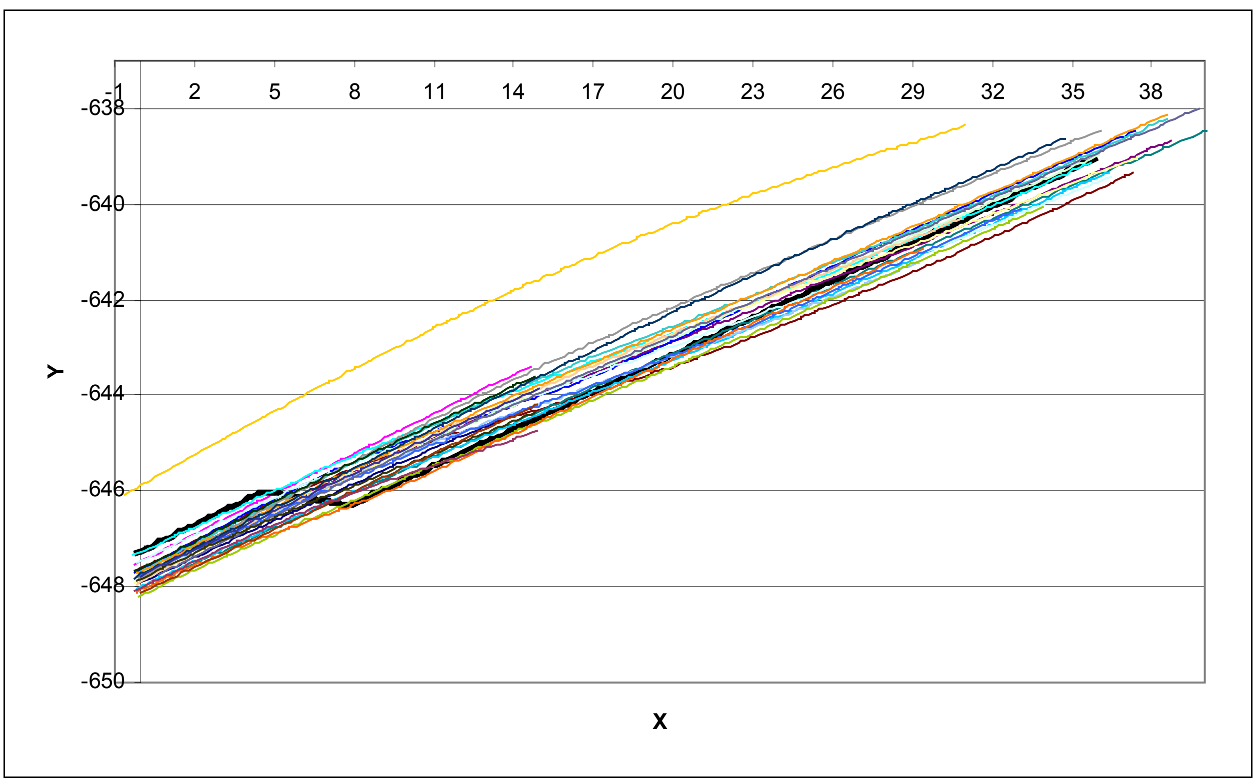

FIGURE 28. Vehicle Paths, No Centerline Rumble Strip, Database 2, Module 1, Scenario 7.

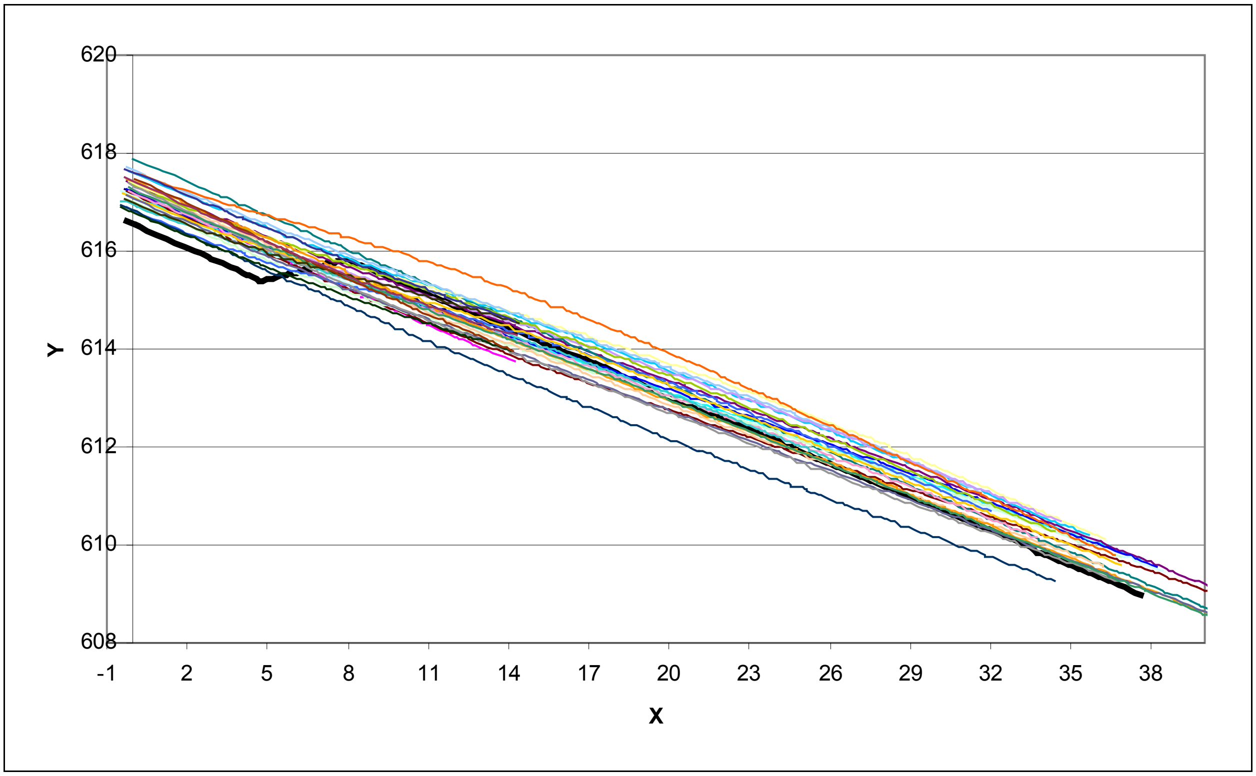

FIGURE 29. Vehicle Paths, No Centerline Rumble Strip, Database 2, Module 2, Scenario 6.

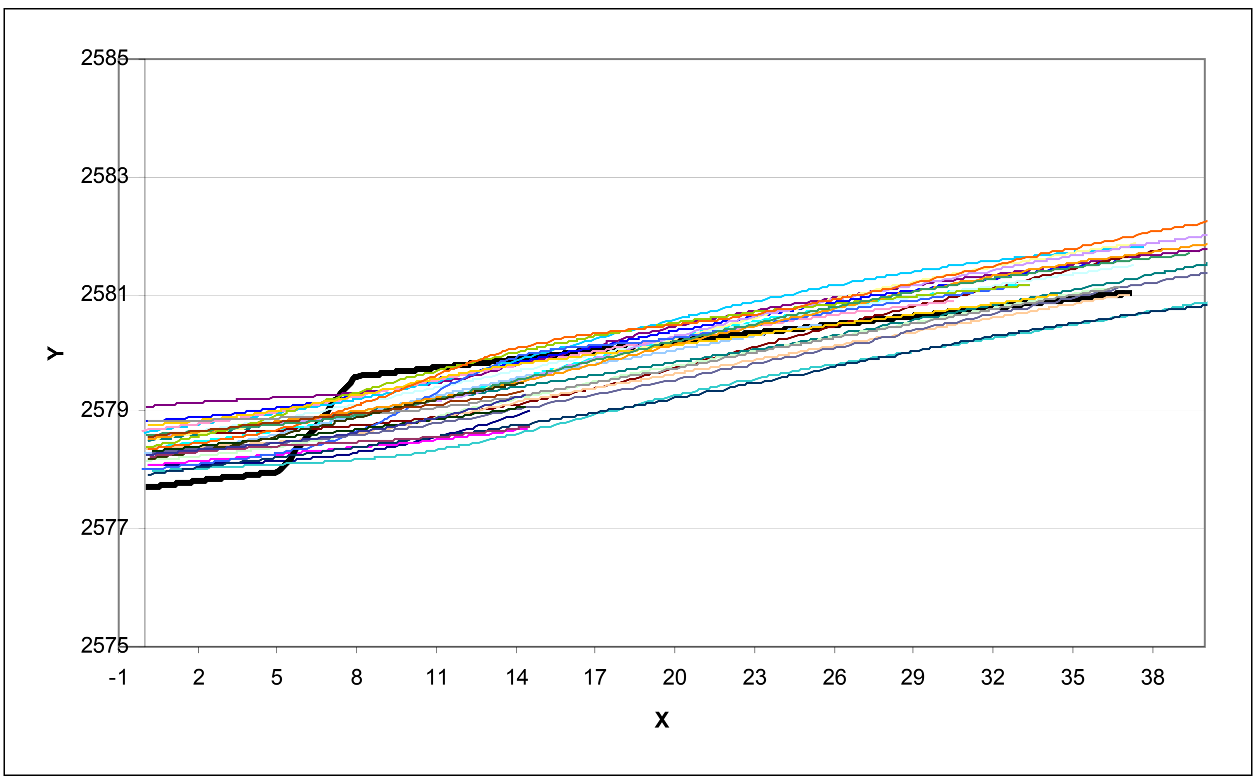

FIGURE 30. Vehicle Paths, Centerline Rumble Strip, Database 2, Module 2, Scenario 4.

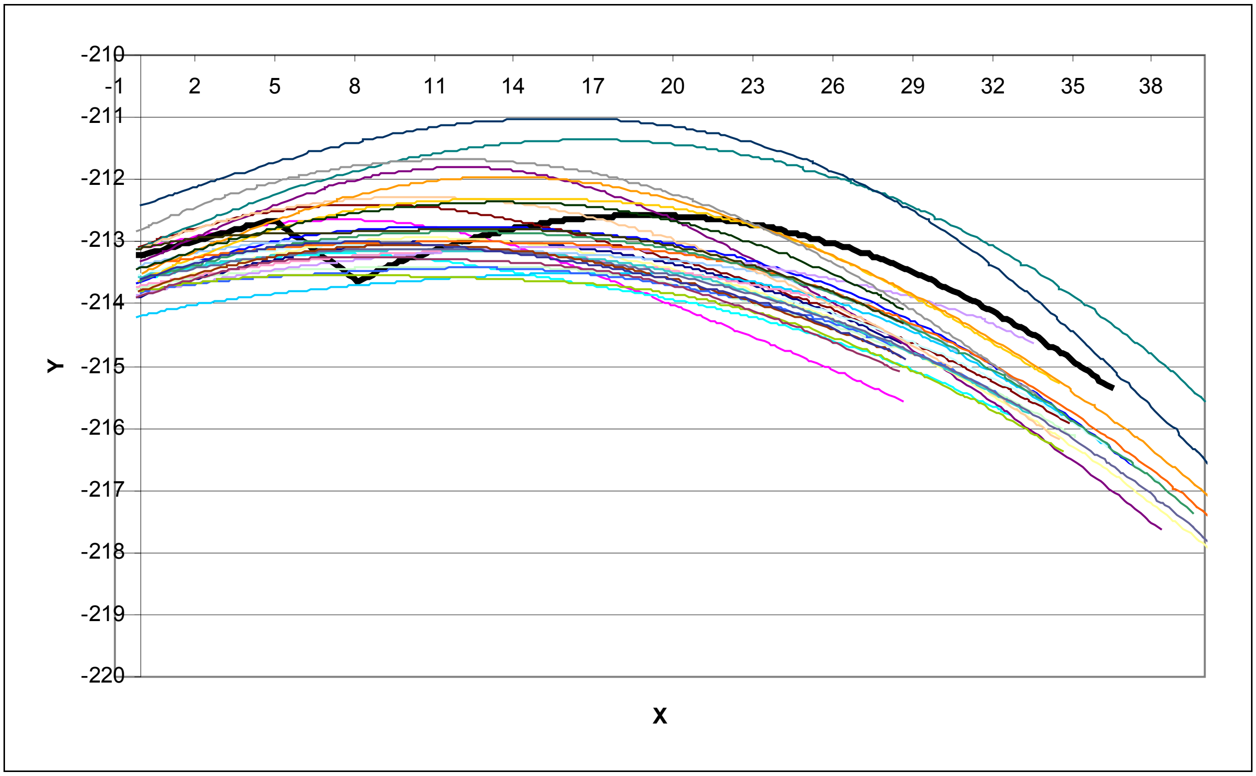

FIGURE 31. Vehicle Paths, Centerline Rumble Strip, Database 2, Module 2, Scenario 7.

TABLE 13. ANOVA Data for All Scenarios

For All Scenarios
One-way ANOVA: No Crs, Crs

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	1	0.043	0.043	0.13	0.723
Error	464	157.721	0.340		
Total	465	157.764			

Level	N	Mean	StDev	-----+---------+---------+-----
No Crs	233	1.6528	0.5813	(--------------*---------
Crs	233	1.6720	0.5848	(--------------*---------

Pooled St Dev = 0.5830   1.600   1.650   1.700

The next analysis considered time for drivers to return to their lane in scenarios that drivers first encountered centerline rumble strips in the visual database. The results of this analysis are presented in Table 14. Drivers took approximately 125 milliseconds more time to return to their travel lane when centerline rumble strips were encountered as compared to cross-over-the-centerline scenarios with no centerline rumble strips. The difference in mean times was not statistically significant (p = 0.112). The results imply that drivers took more time to return to the travel lane when they encountered centerline rumble strips. This difference became smaller as the number of encounters with centerline rumble strips increased. It appeared that, with experience, drivers were quicker to return to the appropriate travel lane.

The next evaluation considered the effects of passing/no passing and curved/straight on the time to return back to the travel lane. The difference between the times it takes to return when centerline rumble strips is present and not present is used as the data in this analysis. The results are presented in Table 15. Findings show that there was a statistically significant difference in mean time on curved sections (p = 0.001). This result implies that geometry of the road has an effect on the time to return to the travel lane when centerline rumble strips are present. There was no statistically significant difference when passing/no passing was considered (p = 0.255). Therefore, passing versus no passing locations did not have direct effect on the time to return to the travel lane.

TABLE 14. ANOVA Data for First Encounter with CRS Scenarios

First Encounter of Centerline Rumble Strips
One-way ANOVA: No CRS, CRS

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	1	0.448	0.448	2.57	0.112
Error	112	19.556	0.175		
Total	113	20.004			

Level	N	Mean	StDev	
				--+---------+---------+---------+--
No CRS	57	1.2968	0.4579	(----------*---------
CRS	57	1.4222	0.3735	(----------*---------

Pooled StDev = 0.4179   1.20   1.30   1.40   1.5

TABLE 15. ANOVA Data for Geometry and Passing Zones

Interaction and Main Effects
Two-way ANOVA: Time Difference versus Geometry, Passing/No Passing

Analysis of Variance

Source	DF	SS	MS	F	P
Geometry	1	3.478	3.478	11.74	0.001
Passing	1	0.386	0.386	1.30	0.255
Interaction	1	11.276	11.276	38.05	0.000
Error	220	65.194	0.296		
Total	223	80.335			

The next analysis compared the performance of drivers on shoulder rumble strips and centerline rumble strips. The results of this analysis are presented in Table 16. The results showed that on average, drivers took approximately 250 milliseconds more time to return to the travel lane after encountering shoulder rumble strips when compared to the average time it took to return to the travel lane after encountering centerline rumble strips. These results were statistically significant (p = 0.0001).

TABLE 16. ANOVA to Compare Shoulder and Centerline Rumble Strips

One-way ANOVA: SRS, CRS

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	1	8.960	8.960	12.33	0.0001
Error	508	369.225	0.727		
Total	509	378.185			

Level	N	Mean	StDev	------+---------+---------+---------+
SRS	277	1.9381	1.0248	(------*-
CRS	233	1.6720	0.5848	(------*-------)

Pooled StDev = 0.8525   1.65   1.80   1.95   2.10

The last analysis determined the percentage of drivers who turn incorrectly when they encountered centerline rumble strips. The results are presented in Figures 32 through 34. Considering all scenarios, approximately 27 percent of drivers initially corrected left (versus right) after encountering centerline rumble strips. Nearly 37 percent of the drivers corrected left when they encountered centerline rumble strips in curve and no passing segments of the roads, and 27 percent of the drivers in curve and passing segments of the roads. Twenty-eight percent of the drivers corrected left initially when they encountered centerline rumble strips for the first time. Between 20 and 23 percent of drivers corrected left on the straight roadway segments. There were no significant sex or age effects in the results. Note that no opposing traffic was present in any of the scenarios although the nighttime and fog conditions limited visibility.

As a comparison, an evaluation was completed on the shoulder rumble strip encounters to determine how many drivers corrected right instead of the desired left correction. From review of the observations and simulator data, the results showed that no drivers initially corrected right when encountering a shoulder rumble strip. Further, drivers appeared more comfortable when they encountered shoulder rumble strips whereas they were alarmed when they encountered centerline rumble strips. The hypothesis that drivers may correct left instead of right with centerline rumble strips because of previous a priori expectancies appears to be valid.

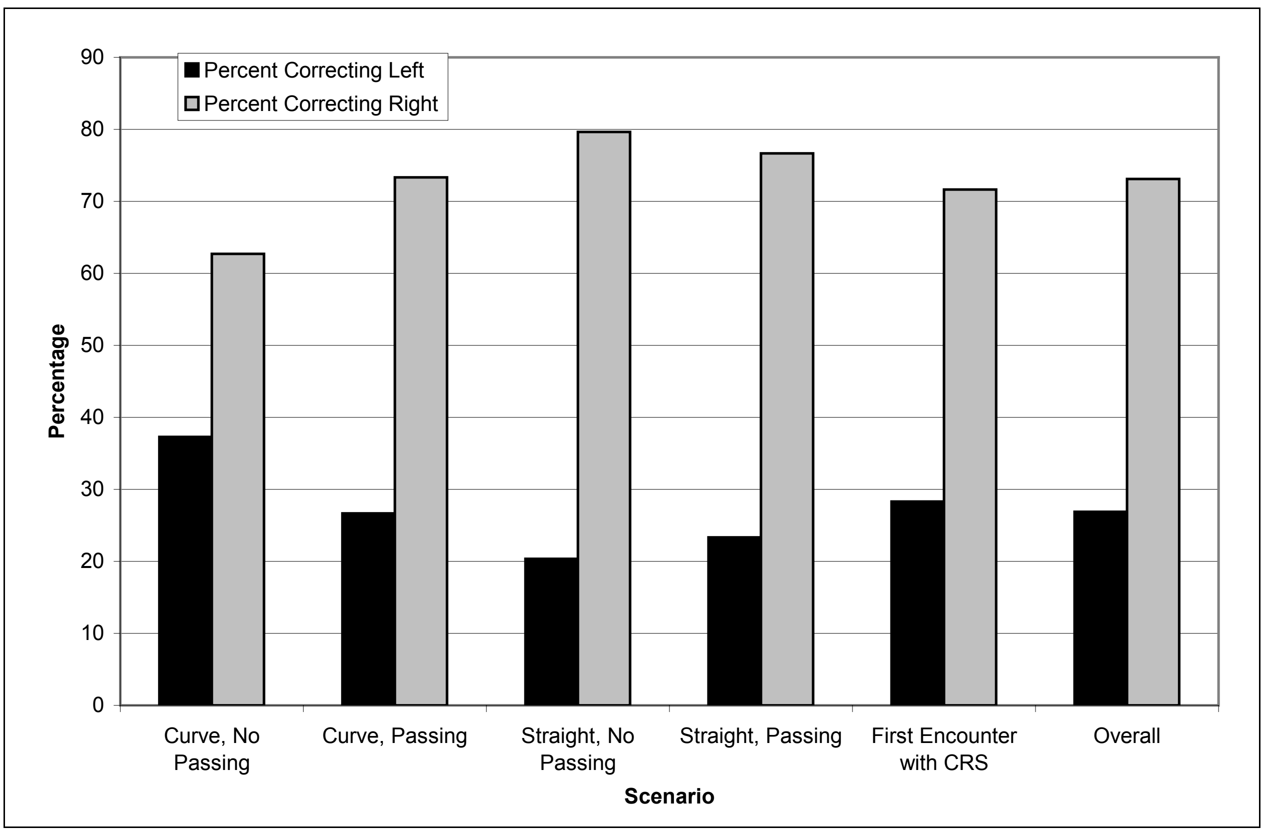

FIGURE 32. Percentage of Drivers Who Turned Left or Right.

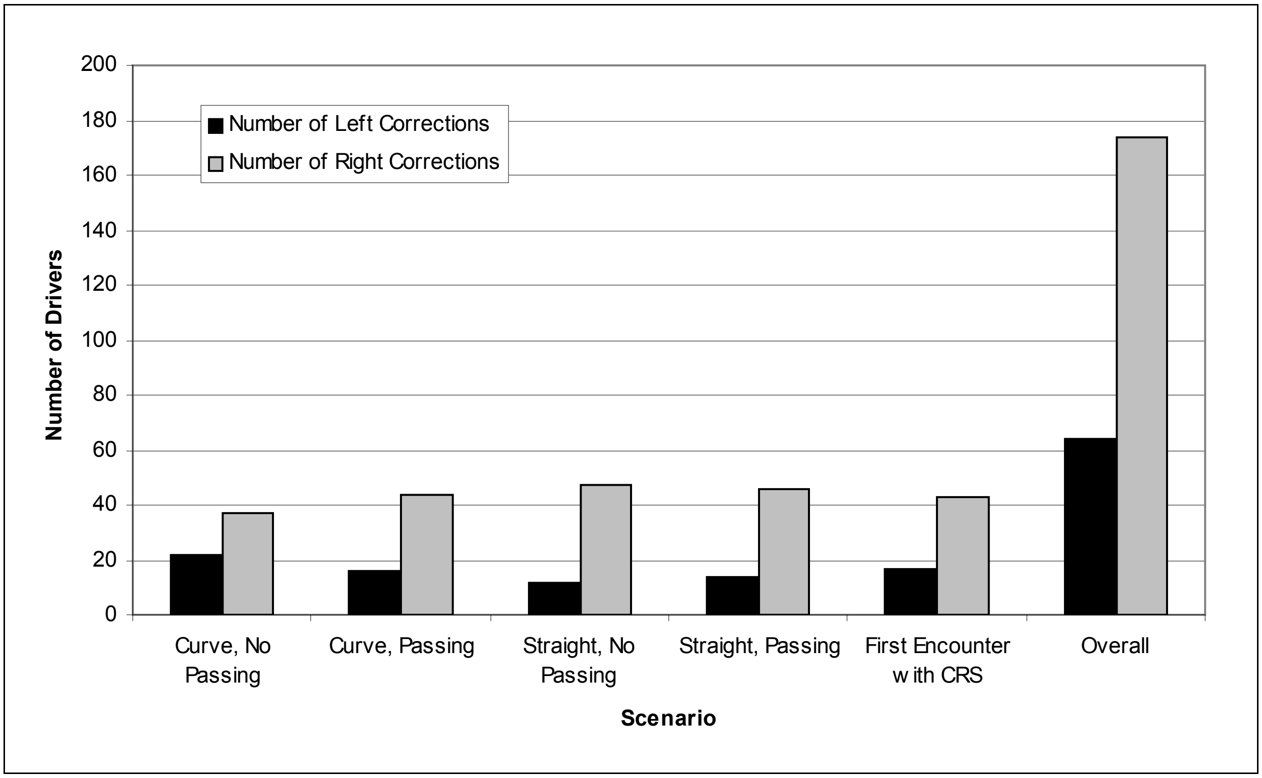

FIGURE 33. Number of Drivers Who Turned Left or Right.

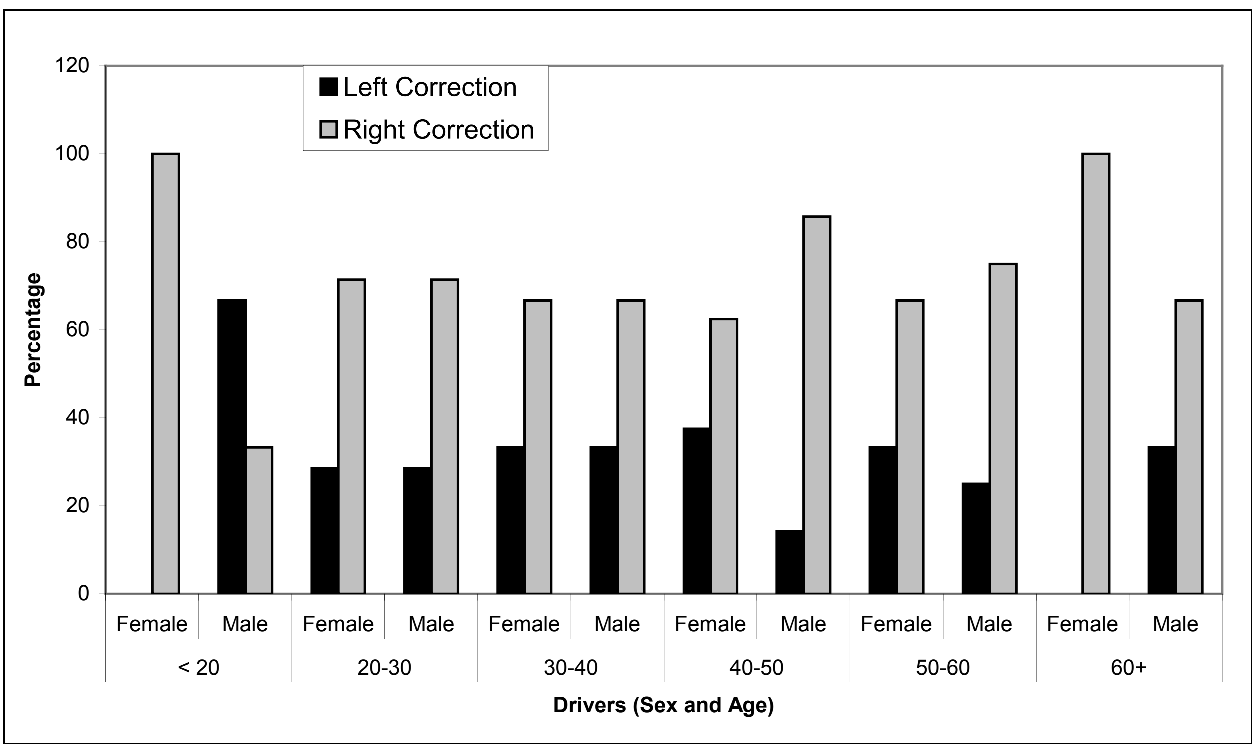

FIGURE 34. Driver Correction at Centerline Rumble Strips by Sex and Age.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

The overall objective of this research was to evaluate the effectiveness of centerline rumble strips in reducing cross-over-the-centerline crashes and improving the safety of undivided roadways. Three research phases were completed. The objective of Phase I was to identify the current use of centerline rumble strips in the United States and around the world. Phase I also incorporated the current state-of-the-knowledge related to centerline rumble strips and included a review of safety data found in the literature and through transportation agencies. Phase II evaluated the safety effects of the centerline rumble strips installed on State Routes 2, 20, and 88 in Massachusetts. Phase III evaluated driver reaction to centerline rumble strips using a full-scale driving simulator.

CONCLUSIONS

Phase I results found that 20 of the 50 state Departments of Transportation, along with several provinces in Canada, are using centerline rumble strips. Several more states plan to use centerline rumble strips in the future. Massachusetts is clearly a national leader in the proactive use of centerline rumble strips as a safety measure. States who do not plan to use centerline rumble strips had concerns with noise, pavement deterioration, pooling of water in the rumble strips and freezing in winter, and the safety of motorcyclists and bicyclists. Several states have completed research on the effectiveness and safety benefits of centerline rumble strips and have identified positive results. Most of the state officials have noted a reduction in the number of crashes where centerline rumble strips have been used.

A detailed analysis of crashes on Routes 2, 20, and 88, before and after the installation of centerline rumble strips, was completed in Phase II. Route 2 experienced a slight decrease in the annual frequency of targeted crash types while Route 20 and Route 88 remained relatively consistent. Several of the comparison sites, specifically Route 18 and Route 131, witnessed significant increases in targeted crash types.

An analysis of fatal crashes at the study locations, during the analysis period, provides more insight into the effectiveness of centerline rumble strips. No fatal crashes were experienced on Routes 2 and 88 in the analysis area since the installation of the centerline rumble strips. Route 20 experienced two fatal crashes in 1997 and one in 1998, all after the installation of centerline rumble strips. No fatal crashes were experienced in 1999 and 2000. Both fatal crashes in 1997 occurred at nearly the same location, approximately 200 feet east of the Charlton/Oxford Town Line near mile marker 104.1. This location is adjacent to an 819 foot radius horizontal curve. The fatal crash in 1998 was also close to the location of the 1997 fatal crashes, taking place approximately 300 feet west of the Charlton/Oxford Town Line near mile marker 103.9. Therefore, it is not believed that these fatal crashes on Route 20 after the installation of centerline rumble strips reflect the potential effectiveness of their use.

The before and after crash data were statistically analyzed in a number of different ways. In the first analysis, targeted crashes were considered at both the study and comparison sites. The results of the statistical analysis showed that the overall number of predicted crashes increased by approximately 3 crashes/year. Recall that predicted crashes were a function of the previous year crash frequencies and trends at the comparison sites. This result was not statistically significant. The number of actual crashes on Route 2 was approximately 1 crash per year lower than predicted. Route 20 data showed that actual crashes were approximately 2.2 crashes/year greater than predicted. Route 88 data showed that actual crashes were approximately 1 crash per year higher than predicted. None of these results were statistically significant.

The effect of traffic volume was considered using the same comparison sites. Results were consistent with the previous analysis. Overall, approximately 3 more crashes occurred than predicted, with a standard deviation of approximately 6. Each of the individual roadways showed that there was no statistically significant difference in crash frequencies before and after the centerline rumble strip installation.

An analysis was completed considering only injury crashes in the before and after conditions. Expected injury crashes were approximately one crash/year higher on Routes 2 and 88 than actual injury crashes, showing positive results. Neither result was statistically significant. However, Route 20 experienced a 2.6 crash/year increase in injury crashes (standard deviation 2.5) showing a statistically significant increase in this crash type.

Additional evaluations considering all crashes before and after the installation of centerline rumble strips as well as different combinations of comparison sites were completed. Results were consistent with the previous analysis.

The results of the crash data analysis in Phase II showed no significant change in crash frequencies before and after the installation of centerline rumble strips. There were no significant trends in the comparison sites to conclude that the stability of the crash frequencies at the study location were a function of the environment. There is no evidence to suggest that the installation of the centerline rumble strips significantly reduced crash rates. Some positive reductions in injury crashes were observed on Routes 2 and 88, although the results were not significant. No fatal crashes have occurred on Routes 2 and 88 since the installation of centerline rumble strips which may be attributed to the benefits of centerline rumble strips. Three cross-over-the-centerline fatal crashes did occur on Route 20 after the centerline rumble strips were installed, all near the same geometric feature. Roadway improvements are currently be made in this area.

Phase III considered the human factors elements of rumble strips and evaluated drivers reaction to encounters with centerline rumble strips. The results found that drivers took more time to return to the travel lane when centerline rumble strips were present as compared to when centerline rumble strips were not present. This result was probably due to a violation of driver’s expectancy with the centerline rumble strip encounter. Considering all scenarios, the difference in the means of the times to return back to the travel lane was significantly higher during the first encounter, but changed with experience. Drivers reacted to and correct the vehicle trajectory more quickly with shoulder rumble strip encounters than with centerline rumbles strip encounters. Familiarity with shoulder rumble strips is likely the reason for this result.

The initial concern expressed by at least one state that has not installed centerline rumble strips, and hypothesized by the research team, was validated. That is, some drivers did correct left instead of right when encountering centerline rumble strips. Approximately 27 percent of the drivers made an initial leftward correction of the vehicle when encountering centerline rumble strips. Results varied from approximately 20 percent of drivers on straight roadway segments to 37 percent of drivers on curved roadway segments of sufficient radius to require no passing zones. One can argue that this high percentage of drivers correcting left is due to the laboratory conditions, lack of opposing vehicles in the simulation, the experimental nature of this research, less than normal driving conditions, or limited exposure to actual centerline rumble strips. Additionally, the increase in the percentage of left corrections on horizontal curves may be due simply to the uniqueness of the simulated driving environment. Nevertheless, it is difficult to deny the fact that there is some probability of a driver becoming confused and reacting improperly. Considering a drowsy or inattentive driver who is unaware of their roadway position, this result is potentially concerning. Yet centerline rumble strips were effective at gaining drivers' attention, and although a slight correction into the opposing lane is not ideal, the attentiveness gained by the centerline rumble strips may still prevent a crash or result in a far less severe incident than a complete head-on collision with a drowsy driver. The majority of drivers made proper corrections when encountering centerline rumble strips demonstrating the value of centerline rumble strips at improving safety on the Massachusetts roadway system. Furthermore, no improper (rightward) corrections were experienced with shoulder rumble strip scenarios.

Considering all results from the three research Phases presented, centerline rumble strips are an effective traffic control device and safety countermeasure in areas with a history of cross-over-the-centerline fatal and injury crashes. The results show reductions in fatal and injury crashes; however, a statistically significant decrease in all crashes was not observed. The fatal crashes on Route 20 that occurred after the installation of centerline rumble strips demonstrate the fact that centerline rumble strips can only warn but not prevent drivers from crossing over the roadway centerline.

RECOMMENDATIONS

The results of this research, supported by the findings in other states, show that centerline rumble strips are a recommended countermeasure in areas where cross-over-the-centerline crashes occur. The researchers recommend that a follow-up analysis be completed that considers additional years of before and after crash data. A longer analysis period may show more positive trends in crashes. The impact of opposing traffic volumes should also be considered. Additionally, further study should be completed pertaining to the human factors elements of centerline rumble strips. Some consideration should be given to an alternate configuration or intermittent layout of centerline rumble strips to produce a different tone and message to the driver than that which is experienced with continuous shoulder rumble strips.

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APPENDIX A
Agency Survey

University of Massachusetts
Department of Civil and Environmental Engineering
In Cooperation with
The Massachusetts Highway Department
Centerline Rumble Strip Survey

Introduction:

The Department of Civil and Environmental Engineering at the University of Massachusetts is conducting a survey on the current use of **centerline rumble strips** in the United States. **Centerline rumble strips** are defined as rumble strips used along the centerline of an undivided roadway. Please help us by completing the following questions and returning by mail, e-mail, or fax.

RESPONDENT

NAME

Title

Agency

Address
City

State

Zip Code

Telephone

FAX

Email

1. Has your agency used Centerline Rumble Strips?
   - ☐ No
   - ☐ Yes

If your answer to question 1 is Yes, please skip to question 3.

2. Are you planning to install centerline rumble strips within the next three years:
   - ☐ No, we will not use Centerline Rumble Strips
   - ☐ No, but we are considering the use of Centerline Rumble Strips
   - ☐ Yes, we will probably install centerline rumble strips
   - ☐ Yes, we have definite plans to install centerline rumble strips
   - ☐ None of the above

   Comments

   Please skip to Question 14

3. How many separate installations of centerline Rumble strips exist within your state or jurisdiction?
   - ☐ 1-2
   - ☐ 3-4
   - ☐ 5-6
   - ☐ 7-8
   - ☐ >8

4. Approximately how many lane miles of centerline rumble strips has your state or jurisdiction installed?
   - ☐ < 1 miles
   - ☐ 1 to 5 miles
   - ☐ 5 to 10 miles
   - ☐ 10 to 15 miles
   - ☐ 15 to 20 miles
   - ☐ >20 miles

5. Please describe the type of centerline rumble strips installed:
   - ☐ Continuous
   - ☐ In series at specific intervals ⇒ Rumble Strip Length ________ Interval Spacing ________
   - ☐ Other

6. What was the reason for installing Centerline Rumble Strips?
   - ☐ Enhance Road Safety
   - ☐ Countermeasure at high Crash Location
   - ☐ Delineation in Low Visibility Area
   - ☐ Other

7. Please rank from 1 to 7, with 1 being the highest and 7 the lowest, the most significant criteria for installing centerline rumble strips:

   ☐ Crash Frequency/Rate

   ☐ Roadway Geometry

   ☐ Traffic Volume

   ☐ Cost

   ☐ Public/Police Request

   ☐ Meteorological Conditions (fog, snow, etc.)

   ☐ Other (explain)

8. Have the centerline rumble strips used by your agency performed satisfactorily (i.e., improved safety)?

   ☐ No

   ☐ Yes

   Please provide comments:

9. Have any unexpected problems been created by your use of centerline rumble strips (e.g. safety problems, maintenance problems, noise problems, etc)?

   ☐ No

   ☐ Yes

   Please explain

10. Has any formal evaluation or studies been conducted on the safety effects of centerline rumble strips?

☐ No

☐ Yes

If yes what did the evaluation conclude?

If you answered Yes, please send a copy of the evaluation/study report to the address shown at the end of the survey.

11. Has your agency created warrants, policies, guidelines or specifications for the use of centerline rumble strips?

☐ No

☐ Yes

If you answered Yes, please send a copy of the relevant specifications, warrants, policies, guidelines, or manual sections to the address shown at the end of the survey.

12. Please estimate the cost (use appropriate units) of installing centerline rumble strips.

$____ per lineal foot

$____ per lineal mile.

13. Do you have any other positive or negative experiences using centerline rumble strips that you would like to report, or any other general comments?

☐ No

☐ Yes

If Yes, please explain

END

Thank you for completing the survey. Please direct all correspondence to:

Dr. David A. Noyce, P.E.
University of Massachusetts
214C Marston Hall
Amherst, MA – 01003
e-mail: noyce@ecs.umass.edu
Fax: (413) 545-9569
Tel: (413) 545-2509

Submit

Clear

APPENDIX B
Agency Survey Results

Table B1 States Who Responded to the Survey

Alabama	Alaska	Arizona	Arkansas	California
Colorado	Connecticut	Delaware	Florida	Georgia
Hawaii	Idaho	Illinois	Indiana	Iowa
Kansas	Kentucky	Louisiana	Maine	Maryland
Massachusetts	Michigan	Minnesota	Mississippi	Missouri
Montana	Nebraska	Nevada	New Hampshire	New Jersey
New Mexico	New York	North Carolina	North Dakota	Ohio
Oklahoma	Oregon	Pennsylvania	Rhode Island	South Carolina
South Dakota	Tennessee	Texas	Utah	Vermont
Virginia	Washington	West Virginia	Wisconsin	Wyoming
International				
Australia	Canada	Spain		

Table B2 Responses to Question 1

Question 1: Has your agency used centerline rumble strips?	
Responses	**Number of Responses**
Yes	20
No	30

Table B3 States that have installed Centerline Rumble Strips

Alaska	Arizona	California	Colorado	Connecticut
Delaware	Hawaii	Kentucky	Maryland	Massachusetts
Minnesota	Nevada	New Hampshire	New Mexico	Ohio
Oregon	Pennsylvania	Virginia	Washington	Wyoming

Table B4 Summary of Responses to Question 2

Question 2: If your answer to question 1 was 'No', please indicate your potential for using centerline rumble strips within the next three years:	
Responses	**Number of Responses**
We will not use Centerline Rumble Strips	6
We are considering the use of Centerline Rumble Strips	12
We will probably install Centerline Rumble Strips	4
We have definite plans to install Centerline Rumble Strips	1
None of the above (Please Explain)	6

Table B5 Responses to Question 2

State	Question 2: If your answer to question 1 was 'No', please indicate your potential for using centerline Rumble Strips within the next three years:	Comments
Alabama	None of the above	We may experiment with the device.
Arkansas	None of the above	Have not considered.
Georgia	We will probably install centerline rumble strips	
Idaho	We are considering the use of centerline rumble strips	
Illinois	We are considering the use of centerline rumble strips	
Indiana	We will not use centerline rumble strips	
Iowa	We will probably install centerline rumble strips	Funding for a pilot study has been approved. We are waiting for the results of other state studies before proceeding.
Kansas	We have definite plans to install centerline rumble strips	
Louisiana	None of the above	It has not been considered by LADOT for centerline, It has only been used for shoulders.
Maine	We are considering the use of centerline rumble strips	
Michigan	We will note use centerline rumble strips	
Mississippi	We are considering the use of centerline rumble strips	
Missouri	We will probably install centerline rumble strips	
Montana	We are considering the use of centerline rumble strips	
Nebraska	We are considering the use of centerline rumble strips	
New York	We are considering the use of centerline rumble strips	
North Carolina	We are considering the use of centerline rumble strips	

North Dakota	N/A	Would consider them as a crash reduction countermeasure when/where/if we identify a crash problem
Oklahoma	We are considering the use of centerline rumble strips	
Rhode Island	We will not use centerline rumble strips	
South Carolina	We are considering the use of centerline rumble strips	
South Dakota	We are considering the use of centerline rumble strips	
Tennessee	None of the above	We had submitted interest in a pooled study, but was not selected. TDOT has some reservation with weakening an already weak pavement area along the longitudinal joint.
Texas	We are considering the use of centerline rumble strips	
Utah	We will probably install centerline rumble strips	
Vermont	None of the above	We currently have no plans to use CLRS, but we certainly might consider it if we felt they would address a problem.
West Virginia	None of the above	We are interested in exploring the possibility of considering such installations. However, if installed, we would limit it to one or two test locations. As of now, no sites are under active consideration.
Florida	We will not use centerline rumble strips	
New Jersey	We will not use centerline rumble strips	
Wisconsin	We will not use centerline rumble strips	

Table B6 Summary of Responses to Question 3

Question 3: How many separate installations of centerline rumble strips exist within your jurisdiction?	
Responses	**Number of Responses**
1 to 2	14
3 to 4	3
5 to 6	2
7 to 8	0
> 8	1

Table B7 Responses to Question 3

State	Question 3: How many separate installations of Centerline Rumble Strips exist within your jurisdiction?
Alaska	1 to 2
Arizona	1 to 2
California	5 to 6
Colorado	1 to 2
Connecticut	1 to 2
Delaware	1 to 2
Hawaii	1 to 2
Kentucky	1 to 2
Maryland	5 to 6
Massachusetts	3 to 4
Minnesota	3 to 4
Nevada	1 to 2
New Hampshire	1 to 2
New Mexico	1 to 2
Ohio	1 to 2
Oregon	1 to 2
Pennsylvania	> 8
Virginia	1 to 2
Washington	3 to 4
Wyoming	1 to 2

Table B8 Summary of Responses to Question 4

Question 4: Approximately how many lane-miles of centerline rumble strips has your jurisdiction installed?	
Responses	**Number of Responses**
< 1 mile	2
1 to 5 miles	6
5 to 10 miles	3
10 to 15 miles	0
15 to 20 miles	2
>20 miles	7

Table B9 Responses to Question 4

State	Question 4: Approximately how many lane-miles of Centerline Rumble Strips has your jurisdiction installed?
Alaska	5 to 10 miles
Arizona	< 1 mile
California	> 20 miles
Colorado	>20 miles
Connecticut	< 1 mile
Delaware	1 to 5 miles
Hawaii	1 to 5 miles
Kentucky	>20 miles
Maryland	> 20 miles
Massachusetts	1 to 5 miles
Minnesota	15 to 20 miles
Nevada	1 to 5 miles
New Hampshire	5 to 10 miles
New Mexico	> 20 miles
Ohio	1 to 5 miles
Oregon	15 to 20 miles
Pennsylvania	> 20 miles
Virginia	1 to 5 miles
Washington	>20 miles
Wyoming	5 to 10 miles

Table B10 Summary of Responses to Question 5

Question 5: Please describe the type of centerline rumble strips installed	
Responses	**Number of Responses**
Continuous	14
In series of specific intervals	1
Other	2
No Reponse	3

Table B11 Responses to Question 5

State	Question 5: Please describe the type of Centerline Rumble Strips installed	Length	Spacing	Comments
Alaska	Continuous			
Arizona	Other			We have a couple of minor experimental installations.
California	N/A			
Colorado	N/A			Continuous with interruptions at intersections and in areas where passing is allowed.
Connecticut	Continuous			
Delaware	Continuous	24"	12"	
Hawaii	Continuous			
Kentucky	N/A			
Maryland	Others			Both continuous and 2 strips (1ft on center) followed by a 5ft gap (center of last to center of first).
Massachusetts	Continuous			
Minnesota	Continuous			
Nevada	Continuous			
New Hampshire	Continuous			
New Mexico	In series of specific intervals	6 foot	6 foot	Continuous and in series of specific interval.
Ohio	Continuous			
Oregon	Continuous			Our center rumble strips were installed in a painted median.
Pennsylvania	Continuous			
Virginia	Continuous			
Washington	Continuous			
Wyoming	Continuous			

Table B12 Summary of Responses to Question 6

Question 6: What was the reason for installing centerline rumble strips?	
Responses	**Number of Responses**
Enhanced road safety	5
Countermeasure at high crash location	10
Delineation in low visibility area	0
Other	3

Table B13 Responses to Question 6

State	Question 6: What was the reason for installing Centerline Rumble Strips?	Comments
Alaska	Countermeasure at high crash locations	
Arizona	Enhanced road safety	
California	N/A	
Colorado	Other	Research Study.
Connecticut	Countermeasure at high crash location	
Delaware	Countermeasure at high crash location	
Hawaii	Countermeasure at high crash location	
Kentucky	N/A	
Maryland	Enhanced road safety	
Massachusetts	Countermeasure at high crash location	
Minnesota	Countermeasure at high crash location	
Nevada	Enhanced road safety	
New Hampshire	Enhanced road safety	
New Mexico	Other	Enhanced road safety, counter measure at high crash locations and cost.
Ohio	Countermeasure at high crash location	
Oregon	Countermeasure at high crash location	
Pennsylvania	Countermeasure at high crash location	
Virginia	Enhanced Road Safety	
Washington	Enhanced Road Safety	
Wyoming	Countermeasure at high crash location	

Table B14 Responses to Question 7

State	Question 7: Please rank from 1 to 6, with 1 being the highest and 6 the lowest, the most significant criteria for installing centerline rumble strips:						
	Crash Frequency / Rate	**Roadway Geometry**	**Traffic Volume**	**Public/ Police Request**	**Meteorological Conditions (fog, snow, etc.)**	**Other**	**Comments**
Alaska	1	2	4	5	3		
Arizona	4	4	4	4	4	4	We have not set a policy and criteria for installation yet.
California	N/A	N/A	N/A	N/A	N/A	N/A	
Colorado	1	3	2				
Connecticut	1	2	4	5	3		
Delaware	1	2	3	4	5		
Hawaii	2	4	3	1	5		
Kentucky	N/A	N/A	N/A	N/A	N/A	N/A	
Maryland	2	3	5	4	6	1	One or more notable fatal accidents.
Massachusetts	1	2	3	4	5		
Minnesota	1						
Nevada	1	3	2	5	4		
New Hampshire	3	4	2	1	5	6	The above criterion is subjective, as we are not convinced as an agency that we will continue to use this device.
New Mexico	1	1	4	1	3		
Ohio	1	2	3	5	4	6	
Oregon	1	3	5	2	4		My opinion only.
Pennsylvania	1	2	3	4	5		
Virginia	1	2	3				
Washington	1	4	3	2	5	6	
Wyoming	1	2	3	5	4	6	Type of drivers common at the location.

Table B15 Summary of Responses to Question 8

Question 8: Given the most significant criteria for Question 7, will cost also be a significant criteria for installing centerline rumble strips?	
Responses	**Number of Responses**
Yes	6
No	12

Table B16 Responses to Question 8

State	Question 8: Given the most significant criteria for Question 7, will cost also be a significant criterion for installing Centerline Rumble Strips?	Comments
Alaska	No	Maintenance & Operations costs have not been significant.
Arizona	Yes	
California	N/A	
Colorado	No	
Connecticut	No	Although cost is important in the decision, a reduction in crash frequency would be a higher priority
Delaware	No	Our B/C was 110. It was a no brainer.
Hawaii	No	
Kentucky	N/A	
Maryland	No	
Massachusetts	No	
Minnesota	No	
Nevada	No	
New Hampshire	No	
New Mexico	Yes	
Ohio	No	
Oregon	Yes	
Pennsylvania	Yes	Low cost Countermeasure makes it very cost effective to use.
Virginia	Yes	
Washington	Yes	The actual answer should be Yes and No. Yes, cost is a criteria. However, with crashes being the top criteria, the small cost compared to the cost of a few head-on collisions would make it rare to rule out centerline rumble strips due to these criteria.
Wyoming	No	

Table B17 Responses to Question 9

State	Question 9: If conducting a cost/benefit analysis to determine if centerline rumble strips should be installed what benefit must exist to overcome the cost of installation? Please Explain
Alaska	N/A
Arizona	Hard to Quantify.
California	N/A
Colorado	N/A
Connecticut	A significant reduction of crashes.
Delaware	B/C must be >1. Maintenance should be provide if needed by location in the costs.
Hawaii	Cost is not an issue.
Kentucky	N/A
Maryland	Reduced crash costs.
Massachusetts	Safety, low crash rates in the future.
Minnesota	Clear reduction of fatal and severe injury accidents.
Nevada	Crash Reduction Benefits.
New Hampshire	No cost/benefit analysis conducted.
New Mexico	Safer and more efficient roadway.
Ohio	N/A
Oregon	B/C >1.
Pennsylvania	N/A
Virginia	N/A
Washington	As long as a B/C of 1+ exists on the section to have rumble strips installed they would get an OK. C = cost of rumble strip installation. B = reduction in societal cost of collisions that are PREVENTABLE with centerline rumble strips. (This process will likely get more refined as more installations occur.).
Wyoming	Reduction in fatality crashes.

Table B18 Summary of Responses to Question 10

Question 10: Have the centerline rumble strips used by your agency performed satisfactorily?	
Responses	**Number of Responses**
Yes	11
No	4

Table B19 Responses to Question 10

State	Question 10: Have the Centerline Rumble Strips used by your agency performed satisfactorily?	Comments
Alaska	Yes	Statistically significant accident data not yet available. Noise has been biggest issue.
Arizona	N/A	Still under evaluation.
California	N/A	
Colorado	Yes	We had a significant reduction in cross-over type accidents.
Connecticut	No	They were only installed for approximately 6 months, so a proper review of their performance cannot be conducted. They were installed to help reduce crossover crashes.
Delaware	Yes	We have had a 90% reduction in our Head on crashes while the traffic volumes have risen from 12k AADT to 21K AADT 6 yrs. Later.
Hawaii	N/A	No analysis has been run at this time.
Kentucky	N/A	
Maryland	No	
Massachusetts	Yes	They alert and avoid the drivers to go to the wrong direction of Travel.
Minnesota	Yes	The traveling public has had a favorable reaction to the installation of centerline rumble strips, while there appears to be limited conclusive evidence that centerline rumbles are preventing crashes.
Nevada	Yes	
New Hampshire	No	The jury is still out. We are not necessarily tracking crash statistics. I have personally been disappointed in the centerline visibility in these areas. We expected better nighttime retro reflectivity due to the inclined faces of the grooves, however it seems the grooves collect salt, sand, etc. and become less visible day and night time and tend to look like a dashed line.
New Mexico	N/A	Just recently (Nov 21st, 2001) been placed.
Ohio	Yes	
Oregon	Yes	
Pennsylvania	Yes	On going study/evaluation of sites by the Pennsylvania Transportation Institute.
Virginia	Yes	
Washington	Yes	Yes, we have seen a reduction in preventable collisions, and have not had any serious complaints from drivers.
Wyoming	No	they have only been installed for about one month, so we have no data to compare the performance.

Table B20 Summary of Responses to Question 11

Question 11: Have any unexpected problems been created by your use of centerline rumble strips (e.g., safety problems, maintenance problems, noise problems, etc.)?	
Responses	**Number of Responses**
Yes	7
No	10

Table B21 Responses to Question 11

State	Question 11: Have any unexpected problems been created by your use of Centerline Rumble Strips?	Comments
Alaska	Yes	Noise complaints pavement deterioration (if installed in marginal pavement).
Arizona	Yes	Pavement reveling.
California	N/A	
Colorado	No	There may be some concern about motorcycle and bicycle riders.
Connecticut	Yes	The rumble strips were removed (milled and filled in) after approximately 6 months of installation due to noise complaints from neighbors.
Delaware	No	We expected noise. We thought about stripping as no passing to make all noise illegal however due to the high percentage of trucks about 20% we had to allow passing.
Hawaii	No	
Kentucky	N/A	
Maryland	No	Some noise complaints, as were expected.
Massachusetts	No	
Minnesota	Yes	Some of the Emergency vehicle operators are critical of the centerline rumble strips. According to them, the roadway is more difficulty to patrol specially during high-speed chases. Further, an ambulance driver complained that driving across the rumble strips with a patient on monitoring devices may cause the devices to malfunction. Rumble strips could be a particular problem when a patient is on cardiac monitoring.
Nevada	No	
New Hampshire	Yes	The jury is still out. We are not necessarily tracking crash statistics. I have personally been disappointed in the centerline visibility in these areas. We expected better nighttime retro reflectivity due to the inclined faces of the grooves, however it seems the grooves collect salt, sand, etc. and become less visible day and night time and tend to look like a dashed line.
New Mexico	N/A	Just recently installed.
Ohio	Yes	Objectionable noise levels in urban locations.
Oregon	No	
Pennsylvania	Yes	State/Private Paint Trucks needed their carriages adjusted.
Virginia	No	Our application was on a rural primary road.
Washington	No	I am not aware of any safety or maintenance problems. While noise could be an issue, we do not have any installations (currently) near residential areas.
Wyoming	No	They have only been installed for about one month, so we have no data to compare the performance.

Table B22 Summary of Responses to Question 12

Question 12: Has any formal evaluation been conducted on the safety effect of centerline rumble strips?	
Responses	**Number of Responses**
Yes	5
No	13

Table B23 Responses to Question 12

State	Question 12: Has any formal evaluation been conducted on the safety effect of Centerline Rumble Strips?	Comments
Alaska	No	
Arizona	No	Not yet.
California	N/A	
Colorado	Yes	They significantly reduce cross-over type accidents on winding two lane highways.
Connecticut	No	
Delaware	Yes	The yearly Highway Safety Improvement Program has reported all data to the Federal Highway Administration.
Hawaii	No	
Kentucky	N/A	
Maryland	No	
Massachusetts	No	
Minnesota	No	
Nevada	No	
New Hampshire	No	
New Mexico	N/A	A formal evaluation is being conducted and once available will be forwarded as requested.
Ohio	No	
Oregon	Yes	Formal evaluation is in the process of being completed.
Pennsylvania	Yes	On going study/evaluation of sites by the Pennsylvania Transportation Institute. Study not yet completed.
Virginia	No	
Washington	Yes	A significant reduction in crossover crashes was seen in our first (and longest) test section.
Wyoming	No	They have only been installed for about one month, so we have no data to compare the performance.

Table B24 Summary of Responses to Question 13

Question 13: Has your agency created specifications, warrants, policies, or guidelines for the use of centerline rumble strips?	
Responses	**Number of Responses**
Yes	2
No	16

Table B25 Responses to Question 13

State	Question 13: Has your agency created specifications, warrants, policies, or guidelines for the use of Centerline Rumble Strips?
Alaska	No
Arizona	No
California	N/A
Colorado	No
Connecticut	No
Delaware	No
Hawaii	No
Kentucky	N/A
Maryland	No
Massachusetts	No
Minnesota	No
Nevada	No
New Hampshire	No
New Mexico	No
Ohio	No
Oregon	Yes
Pennsylvania	Yes
Virginia	No
Washington	No
Wyoming	No

Table B26 Responses to Question 14

Question 14: Please estimate the cost (use appropriate units) of installing Centerline Rumble Strips.		
State	**per lineal foot**	**per mile**
Alaska		1000
Arizona	N/A	
California	N/A	
Colorado	N/A	
Connecticut	N/A	
Delaware	0.20 to 0.60 depending on roadway conditions	
Hawaii		16,000.00
Kentucky	N/A	
Maryland	N/A	750 to 2,150
Massachusetts		1000
Minnesota	N/A	5000
Nevada	N/A	900
New Hampshire	No different than edge line	No different than edge line
New Mexico	0.2	
Ohio	N/A	1200
Oregon	0.4	
Pennsylvania	1.25	
Virginia	2 to 3	11000
Washington		1000
Wyoming		

Table B27 Summary of Responses to Question 15

Question 15: Do you have any other positive or negative experiences using centerline rumble strips that you would like to report, or any other general comments?	
Responses	**Number of Responses**
Yes	11
No	29

Table B28 Responses to Question 15

State	Question 15: Do you have any other positive or negative experiences using Centerline Rumble Strips that you would like to report, or any other general comments?	
Alabama	No	
Alaska	Yes	Our centerline rumble strips were 12" wide. This may be too wide.
Arizona	No	
Arkansas	No	
California	N/A	
Colorado	Yes	We received several positive comments from the public in the area where the rumble strips were installed.
Connecticut	Yes	There is no current plan to install more centerline rumble strips in Connecticut.
Delaware	Yes	Received a 2001 National FHWA Award for our project.
Florida	N/A	
Georgia	No	
Hawaii	No	
Idaho	N/A	
Illinois	No	
Indiana	No	The CL rumble strips would be a source for pooling water and freezing in the winter, thereby creating an accident potential for any motorist that might drive on the CL. We have 12 ft wide vehicles permitted on our roadways. Some of the roads that are used by these vehicles almost requires that they drive on the CL.
Iowa	No	
Kansas	No	
Kentucky	N/A	
Louisiana	No	
Maine	N/A	
Maryland	Yes	We expect to evaluate them later this year. Would appreciate receiving a copy of your survey results.
Massachusetts	No	
Michigan	N/A	

Minnesota	Yes	Issues for consideration and future research (By Michael Schweyen, District 6, Mn/DOT) 1. Do the rumble strips send a clear, easily understood message to the errant driver resulting in a definite and predictable driver reaction? Can the rumbles result in an incorrect driver reaction or an over-reaction? 2. Should rumble strips be installed only in No Passing Zones, or instead, along the entire stretch of involved roadway-including passing zones? Does the use of rumble strips in both passing and no passing zones send a conflicting message? 3. What precedent is set by installing rumble strips? What criteria should be used to determine where centerline rumble strips should be installed? Will the public demand that rumbles be constructed on other roadways, whether warranted or not? 4. Are the centerline rumbles truly effective? 5. Does the existence of the rumble strips on the centerline affect the nighttime effectiveness of the centerline striping? Are more painting materials required with a resultant higher cost? 6. Is the ponding of water or compaction of snow in the rumbles an issue? 7. What additional long-term maintenance needs are created for the pavement due to grinding of the rumbles? Are additional costs involved? Is the pavement life affected? 8. What maintenance issues for the rumble strips themselves are raised? Do the rumbles need to be re-ground into the pavement every few years? Do certain maintenance practices tend to prolong or decrease rumble strip life?.
Mississippi	No	
Missouri	No	WE have considered centerline rumble strips and are in favor of trying some out. We are presently asking upper management for a final go ahead and think that will happen within the next 12 months. We would appreciate the information you discover from your survey. Thank You.
Montana	N/A	There are some traffic engineers who are still on-the-fence about centerline rumbles. But New information on the effectiveness of centerlines may initiate experimentation.
Nebraska	No	
Nevada	No	
New Hampshire	Yes	As with any other device that is reluctantly installed by an agency to appease a local interest, the initial installations have encouraged others to request similar treatments. The primary function of the devices should be to warn motorists that they have drifted over the centerline, either from inattention or drowsiness, but they seem to be requested to keep aggressive drivers from passing inappropriately.
New Jersey	N/A	
New Mexico	N/A	Still in the evaluation phase will forward additional information as they become available.
New York	N/A	
North Carolina	N/A	
North Dakota	No	
Ohio	No	
Oklahoma	No	How does effect the integrity of the pavement.
Oregon	No	
Pennsylvania	Yes	Feedback from our customers--they like the rumble strips also in the winter, when the roads are snow covered, they alert drivers where the center of the road is located.
Rhode Island	N/A	
South Carolina	No	
South Dakota	No	
Tennessee	No	

Texas	Yes	We have a research project slated for FY03 to investigate the benefits of rumble strips (including this type).
Utah	No	
Vermont	No	
Virginia	No	
Washington	Yes	A general comment. The largest test section runs about 40 miles. It uses spacing of 1 foot AND 2 foot on-center. (Distance between the center of each cut = 1 or 2 feet.) These sections alternate every 5 miles (5 miles of 1 foot spacing followed by 5 miles of 2 foot spacing, etc.). This tested both the effectiveness of the different spacing distances as well as the comfort level for people crossing over the rumble strips when passing (the section is on a 2-lane highway, through both passing and no-passing zones). The crash reduction was higher with the 1 foot spacing, as expected. The comfort level is higher with the 2 foot spacing, also as expected.
West Virginia	No	
Wisconsin	N/A	
Wyoming	No	

APPENDIX C
Crashes Evaluated: 1995 - 2000

APPENDIX D
Crash Analysis Statistical Procedure and Results

Statistical Procedure

After selecting the crashes in each study sections, the Before and After (BAA) statistical analysis with comparison sites was completed (24). As presented in the report, the BAA procedure considers crash frequencies before and after the installation of centerline rumble strips. To estimate the safety effect of the centerline rumble strip installation, the procedure computes a predicted estimate of safety (i.e., crash frequency) in the after period, assuming that the centerline rumble strip had not been installed. This predicted value accounts for the influence of causal factors that change with time by considering crash trends at the study site before the centerline rumble strip installation as well as at one or more comparison sites. Comparison sites were roadways similar in all accounts except that no centerline rumble strips existed. Predicted crash values are compared to actual crash values in the after period to determine the safety effects of the centerline rumble strips. Therefore, if the number of crashes predicted is greater than the actual number of crashes after the installation of centerline rumble strips, and outside of the variability range measured by the standard deviation, a positive safety benefit is found.

Crashes selected and analyzed are presented in Appendix C. The statistical process can be summarized as follows. Let:

λ = expected number of crashes that took place in the after period
π = predicted number of crashes in the after period if the centerline rumble strips were not installed
K = number of crashes in the before period at study site
L = number of crashes in the after period at study site
M = number of crashes in the before period for the comparison site
N = number of crashes in the after period for the comparison site
r_t = ratio of the expected crash counts for the treatment site
r_c = ratio of the expected crash counts for the comparison sites
$\delta = \pi - \lambda$ = reduction in the after period of the expected number of target crashes
$\theta = \lambda/\pi$ = estimated of the safety benefits of installing centerline rumble strips

For each study site λ, π, δ and θ and their variances were calculated. This was done with the help of the following formulae:

$\lambda = L$ | $Var(\lambda)=L$

$r_t = r_c = (N/M)/(1+1/M)$ | $Var(r_r)/r_t^2 = 1/M + 1/N$

$\pi = r_t * K$ | $Var(\pi) = \pi^2[1/K + Var(r_t)/r_t^2]$

$\delta=\pi-\lambda$ | $Var(\delta) = Var(\pi) + Var(\lambda)$

$\theta= (\lambda/\pi)/ [1 + Var(\pi)/ \pi^2]$ | $Var(\theta) = \theta^2[Var(\lambda)/ \lambda^2 + Var(\pi)/ \pi^2]/ [1 + Var(\pi)/ \pi^2]^2$

Once the safety benefit in each site was evaluated, data had to be pooled to get the overall safety effect of the installation. To calculate λ, π, δ, and θ and their variances for the pooled data, the following equations were used:

$\lambda = \Sigma\, \lambda\, (j)$ $\quad$ $Var(\lambda)=\Sigma\, Var\{\lambda(j)\}$

$\pi = \Sigma\, \pi\, (j)$ $\quad$ $Var(\pi)=\Sigma\, Var\{\pi\, (j)\}$

$\delta=\pi-\lambda$ $\quad$ $Var(\delta) = Var(\pi) + Var(\lambda)$

$\theta= (\lambda/\pi)/ [1 + Var(\pi)/ \pi^2]$ $\quad$ $Var(\theta) = \theta^2[Var(\lambda)/ \lambda^2 + Var(\pi)/ \pi^2]/ [1 + Var(\pi)/ \pi^2]^2$

Using the above equations, δ and θ can be determined; thus, evaluating the safety benefits of the centerline rumble strips installations.

Traffic volume is another variable that can affect crash frequencies. Accounting for the effects of traffic volume could provide a better estimate of the safety benefits. Therefore, the next step was to complete a before and after analysis taking traffic volumes into account. A linear relation between the number of crashes and the traffic volume was assumed (24). Let r_{tf} indicate the coefficient for traffic volume. The appropriate equations for this analysis included:

$\lambda = L$ $\quad$ $Var(\lambda)=L$

r_{tf} = Average Traffic volume in After Period / Average Traffic Volume in Before Period

$r_t = r_c = (N/ r_{tf} M)/(1+1/ r_{tf} M)$ $\quad$ $Var(r_r)/r_t^2 = 1/M + 1/N + Var(w) + Var(r_{tf}) / r_{tf}^2$

$\pi = r_t{*}r_{tf}{*}\, K$ $\quad$ $Var(\pi) = r_{tf}^2{*}K^2{*}Var(r_t) + r_{tf}^2{*}r_t^2{*}Var(K) + r_t^2{*}K^2{*}Var(r_{tf})$

$\delta=\pi-\lambda$ $\quad$ $Var(\delta) = Var(\pi) + Var(\lambda)$

$\theta= (\lambda/\pi)/ [1 + Var(\pi)/ \pi^2]$ $\quad$ $Var(\theta) = \theta^2[Var(\lambda)/ \lambda^2 + Var(\pi)/ \pi^2]/ [1 + Var(\pi)/ \pi^2]^2$

Once the δ and θ for each of the treatment sites were calculated, an evaluation of the overall safety benefits of centerline rumble strips was completed. To calculate λ, π, δ, and θ, and their variances for the pooled data, the following equations were used:

$\lambda = \Sigma\, \lambda\, (j)$ $\quad$ $Var(\lambda)=\Sigma\, Var\{\lambda(j)\}$

$\pi = \Sigma\, \pi\, (j)$ $\quad$ $Var(\pi)=\Sigma\, Var\{\pi\, (j)\}$

$\delta=\pi-\lambda$ $\quad$ $Var(\delta) = Var(\pi) + Var(\lambda)$

$\theta= (\lambda/\pi)/ [1 + Var(\pi)/ \pi^2]$ $\quad$ $Var(\theta) = \theta^2[Var(\lambda)/ \lambda^2 + Var(\pi)/ \pi^2]/ [1 + Var(\pi)/ \pi^2]^2$

Using the above equations δ and θ can be determined, thus evaluating the safety benefits of the rumble strips installations.