Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Audible Edge Stripe

Prepared by the

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California Department of Transportation
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16. ABSTRACT

In order to find a rumble strip which is both effective in preventing run-off-road collisions and bicycle friendly, eleven prototypes of incised, pressed and proprietary rumble strip configurations were installed at the Caltrans Dynamic Test Facility in West Sacramento, California for testing. The objectives were (1) to collect sound level and vibration data from various test vehicles equipped with recording instruments while being driven over the rumble strips, and (2) to collect subjective driver input on vehicle sound, vibration and vehicle controllability while driving over the same rumble strips and (3) evaluate the installed rumble strip treatments with bicycle and motorcycle rideability.

Results of the instrumented and subjective testing of the rolled and milled-in strips using light vehicles concluded that all five strips provided adequate alerting properties for both sound and vibration. However, due to the commercial vehicles size, weight and operating noise levels, it was found that the strips had alerting values ranging from low to insignificant. Results of the instrumented and subjective testing for the proprietary materials using light vehicles found that the chip seal and raised profile thermolastic had alerting values ranging from low to insignificant. The raised pavement markers, Carsonite bars, and raised and inverted profile thermoplastic provided adequate alerting properties for both sound and vibration.

EXECUTIVE SUMMARY

The goal of this study was to evaluate and provide a ground in rumble strip treatment that could be traversed by bicyclists. The new rumble strip treatment would maintain sufficient audible noise and/or tactile vibration to alert the driver of an errant vehicle and to prevent a potential run off road collision. Ground in strips of various widths and depths have been used at various locations on the state highway system to provide a fast response to run off road collisions, which result in severe injuries and fatalities. They have been demonstrated to provide substantial reductions in run off road collisions similar to those provided by rolled in rumble strips, which are commonly used on the California highway system. Concerns about the use of ground in rumble strips from the bicycle community were expressed to the Department by the California Bicycle Advisory Council and the Caltrans representative to this group Mr. Rick Blunden.

In response to the concerns voiced by the bicycle community and interested in obtaining the use of a new rumble strip tool that could be used to minimize run off road collisions This report "The Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Proprietary Applications" was completed. The report was developed at the request of a Rumble Strip Task Force, which was convened in August of 1998 by Ms. Kim Nystrom, Chief of the Caltrans Office of Transportation Safety Program and Research. The committee chaired by Mr. Craig Copelan of the Traffic Safety Research branch recommended that a study be prepared to evaluate types of ground in rumble strips that would be most suitable for use on the state highway system where bikes are allowed and to incorporate feedback from the bicycle community in the development of these rumble strips.

In February of 1999, the Rumble Strip Task Force requested that the Office of Transportation Safety place a moratorium on the installation of ground in rumble strips (where bicycles were allowed), until a study of ground in rumble strips, as well as other rumble strip types, could be conducted. In March of 1999, the Office of Transportation Safety placed the moratorium on the installation of ground in rumble strips and directed the Traffic Research

Branch to conduct a study on a variety of rumble strips types which would incorporate input from the bicycle community.

The criteria outlined by the Rumble Strip Task Force were,

1) to review current practices of Rumble Strip Treatments where bicycles are allowed access,
2) to compare current and newly developed treatments that may produce similar results in reducing run off road collisions, and provide a surface that was traversible by bicyclists, and
3) to maintain current noise and vibration acceptability factors for rumble strip treatments.

As a result of this study, the following changes in current practice and policy are recommended:

1. Adopt a *new* Standard Plan A40 for rolled-in indentations and ground-in indentations as shown on page 65. The new standard plan would reduce the effective width of the current rolled in indentation (see page 9) from 600 mm (2 feet) to 300 mm (1 foot), and add a ground in indentation with a depth range of 8 ± 1.5 mm (5/16 ± 1/16 inch) and an effective width of 300 mm (see page 65). The new standard plan requires a minimum 1.5 m (5 foot) shoulder for installation.
2. Allow for the installation of raised/inverted profile thermoplastic traffic stripe as a substitute for rumble strip treatment in areas where the shoulder is less than the required 1.5 m for ground in and rolled in indentations, and to provide a continuous rumble strip pattern over bridge decks where rumble strips may be place on either or both sides of a bridge deck.
3. Adopt the installation (page 66) which guides the placement of rumble strip treatments based on shoulder width and bicycle use.
4. Revise the Caltrans Traffic Manual to address changes in the current policy and include the Rumble Strip Installation Guide, as well as a reference to the Rumble Strip Indentation Construction Detail, for the placement of rumble strip indentations on the shoulder, over

bridge decks and at the approach and exit of entrance/ exit ramps (See Appendix F: TOP D#00-04).

It is recommended that these changes take effect immediately and manuals and plans be updated as soon as possible. It is further recommended that the Highway Safety Improvement Program conduct a before and after studies, at those locations where ground in rumble strips are installed using this new policy to evaluate the new policy change and to measure the effectiveness of the new type of rumble strips in reducing run off road collisions. The results of these before and after studies should be reported in the Highway Safety Improvement Program Annual report.

1.0 INTRODUCTION

1.1 BACKGROUND

Research regarding run-off-road and over-embankment collisions by the California Department of Transportation (Caltrans) began in the 1960's. One of the most comprehensive studies done by Caltrans was done in 1977. In this 1977 study, a test car equipped with instrumentation was driven across different configurations of rumble strips to collect data about sound and vibration that was produced by the test strips. The strips were tested for optimum sound and vibration at varying ranges of speed. In 1989, a shoulder rumble strip study was completed by Caltrans to evaluate shoulder rumble strips. The findings were that installations of rumble strips on both the median and right shoulder decreased drift-off-the-road collisions by approximately 49% on Interstates 5 and Interstate 40. Where rumble strips were installed on the right side of the road only on I5 and I40, a 63 percent reduction was realized. No testing of rumble strips by the State of California to date has examined the effects that rumble strips may have on bicyclists level of comfort and safety, and their use of these state routes.

Nationally, single vehicle run-off-road collisions account for one out of every three fatal collisions and 36 percent of the total fatalities (FHWA Website (http://www.fhwa.dot.gov., September 2000). In 1997, 11,126 collisions were coded in the Fatal Analysis Reporting System (FARS) as single vehicle run-off-road collisions.

1.2 NATURE OF THE PROBLEM TO BE ADDRESSED

To address the problem of run-off-road collisions on California's highways, rolled-in rumble strips have been used extensively. In a few test locations ground (milled)-in shoulder rumble strip (MSRS) treatments have been installed on an experimental basis to alert drivers who are drifting to the right of the traveled way. Rolled in rumble strips are commonly included in projects, which include installation of asphalt concrete paving on the shoulders of a roadway section. Milled-in rumble strips have been installed in locations where a means to reduce run-off-road collisions was needed and no construction project was not planned in the near future.

Caltrans currently has a standard plan (Figure 1 - 1999 Standard Plan A40) for rolled-in rumble strips. This treatment type has typically been installed on asphalt concrete (AC) shoulders during new construction or rehabilitation, resurfacing or reconstruction (RRR projects).

Since experimental MSRS applications have been installed on the state highway system where bicycles are allowed, the bicycle community has raised concerns. These concerns revolve around both the design and placement of the rumble strip application on the shoulder. MSRS have caused the greatest concern for bicyclists because of the depth of the MSRS (typically ½" to 5/8" in depth). Some bicyclists have stated that MSRS can cause discomfort, instability and the potential for loss of control.

Cycling along the shoulder of a roadway requires an area of clear smooth pavement between the edge stripe and the outer edge of the shoulder or guardrail for the cyclist to navigate freely. When obstacles are encountered in this area, it is often necessary for the cyclist to leave the shoulder by crossing over the edge stripe into the traffic lane then crossing back over the edge stripe back into the shoulder area. The average cyclist should be able to traverse back and forth across rumble strips at normal bicycle speeds. Cyclist should not have to experience fatigue and anxiety created from long rides where they must continuously ride next to, on or over rumble strips.

To date not enough research or testing has been compiled to satisfy the rumble strip bicycle compatibility and safety problems.

1.3 STUDY OBJECTIVES

The objective of this study is to test a variety of rumble strip and edge stripe treatments to determine which applications are the most acceptable to bicyclists, and still provide sufficient audible and vibratory sensation to alert automobile drivers. The Traffic Operations Program, through the Office of Transportation Safety and Research (OTSR), organized a Rumble Strip Task Force (RSTF) to evaluate and make recommendations to the OTSR. The

RSTF made a recommendation that MSRS should not be placed on shoulders where bicyclists are allowed until further testing was completed to evaluate the safety of the treatments. In March of 1999, the OTSR sent a letter to all Caltrans districts suspending the use of MSRS on routes were bicyclists where allowed (See Appendix G).

This suspension did not affect installation on limited access freeways nor did it affect median rumble strip applications. In May, 1999, the OTSR began developing a project to test rumble strip treatments and develop several rumble strip patterns, styles and configurations. The goal of these tests were to find treatments(s) that were effective in alerting inattentive/drowsy drivers to reduce run-off-road collisions through audible and tactile sensations in the vehicle, and to also provide a treatment that could be comfortably traversed by a bicyclist if required.

1.4 SCOPE OF THE RESEARCH

In September of 1999, the OTSR obtained research funds to conduct a study on the use of shoulder rumble strips (SRS) where bicycles are allowed. To achieve the objective, the OTSR team developed, installed, and tested selected rumble strip designs at the Caltrans Dynamic Test Facility test track in West Sacramento, California. The selection of designs was done in consultation with the California Bike Advisory Committee, American League of Bicyclists, Federal Highway Administration, American Association of State Highway and Transportation Officials, and the Caltrans Rumble Strip Task Force.

The initial testing involved instrumentation and subjective testing of six vehicle types (Chevy Lumina, Dodge Spirit and Dodge Ram 150 pick up at 80 and 100 kph and truck tests using a International tractor, Volvo 10 wheel dump truck, and a Hertz Penske cargo truck).

A survey questionnaire was developed prior to testing to obtain information regarding Californians experience with SRS treatments. The survey was sent out to over 22,000 individuals via the Internet. Volunteer bicyclists from the community and Caltrans were invited to participate in bicycle research of the eleven rumble strip treatments selected. A separate questionnaire was tailored to correspond with a survey conducted by Pennsylvania

DOT on this topic so that information could be easily compared. The website survey was also intended to develop a list of participants who would be willing to volunteer in a follow-up bicycle field test. After developing this list, the volunteers were invited to a field test where they rode with various bicycle types over eleven rumble strip patterns. A questionnaire had been provided to each volunteer to complete. The questionnaire was completed on site after participants rode over the eleven selected rumble strip treatments. Analysis of this data along with field test results of the vehicle test, subjective drivers ratings, and collision data on run-off-road collisions were used to develop recommendations.

The recommendations developed were the basis for Caltrans Management's decision to select road sites that will be chosen for the installation of rumble strips and audible edge stripe at locations that have experienced high run off road collisions. The sites will be categorized by type(s) of treatment that will be appropriate at that site (e.g. narrow shoulder use audible edge stripe). A report will be completed of the findings based upon the before and after run-off-road experience at these locations. Rumble strips that are determined to be most efficient will be installed at selected locations throughout the state on the state highway system.

This report is the final product of this research project and summarizes the research conducted by Caltrans to develop and evaluate the potential of "bicycle-friendly" rumble strips and compare results with other DOT's who had completed similar studies.

2.0 LITERATURE REVIEW

The purpose of the literature review was to examine previous work completed on this subject matter on the safety benefits of shoulder rumble strips and the affects on bicyclists in locations where bicyclists are allowed on the state highway system as outlined under the 2000 California Vehicle Code sections 21200-21210, 21,960, 39000 – 39009 and 39011.

A number of studies have been conducted to determine the most effective rumble strip designs. As stated earlier, few studies considered the effect of rumble strip designs on bicycles.

2.1 PURPOSE OF RUMBLE STRIPS

A rumble strip is a raised or grooved pattern placed on the pavement surface of a travel lane or shoulder (Harwood 1993). Rumble strips are intended to provide motorists with an early warning audible and tactile sensation as they approach a decision point of critical importance to their safety or to alert the motorist that their motor vehicle has partially or completely left the travel lane.

The noise generated as a motor vehicles tires pass over a rumble strip treatment designed to reduce run-off-road collisions provides an audible warning to the motorist, while vibration induced in the motor vehicle by the rumble strips provides a tactile warning typically felt from the steering wheel and floorboard. Although rumble strips alert motorists of potential decision points or roadside hazards, rumble strips do not identify what type of action is appropriate.

Rumble strip applications fall into three general categories:

1. Rumble strips placed in the travel lane
2. Rumble strips placed on highway shoulders
3. Rumble strips placed in the median

When rumble strips are placed in the travel lane, their purpose is to alert motorists of approaching intersections, toll plazas, horizontal curves, work zones, or any other unexpected conditions. Rumble strip treatments currently are not recommended in the traveled way as outlined in the Caltrans Traffic Manual section 6-03.2 (July 1996) item 1. When rumble strips are placed on highway shoulders or in the median, they are used to alert motorists that they are departing from the traveled lane and that a steering correction is necessary. Rumble strip treatments that have been installed in California in a median have been used primarily to reduce cross-centerline median collisions. This type of treatment is typically installed in rural locations where concrete median barrier is not feasible due to right-of-way limitations. This study focuses on applications of rumble strips in the shoulder, which are most likely to affect bicyclists. Sufficient data from vehicle testing and motorcycle testing was collected as part of this study to make recommendations for rumble strip treatments in a variety of placement locations on the state highway system.

Several highway agencies have placed shoulder rumble strips on multilane divided freeways, multilane undivided non-freeways, and two-lane highways. Rumble strips have been placed on both the right (outside) and left (median) shoulders of divided highways. A recent nationwide survey completed in February 2000 by the Minnesota Department of Transportation summarizes uses of continuous milled shoulder rumble strips by 36 of 50 states that responded to the survey. Caltrans was one of the 36 states that did participate in this survey.

2.2 TYPES OF RUMBLE STRIPS

According to the Federal Highway Administration, rumble strips are raised or grooved patterns on, or in the travel lane and shoulder pavements. Road agencies use rumble strips to warn motorists of an upcoming change. For example, the need to slow down for a toll plaza ahead, change lanes for a work zone around the curve, stop for a traffic signal, or steer back onto the roadway. Rumble strips in travel lanes often precede intersections. They are used primarily on expressways, interstate highways, and parkways, although some States install them on 2-lane rural roads. There are four types of rumble strips: milled, rolled, formed, and raised. They differ primarily in the installation method, their shapes and sizes. Different amounts of vibration and noise levels are produced by each of the four types.

Milled rumble strips are currently the prevalent type of rumble strip among highway agencies (http://www.ohs.fhwa.dot.gov/rumblestrips/). They are installed on new or existing asphalt and Portland cement concrete shoulders. This type of rumble strip is made by a machine, which cuts a smooth, uniform groove in the shoulder surface.

Rolled rumble strips must be installed when the constructed or reconstructed asphalt concrete shoulder surface is compacted. Grooves are pressed into the hot asphalt surface by a roller with steel pipes welded to the drums. Depressions are created as the roller passes over the hot asphalt surface.

Formed, or corrugated, rumble strips are installed along Portland concrete cement (PCC) shoulders. Grooves or indentations are formed into the concrete surface during the finishing process.

Raised rumble strips are strips of material that adhere to new or existing shoulder surfaces. Different materials that have been used include asphalt bars and raised pavement markers. Thermoplastic materials that are configured with raised bumps are also used in California where there is a limited shoulder or as an addition (striping with raised bump for added vibration and noise) to a milled rumble strip section. Use of raised rumble strips is usually restricted to warmer climates due to maintenance difficulties resulting from snow removal. Some difficulties may arise with Maintenance in locations that have high rock fall concentrations due to the scrapping or sweeping of the road t clear rock debris.

2.2.1 SHAPES AND DIMENSIONS

Shoulder rumble strips are constructed in various shapes. Figure 1 illustrates the July 1999 California Standard Plan (A40) for a rolled-in rumble strip for installation in an asphalt concrete shoulder. Typically, along asphalt shoulders, rounded or v-shaped grooves are installed, but the strips may also take rectangular and tapered shapes. Figure 1A is an illustration of a typical asphalt or Portland concrete cement installation.

Rumble strips may be placed continuously along the shoulder or spaced intermittently. California installs all rumble strip treatments in a continuous manner with natural breaks at ramp intersections. Figure 1B illustrates typical rumble strip applications across the United Stated on asphalt shoulders, and Figure 1C illustrates typical applications on PCC shoulders.

Figure 1. 1999 Standard Plan A40

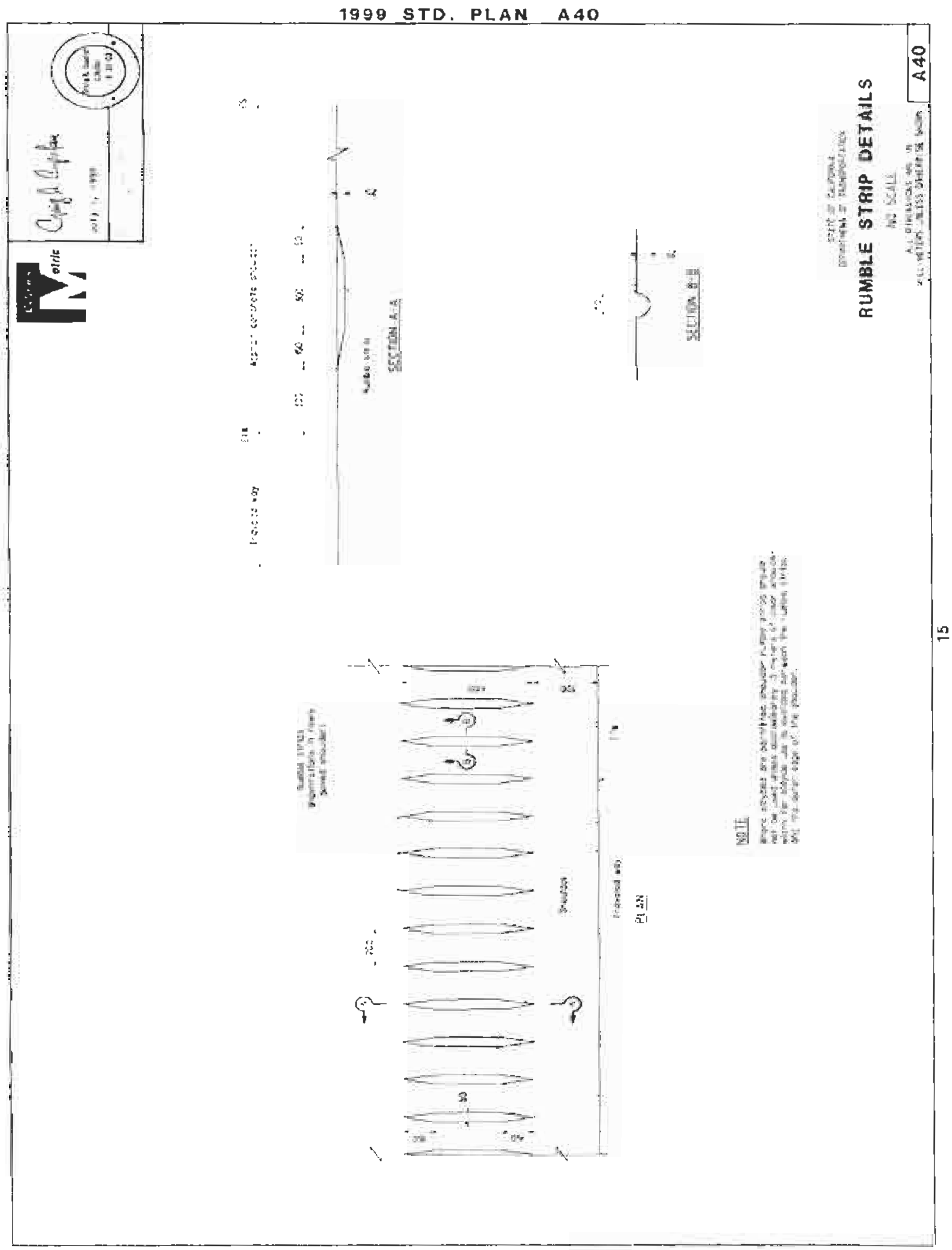


Figure 1A

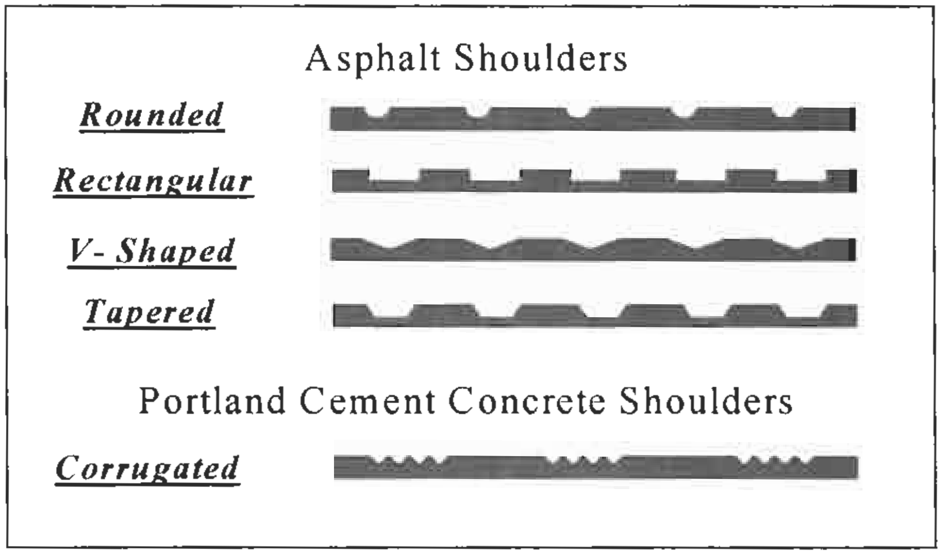


Figure 1A. Typical shapes of rumble strips along shoulders.

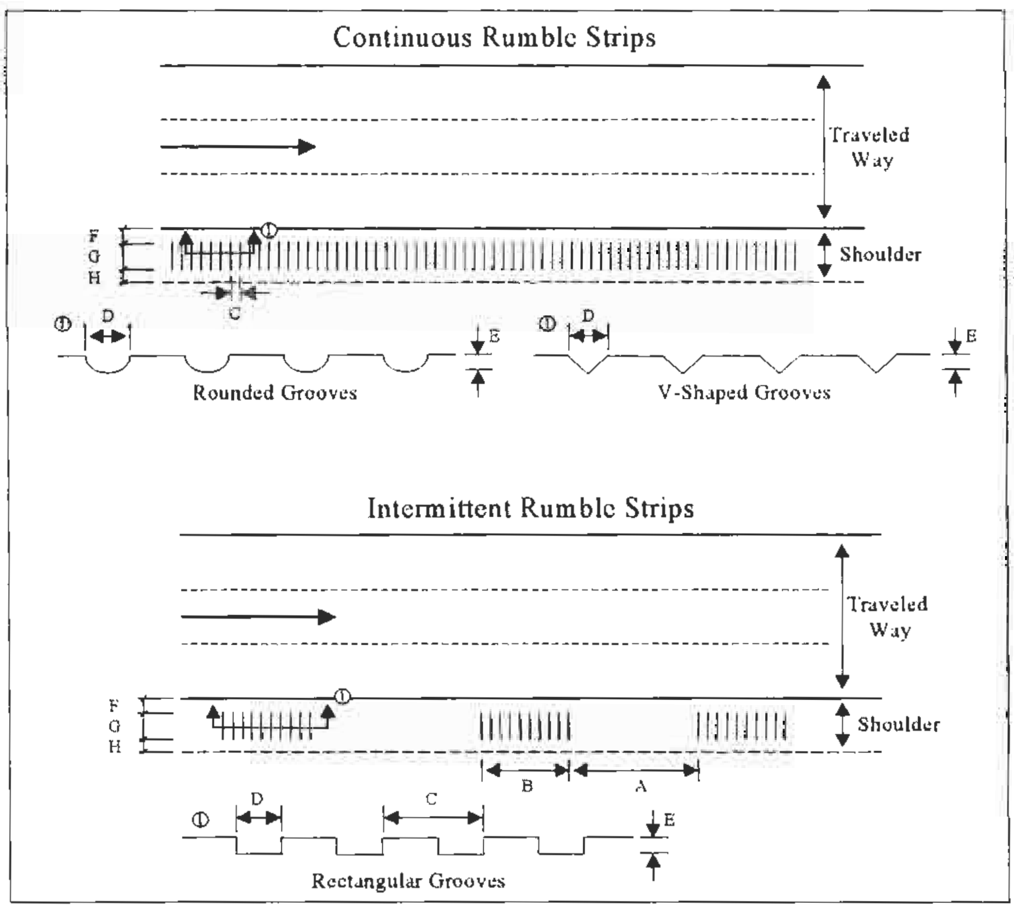


Figure 1B. Typical rumble strip applications on asphalt shoulders (Harwood 1993).

Some problems have been reported associated with the installation of shoulder rumble strips. Reported problems related to the installation of rolled rumble strips include the aggregate being crushed by the ribs of the roller, shoving of the asphalt, and the pipes of the roller flattening with use. The major installation concern with milled rumble strips is the high price of installation, and some problems with asphalt breakup between grooves have been reported (PENN DOT, 1999).

A request for evaluation by Caltrans Maintenance personnel on the maintainability of the eleven rumble strip treatments that were tested resulted in no unfavorable responses. Although each treatment requires specific machinery to maintain, none of the treatments were discouraged for use on the State Highway System.

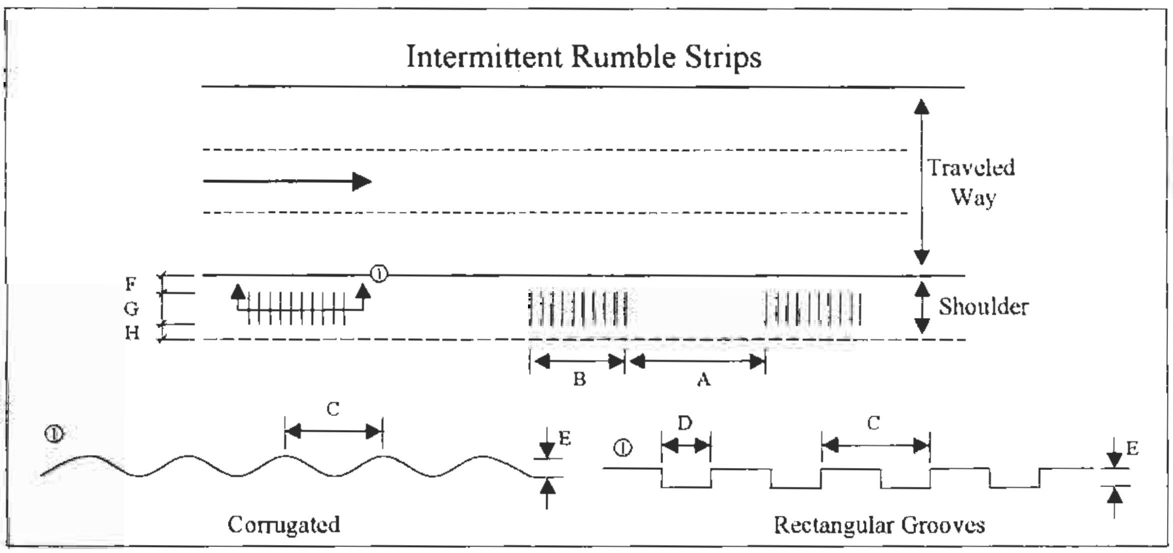


Figure 1C. Typical rumble strip application on PCC shoulders (Harwood 1993).

3.0 STATEWIDE RUMBLE STRIP SURVEY

In order to select a sample of bicyclists for the field test, a survey (See appendix A for survey) was designed to be completed by a large pool of participants. Given scheduling and funding limitations, the designed survey was made available on a Caltrans internet web site. The entire Caltrans staff as well as several hundred bicycle groups nationwide were e-mailed the site address. From the survey results, we intended to get a sense of who the target audience was, and based on that, make more intelligent choices in selecting rumble strip type. The responses from the survey would be used to select an appropriate sample of bike riders who would participate in a follow up field test of various rumble strips.

The survey made available on the Caltrans internet web site was filled out by more than five thousand people including many experienced bicyclists who were contacted through bike clubs.

4.0 VEHICLE TESTING

4.1 BACKGROUND

The Caltrans Traffic Operations Program, Traffic Safety Branch was involved in a research project titled "Incorporating Shoulder Improvements, Rumble Strips, and Audible Edge Stripe Under the Clean Up the Roadside Environment (CURE) Program". The purpose of this project was to study a variety of rumble strip treatments to determine which are the most acceptable to bicyclists and still perform adequately to prevent vehicle run-off-road collisions. The Traffic Safety Branch requested the Caltrans Roadside Safety Technology Branch of the Division of Materials Engineering and Testing Services to evaluate five different configurations of recessed rumble strips and six different audible edge strips for their vibration and sound characteristics. Current configurations of rumble strips have become a safety concern for bicyclists who share routes with the motoring public.

Caltrans has been utilizing certain test configurations of milled or rolled-in shoulder rumble strips as a means to alert vehicle drivers who are drowsy or asleep and prevent run-off-road collisions. Some of these types and installations of rumble strips were studied in a 1976 Caltrans report, "Devices to Prevent Run Off Road Collisions". Although these roadside treatments have been effective in keeping vehicles and their passengers on the road, they may have caused difficulty for bicyclists.

4.2 OBJECTIVE

The objectives in vehicle testing were twofold. The first was to collect and evaluate sound level and vibration data taken from various vehicles being driven over eleven different rumble strip designs. The second objective was to collect and analyze subjective driver input on vehicle sound, vibration and controllability when driving over these rumble strip designs. Results from this study, along with results from recent testing conducted by Pennsylvania State Department of Transportation, will be to develope a standard milled-in, rolled-in, and/or audible edge stripe that are effective in addresing run-off-road collisions and are bicycle compatible.

4.3 TECHNICAL DISCUSSION

4.4 TEST FACILITY

The Caltrans Dynamic Test Facility, located at the California Highway Patrol Academy in West Sacramento, California, consists of 6.5 acres of asphalt pavement designed for full scale testing of roadside safety features. The test site map for the facility is provided in Appendix D.

4.5 TEST RUMBLE STRIP CONSTRUCTION

The Traffic Safety Branch coordinated the installation of a new asphalt overlay and rumble strips at the Caltrans Dynamic Test Facility. Five different rumble strip configurations were installed, in series, 4.6 m from the west edge of pavement of the newly resurfaced test area. Series "A" rumble strips included one rolled-in and four milled-in rumble strips and were numbered one through five. Each rumble strip section was 30.5-m long and spaced 15.2 m from the next strip (Figure 1.1).

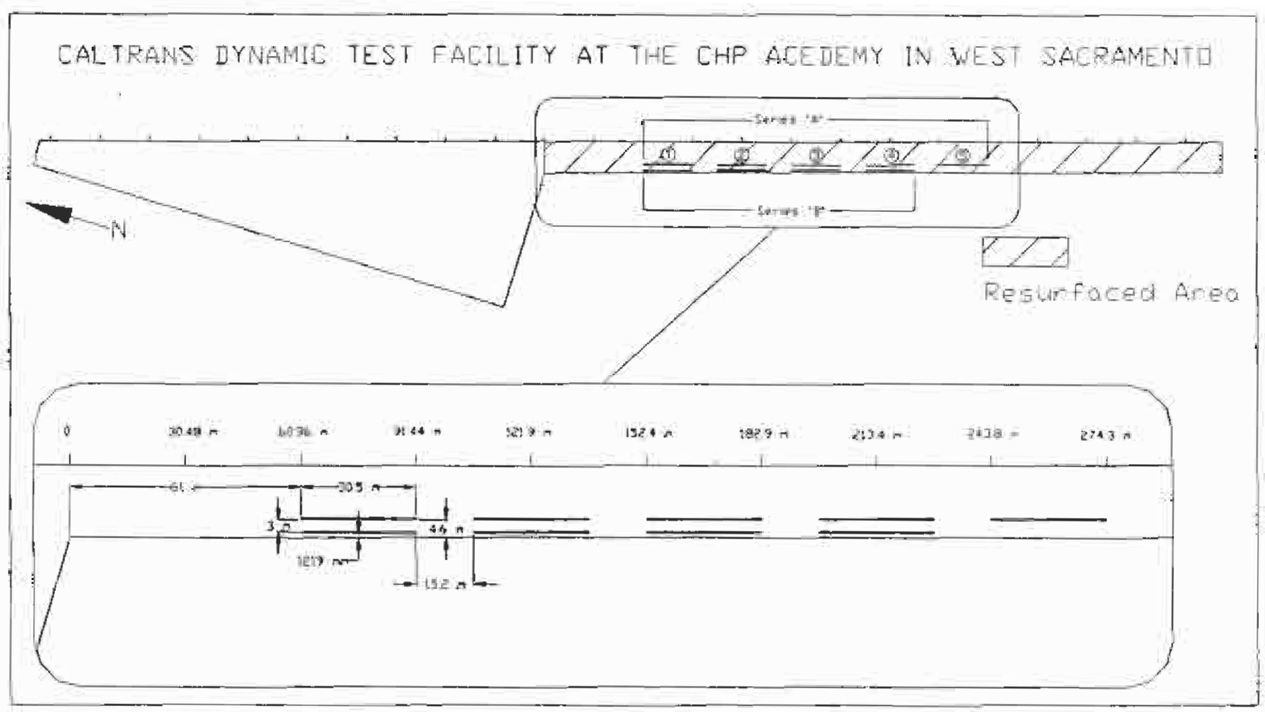


Figure 1.1. Rumble Strip Layout

4.6 SERIES "A" RUMBLE STRIPS

4.6.1 STRIP #1 - ROLLED-IN RUMBLE STRIP

Strip #1, a rolled-in rumble strip, was installed according to Caltrans Standard Plan A40 (Figure 1). The 600 mm-wide, rolled-in rumble strip requires new hot asphalt for installation. A series of steel half-pipes with a radius of 25 mm were welded onto a 3-meter steel plate that was pressed into the hot asphalt with an 11-ton roller, indenting the asphalt with the desired pattern (Figure 2). The first attempt at installing strip #1 was not accepted because the strip was not rolled-in straight, and wasn't uniform in depth and width. It was necessary to saw-cut and remove the unsatisfactory strip then re-pave and re-roll a new strip. The replacement resulted in a slightly less than flat asphalt surface around strip #1, but was determined to be acceptable for the tests. The final constructed strip is shown in Figure 3.

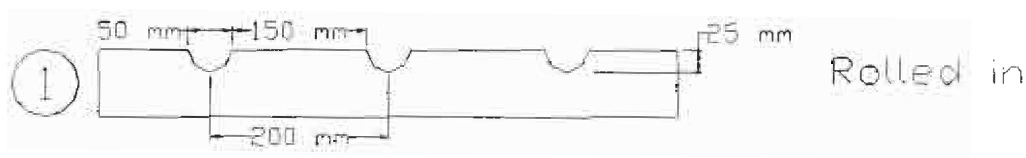


Figure 2. Rolled-In Rumble Strip Pattern

Figure 3. Strip #1 - Rolled-In Rumble Strip Standard Plan A40

4.6.2 STRIPS #2, #3, #4, #5 - MILLED IN RUMBLE STRIPS

Rumble strips 2, 3, 4, and 5 were all installed by milling out the asphalt according to design specifications determined by the Traffic Safety Branch and what the industry could grind at the time of installation. Due to grinding wheel limitations and availability, depths were selected and the resulting length and width were a result of the grinding wheel dimensions. A cold milling machine with a 406 mm wide x 610 mm diameter adjustable depth cutting drum shown in Figure 4 was used to install strips 2, 3, 4, and 5 (Figure 5).

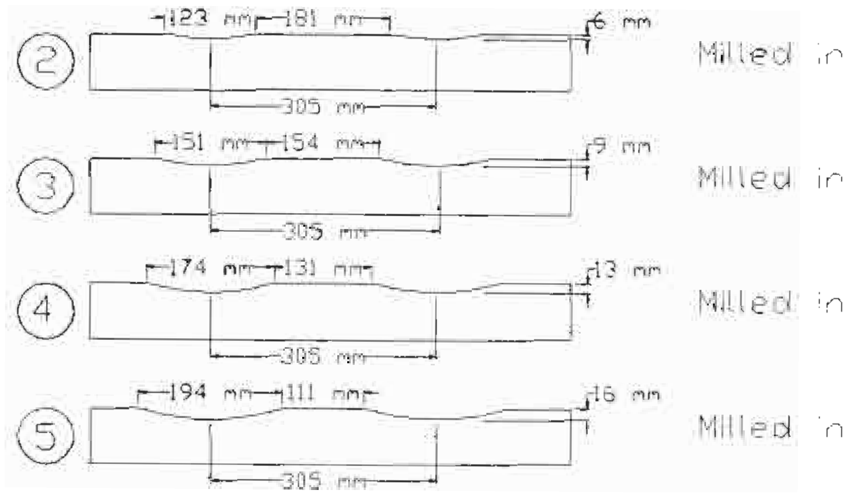


Figure 4. Milled-In Rumble Strip Patterns

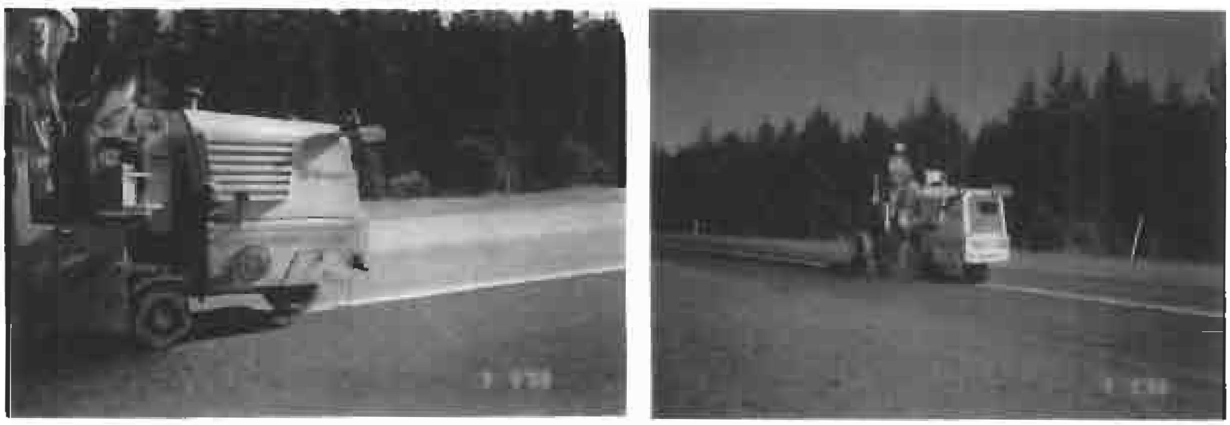


Figure 5. Cold Milling Machine

Figure 6. Strip #2 – ¼" Milled Strip

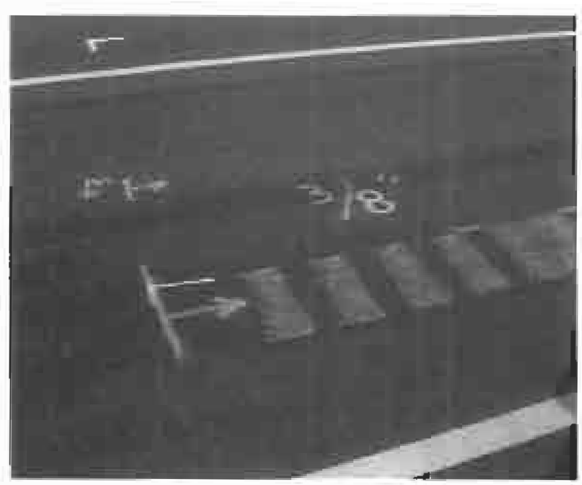


Figure 7. Strip #3 – 3/8" Milled Strip

Figure 8. Strip # 4 – ½" Milled Strip

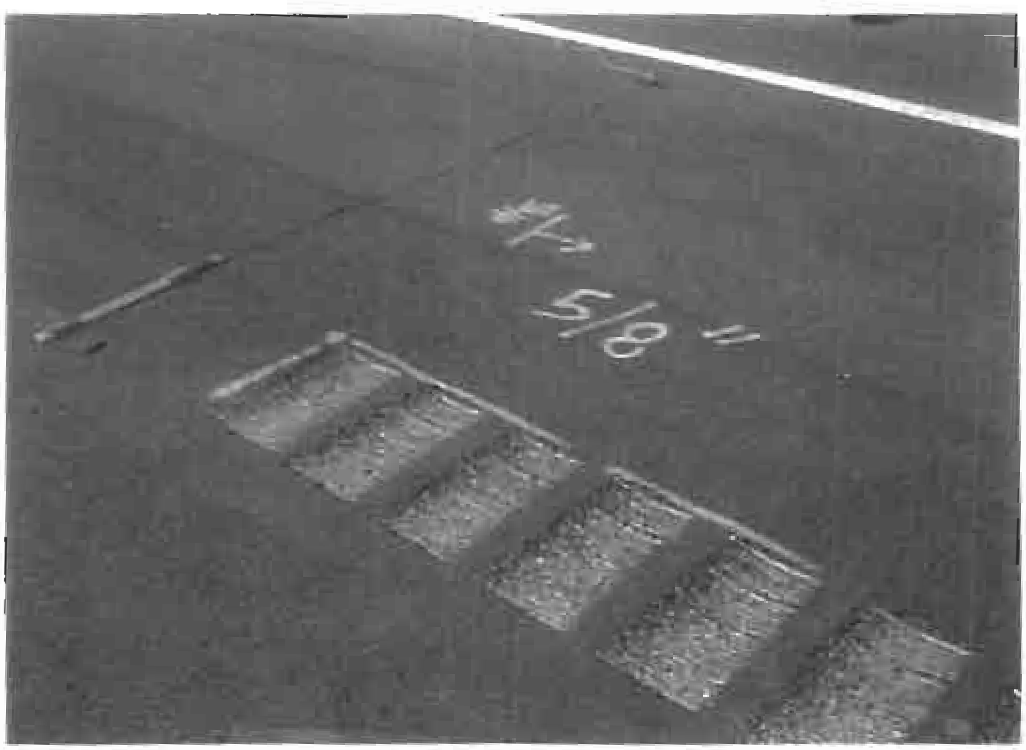


Figure 9. Strip # 5 – 5/8" Milled Strip

4.7 SERIES "B" RUMBLE STRIPS

Series "B" rumble strips were installed and tested at a later date as a result of bad weather. They were labeled strips #6 – 11.

4.7.1 STRIP #6 – CHIP SEAL APPLICATION

Strip #6, a chip seal application, was installed using a tar epoxy and chip seal grade aggregate.

4.7.2 STRIP #7 – RAISED PAVEMENT MARKER (SINGLE RUN)

Strip #7, raised pavement marker single run, was installed using Caltrans standard Botts' Dot pavement markers on 12 inch centers for 100 feet.

4.7.3 STRIP #8 – RASIED PAVEMNT MARKER (SKEWED DOUBLE RUN)

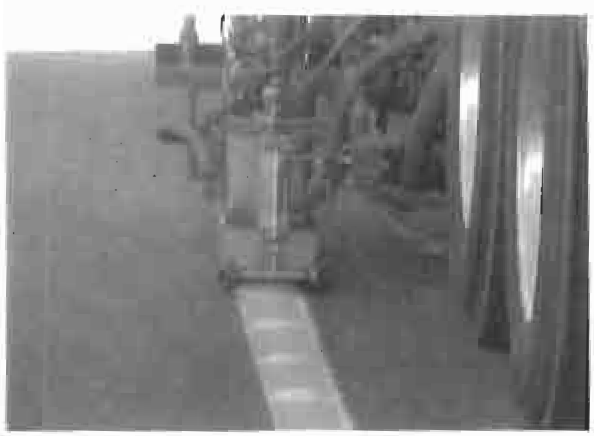
Strip #8, raised pavement marker skewed double run, were installed using Caltrans standard Bott's Dot pavement markers on 12 inch centers. A second run was placed 6 inches to the right of section one and skewed 6 inches for two skewed runs of pavement markers.

4.7.4 STRIP #9 – CARSONITE BARS

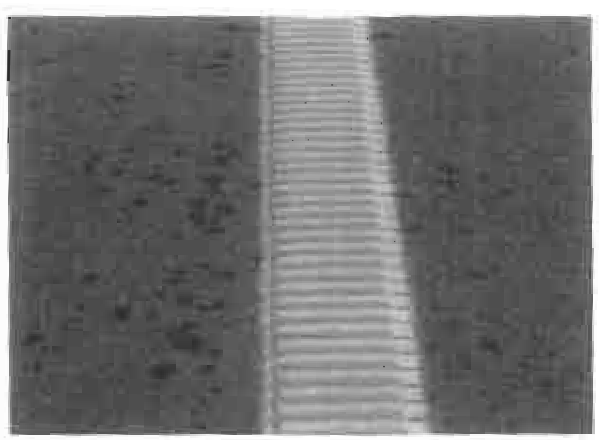
Strip #9, Carsonite "Rumble Strip" Bars, were placed 2 feet on center and were 2 feet in width.

4.7.5 STRIP #10 – RAISED AND INVERTED THERMOPLASTIC STRIPE

4.7.6 STRIP #11 – RAISED THERMOPLASTIC STRIPE



STRIP #10 – RASIED AND INVERTED THERMOPLASTIC



STRIP #11 – RAISED THERMOLASTIC

4.8 TEST VEHICLES

Six different vehicles specified in Table 1 and shown in Figure 10 were used to collect data for instrumented and subjective testing. Three of the vehicles were light passenger vehicles, including a Chevrolet Lumina, Dodge Spirit, and Dodge Ram 150 Pick up Truck. The other three vehicles were commercial style trucks including an International 10-wheel tractor (without trailer), an Autocar 10-yard dump truck, and a GMC Topkick single unit van. All Vehicles were inspected prior to testing to make sure they were in good working order and tire pressures were adjusted to meet the vehicle manufacturers' recommendations. Odometer readings and tire pressures were recorded on the test checklist.

Table 1.
TEST VEHICLES

1) Light passenger vehicles used for testing:

Veh. Ref	Year	Make	Model	Miles	Equip #
P-1	1992	Chevrolet	Lumina	109,228	8807
P-2	1993	Dodge	Spirit	83,430	9397
P-3	1997	Dodge	150 RAM P.U.	72,797	9219

2) Commercial style trucks used for testing:

Veh. Ref	Year	Make	Model	Miles	Equip #
T-1	1999	Interna-tional	Loadstar, 3 axle, conventional cab	1,662	7400
T-2	1991	Autocar	10-yard dump bed	78,430	5223
T-3	1996	GMC	TopKick, 2 axle, Single unit van	88,810	N/A

Chevrolet Lumina

Dodgc Spirit

Dodge Ram 150

International

Autocar Dump Truck

GMC Topkick

Figure 10. Test Vehicles

4.9 INSTRUMENTED TESTS

Instrumented tests were conducted by driving each test vehicles right side tires onto and following a straight path over the series of five rumble strips. Light vehicles were tested three times at 80 kph and then three more times at 100 kph. Commercial vehicles were only tested at 80 kph because the vehicles could not be brought up to 100 kph safely within the area at the test facility. Vehicle drivers used traffic cones aligned along the left side of the vehicle as a visual reference to help them stay centered and aligned on the rumble strips. Two spotters located at the beginning of strip #1 and end of the strip #5 were used to verify that the vehicle remained centered on the rumble strips during testing. If the vehicle was equipped with a cruise control it was set at the desired speed and reset at the same speed for the subsequent runs. Speed traps set-up at the beginning and end of the rumble strip series were used to verify that the vehicle obtained and maintained the correct speed. Vehicle drivers positioned their hands on the steering wheels below the accelerometers and attempted to use the same hand grip strength for each run. Sound and vibration data were recorded by a data acquisition system being operated by the instrumentation engineer sitting in the front passenger seat.

4.9.1 DATA ACQUISITION SYSTEM

The data acquisition system consisted principally of 4 *EG&G IC Sensors* piezoresistive accelerometers, a *Brüel & Kjær* sound level meter and a *Fieldworks* laptop computer all as listed in the section "Instrumentation Equipment List" and connected as shown in Figure 11.

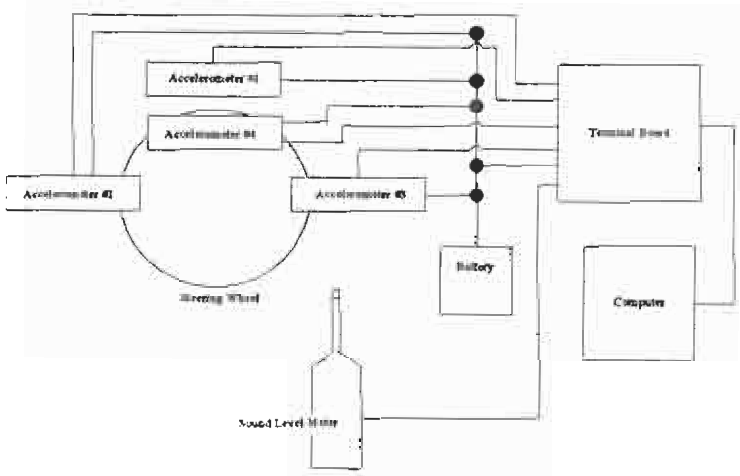


Figure 11. Instrumentation Diagram

The four accelerometers were attached to the steering wheel as shown in Figure 12. These positions were chosen because in addition to providing direct values from each accelerometer, they allowed the calculation of several other motions parameters as follows:

(1) The translation of the steering wheel can be obtained by averaging the data from accelerometers number one and accelerometer number three.

(2) The rotation component can be obtained by subtracting the translation component, just calculated, from the value of accelerometer number one.

(3) A "resultant" component can be obtained from the square root of the sum of the squares of the translation component, data from accelerometer number 2, and data from accelerometer number 4.

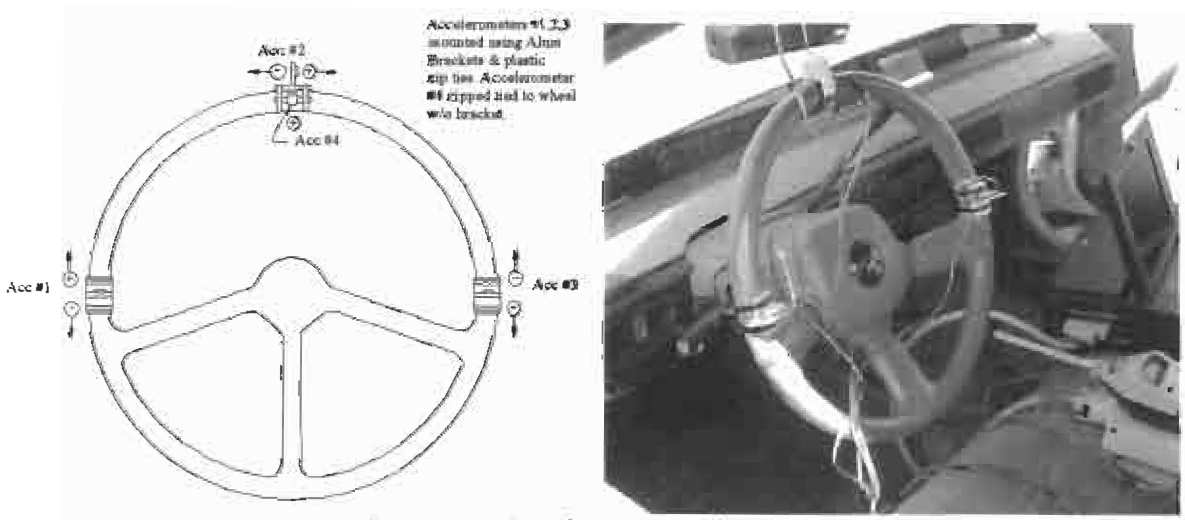


Figure 12. Accelerometer Placement

The data acquisition program was the LabView routine "High Speed Data Logger.vi". The data sets recorded in each test run included the accelerometer excitation voltage (supplied by a 6-volt lantern battery), the four accelerometer output voltages and the sound level meter AC output, all at 10,000 samples per second. Data collection was manually initiated at approximately 300 feet before the first rumble strip. Data in the form of raw voltages was continuously buffered and written to a binary data file, which was later scaled into appropriate engineering units as discussed in the following section.

During testing, the sound level meter was held at ear level close to the center of the vehicle front passenger seat. Pre-test setup procedures included turning off the vehicle fan and radio and rolling up all windows to reduce the vehicle's interior and exterior background noise. The vehicle driver maintained a constant grip on the steering wheel.

4.9.2 INSTRUMENTATION CALIBRATION AND DATA SCALING

The accelerometers used in this investigation where calibrated both before and after each daily test series. The calibration procedure used the gravity positioning method. Each accelerometer was positioned on a horizontal surface and voltage values where measured for several seconds. The accelerometer was then rotated 180 degrees and the voltage measurements repeated. From these voltage measurements the scaling factor "S" equals $\frac{1}{2}(V_{up}-V_{down})/G$, where V is voltage and G is gravitational acceleration.

For example, during one calibration test for accelerometer number 2, V_{up} was 9.23 mV and V_{down} was –29.9 mV, so:

$$S = \tfrac{1}{2}(9.23+29.90\text{mV})/G$$

or

$$19.565 \text{ mV/G}$$

The scaling factor used to calculate acceleration values was the average of the calibration done before the test series and the calibration done after the test series, for each accelerometer.

The calibration of the sound level meter is done using a known signal (this study used a Brüel & Kjær Type 4230 calibration device which generates a 94dB, 1000 Hz tone) and adjusting a calibration potentiometer to achieve the proper output. This was done before each day's tests.

The data scaling uses the RMS output voltage from the sound level meter for both the calibration and for the selected data segment according to the following relation:

$$dB_{test} = 94 + 20 \log(V_{test}/V_{calibration}).$$

4.9.3 INSTRUMENTATION EQUIPMENT LIST

Accelerometers:

EG&G IC Sensors – General Purpose Solid-state Piezoresistive Accelerometers
Model 3022-005-P

Sound Level Meter:

Brüel & Kjær Type 2230 Precision Integrating Sound Level Meter with Prepolarized Condenser Microphone Type 4155 and Sound Level Calibrator Type 4230

A/D Board:

- National Instruments Model AT-MIO-16XE-10, 16-channel, 16-bit A/D
- National Instruments Model SCB-68, 68-Pin Shielded Connector Block
- National Instruments Type SH6868 Shielded Cable for MIO Devices

Computers:

Fieldworks computer – Pentium 166 kHz with Windows 95

Data Acquisition Software

- National Instruments -- Labview 5.0
- Virtual Instrument (VI) Programs:
  - High Speed Data Logger.vi -- Receives data from any source connected to an analog input channel.

- High Speed Data Reader.vi -- Retrieves and displays logged data from the data file generated with the High Speed Data Logger.vi above.

Digital Camera:

Kodak DC200 Camera with Picture Easy 2 software

Data Reduction Software:

National Instruments -- Labview 5.0

4.9.4 DATA ANALYSIS

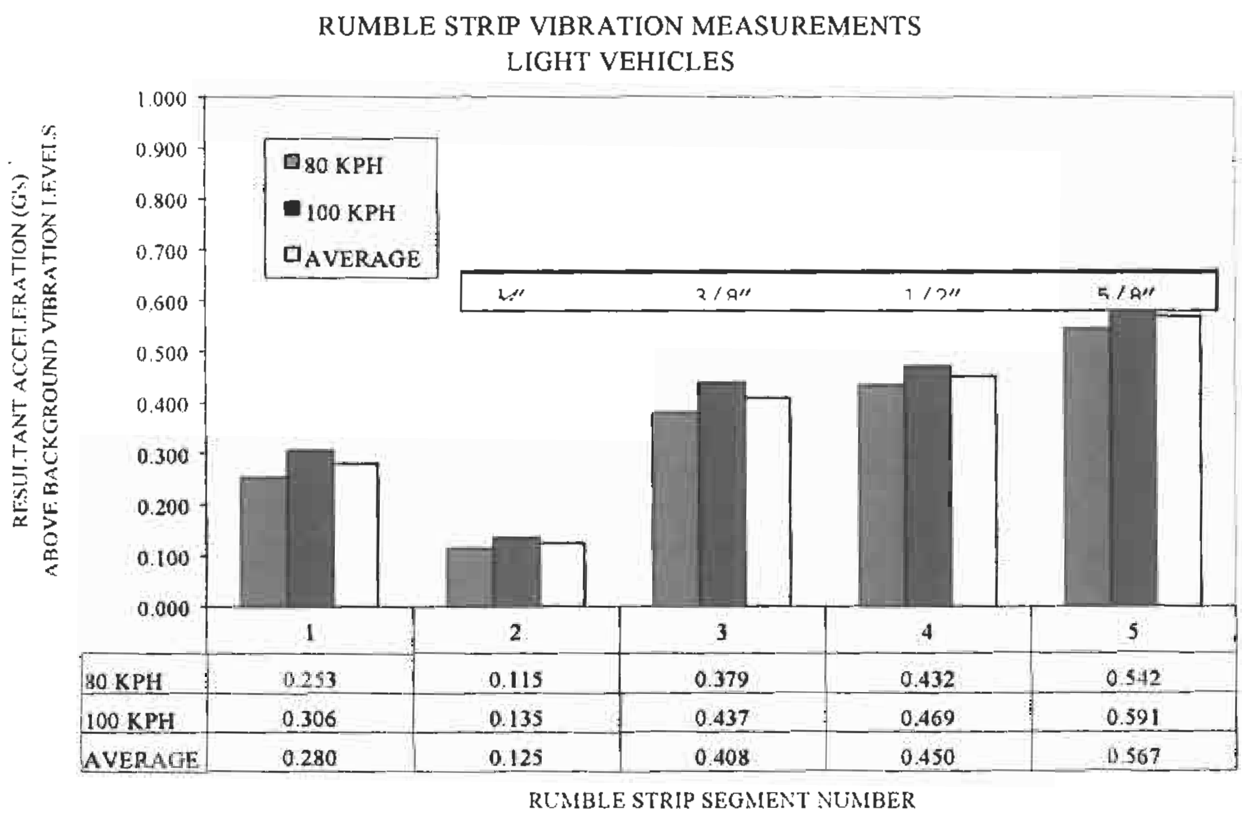
During the testing, the vehicle was in contact with each 30.5-meter rumble strip segment for approximately one second. No attempt was made to identify the beginning or ending point of vehicle contact with any of the rumble strips. Instead, analysis identified a 4096-sample region (.41 seconds) that is representative of the data for each rumble strip type. This 4096-sample region over each rumble strip type was then extracted from the test data set for individual analysis. Sound data were used to locate each rumble strip segment and the representative region was generally taken as the center of this segment.

This procedure generated a large number of individual data sets. Each vehicle run sampled 5 data channels (four vibration channels and one sound channel) over 6 different rumble strip types. The series of tests presented here consisted of 27 separate instrumented vehicle runs; hence, 675 sets of data were extracted and analyzed. Consequently, not all data are presented in this report.

In addition to data from the rumble strips, background noise and vibration levels were extracted from the test data both before and after the rumble strip segments. Background values extracted from the test data in this manner where found to be artificially high. The reason for this is that the driver was usually making adjustments to the speed and steering of the vehicle just before and just after contacting the rumble strips. Therefore, the background level used in the analysis was the lowest of the three test run values for each vehicle tested.

4.9.5 VIBRATION MEASUREMENTS ON LIGHT VEHICLES

The average rumble strip vibration values for all light vehicles shown in Figure 13 are the "resultant" vibration, above the background level, calculated from the 4 accelerometers mounted on the steering wheel. Figure 14. Depicts vibration values for individual light passenger vehicles. The general trend is similar for both the noise data (Figure 15) and the drivers subjective measured results (Figure 18).

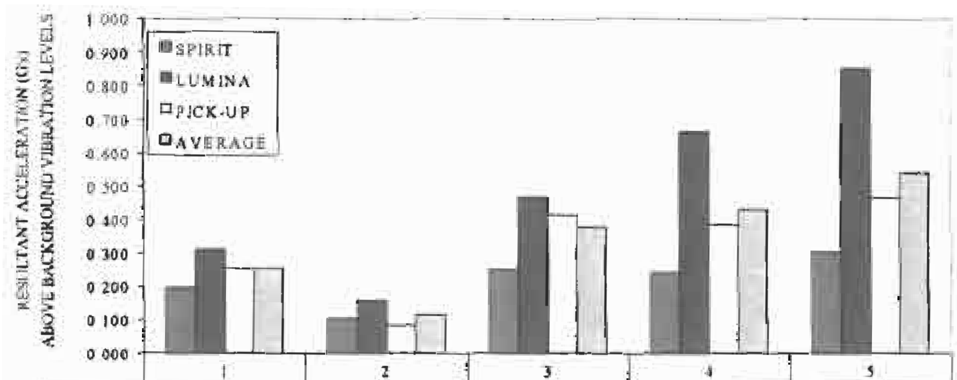


	1	2	3	4	5
80 KPH	0.253	0.115	0.379	0.432	0.542
100 KPH	0.306	0.135	0.437	0.469	0.591
AVERAGE	0.280	0.125	0.408	0.450	0.567

Figure 13. Average Vibration Measurements for Light Passenger Vehicles

There are several factors that may account for the minor differences in the instrumentation vibration data and the subjective vibration data. Since vibration was measured on the steering wheel, one factor may be the damping effect caused by the driver's grasp on the steering wheel; another factor may be quick steering changes between rumble strip sections to correctly align the vehicle with the strips. In addition to these, vibration caused by the transition in the pavement surface immediately before the first strip, and the extent to which the vehicle remained centered in the rumble strip section vs. drifting off to the edge of the test strip could also account for differences in the results.

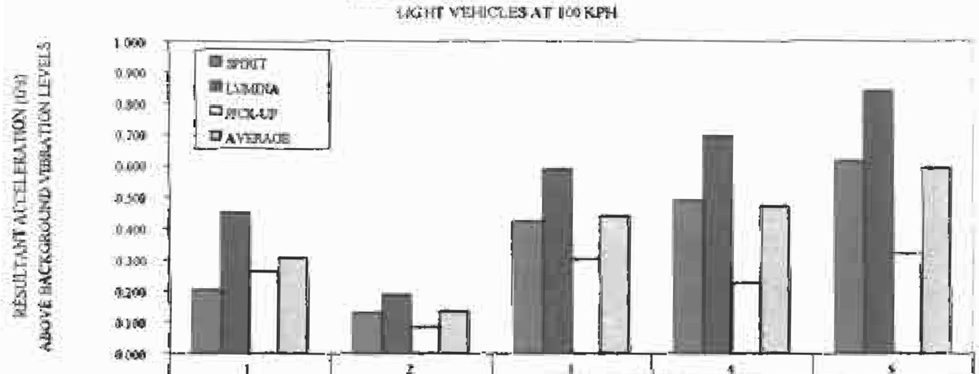
RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES AT 80 KPH



	1	2	3	4	5
SPIRIT	0.195	0.103	0.252	0.243	0.306
LUMINA	0.312	0.159	0.468	0.664	0.853
PICK-UP	0.253	0.082	0.416	0.387	0.467
AVERAGE	0.253	0.115	0.379	0.432	0.542

RUMBLE STRIP SEGMENT NUMBER

RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES AT 100 KPH



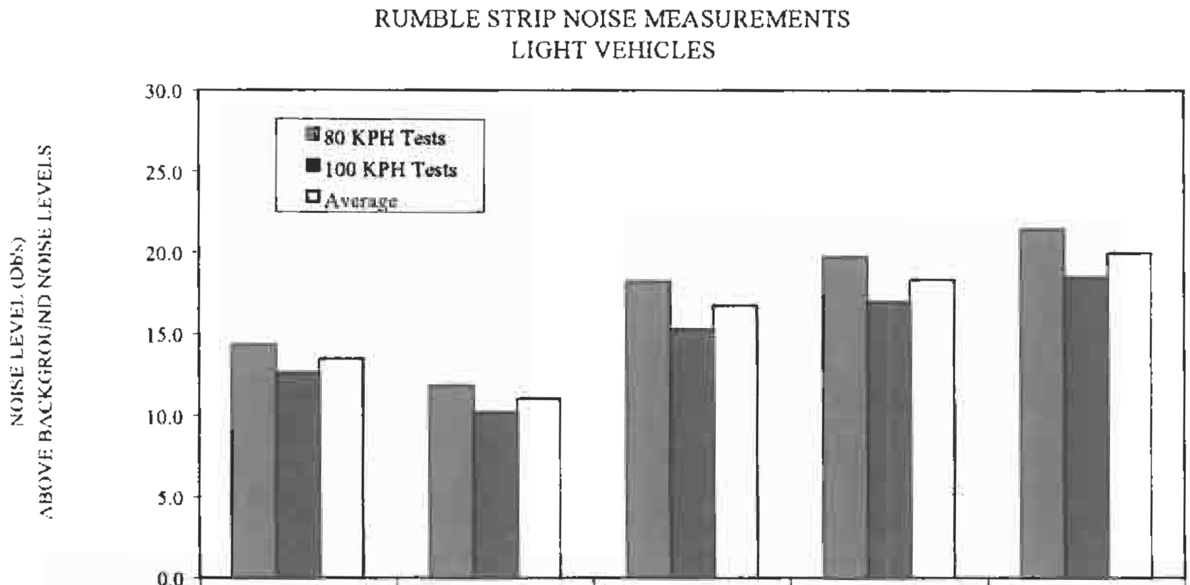
	1	2	3	4	5
SPIRIT	0.204	0.131	0.425	0.488	0.615
LUMINA	0.452	0.189	0.587	0.695	0.837
PICK-UP	0.263	0.086	0.302	0.223	0.322
AVERAGE	0.306	0.135	0.437	0.469	0.591

RUMBLE STRIP SEGMENT NUMBER

Figure 14. Vibration Measurements for Light Passenger Vehicles.

4.9.6 NOISE MEASUREMENTS ON LIGHT VEHICLES

The average rumble strip noise/sound values shown in Figure 15 are the resultant noise averaged across different light vehicles and across two speeds above the background level, which was calculated from test runs made on bare pavement (See Figure 16, noise measurements for individual light vehicles at different speeds). The noise levels tend to follow the same trend as the vibration data (Figure13) and the drivers subjective results (Figure 19).

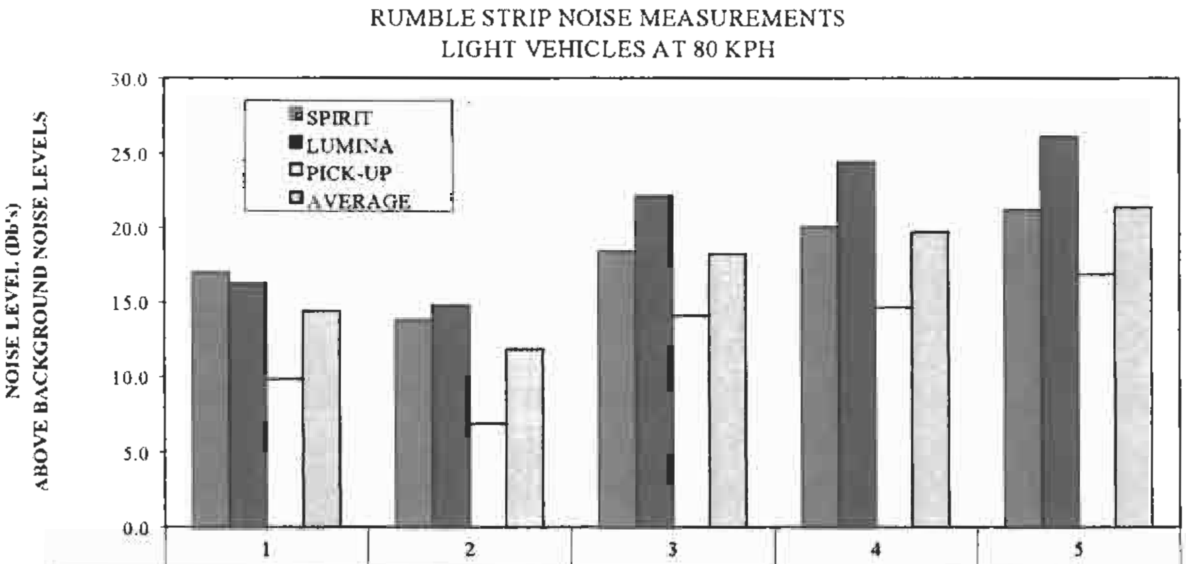


	1	2	3	4	5
80 KPH Tests	14.4	11.8	18.2	19.7	21.4
100 KPH Tests	12.6	10.2	15.2	16.9	18.5
Average	13.5	11.0	16.7	18.3	19.9

RUMBLE STRIP SEGMENT NUMBER

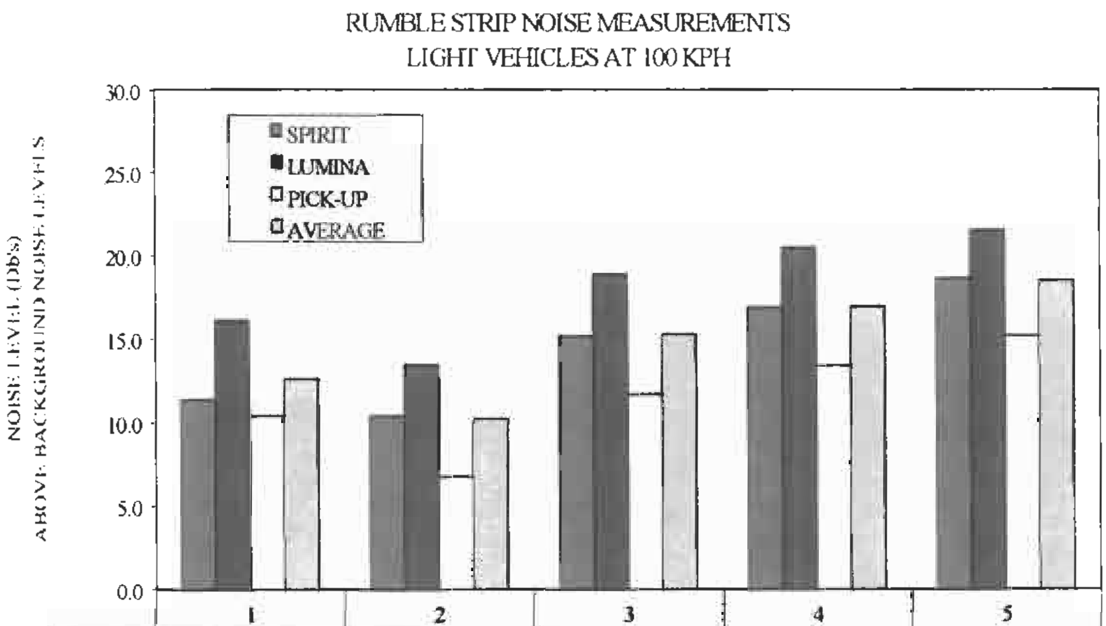
Figure 15. Average Noise Measurements for Light Passenger Vehicles

There are several factors that may account for the minor differences in the instrumentation noise data and the subjective noise data. For example, instrumentation data shows a slightly higher noise level for strip #1 over strip #2 (subjective results are very close for these two strips): this may be due to additional engine noise associated with the high speed acceleration into the first set of rumble strips. Other factors that may contribute to variations include how background levels were determined, how differently pitched sounds (different frequency vibrations) are perceived by the individual drivers, or how effectively the driver maintains the alignment within the center of the strips.



	1	2	3	4	5
SPIRIT	17.0	13.8	18.4	20.1	21.2
LUMINA	16.2	14.8	22.1	24.4	26.2
PICK-UP	9.9	6.9	14.1	14.6	16.8
AVERAGE	14.4	11.8	18.2	19.7	21.4

RUMBLE STRIP SEGMENT NUMBER



	1	2	3	4	5
SPIRIT	11.4	10.4	15.1	16.9	18.6
LUMINA	16.1	13.5	18.9	20.5	21.6
PICK-UP	10.4	6.8	11.7	13.4	15.2
AVERAGE	12.6	10.2	15.2	16.9	18.5

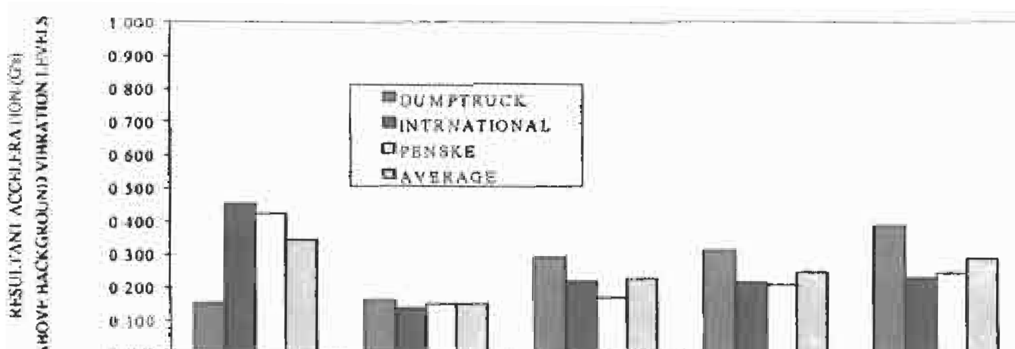
RUMBLE STRIP SEGMENT NUMBER

Figure 16. Noise Measurements for Light Passenger Vehicles.

4.9.7 VIBRATION AND NOISE MEASUREMENTS ON COMMERCIAL VEHICLES

The commercial vehicles used to collect noise and vibration data while being driven over the rumble strips were only tested at 80 kph. The vibration and noise measurement averages follow the same trend as the passenger vehicles (Figures 14 and 16) but at a significantly reduced decibel and vibration level. Commercial vehicles of this size and weight produce higher operating vibration and noise levels, significantly reducing the above-background instrumentation readings for both vibration and noise. Results from the instrumented tests on commercial vehicles are contained in the following graphs.

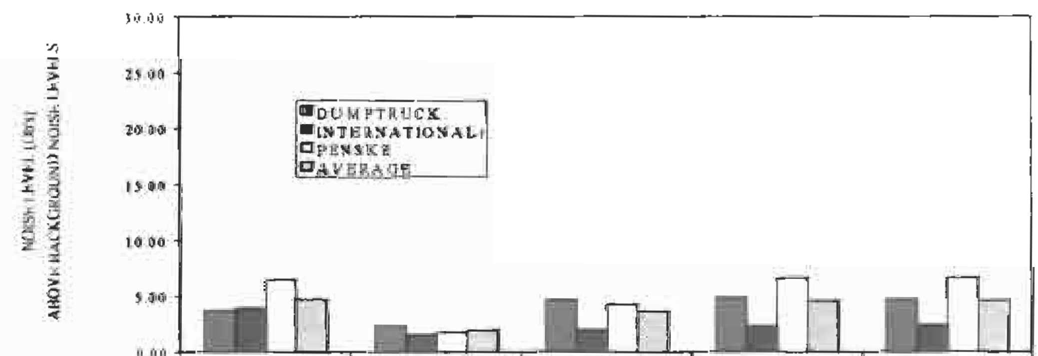
RUMBLE STRIP VIBRATION MEASUREMENTS
COMMERCIAL VEHICLES AT 80 KPH



	1	2	3	4	5
DUMPTRUCK	0.152	0.162	0.291	0.312	0.386
INTERNATIONAL	0.452	0.137	0.218	0.218	0.230
PENSKE	0.423	0.151	0.170	0.209	0.241
AVERAGE	0.342	0.150	0.226	0.246	0.286

RUMBLE STRIP SEGMENT NUMBER

RUMBLE STRIP NOISE MEASUREMENTS
COMMERCIAL VECHICLES AT 80 KPH



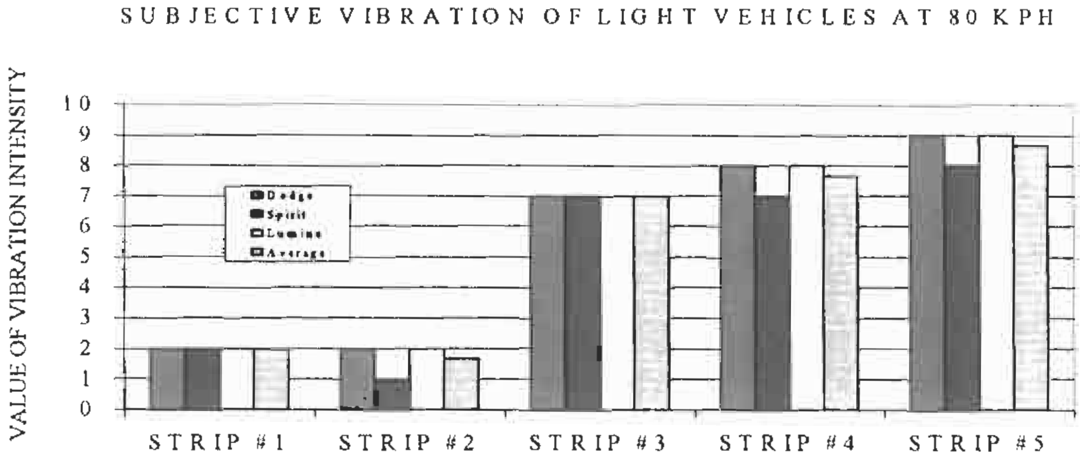
	1	2	3	4	5
DUMPTRUCK	3.72	2.31	4.69	4.86	4.78
INTERNATIONAL	3.92	1.57	1.91	2.30	2.41
PENSKE	6.52	1.76	4.27	6.67	6.59
AVERAGE	4.72	1.88	3.62	4.61	4.62

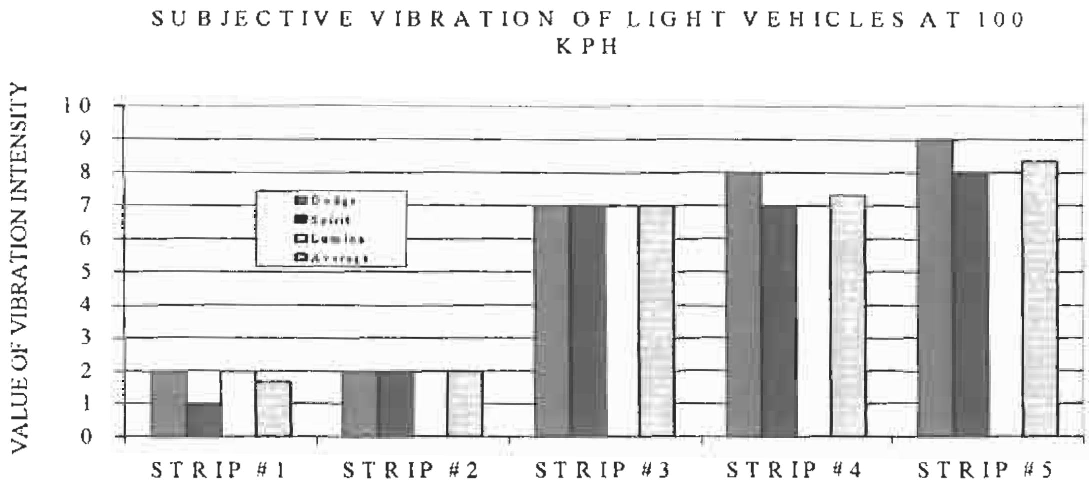
RUMBLE STRIP SEGMENT NUMBER

Figure 17. Vibration & Noise Measurements for Commercial Vehicles.

4.10 SUBJECTIVE EVALUATION TESTS

Subjective tests were conducted to determine the driver's sense of noise, vibration and vehicle handling by driving each vehicle's right side tires onto and following a straight path through the series of rumble strips. Light passenger vehicles were tested at 80 kph and then at 100 kph. Commercial vehicles were tested only at 80 kph because there was not enough run out length at the test facility to get them to 100 km/h safely. The subjective evaluators were not professional drivers and their evaluations were based solely on their own opinions. The driver made repeated runs at each speed, stopping at the end of each pass to fill out an evaluation form rating each rumble strip for sound, vibration and vehicle control on a scale of 1 through 10. Traffic cones aligned along the left side of the vehicle were used as a visual reference to help the driver stay centered on the rumble strips. Spotters were used to verify that the vehicle tires remained centered on the rumble strips during the tests. If the test vehicle was equipped with a cruise control it was set at the desired speed and set to resume the same speed for subsequent runs. Speed traps were used to verify that the vehicles obtained and maintained the correct speed. The Driver was allowed to hold the steering wheel in a position of comfort but was requested to duplicate that position for each run. Two evaluators were used to do the subjective tests, with the intent simply to get an idea of what a driver would experience. Results obtained from the combined opinions of two evaluators for the subjective tests are contained in the following graphs.





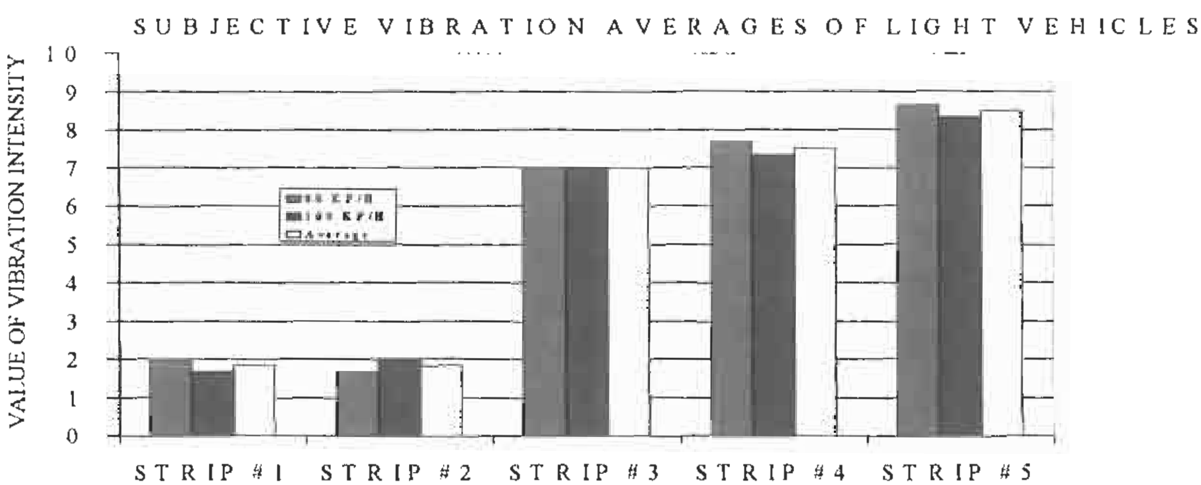


Figure 18. Subjective Drivers Evaluation and Rating of Light Vehicle Vibration

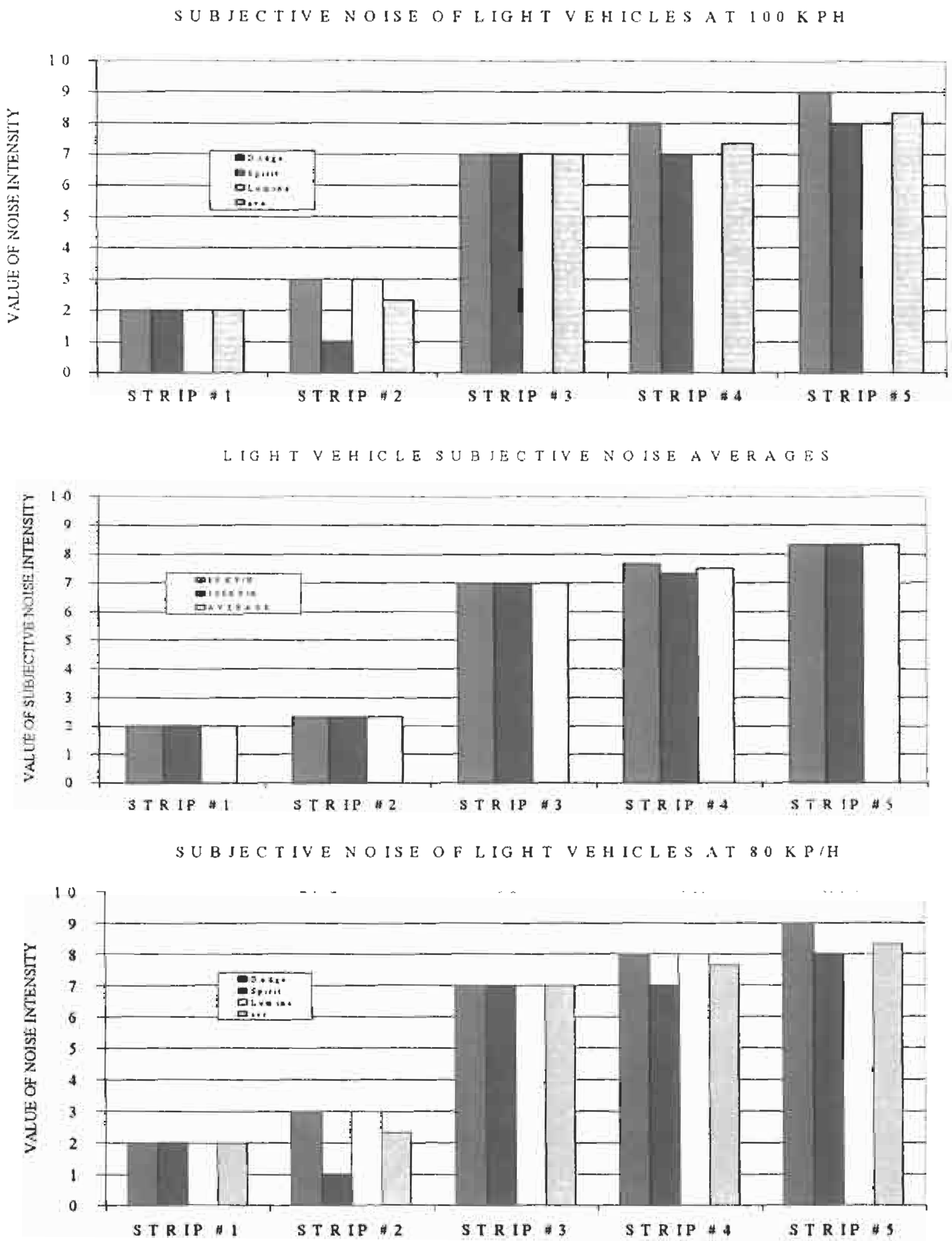


Figure 19. Subjective Drivers Evaluation and Rating of Light Vehicle Noise

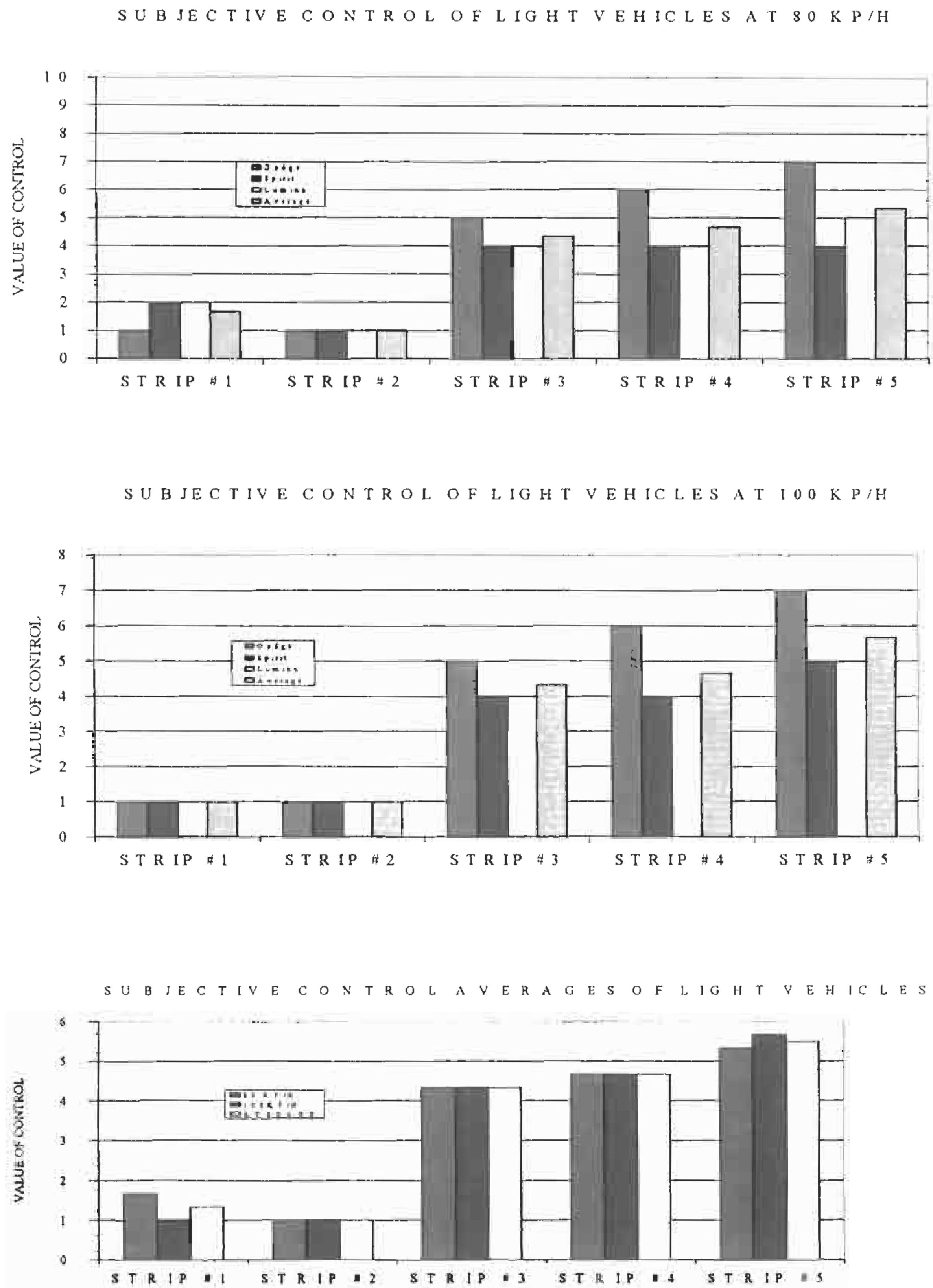


Figure 20. Subjective Drivers Evaluation and Rating of Control Level for Light Vehicles

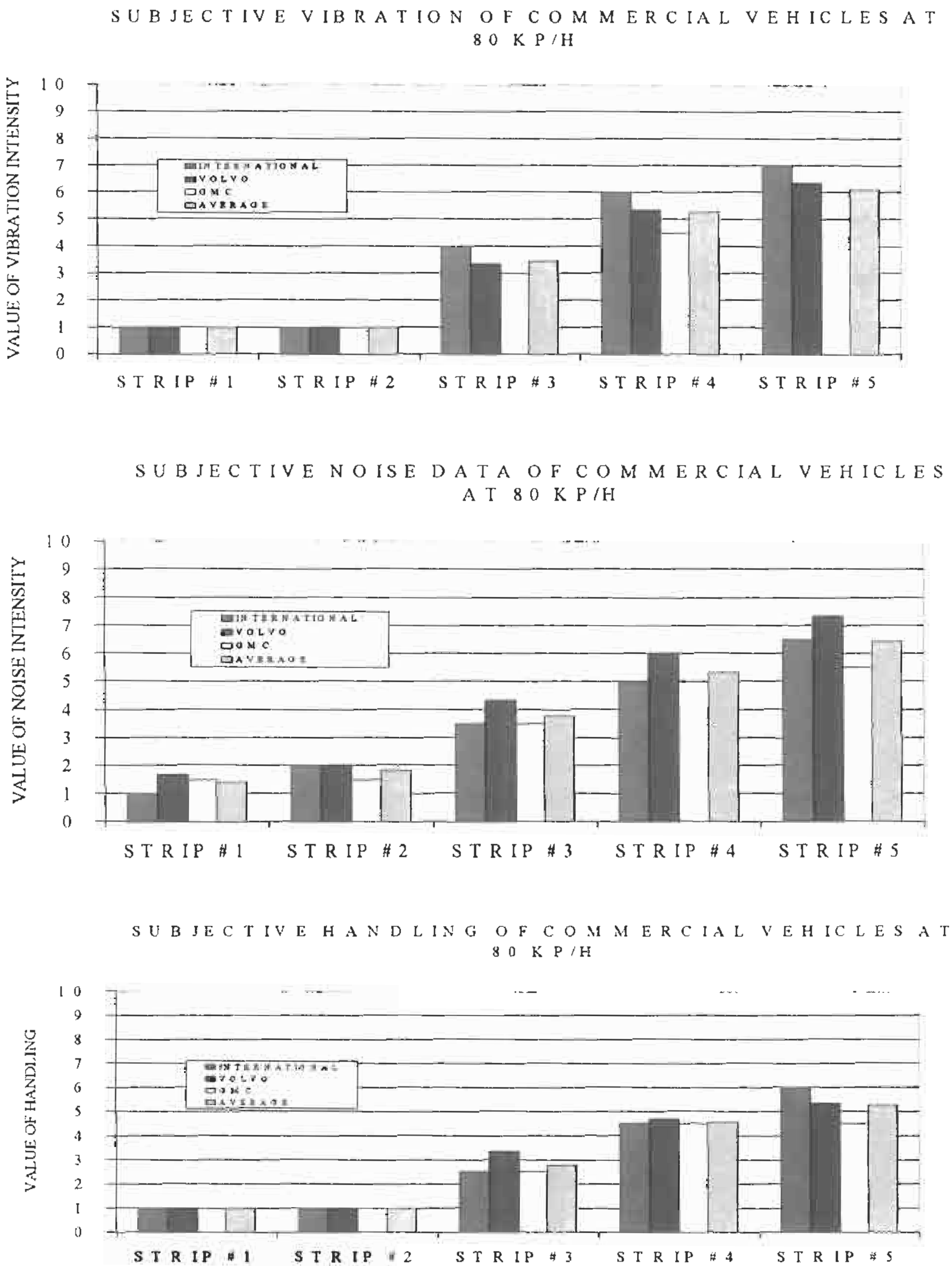
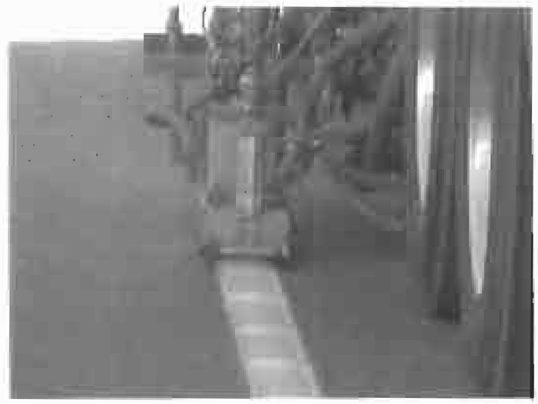


Figure 21. Subjective Vibration, Noise and Control of Commercial Vehicles

Vehicle raised pavement marking test

Vehicle Carsonite Bar Test

Dynamic Test Facility RS Layout



Raised Inverted Thermoplastic Application

Bike Test and Field Questionnaire Completion and Rumble Strip Bicycle Test Day Event

4.11 ASSESSMENT OF TEST RESULTS

4.12 ASSESSMENT OF INSTRUMENTED TESTS

4.12.1 AVERAGE VIBRATION ON LIGHT VEHICLES

The data averages for vibration recorded during instrumented tests for light vehicles being driven over series "A" rumble strips showed that:

- The vibration for strip #1, the rolled-in rumble strip, was greater than milled-in strip #2 and less than strips #3, #4, and #5, all milled-in rumble strips. Rolled in strip #1, the existing standard, was considered to provide the desirable level of sound and vibration.
- Vibration for strips #3, #4 and #5 appeared to be linear in ascending order. However, strip #2 produced substantially less vibration than the other milled-in strips and consequently was not linear when compared to them.

4.12.2 AVERAGE NOISE IN LIGHT VEHICLES

The data averages for noise recorded during instrumented tests for light vehicles being driven over series "A" rumble strips showed that:

- In relationship to the instrumented vibration tests of light vehicles, the noise tests followed the same trend.
- The noise created by strip #1, the rolled-in rumble strip, was greater than milled-in strip #2 and less than strips #3, #4, and #5, all milled-in rumble strips.
- Noise levels for strips #3, #4 and #5 appeared to be linear in ascending order. However, strip #2 produced substantially less noise than the other milled-in strips and consequently was not linear when compared to them.

4.12.3 VIBRATION ON COMMERCIAL VEHICLES

The data averages for vibration recorded during instrumented tests for commercial vehicles being driven over series "A" rumble strips showed that:

- When compared to the averages of the 80 kph instrumented vibration tests of light vehicles, the vibration averages of the commercial vehicles were less, but followed the same general trends.
- For the International and the Penske, vibration for strip #1, the rolled-in rumble strip was greater than for strips #2, #3, #4 and #5, all milled-in rumble strips. Significantly less vibration was produced in the dump truck on test strip #1 than on any of the other strips.
- Vibration for strips #2, #3, #4 and #5 appeared to be linear in ascending order.

4.12.4 ASSESSMENT RESULTS OF NOISE ON COMMERCIAL VEHICLES

The data averages for noise recorded during instrumented tests for commercial vehicles being driven over series "A" rumble strips showed that:

- When compared to the averages of the 80 kph instrumented noise tests of light vehicles, the noise averages of the commercial vehicles were significantly less but also tended to follow similar trends.
- The average noise created by strip #1, the rolled-in rumble strip, was greater than strips #2 and #3 and less than strips #4, and #5, milled-in rumble strips.
- Noise averages for strips #2, #3, #4 and #5 appeared to be linear in ascending order.

4.13 ASSESSMENT OF SUBJECTIVE TESTS

4.13.1 SUBJECTIVE EVALUATIONS OF VIBRATION ON LIGHT VEHICLES

The combined opinions of the evaluators of the subjective vibration evaluations for light vehicles being driven over series "A" rumble strips was that:

- The vibration for strips #1 and #2 was relatively similar to each other at both 80 and 100 kph.
- Strips #3, #4, and #5 produced a higher degree of vibration than strips #1 and #2 at 80 and 100 kph.
- The degree of vibration increased in ascending order with strip #1 having the lowest vibration and strip #5 having the highest.
- The test drivers concluded that the vibration felt through the steering wheel was negligible in alerting the vehicle driver compared to the noise level produced while driving over the same rumble strips.

4.13.2 SUBJECTIVE EVALUATIONS OF NOISE ON LIGHT VEHICLES

The combined opinions of the evaluators of the subjective noise evaluations for light vehicles being driven over series "A" rumble strips was that:

- The noise intensity averages for strips #1 and #2 were relatively similar to each other at 80 and 100 kph and were considered to have a low to moderate alerting value when compared to strips #3, #4, and #5 which were considered to have a high alerting value.
- The test drivers concluded that the noise produced from the strips had a greater effect in alerting a driver than the vibration produced by the same rumble strip.

4.13.3 SUBJECTIVE EVALUATIONS OF HANDLING OF LIGHT VEHICLES

The combined opinions of the evaluators of the subjective handling for light passenger vehicles being driven over series "A" rumble strips was there were negligible handling problems. All vehicles tracked easily and there was very little steering wheel pull.

- During subjective vehicle handling tests, the average value of vehicle handling was negligible for all of the passenger vehicles. The drivers agreed that there was no loss of vehicle control with any of the test strips.
- The vehicle handling for Strips #1 and #2 was considered to be easier than for strips #3, #4, and #5.
- Strips #2, #3, #4, and #5 all required an additional amount of hand-grip strength/steering corrections to keep the vehicle centered on the straight path through the rumble strips.
- None of the strips caused any fishtailing or loss of control of the vehicles.

4.13.4 SUBJECTIVE EVALUATIONS OF VIBRATION ON COMMERCIAL VEHICLES

The combined opinions of the evaluators of the subjective vibration evaluations for commercial vehicles being driven over series "A" rumble strips were that:

- The vibration for strips #1 and #2 was judged to be minimal and to have a low to negligible alerting value.
- The degree of vibration increased in linear ascending order with strips #3, #4, and #5.
- Strips #3, #4, and #5 produced a higher degree of vibration than strips #1 and #2. However, the test drivers concluded the vibration was dampened considerably because of the size and weight of the commercial vehicles and alerting values were essentially insignificant.

4.13.5 SUBJECTIVE EVALUATIONS OF NOISE ON COMMERCIAL VEHICLES

The combined opinions of the evaluators of the subjective noise evaluations for commercial vehicles being driven over series "A" rumble strips was that:

- The noise intensity averages for strips #1 and #2 were considered to have a low alerting value when compared to strips #3, #4, and #5 that were considered to have a moderate alerting value.
- The test drivers concluded that the noise produced from the strips had a greater effect in alerting a driver than the vibration produced by the same rumble strips. However, because of the larger size, weight and noise levels of the commercial vehicles, the test drivers also concluded that the noise produced while driving over the strips, although rated low-to-moderate in alerting values, was less significant in noise alerting values when compared to light vehicles in the same moderate category.

4.13.6 SUBJECTIVE EVALUATIONS OF HANDLING OF COMMERCIAL VEHICLES

The combined opinions of the evaluators of the subjective handling for commercial vehicles being driven over series "A" rumble strips was:

- During subjective vehicle handling tests, the average effect on vehicle handling was negligible for all of the commercial vehicles. The drivers agreed that there was no loss of vehicle control with any of the test strips and only a minimal amount of steering correction was noticed.
- The vehicle handling for Strips #1 and #2 was considered to be easier than for strips #3, #4, and #5.
- None of the strips caused any fishtailing or loss of control of the vehicles.

5.0 BICYCLE TESTING

5.1 OBJECTIVE

The objectives of this portion of the test was to collect subjective data from bicycle riders of all ages and experience levels while riding over eleven different rumble strip designs. Results from this testing will be compared with results from Pennsylvania State Department of Transportation results and be used by the Caltrans Traffic Safety Branch to aide in developing a standard MSRS and audible edge stripe treatments which are both effective in preventing run-off-road collisions and are bicycle friendly.

5.2 BACKGROUND

At the request of the Rumble Strip Task Force, California Bike Advisory Committee and the Office of Transportation Safety, the Traffic Safety Research Branch developed a research test project to evaluate rumble strip treatments that could be traversed by bicyclists and provide an adequate warning to errant drivers. The California State highway system currently has approximately 1000 miles of its limited access roadways open to bicyclists. Shoulder rumble strips have been placed on shoulders where bicyclist are allowed. Until a moratorium on the experimental installation of MSRS was established in March of 1999, MSRS, rolled-in and audible edge stripe were all placed on or near a shoulder where a bicyclist may ride. The dimensions of the treatments varied by shoulder width and typically were not installed on shoulders with less than 5 feet in width if bicycles were allowed access to the facility. Most MSRS and rolled-in treatments ranged in width from 18 inches to 3 feet or more in some situations. The typical placement was 6 inches to 12 inches from the traveled way or fog line. Debris, narrow shoulders and some bicyclists' need to ride on or near the fog line or traveled way sometimes forced the bicyclist to travel on or over a rumble strip treatment. Crossing over the MSRS at ½" and 5/8" depths was a change from the smooth riding surface that a cyclist prefers. Cyclists noted that MSRS caused severe vibration of their bikes, potential loss of control and in general an uncomfortable ride. These concerns lead to a request for testing to find an MSRS that would provide an audible or tactile warning to errant drivers and be compatible with cyclists using the state highway facilities.

5.3 TECHNICAL BACKGROUND

Pennsylvania State Department of Transportation completed extensive testing on bicycle and user reactions to MSRS in the Winter of 1999. The testing consisted of instrumenting a bicycle and collecting data of various movements and conditions of the bicycle as it traversed over MSRS. The Caltrans Traffic Safety Research Branch felt that the extensive objective review done by PENN State DOT was sufficient in gathering data from instrumenting a bicycle. The Caltrans Traffic Safety Research Branch felt that subjective feedback from roadway cyclist users would be more useful in evaluating rumble strip treatments. Therefore, 55 cyclists from around the state, with varying ages, and experience levels were randomly selected from a group of over 200. Volunteers who responded to the Statewide Rumble Strip survey and indicated an interest in participating in a field test that would be organized by the Traffic Safety Research Branch.

5.4 BICYCLE RIDEABILITITY EVALUATION

5.4.1 Test Track Procedures for Bicyclists

When each participant arrived at the test track, the purpose of the study was reiterated to the participant, and some of the basic procedures of the testing were explained. The participant were then asked if he/she had any questions. Minimal information was supplied if the participant did have any questions so as not to bias the participant's data. After the brief explanation, each participant was given a questionnaire designed to gather background information such as age, weight, height, skill level, etc. The questionnaire was modeled after the Pennsylvania State Department of Transportation questionnaire to make it easy to compare subjective results. The definitions of beginner, intermediate and advanced riders were also provided with the questionnaire to help the participant rate his/her skill level.

After the participant finished with the background information, the content of questionnaire was reviewed with the participant. This form was used by each participant to rate the comfort and controllability of each rumble strip configuration.

The participant then selected one of the 18 bicycles available for the testing or used their own road bicycle. In most cases, riders chose to use their own bicycle. Before any of the actual testing started, the participant was able to ride around the track area for a while to become comfortable with the track area and rumble strip application placement. Participants were allowed to ride over the eleven rumble strip treatments as many times as desired to give each section a fair evaluation. Participants also rode over the rumble strips at varying speeds to simulate speeds that may be traveled on the state highway system. Since cyclists do not maintain one speed during a ride it was advantageous to have them vary speeds from very slow to top speed.

Participants traversed the eleven rumble strip patterns at varying speeds, angles, in groups, and as a single rider. After traversing the rumble strip treatments, the participants stopped and subjectively rated the comfort and control level of the rumble strips. The runs of the cyclists were video taped as well. The exact text of the questionnaire is provided in Section 4.4.2

5.4.2 BICYCLE SUBJECTIVE QUESTIONAIRRE

The Questionnaire was designed to effectively evaluate shoulder rumble strip applications and any effect they may have on a bicyclist. The California Department of Transportation (Caltrans) will use the feedback you provide as part of an ongoing extensive evaluation of shoulder rumble strip applications.

You will be riding over two separate sections of rumble strip applications. One section is labeled (1-5) and the other labeled (6-11). You may ride over the entire section and go back and ride over each individual rumble strip pattern within the section separately as many times as needed to fairly evaluate the rumble strip applications.

Staff from Caltrans will be on hand to answer any questions that you may have. For the purpose of breaking the participants into riding experience levels, we have described experience as follows:

Novice: Those that do not fit into the Intermediate or Advanced category.
Intermediate: Someone who knows how to handle his/her bicycle easily and comfortably who can shift gears and steer smoothly, and who has a smooth pedaling style and reasonable cadence (at least 60 rpm). Intermediates can ride comfortably and confidently in light or moderate traffic environments on adequately wide roads. Intermediates can climb most hills without dismounting.
Advanced: Someone who has many years and thousands of kilometers (miles) of bicycling experience, who can do everything the intermediate cyclist can do, plus ride skillfully, comfortably, and confidently in heavy traffic (urban, suburban, or rural) and on narrow or wide high-speed roads, who can (and at least occasionally) does ride at night and/or in rain, and who can negotiate very demanding terrain (both up and down), and who does all these things without getting flustered.

6.0 ANALYSIS OF DATA

The statistical analysis used to select the most effective rumble strip type was comprised of three separate analyses. The first analysis in section 6.1 is based on the field data collected from a sample of bicyclists to find out the degree of comfort and safety bicyclist rate different rumble strip types. The analysis in section 6.2 pertains to vehicle tests and how various rumble strip types rank with respect to the level of vibration and noise they produce when passenger vehicles and truck tires pass over them. Section 6.3 include analysis of the fatal run-off the road single vehicle accidents both for trucks and for passenger vehicles. At the end, findings from the three separate data analyses are used to select the rumble strip type/types that provide a relatively high level of comfort and safety for bicyclists and at the same time provide adequate warning to vehicles drifting off the roads.

6.1 Bicycle field test

Data for this portion of the analysis was obtained from feedback provided by a group of 55 bicyclists riding over eleven different rumble strip types. In order to select a sample of bicyclists for the field test, a questionnaire survey was designed that was completed by a large group of participants. Given the scheduling and funding limitations of this research project, the survey was distributed via an internet web site. The web site survey questionnaire is provided in Appendix A. From the web site survey results, we obtained a sense of who the target audience was. The responses from the survey were used to select a sample of bike riders to participate in the follow up field test of the various rumble strips. The survey made available on the internet web site was completed by more than five thousand people including Caltrans employees and experienced bicyclists who were identified through local bike clubs.

In the next stage of this evaluation, bicyclist volunteers were instructed to ride over eleven sections of various types of rumble strip. Two sets of rumble strip patterns with a short description of different patterns are shown in figure 6.1. Strip type "1" through type "5" are rolled-in and ground-in applications and strip type "6" through type "11" are proprietary applications. The bicyclists were asked to ride over the entire group of rumble strip sections and go back and ride over each individual section separately as many times as needed to fairly evaluate the rumble strip types. Staff from Caltrans were available to answer any questions that the bicyclists had. The bicyclist were asked to provide responses to a series of questions. The field test questionnaire completed by the bicyclists is shown in the Appendix B.

The field test questionnaire consisted of two parts. The first part pertained to the bicyclists' characteristics and experience as well as demographic information, and the second part consisted of questions that rated the degree of comfort/discomfort, and the level of control experienced when riding over various rumble strip types. The general focus of the questionnaire was to evaluate the level of comfort and relative safety of riding over various rumble strip types based on subjective responses provided by the bicyclists. In the second section of the questionnaire, the field test participants were asked to mark their responses to a series of questions related to the level of comfort or pain in body and also level of control as they ride over a specific rumble strip type. The responses to questions were marked on a scale ranging from very uncomfortable to very comfortable. The marked responses were then converted to a numerical values equivalent to the marked location on the scale, one being very uncomfortable and five being very comfortable.

6.2 Analysis of bicycle field test data

A series of repeated measures analyses of variance were done on the field test response data (the trial in which bicyclists passed over various rumble strip segments and rated them for comfort). The data set contained demographic information as well as, rider's experience level, weight, and whether they regularly experienced pain in various body areas. The rumble strip types and body areas are coded as in the following:

Body areas and rumble strip codes

Rumble strip type	Code	Area	Code
Rolled-in Section A	1	Wrist/Fingers/Elbows	1
Ground-in Section B	2	Shoulder/Neck	2
Ground-in Section C	3	Back	3
Ground-in Section D	4	Seat	4
Ground-in Section E	5	Knee/Ankle/Foot	5
Chip Seal Section 1	6	Overall	6
Raised Pavement Section 2	7		
Double Raised Pavement Sect. 3	8		
Carsonite product Section 4	9		
Raised Profile Section 5	10		
Rainline Section 6	11		

Detailed descriptions of the various rumble strip types are discussed in previous sections of this report. The layout for various rumble strip types is shown on Figure 6.1. Data was also collected and analyzed on the level of control bicyclists experienced riding over various rumble strip types. Figure 6.2 and Figure 6.3 summarize the relative ranking of comfort level and control level for various rumble strip types respectively.

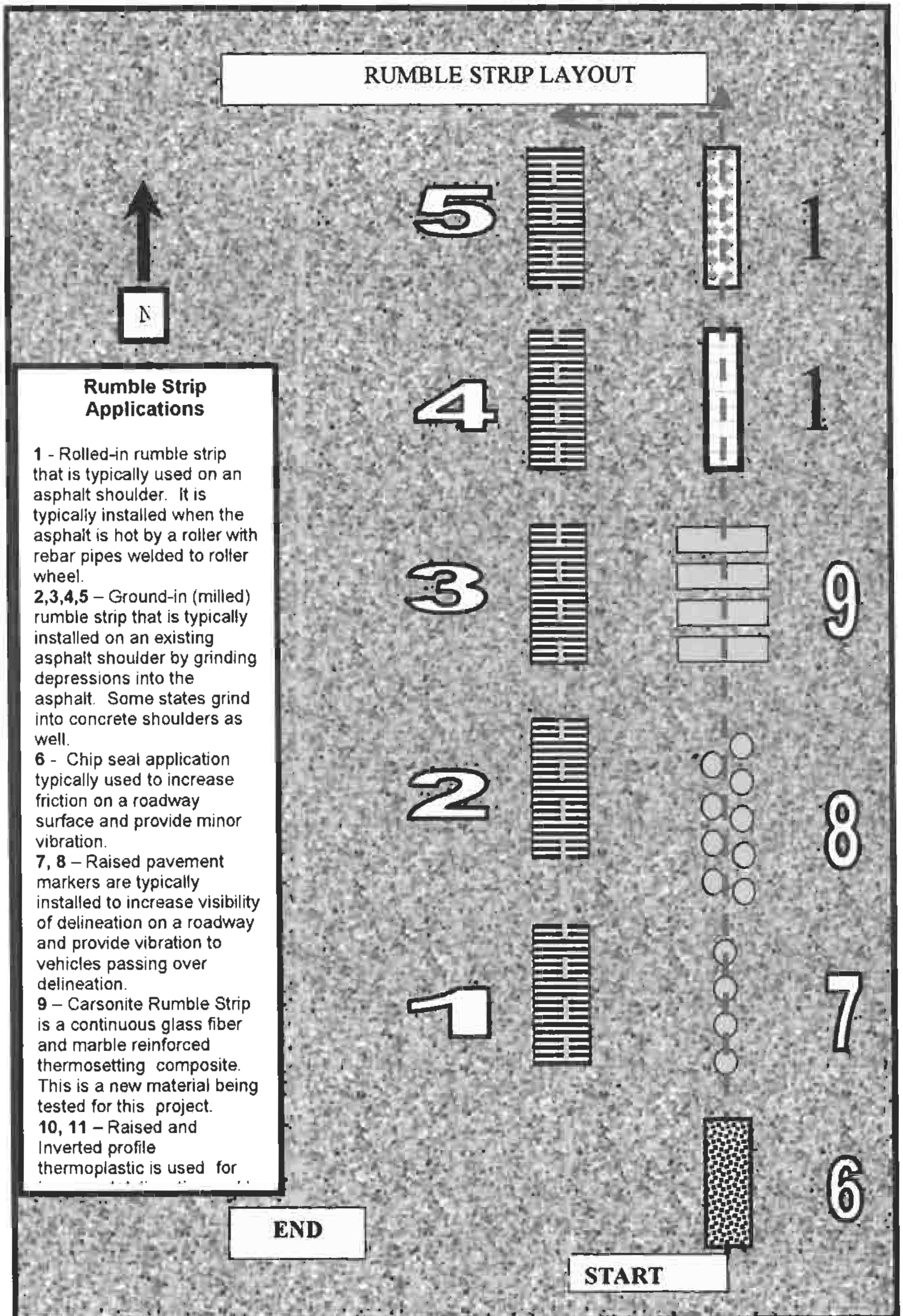


Figure 6.1 Rumble Strip Layout

The bicycle data analysis was based on responses obtained from a fairly limited number of bicyclists (55 bicyclists). Therefore, some restraint had to be exercised in determining the complexity of the questions we wanted to address due to the limited sample size. Two sets of analysis were performed. First, whether the different rumble strip types exhibited different levels of discomfort, averaging over the various measures of discomfort, and second, whether the magnitude of these differences related to the major demographic variables. Because very few demographic variables turned out to be statistically significant in the second set of analyses, additional complicated models involving two or more of the demographic variables were not constructed.

In determining the impact of demographic factors, the analysis looked for the interaction between the segments and the demographic variables, meaning whether the status of the demographic variable affects the relative ordering of the segments. Few variables turned out to be significant (i.e., riding in inclement weather, age, and whether a rider has ridden on rumble strips).

In the next level of analysis we looked at how the roadway segments compared within the demographic subgroups. The analyses that were stratified on whether a rider rode in inclement weather or had ridden on rumble strips indicated that the interactions did not so much affect the order of the segment types, but more by how much one segment is different from the others (i.e. relative spacing).

The analysis for roadway segments comparison within age subgroups was not done due to data limitations including small sample sizes for the various age subgroups. High numerical value for a comfort rating corresponded to a ***high*** level of comfort. Tukey's Studentized Range (HSD) statistical test for ranking different rumble strip types with respect to bicyclist comfort level is shown in Table 6.1. In this table, response values with the same letter indicate that group of rumble strips are not significantly different in their comfort ratings. The mean subjective comfort ratings are plotted in Figure 6.2. Lower values of mean responses in Figure 6.2 represent rumble strip type with lower level of comfort for bicyclists.

Table 6.1 Tukey multiple comparison of mean comfort rating
(Ignoring demographics)

Tukey Groupings			Ignoring demographics	Segment Code
	M		4.5541	11
N			4.1476	10
N			3.927	6
		P	3.2038	1
R		P	2.9042	2
R			2.6789	9
		S	2.0958	3
T		S	2.0048	7
T		S	1.9089	8
T	U		1.6019	4
	U		1.3397	5

The overall analysis indicated that averaging over various measures of discomfort, the rumble strip types are ordered as in Figure 6.2. Rumble strip type "1" has been the standard installation by the California Department of Transportation as a means of preventing run-off road accidents caused by drivers falling asleep. Using type "1" as a reference comparison type, rumble strip types 6, 10, and 11 provide a higher level of comfort as shown from Figure 6.2. Although type "2" is less comfortable than type "1", the difference is not statistically significant as indicated in table 6.1. In comparing the differences the level of comfort and safety it is important to take into account the subjective nature of the data that was collected from relatively small number of bicycle volunteers.

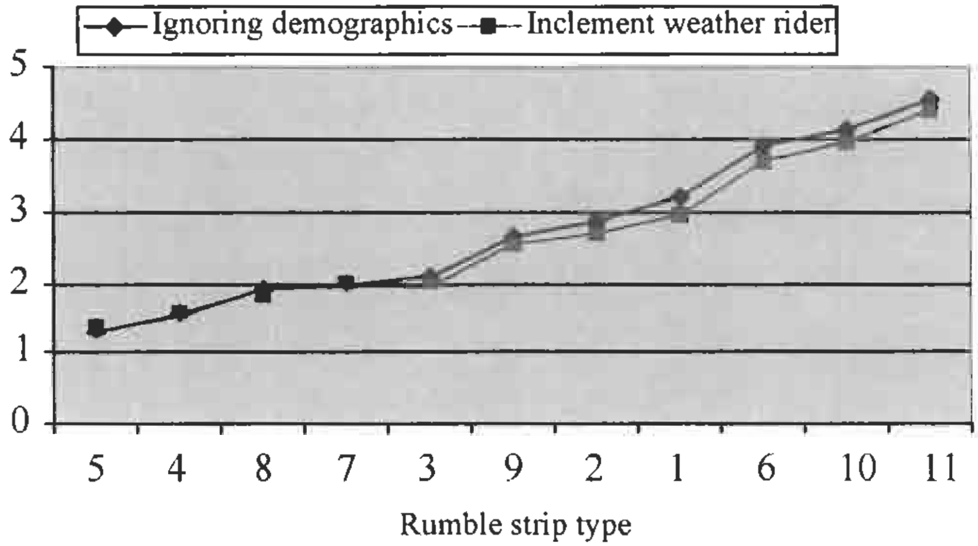


Figure 6.2 Bicyclist comfort rating averaged across various factors

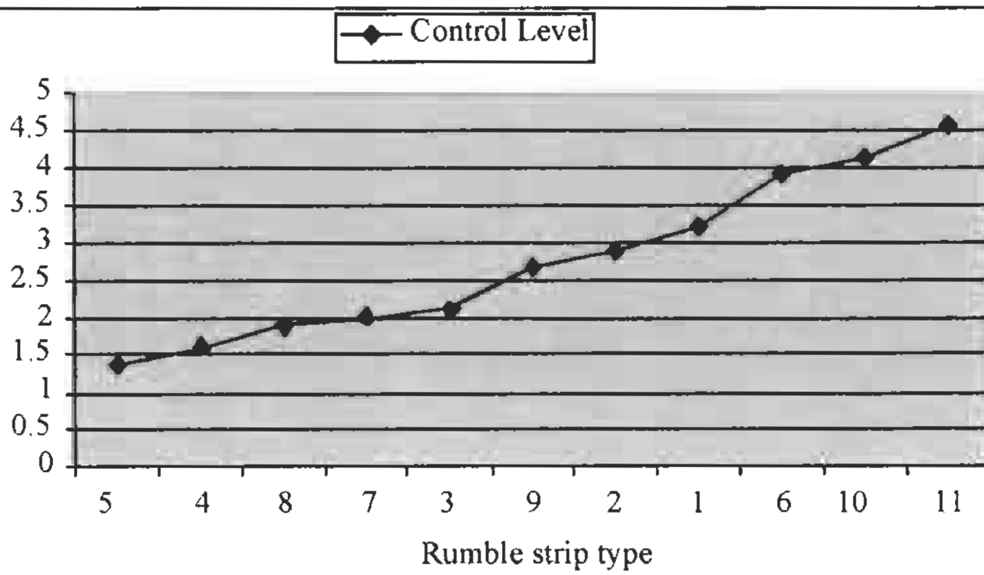


Figure 6.3 Bicyclist control rating averaged across various factors

Considering the limitation of the subjective bicyclists' rating, and using engineering judgment, the decision was made to consider the following rumble strip type in our initial selection process based on the relative ordering of rumble strip types (see Figure 6.2 and Figure 6.3 Types 1, 2, and 9 appear to provide approximately the same level of comfort and control rating for bicyclists. The next best choice with somewhat lower level of comfort and control is rumble strip type-3. Rumble strip type-3 provides approximately 70% of comfort level of type-1. These initial findings from bicycle test will be considered along with many other factors in recommending alternative rumble strip type/types. The factors in this consideration include: rumble strip effectiveness in producing vehicle noise and vibration, rumble strip potential in preventing fatal run-off road accidents, installation cost, and maintenance problems.

6.3 VEHICLE TEST DATA ANALYSIS

Six different vehicles were used to collect data for instrumented and subjective testing. Three of the vehicles were light passenger vehicles, including a Chevrolet Lumina, Dodge Spirit, and Dodge Ram 150 Pick up Truck. The other three vehicles were commercial style trucks including an International 10-wheel tractor (without trailer), an Auto Car 10-yard dump truck, and a GMC Topkick moving van. A detailed discussion on instrumentation for this test, the test facility, rumble strip construction, test vehicles, and data acquisition system is in previous chapters of this report. The vehicle tests provided noise and vibration levels caused by driving selected vehicle types on the various rumble strip types. The data collected for the vehicle testing of rumble strips is summarized in a series of plots presented in Appendix C. The plots provided in Appendix C are organized as described in the Table 6.2. The plots illustrate the effectiveness of various rumble strips in producing different levels of vibration and noise for various conditions. The conditions specified in Table 6.2 are: vehicle type (passenger vehicle vs. trucks), vehicle test speeds (80, and 100 KPH), rumbles strip types (ground-in / rolled-in, and raised thermoplastic), and measurements recorded (vibration, and noise).

Table 6.2 Organization of vehicle test plots in Appendix C

Plot description	Test Vehicle	Test Speed (KPH)	Rumble strip type	Measurement
Figure C1	Passenger Veh.	80 & 100	1 to 5	Vibration
Figure C2	Passenger Veh.	80	1 to 5	Vibration
Figure C3	Passenger Veh.	100	1 to 5	Vibration
Figure C4	Passenger Veh.	80 & 100	1 to 5	Noise
Figure C5	Passenger Veh.	80	1 to 5	Noise
Figure C6	Passenger Veh.	100	1 to 5	Noise
Figure C7	Trucks	80	1 to 5	Vibration
Figure C8	Trucks	80	1 to 5	Noise
Figure C9	Passenger Veh.	80 & 100	6 to 11	Vibration
Figure C10	Passenger Veh.	80	6 to 11	Vibration
Figure C11	Passenger Veh.	100	6 to 11	Vibration
Figure C12	Passenger Veh.	80 & 100	6 to 11	Noise
Figure C13	Passenger Veh.	80	6 to 11	Noise
Figure C14	Passenger Veh.	100	6 to 11	Noise
Figure C15	Trucks	80	6 to 11	Vibration
Figure C16	Trucks	80	6 to 11	Noise

Note that the differences in both vibration and noise level demonstrated in the plots in Appendix C are not significant for two speed levels (80 KPH and 100 KPH). Furthermore, while there were some differences in vibration and noise measurements among various light vehicles, and among various truck types, the relative ranking of various rumble strip types with respect to the level of vibration and noise did not change. This allowed for aggregating the data across various speeds and across light vehicles and across trucks. To do this, we assumed that: (i) the test vehicles are a representative sample of vehicle fleet, and (ii) the test vehicle have similar usage rate on different roadways. We also took into consideration the limitation of the test since we have a limited number of vehicles each generating a single data point. Figure 6.4 and Figure 6.5 are developed based on aggregated data. Vibration and noise measurements across two speeds and various vehicle types are aggregated. The average response values for vibration and noise are also calculated and plotted as: 'Avg. Resp'. Note that for both trucks and passenger vehicles, the rumble strip types that provide higher level of vehicle vibration compared to type 1 (i.e., the base case) are: Type-3, type-4, Type-7, type-8 and type-9. The rumble strip types that provide higher levels of vehicle noise compared to type 1 (base case) are: Type-3, Type-8, type-9, type-7, type-4, and type-5.

The relative noise and vibration levels compared to the base case (type-1) is shown in Table 6.5. The same data is also plotted in Figure 6.6. Note from Figure 6.6 that with the exception of rumble strip types 6, 10, 11, and 2, all the other rumble strip types produce higher level of noise and vibration. Table 6.3 and Figure 6.6 will be utilized again in section 6.4 in conjunction with the results from the bicycle test, accident data analysis in Section 6.3 and other factors to select the most effective rumble strip type/types.

Truck filed test data were considered but was not instrumental in comparing various rumble strip types for three reasons. First, there is not a significant variation in the level of noise and vibration produced by trucks for the rumble strip types that were superior to type-1. The second reason as described in more detail in section 6.3, is that trucks' fatal run-off the road accidents constitute a very minor portion of all the fatal run-off the road accidents for all vehicles. Finally, various rumble strip noise and vibration level for trucks followed a similar ranking and order as that of passenger vehicle trend.

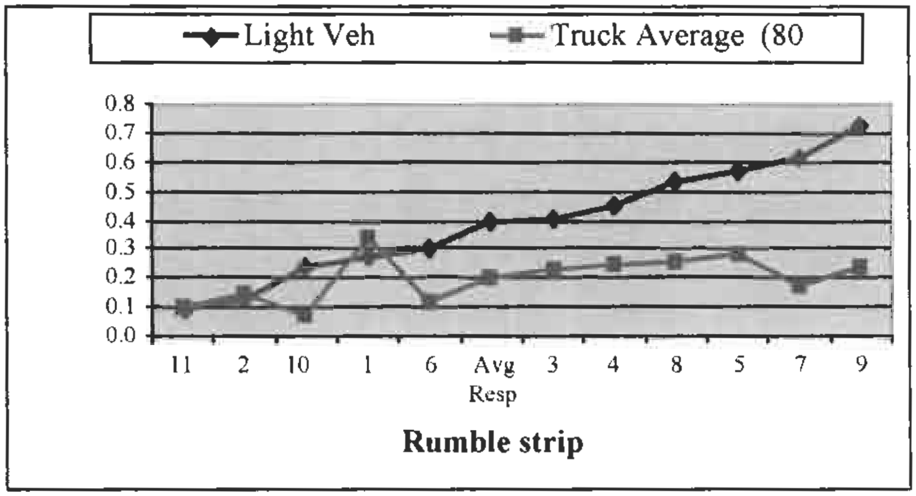


Figure 6.4 Rumble strip vibration measurements

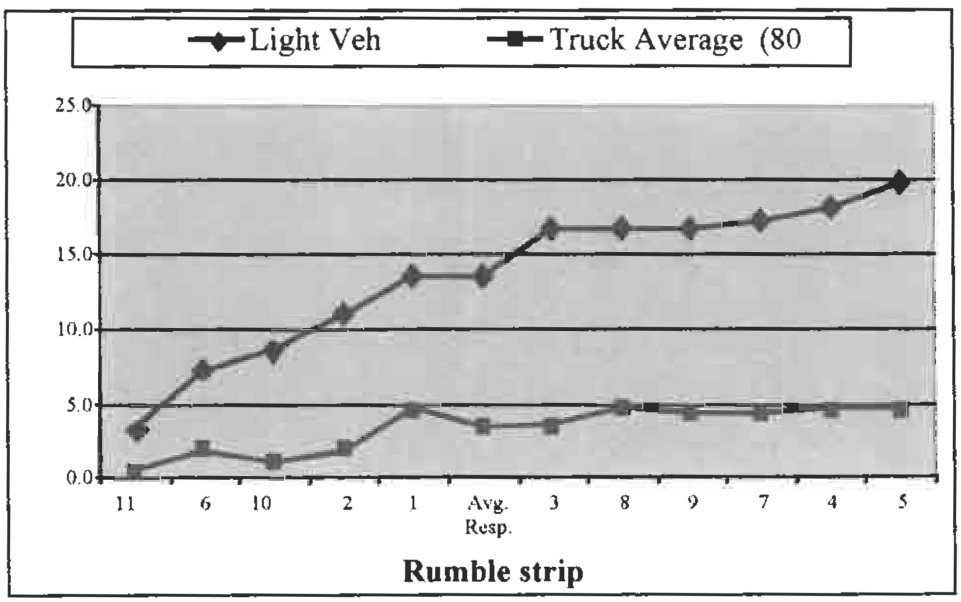
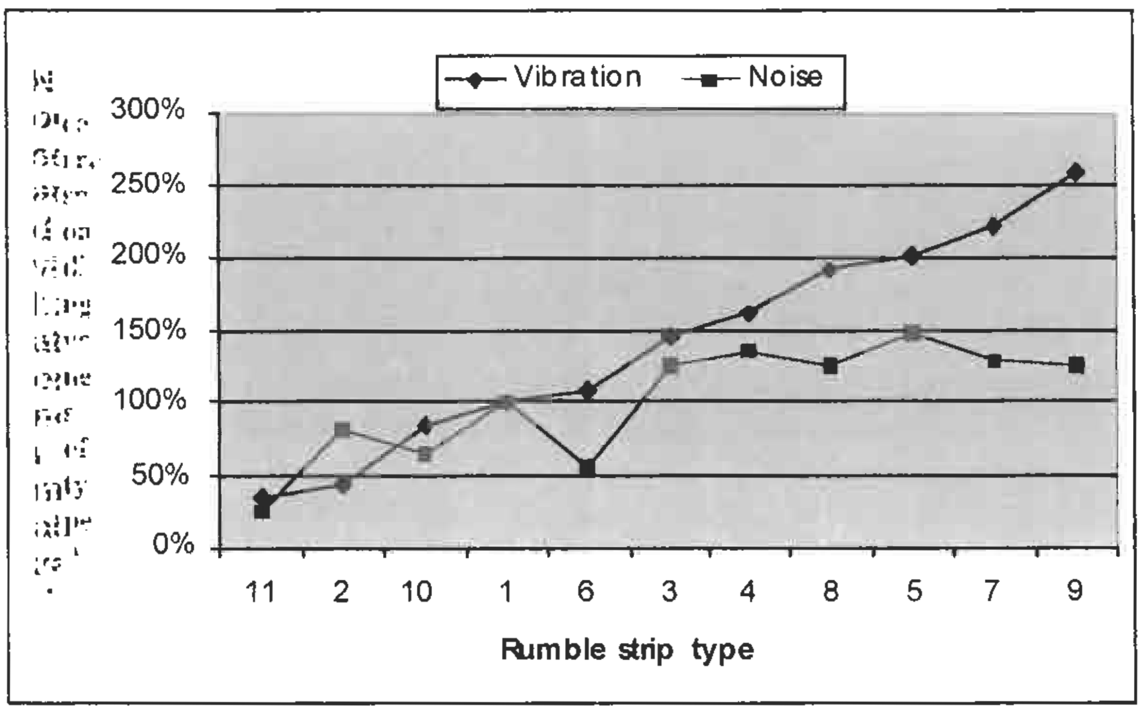


Figure 6.5 Rumble strip noise measurements

Table 6.3 Relative noise and vibration compared to base case type 1 (Passenger Vehicles)

Rumble strip type	Percent Vibration Compared to type 1	Percent Noise Compared to type 1
11	36%	25%
2	45%	81%
10	85%	63%
1	100%	100%
6	109%	55%
3	146%	124%
4	161%	136%
8	192%	124%
5	203%	147%
7	220%	129%
9	259%	124%

Figure 6.6 Comparison of rumble strip types with the base case type-1



6.4 ANALYSIS OF RUN-OFF ROAD ACCIDENTS

Accident data retrieved from the Caltrans' Traffic Accident Surveillance and Analysis System (TASAS) database are summarized in the following tables. There were a total of 929 fatal run-off road accidents during 1997-1999 period. A small portion of these fatal crashes involved single large trucks with 3 axles or more (41 fatal crashes or approximately 4%) and the remaining 888 fatal crashes (i.e., 95.6% of the 929 crashes) involved passenger vehicle.

Table 6.4 provides a breakdown of the truck fatal crashes by primary accident causes. Installation of rumble strip on roadway shoulders is intended to prevent only a portion of the run-off road fatal crashes that are attributed to drivers falling asleep. There are only four fatal truck crashes out of the total of 41 fatal truck fatal crashes that are attributed to driver falling asleep during the 3-year period 1997-1999. The remaining truck crashes were due to primary causes including driving under influence (DUI), alcohol, speeding, etc. Table 6.5 provides similar breakdown of the fatal run-off road accidents for passenger vehicle types. From the 888 passenger vehicle fatal crashes, 54 involved drivers falling asleep.

In conclusion, rumble strips have shown through repeated installations to reduce run-off road collisions for vehicles as discussed in the literature review section of the report. The incidents of run-off road collisions for trucks are very low. This may be in part, due to stricter requirements for licensing of commercial vehicle drivers as well as restrictions on the number of hours they are allowed to drive daily. Accordingly, the recommendations for rumble strip placement should focus on passenger vehicle run-off road and the needs of bicyclists if they are permitted on the roadways where the rumble strips are installed.

Table 6.4. Truck fatal run-off road accidents

(By Primary collision factor)

	Fatal	Fall asleep	Speeding	Improper Turn	DUI	Other Factors
1997	22	2	2	6	7	5
1998	10	1	2	4	3	0
1999	9	1	0	3	3	2
Total	**41**	**4**	**4**	**13**	**13**	**7**

Table 6.5. Passenger vehicle fatal run-off road accidents

(By Primary collision factor)

	Fatal	Fall asleep	Speeding	Improper Turn	DUI	Other Factors
1997	283	23	30	90	94	46
1998	300	16	28	102	96	58
1999	305	15	25	102	116	47
Total	**888**	**54**	**83**	**294**	**306**	**151**

6.5 FINDINGS (COMBINING THE THREE ANALYSES)

The criteria for recommending effective rumble strip alternatives that provide acceptable levels of comfort and control for bicyclist were based on many factors including: vehicle test data analysis, bicycle field test analysis, fatal run-off road accident analysis, cost and funding consideration, maintenance concerns and engineering judgment. Therefore, the following recommendations are based on combining the findings of the analyses in Sections 6.1.2, 6.2, 6.3, and in light of engineering judgement.

The installation cost for ground-in and rolled-in rumble strip types are significantly different. Type 1 can only be installed as a rolled-in application. This means that installation of this type on the existing road shoulder requires replacement of shoulder with new asphalt concrete at significant cost. Type 3 on the other hand can be installed as ground-in application at a significantly lower construction cost.

Based on findings from the bicycle field test, the decision was made to consider the rumble strip types 9, 2, and 3. Although type-2 produces 81% of the vehicle noise level compared to type 1, it produces only 45% of the vehicle vibration compared to type 1. Rumble strip type- 9 ranks approximately the same as type 1 with respect to bicyclist level of comfort and safety, and at the same time provides a higher level of vehicle noise and vibration, it is not a viable alternative due to maintenance problem. Other viable alternatives that demonstrated a more effective level of vehicle noise and vibration (types 8, 4, and 5) were excluded based on low level of comfort and control for bicyclists.

Based on the above findings and analysis of data, and engineering judgment, type 3 remains as a practical alternative that is both acceptable from the standpoint of bicyclists, provides superior level of vehicle noise and vibration compared to type 1 (124% and 146% respectively) and is economically feasible. It is further recommended that in order to increase the level of comfort and control for the bicyclist, the dimensions for the type 3 (3/8 of inch depth) be modified and reduced by one sixteenth of inch. This modification provide an alternative rumble strip type with 5/16 of an inch depth that is a mid-point transition between type 2 (with 1/4 of inch depth) and type 3 with 3/8 of inch depth.

6.6 Motorcycle Rumble Strip Test Results

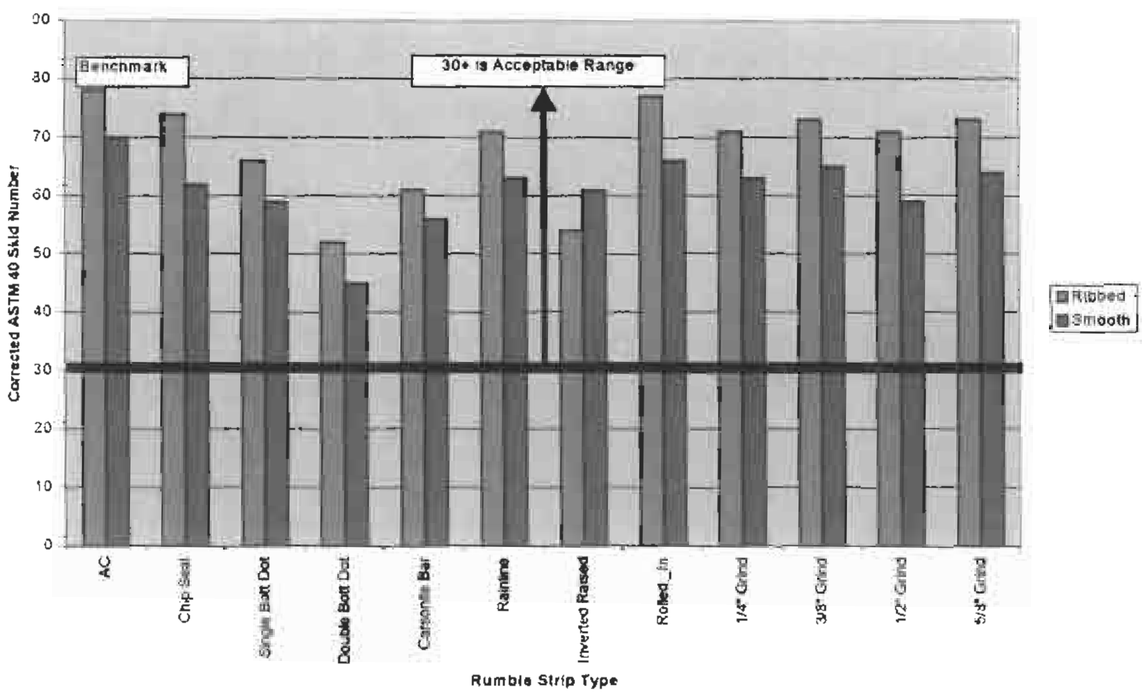
The California Highway Patrol (CHP) was asked to complete a limited field test on rumble strip treatments that were installed at the Dynamic Test Facility. Although statistically insignificant, the experience and rider miles of the CHP team was weighted heavily in the evaluation as they were testing and evaluating the rumble strip treatments from a safety point of view for the average rider.

The CHP used the BMW R1100RTP and Harley Davidson FX motorcycles within their pool for testing purposes. The results of this evaluation can be reviewed in Appendix E.

The results of the test were quite positive. While traveling 50 MPH and 65 MPH over the rumble strip patterns, no significant deficiencies were found. All treatments rated very high. The only concerns noted from the CHP team were that the raised pavement markers and Carsnite Bars were slick when wet.

6.7 Rumble Strip Skid Test – No significant deficiencies found.

Figure 6.7: Rumble Strip Skid Test Results



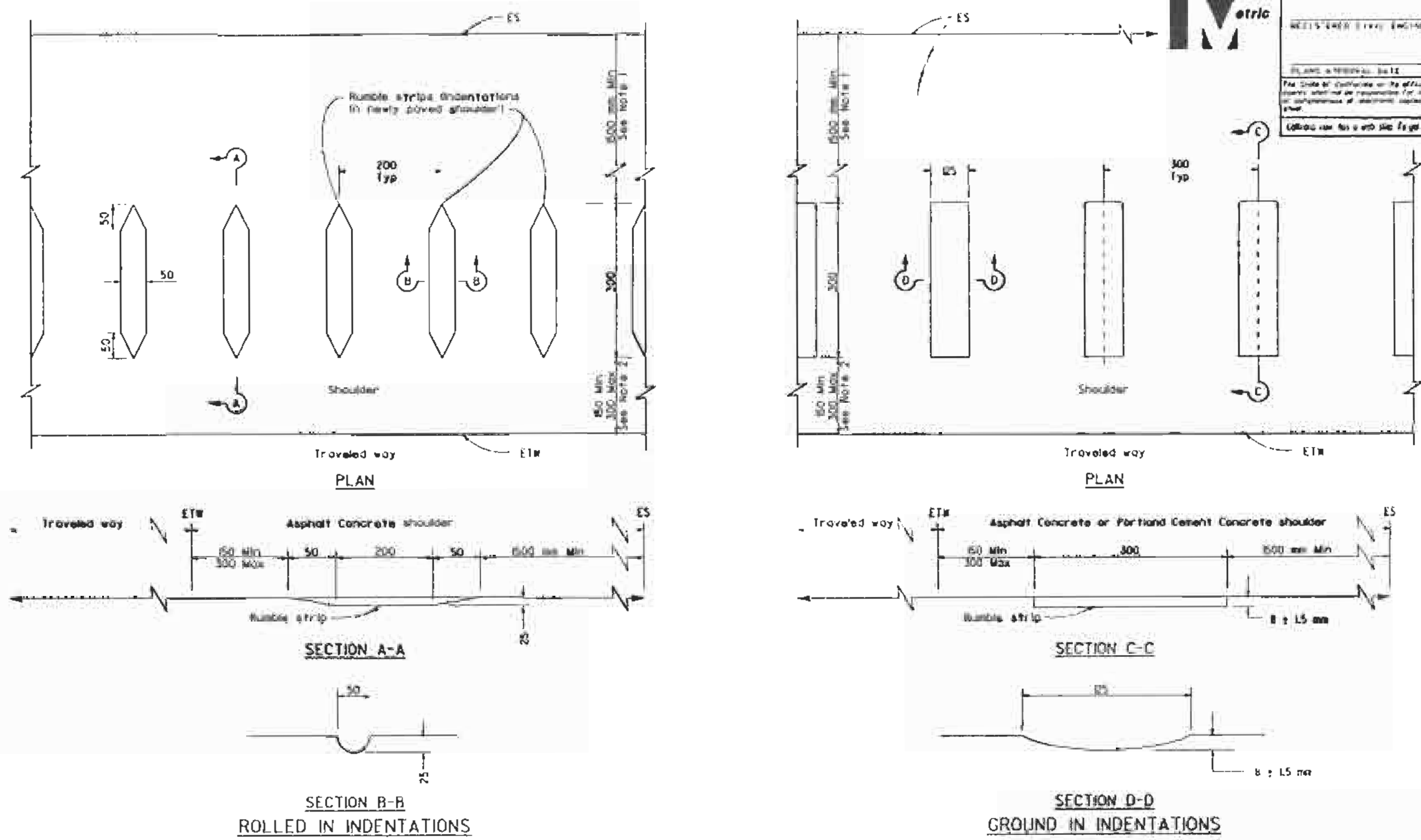
7.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the final analysis of this report, it is recommended that Caltrans move forward with implementation of the following recommendations for the installation of rumble strip treatments on the state highway system, and amend the Caltrans Traffic Manual in the next revision cycle to incorporate the recommendations outlined in this report.

As a result of this study, the following changes in current practice and policy are recommended:

1. Adopt a *new* Standard Plan A40 for rolled-in indentations and ground-in indentations as shown on page 65. The new standard plan would reduce the effective width of the current rolled in indentation (see page 9) from 600 mm (2 feet) to 300 mm (1 foot), and add a ground in indentation with a depth range of 8 ± 1.5 mm (5/16 ± 1/16 inch) and an effective width of 300 mm (see page 65). The new standard plan requires a minimum 1.5 m (5 foot) shoulder for installation.
2. Allow for the installation of raised/inverted profile thermoplastic traffic stripe as a substitute for rumble strip treatment in areas where the shoulder is less than the required 1.5 m for ground in and rolled in indentations, and to provide a continuous rumble strip pattern over bridge decks where rumble strips may be placed on either or both sides of a bridge deck (See Appendix F TOP D#00-04).
3. Adopt the installation (page 66) which guides the placement of rumble strip treatments based on shoulder width and bicycle use.
4. Revise the Caltrans Traffic Manual to address changes in the current policy and include the Rumble Strip Installation Guide, as well as a reference to the Rumble Strip Indentation Construction Detail, for the placement of rumble strip indentations on the shoulder, over bridge decks and at the approach and exit of entrance/ exit ramps.

The following recommendations are based on extensive research study by the Office of Transportation Safety and Research of a variety of rumble strip treatments that were tested using vehicles, bicycles and motorcycles. The following recommendations are the best possible course of action based on the research completed and produce the best desirable results for bicyclists while still maintaining critical noise and vibration to the vehicle.



NOTES

1. Where bicycles are permitted, shoulder rumble strips should not be used unless a minimum of 1.5 meters of clear shoulder width for bicycle use is available between the rumble strips and the outer edge of the shoulder.

2. The minimum 150 mm offset from the ETW to the edge of the rumble strip should be used whenever possible to minimize encroachment into clear shoulder area.

3. Rumble strips, as shown on this plan, shall not be constructed on bridge decks or bridge approach slabs, or across the full width of ramps and public or private (residential and commercial) road approaches.

CONSTRUCTION DETAILS
RUMBLE STRIP

NO SCALE

ALL DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SHOWN

C-1

STATE OF CALIFORNIA - DEPARTMENT OF TRANSPORTATION

ESC-DE LAST REVISED DATE 11-01-00

CU 00000 EA 000000

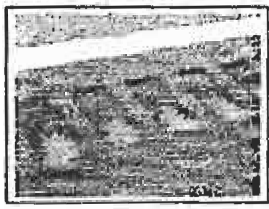
RUMBLE STRIP INSTALLATION GUIDE

RUMBLE STRIP TREATMENT	RUMBLE STRIP DEPTH (mm)	SHOULDER TYPE	BICYLES PERMITTED	SHOULDER WIDTH
Rolled In Rumble Strip Treatment Standard Plan A40	25	ACC Only	YES	1.5 meters minimum
			NO	1.2 meters mimimum
Ground In Rumble Strip Treatment Standard Plan A40	8 (+/- 1.5)	ACC and PCC	YES	1.5 meters minimum
			NO	1.2 meters minimum
Raised and Inverted Profile Thermoplastic	N/A	ACC and PCC	YES	No minimum
			NO	No Minimum
Centerline Ground In Rumble Strip Treatment Experimental	13 max	ACC and PCC	N/A	N/A

NOTE: Ground In Rumble Strip Treatments that are greater than 8.5 +/- 1.5 mm in depth shall not be installed on shoulders where bicyclists are allowed.

APPENDIX A

Rumble Strip Survey



Ground-in (Milled) rumble strip is generally minimally offset from the traveled lane. Tires passing over milled rumble strips make noise and vehicle vibration that are particularly effective in warning large trucks. Milled rumble strips are made by a machine with a rotary cutting head which creates a smooth, uniform, and consistent groove into the road shoulder.

Rolled-in rumble strip is wide rounded or V-shaped grooves pressed into hot asphalt pavements and shoulders when the constructed or reconstructed surface is compacted.

Raised thermoplastic rumble strip is an application combine superior reflective visibility in wet weather with both a tire vibration and audible sound when driven on. Height and frequency of ribs can be varied to establish specific needs.

Rumble Strip Survey

Please complete the following survey and answer all questions that apply to you. The survey is separated into two sections. The first section pertains to automobile use and section two to bicycle use on the state highway system. If both sets of questions are applicable to you then please complete both sections.

AUTOMOBILE USE (SECTION 1)

1. Is the main vehicle that you drive a?

- ☐ Motorcycle
- ☐ Compact-car (small or mid size)
- ☐ Car (big size)
- ☐ Light Duty Truck
- ☐ Commercial Truck (ie truck and trailer)
- ☐ None of the above

2. Have you seen a rumble strip application?

- ☐ Yes
- ☐ No (If No, please skip to question 6)

3. If you have driven over a rumble strip, please check the type of rumble strips. (if you are not sure of the type, please revisit the Rumble Strip Description)?

- ☐ Rolled-In Rumble Strip
- ☐ Ground-In Rumble Strip
- ☐ Raised Thermoplastic
- ☐ Not sure what type but I have encountered them.

4. Was your experience on the rumble strip due to?

- ☐ Drowsiness
- ☐ Momentarily distraction
- ☐ Pulling off the traveled way to the shoulder
- ☐ Other ______________

5. If drowsiness or inattention caused drifting off roadway, did the rumble strip alert you in a fashion that you can maneuver your vehicle back onto the highway safely?

- ☐ Yes
- ☐ No
- ☐ Not applicable to my experience

6. What sensation(s) did you experience while driving over the rumble strip?

- ☐ Vibration of the steering wheel
- ☐ Vibration of the vehicle
- ☐ Audible sound
- ☐ Other ______________

BICYCLE USE (SECTION 2)

7. Do you ride bicycle for?

- ☐ Recreation
- ☐ Utility (commuting, sole or preferred means of transportation)
- ☐ **Both**
- ☐ Other ______________

8. What type of Bike do you ride?

- ☐ Road Bike (narrow tires, "sport touring" type)
- ☐ Mountain Bike
- ☐ Other ____________

9. What is your bicycle's estimated tire width (in inches)?

Estimated width (inches) ____

10. What percent of your riding is in darkness on roads that have shoulder rumble strip?

- ☐ None
- ☐ Less than 15%
- ☐ Between 15% and 30%
- ☐ Above 30% and less than 50%
- ☐ Above 50%

11. What percent of your riding is in the rain on roads that have shoulder rumble strip?

- ☐ None
- ☐ Less than 15%
- ☐ Between 15% and 30%
- ☐ Above 30% and less than 50%
- ☐ Above 50%

12. Does your bicycle have shock absorbers?

- ☐ Yes
- ☐ No

13. Have you ever bicycled over rumble strips applications when bicycling on a highway?

- ☐ Yes
- ☐ No
- ☐ I do not ride my bike on highways.

14. If you bicycle on the state highways, what part of the road do you ride on?

- ☐ Shoulder
- ☐ The traveled way or within a lane
- ☐ Other ____________

15. What makes you deviate from your typical bicycling location when bicycling on a state highway?

- ☐ Debris
- ☐ Approaching-vehicle
- ☐ Rumble Strip Application
- ☐ Other ______________

16. How many miles per month do you ride your bike on highway with shoulder?

I make ____ trips per month, averaging ____ miles per trip

17. How many miles per month do you ride your bike on city streets and pathways?

I make ____ trips per month, averaging ____ miles per trip

18. How would you characterize your bicycle riding skills?

- ☐ Top 75%-(Very confident bicycle enthusiast)
- ☐ Top 50 to 75%-(Bicycling to work and/or recreational)
- ☐ Below 50% (Infrequent bicyclist)

19. How would you characterize your riding on city streets and pathways?

- ☐ Prefer bicycling to auto or transit for most or all trips
- ☐ Bicycle for short trips, shopping, school
- ☐ Bike around the neighborhood

20. What type of rumble strips have you bicycled over while riding your bike? (if you are not sure of the type please revisit the <u>Rumble Strip Description</u>)?

- ☐ Rolled-In Rumble Strip
- ☐ Ground-In (milled) Rumble Strip
- ☐ Raised Thermoplastic
- ☐ Not sure what type
- ☐ None

21. What sensation(s) did you experience riding your bike over the rumble strip?

- ☐ Vibration of the handle bar
- ☐ Shaking of the bicycle
- ☐ Other ______________

22. What is your bicycle's estimated weight?

Estimated weight (pounds) ☐

23. The bicyclist weight will help us determine the best rumble strip design. Please provide your weight (optional).

Estimated weight (pounds) ☐

24. How many bicycle accidents have you been involved in?

On highway	1997 ☐	1998 ☐	1999 ☐
On non-highway	1997 ☐	1998 ☐	1999 ☐

25. For the total number of highway accidents listed above

How many involved injury? ☐
How many included collision with a motor vehicle? ☐
How many were reported to a law enforcement agency? ☐

26. For the total number of non-highway accidents listed above

How many involved injury? ☐
How many included collision with a motor vehicle? ☐
How many were reported to a law enforcement agency? ☐

27. Would you be willing to participate in an evaluative field test to ride a bike on different rumble strip applications?

☐ Yes (if yes, you must provide the information requested at the end of survey)
☐ No

28. If interested in the field test, please indicate which of the following days and time is convenient for you?

☐ Monday ☐ Tuesday ☐ Wednesday ☐ Thursday ☐ Friday ☐ Saturday

29. What would be the best time for you?

☐ Morning 9:00-1:00pm
☐ Afternoon 1:00-4:00pm

We appreciate your participation in this survey and ask you to provide us with the following optional information in case we need to contact you regarding this questionnaire. A percentage of those who express an interest in participating in the field test will be notified by mail/e-mail. A date and location of the field test will be provided with this mailing.

Name

E-mail

Address

Age range:

- Please select one -

City/ZIP

Gender:

- Please select one -

Phone

Comment Section:

Submit Reset

Thank you very much for providing this survey information and for helping your Transportation department provide a better highway for our customers.

You may also contact:

Mr. Ahmad Khorashadi
Telephone: (530) 757-2817
E-mail: Ahmad_khorashadi@dot.ca.gov

Mr. Troy Bucko
Telephone: (916) 654-3917
E-mail:Troy_Bucko@dot.ca.gov

By writing:
California Department of Transportation
Traffic Operations/Traffic Safety Research
Attn: Troy Bucko or Ahmad Khorashadi
1120 N street, Room 4500
Sacramento, CA 95814

APPENDIX B

Appendix B: Field Test Bicycle Questionnaire

Rumble Strip Evaluation Process

1. Each participant will pick up a questionaire form at the Rumble Strip Check in table.
2. Participants will be asked to start at the north end of the rumble strip track which is marked starting point. The participants may travel over the rumble strip at a speed they are compfortable with. Speeds will be measured by a staff member and reported to participant.
3. Participants are asked to ride over all the rumble strips (sections A-E) at once and then if necessary they may go back to the start and complete the course again either by riding over all the strips or individually. Particpants can ride over strips, swerve back and forth over strips etc to get a true feel for the strips.
4. Once they have completed the section (A-E), they will evaluate each rumble strip pattern on the questionaire form for that section.
5. After completion of section (A-E), participants will move over to section (1-6) and complete the same process as above.
6. Once participants have riden over all sections and completed the questionaire form, they should proceed to the check-in table to turn in their questionaire form and complete paperwork for research participation stipend.
7. Caltrans staff are available to assist you with any part of this evaluation or answer questions you may have.

Questionnaire to gather background information

Question	Answer
May I have your name please?	
Your phone number? (Optional)	
Do you ride comfortably in traffic? Heavy traffic?	Yes No / Yes No
Do you ride in inclement weather? Does it bother you?	Yes No / Yes No
Can you climb most hills without dismounting?	Yes No
Please estimate the number of miles you ride per year.	<1,000 3,000-4,000 1,000-2,000 4,000-5,000 2,000-3,000 >5,000
Do you consider yourself a novice, intermediate or advanced rider?	Novice / Intermediate / Advanced
What percentage of your riding is "off-road"?	0-25% 26-50% 51%-75% 76-100%
What is your age range?	15-19 20-25 41-45 26-30 45-50 31-35 51-55 35-40 56-60
What is your sex?	Male / Female
Approximately how much do you weigh? (Lbs)	<100 100-115 176-190 117-130 191-205 131-145 206-220 146-160 221-235 161-175 236-250
How tall are you?	
Do you have any health problems?	Yes No
Do you have pain in any of the following body parts or areas:	
Wrists/fingers/elbows?	Yes No
Shoulders/neck?	Yes No
Back?	Yes No
Seat area?	Yes No
Knee/ankle/foot?	Yes No
Do you know what a shoulder rumble strip is?	Yes No
Have you ever ridden your bicycle over rumble strips?	Yes No

Subjective rider comfort and control questionnaire:

Trial Characteristics		**RIDER COMFORT AND CONTROL RATING**
Rolled-In Section (Labeled A)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1-----2-----3-----4-----5
	Shoulder/Neck	1-----2-----3-----4-----5
	Back	1-----2-----3-----4-----5
	Seat Area	1-----2-----3-----4-----5
	Knee/Ankle/Foot	1-----2-----3-----4-----5
	Overall	1-----2-----3-----4-----5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1-----2-----3-----4-----5
Ground-In Section (Labeled B)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1-----2-----3-----4-----5
	Shoulder/Neck	1-----2-----3-----4-----5
	Back	1-----2-----3-----4-----5
	Seat Area	1-----2-----3-----4-----5
	Knee/Ankle/Foot	1-----2-----3-----4-----5
	Overall	1-----2-----3-----4-----5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1-----2-----3-----4-----5
Ground-In Section (Labeled C)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1-----2-----3-----4-----5
	Shoulder/Neck	1-----2-----3-----4-----5
	Back	1-----2-----3-----4-----5
	Seat Area	1-----2-----3-----4-----5
	Knee/Ankle/Foot	1-----2-----3-----4-----5
	Overall	1-----2-----3-----4-----5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1-----2-----3-----4-----5

Subjective rider comfort and control questionnaire:

Trial Characteristics		RIDER COMFORT AND CONTROL RATING
Ground-In Section (Labeled D)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1----------2----------3----------4----------5
	Shoulder/Neck	1----------2----------3----------4----------5
	Back	1----------2----------3----------4----------5
	Seat Area	1----------2----------3----------4----------5
	Knee/Ankle/Foot	1----------2----------3----------4----------5
	Overall	1----------2----------3----------4----------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1----------2----------3----------4----------5
Ground-In Section (Labeled E)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1----------2----------3----------4----------5
	Shoulder/Neck	1----------2----------3----------4----------5
	Back	1----------2----------3----------4----------5
	Seat Area	1----------2----------3----------4----------5
	Knee/Ankle/Foot	1----------2----------3----------4----------5
	Overall	1----------2----------3----------4----------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1----------2----------3----------4----------5
CHIP SEAL **(Labeled 1)**	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1----------2----------3----------4----------5
	Shoulder/Neck	1----------2----------3----------4----------5
	Back	1----------2----------3----------4----------5
	Seat Area	1----------2----------3----------4----------5
	Knee/Ankle/Foot	1----------2----------3----------4----------5
	Overall	1----------2----------3----------4----------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1----------2----------3----------4----------5

Subjective rider comfort and control questionnaire:

Trial Characteristics		RIDER COMFORT AND CONTROL RATING
Raised Pavement Marker (Single) (Labeled 2)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1------------------2------------------------3------------------4----------------------5
	Shoulder/Neck	1------------------2------------------------3------------------4----------------------5
	Back	1------------------2------------------------3------------------4----------------------5
	Seat Area	1------------------2------------------------3------------------4----------------------5
	Knee/Ankle/Foot	1------------------2------------------------3------------------4----------------------5
	Overall	1------------------2------------------------3------------------4----------------------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1------------------2------------------------3------------------4----------------------5
Raised Pavement Marker (Double) (Labeled 3)	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1------------------2------------------------3------------------4----------------------5
	Shoulder/Neck	1------------------2------------------------3------------------4----------------------5
	Back	1------------------2------------------------3------------------4----------------------5
	Seat Area	1------------------2------------------------3------------------4----------------------5
	Knee/Ankle/Foot	1------------------2------------------------3------------------4----------------------5
	Overall	1------------------2------------------------3------------------4----------------------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1------------------2------------------------3------------------4----------------------5
Carsonite Product **(Labeled 4)**	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1------------------2------------------------3------------------4----------------------5
	Shoulder/Neck	1------------------2------------------------3------------------4----------------------5
	Back	1------------------2------------------------3------------------4----------------------5
	Seat Area	1------------------2------------------------3------------------4----------------------5
	Knee/Ankle/Foot	1------------------2------------------------3------------------4----------------------5
	Overall	1------------------2------------------------3------------------4----------------------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1------------------2------------------------3------------------4----------------------5

Subjective rider comfort and control questionnaire:

Trial Characteristics		RIDER COMFORT AND CONTROL RATING
Raised Thermoplastic **(Labeled 5)**	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1----------------2--------------------3----------------4--------------------5
	Shoulder/Neck	1----------------2--------------------3----------------4--------------------5
	Back	1----------------2--------------------3----------------4--------------------5
	Seat Area	1----------------2--------------------3----------------4--------------------5
	Knee/Ankle/Foot	1----------------2--------------------3----------------4--------------------5
	Overall	1----------------2--------------------3----------------4--------------------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1----------------2--------------------3----------------4--------------------5
Inverted Profile Thermoplastic **(Labeled 6)**	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	1----------------2--------------------3----------------4--------------------5
	Shoulder/Neck	1----------------2--------------------3----------------4--------------------5
	Back	1----------------2--------------------3----------------4--------------------5
	Seat Area	1----------------2--------------------3----------------4--------------------5
	Knee/Ankle/Foot	1----------------2--------------------3----------------4--------------------5
	Overall	1----------------2--------------------3----------------4--------------------5
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling 1----------------2--------------------3----------------4--------------------5

QUESTIONNAIRE RESULTS AND ANALYSIS

Questionnaire to gather background information	**55 RESPONSES**	
May I have your name please?		
Last		
Your phone number? (Optional)		
	TOTAL	**% OF TOTAL**
Do you ride comfortably in traffic?		
Yes	54	98.2
No	1	1.8

Heavy traffic?	TOTAL	% OF TOTAL
Yes	31	62.0
No	19	38.0
Do you ride in inclement weather?		
Yes	41	75.9
No	13	24.1
Does it bother you?		
Yes	32	64.0
No	18	36.0
Can you climb most hills without dismounting?		
Yes	51	94.4
No	3	5.6
Please estimate the number of miles you ride per year.		
<1,000	14	25.5
1,000-2,000	9	16.4
2,000-3,000	13	23.6
3,000-4,000	5	9.1
4,000-5,000	3	5.5
>5,000	11	20.0
Do you consider yourself a novice, intermediate or advanced rider?		
Novice	3	5.5
Intermediate	24	43.6
Advanced	28	50.9
What percentage of your riding is "off-road"?		
0-25%	50	90.9
26-50	4	7.3
51-75	1	1.8
76-100	0	0.0
What is your age range?		
15-19	0	0.0
20-25	0	0.0
26-30	3	5.6
31-35	3	5.6
35-40	6	11.1
41-45	14	25.9
45-50	15	27.8
51-55	6	11.1
56-60	6	11.1
<60	1	1.9

	TOTAL	% OF TOTAL
What is your sex?		
Male	45	83.3
Female	9	16.7
Approximately how much do you weigh? (Lbs)		
<100	1	1.8
100-116	0	0.0
117-130	4	7.3
131-145	8	14.5
146-160	7	12.7
161-175	12	21.8
176-190	9	16.4
191-205	8	14.5
206-220	2	3.6
221-235	3	5.5
236-250	1	1.8
How tall are you?		
Do you have any health problems?		
Yes	4	7.3
No	51	92.7
Do you have pain in any of the following body parts or areas:		
Wrists/fingers/elbows?		
Yes	2	5.7
No	33	94.3
Shoulders/neck?		
Yes	3	8.6
No	32	91.4
Back?		
Yes	5	14.3
No	30	85.7
Seat area?		
Yes	1	2.9
No	34	97.1
Knee/ankle/foot?		
Yes	4	11.4
No	31	88.6
Do you know what a shoulder rumble strip is?		
Yes	33	97.1

No	1	2.9
	TOTAL	**% OF TOTAL**
Have you ever ridden your bicycle over rumble strips?		
Yes	27	77.1
No	8	22.9
Subjective rider comfort and control questionnaire:		
Trial Characteristics		
RIDER COMFORT AND CONTROL RATING		
	Average Rating	
Rolled-In Section A		
Wrist/Fingers/Elbows	3.09	
Shoulder/Neck	3.34	
Back	3.33	
Seat area	3.08	
Knee/Ankle/Foot	3.14	
Overall	3.24	
Control Level	3.51	
Ground-In Section B		
Wrist/Fingers/Elbows	2.85	
Shoulder/Neck	3.03	
Back	2.97	
Seat area	2.87	
Knee/Ankle/Foot	2.85	
Overall	2.86	
Control Level	3.15	
Ground-In Section C		
Wrist/Fingers/Elbows	2.09	
Shoulder/Neck	2.21	
Back	2.13	
Seat area	2.01	
Knee/Ankle/Foot	2.10	
Overall	2.05	
Control Level	2.31	
Ground-In Section D		
Wrist/Fingers/Elbows	1.59	
Shoulder/Neck	1.70	
Back	1.62	
Seat area	1.50	
Knee/Ankle/Foot	1.64	

Overall	1.56	
Control Level	1.72	
	TOTAL	
Ground-In Section E		
Wrist/Fingers/Elbows	1.36	
Shoulder/Neck	1.37	
Back	1.37	
Seat area	1.27	
Knee/Ankle/Foot	1.39	
Overall	1.29	
Control Level	1.47	
Chip Seal Section 1		
Wrist/Fingers/Elbows	3.85	
Shoulder/Neck	4.00	
Back	4.02	
Seat area	3.90	
Knee/Ankle/Foot	3.90	
Overall	3.89	
Control Level	4.07	
Raised Pavement Marker Section 2		
Wrist/Fingers/Elbows	2.00	
Shoulder/Neck	2.10	
Back	2.11	
Seat area	1.77	
Knee/Ankle/Foot	2.10	
Overall	1.96	
Control Level	2.08	
Double Raises Pavement Marker Section 3		
Wrist/Fingers/Elbows	1.90	
Shoulder/Neck	1.91	
Back	2.01	
Seat area	1.82	
Knee/Ankle/Foot	1.98	
Overall	1.83	
Control Level	1.97	
Carsonite Product Section 4		
Wrist/Fingers/Elbows	2.64	
Shoulder/Neck	2.77	
Back	2.75	
Seat area	2.56	

Knee/Ankle/Foot	2.70	
Overall	2.65	
Control Level	2.80	
	TOTAL	
Raised Profile Thermoplastic Section 5		
Wrist/Fingers/Elbows	4.14	
Shoulder/Neck	4.13	
Back	4.18	
Seat area	4.07	
Knee/Ankle/Foot	4.22	
Overall	4.14	
Control Level	4.14	
Rainline Section 6		
Wrist/Fingers/Elbows	4.54	
Shoulder/Neck	4.55	
Back	4.54	
Seat area	4.58	
Knee/Ankle/Foot	4.57	
Overall	4.56	
Control Level	4.58	

APPENDIX C

Appendix C Vehicle test data

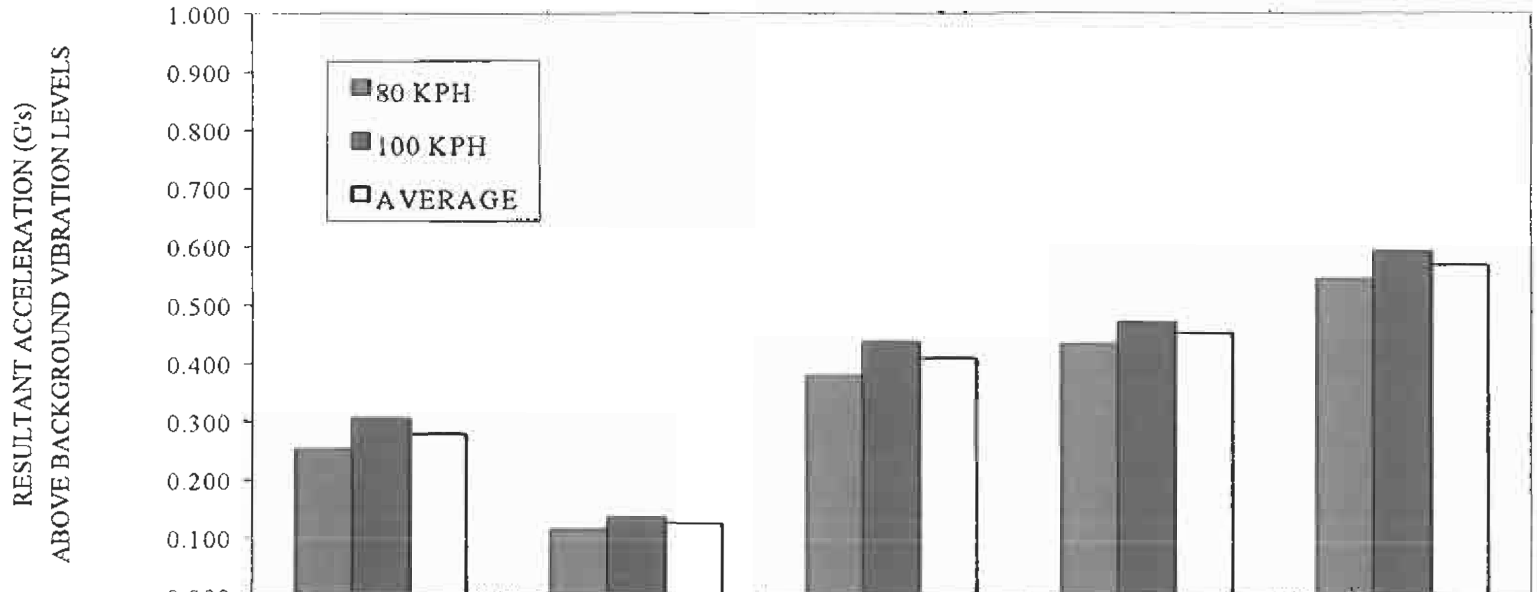
Organization of plots

Plot description*	Test Vehicle	Test Speed (KPH)	Rumble strip type	Measurement
Figure C1	Passenger Veh.	80 & 100	1 to 5	Vibration
Figure C2	Passenger Veh.	80	1 to 5	Vibration
Figure C3	Passenger Veh.	100	1 to 5	Vibration
Figure C4	Passenger Veh.	80 & 100	1 to 5	Noise
Figure C5	Passenger Veh.	80	1 to 5	Noise
Figure C6	Passenger Veh.	100	1 to 5	Noise
Figure C7	Trucks	80	1 to 5	Vibration
Figure C8	Trucks	80	1 to 5	Noise
Figure C9	Passenger Veh.	80 & 100	6 to 11	Vibration
Figure C10	Passenger Veh.	80	6 to 11	Vibration
Figure C11	Passenger Veh.	100	6 to 11	Vibration
Figure C12	Passenger Veh.	80 & 100	6 to 11	Noise
Figure C13	Passenger Veh.	80	6 to 11	Noise
Figure C14	Passenger Veh.	100	6 to 11	Noise
Figure C15	Trucks	80	6 to 11	Vibration
Figure C16	Trucks	80	6 to 11	Noise

* Figure C1 through C8 pertain to ground-in or rolled-in rumble strips (types 1 through 5)
* Figure C9 through C16 pertain to raised rumble strips (types 6 through 11)

FIGURE C1

RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES

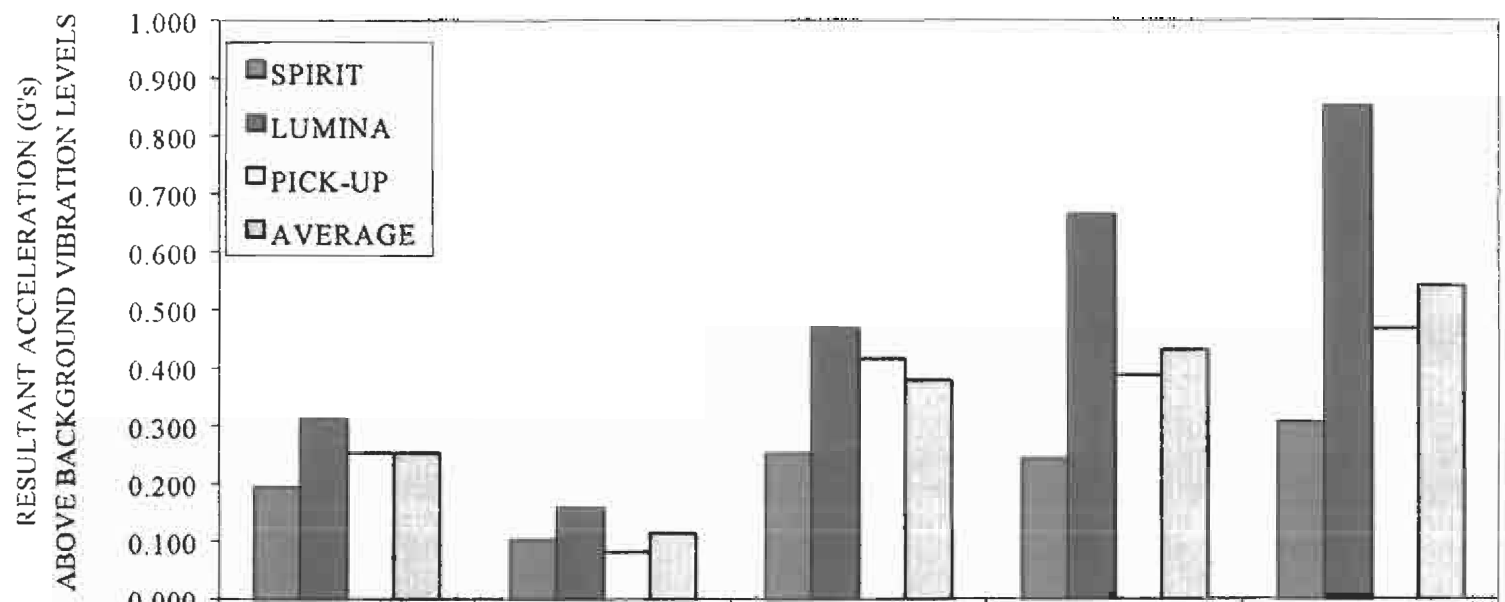


	1	2	3	4	5
80 KPH	0.253	0.115	0.379	0.432	0.542
100 KPH	0.306	0.135	0.437	0.469	0.591
AVERAGE	0.280	0.125	0.408	0.450	0.567

RUMBLE STRIP SEGMENT NUMBER

FIGURE C2

RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES AT 80 KPH

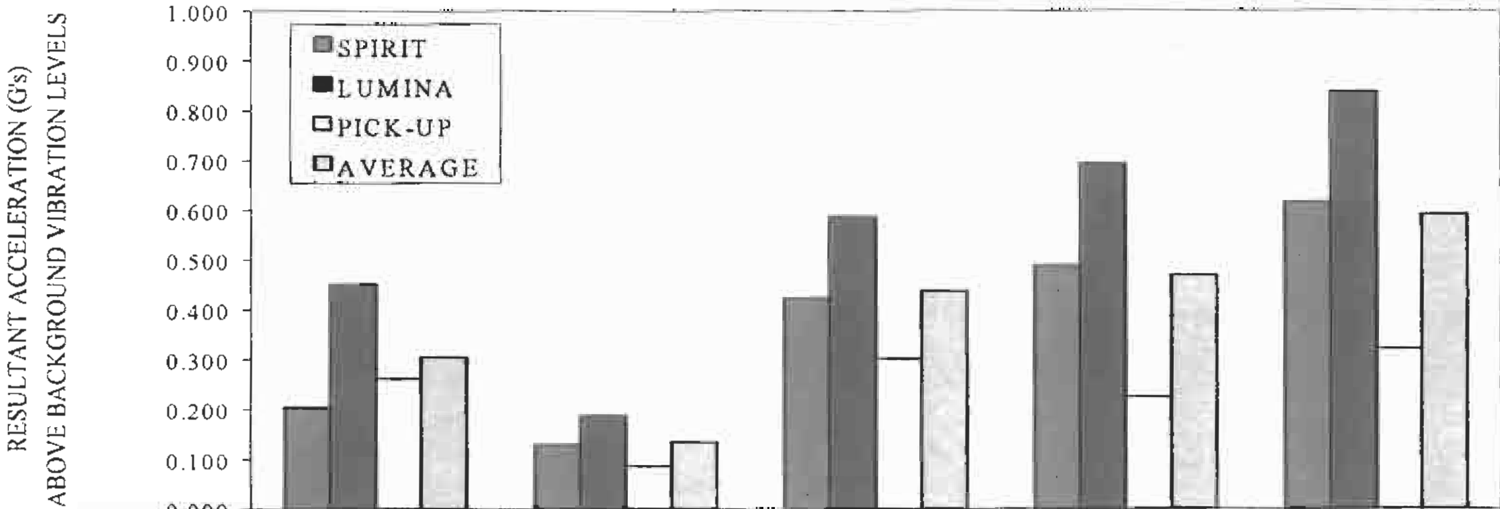


	1	2	3	4	5
SPIRIT	0.195	0.103	0.252	0.243	0.306
LUMINA	0.312	0.159	0.468	0.664	0.853
PICK-UP	0.253	0.082	0.416	0.387	0.467
AVERAGE	0.253	0.115	0.379	0.432	0.542

RUMBLE STRIP SEGMENT NUMBER

FIGURE C3

RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES AT 100 KPH

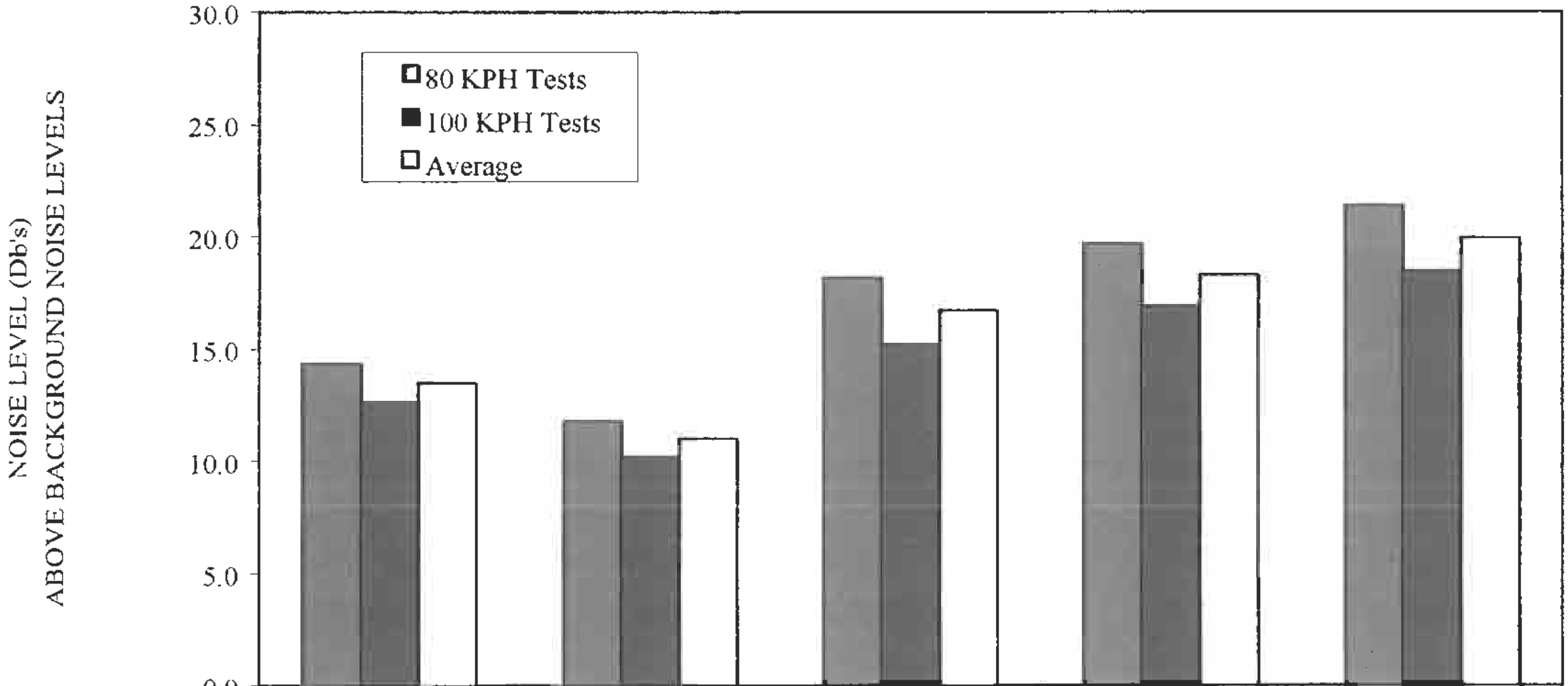


	1	2	3	4	5
SPIRIT	0.204	0.131	0.423	0.488	0.615
LUMINA	0.452	0.189	0.587	0.693	0.837
PICK-UP	0.263	0.086	0.302	0.225	0.322
AVERAGE	0.306	0.135	0.437	0.469	0.591

RUMBLE STRIP SEGMENT NUMBER

FIGURE C4

RUMBLE STRIP NOISE MEASUREMENTS
LIGHT VEHICLES

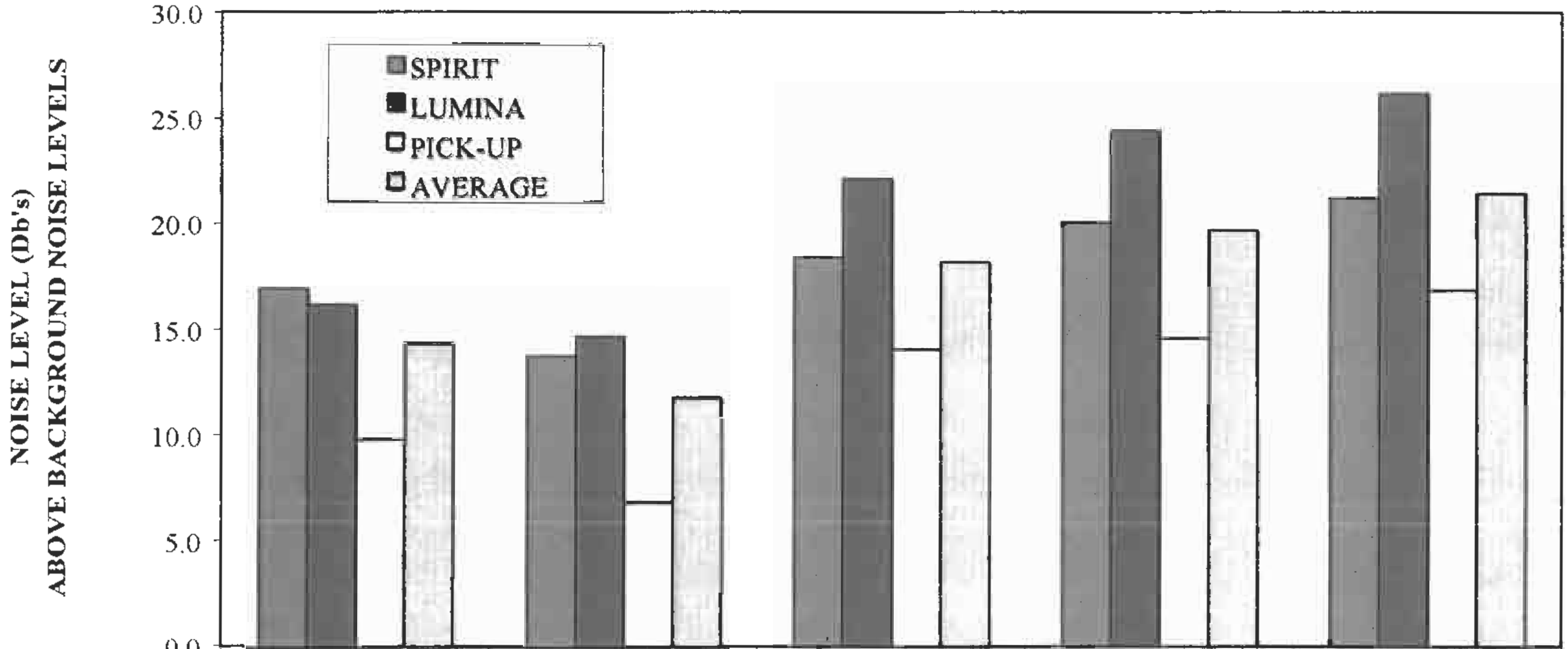


	1	2	3	4	5
80 KPH Tests	14.4	11.8	18.2	19.7	21.4
100 KPH Tests	12.6	10.2	15.2	16.9	18.5
Average	13.5	11.0	16.7	18.3	19.9

RUMBLE STRIP SEGMENT NUMBER

FIGURE C5

RUMBLE STRIP NOISE MEASUREMENTS
LIGHT VEHICLES AT 80 KPH

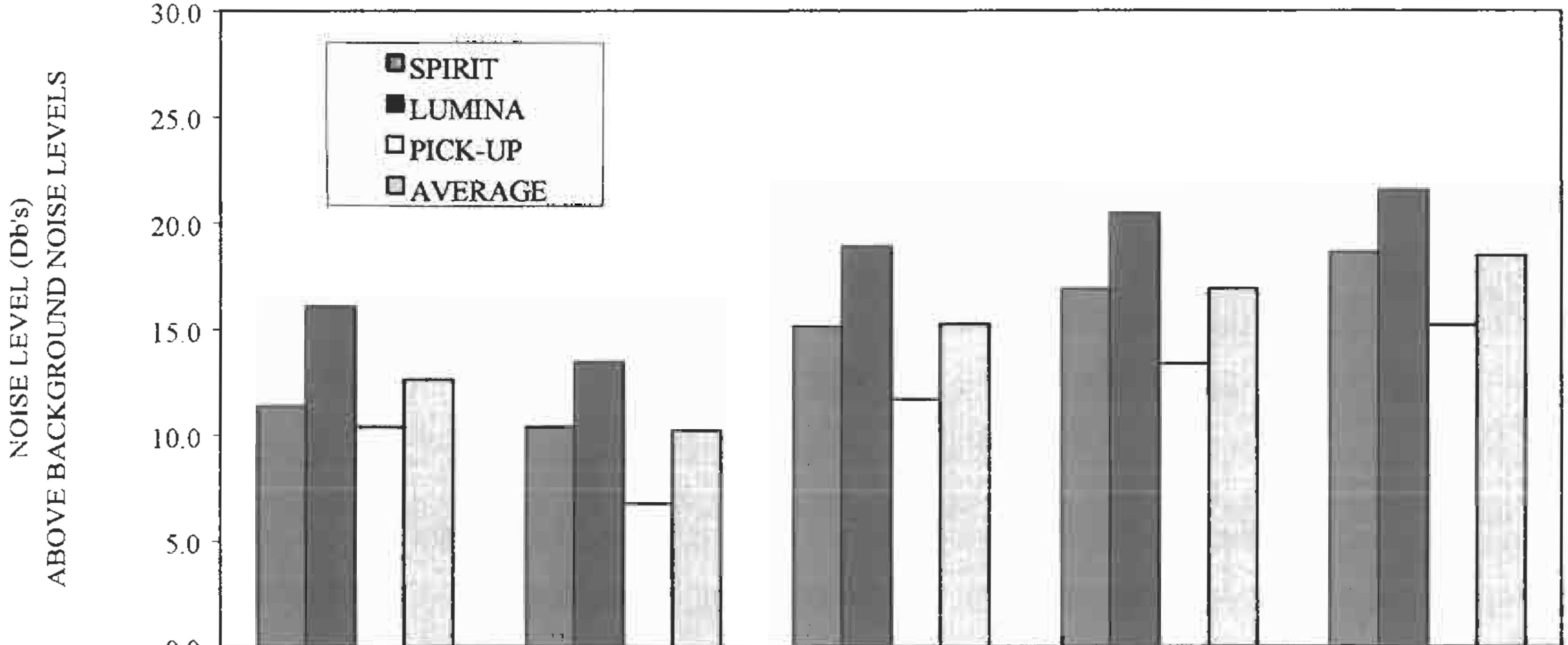


	1	2	3	4	5
SPIRIT	17.0	13.8	18.4	20.1	21.2
LUMINA	16.2	14.8	22.1	24.4	26.2
PICK-UP	9.9	6.9	14.1	14.6	16.8
AVERAGE	14.4	11.8	18.2	19.7	21.4

RUMBLE STRIP SEGMENT NUMBER

FIGURE C6

RUMBLE STRIP NOISE MEASUREMENTS
LIGHT VEHICLES AT 100 KPH

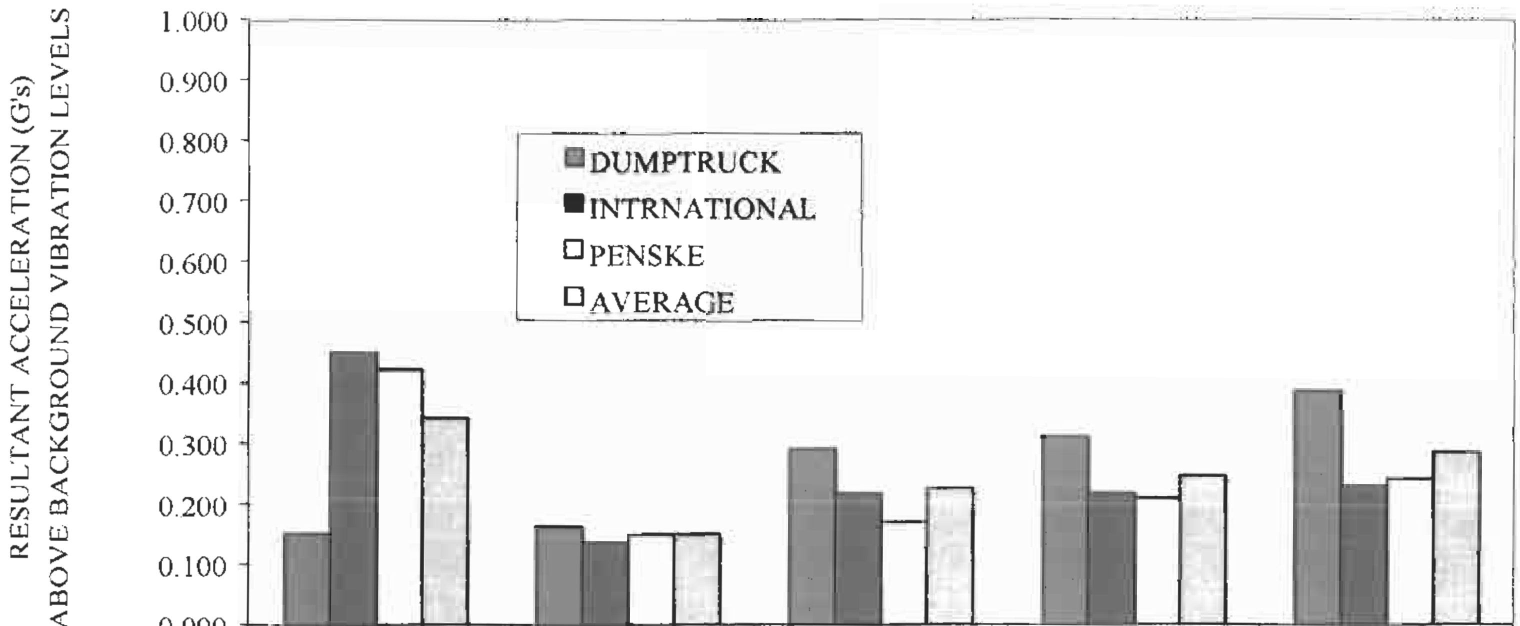


	1	2	3	4	5
SPIRIT	11.4	10.4	15.1	16.9	18.6
LUMINA	16.1	13.5	18.9	20.5	21.6
PICK-UP	10.4	6.8	11.7	13.4	15.2
AVERAGE	12.6	10.2	15.2	16.9	18.5

RUMBLE STRIP SEGMENT NUMBER

FIGURE C7

RUMBLE STRIP VIBRATION MEASUREMENTS
COMMERCIAL VEHICLES AT 80 KPH

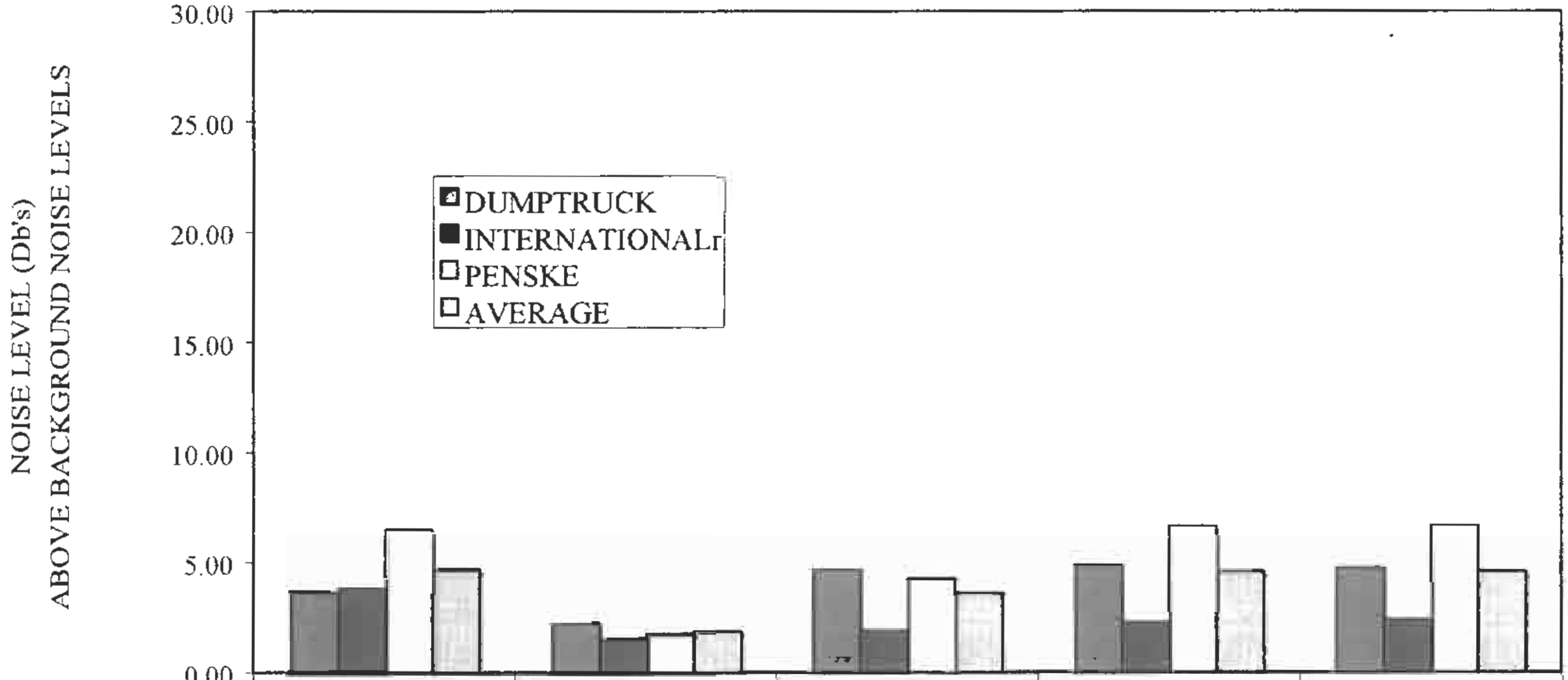


	1	2	3	4	5
DUMPTRUCK	0.152	0.162	0.291	0.312	0.386
INTRNATIONAL	0.452	0.137	0.218	0.218	0.230
PENSKE	0.423	0.151	0.170	0.209	0.241
AVERAGE	0.342	0.150	0.226	0.246	0.286

RUMBLE STRIP SEGMENT NUMBER

FIGURE C8

RUMBLE STRIP NOISE MEASUREMENTS
COMMERCIAL VECHICLES AT 80 KPH

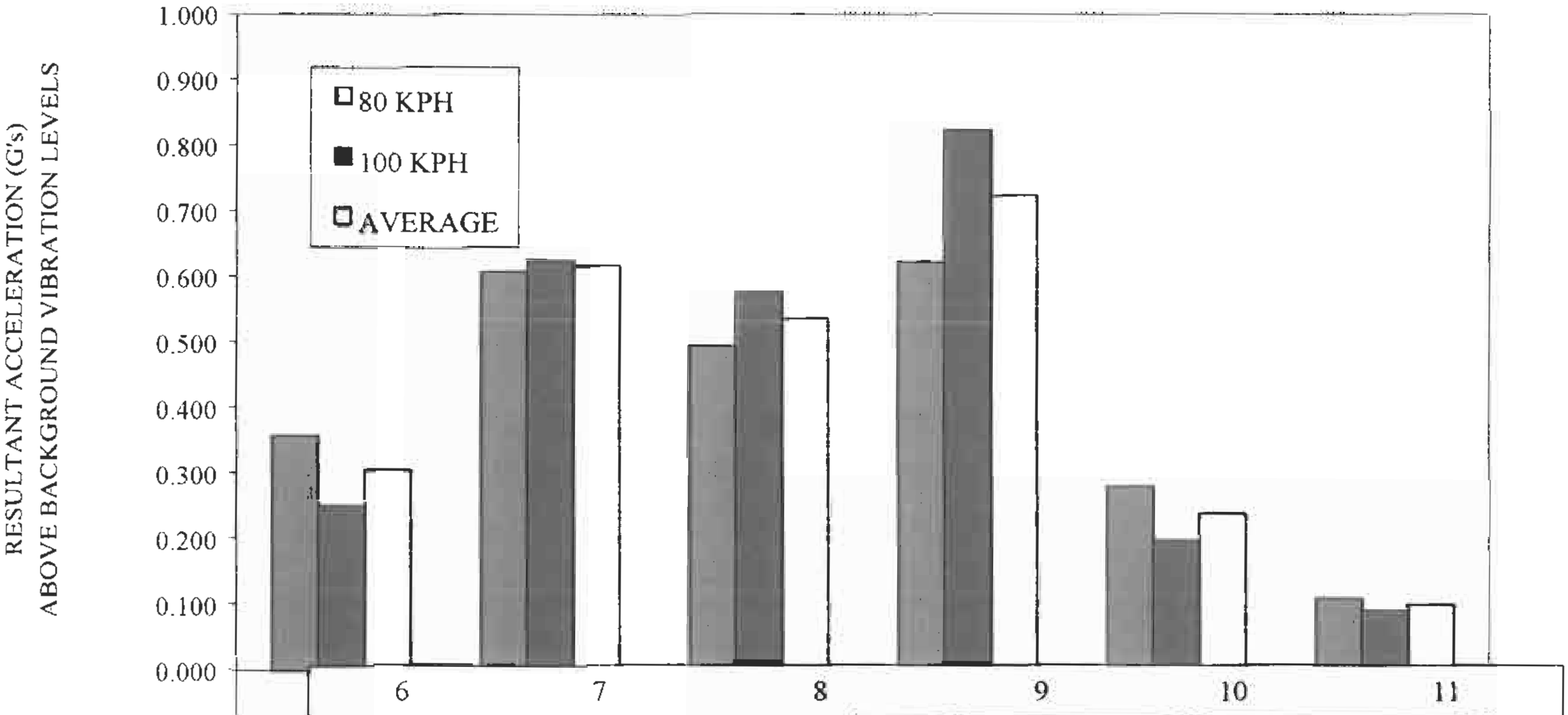


	1	2	3	4	5
DUMPTRUCK	3.72	2.31	4.69	4.86	4.76
INTERNATIONALr	3.92	1.57	1.91	2.30	2.41
PENSKE	6.52	1.76	4.27	6.67	6.69
AVERAGE	4.72	1.88	3.62	4.61	4.62

RUMBLE STRIP SEGMENT NUMBER

FIGURE C9

RAISED RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES

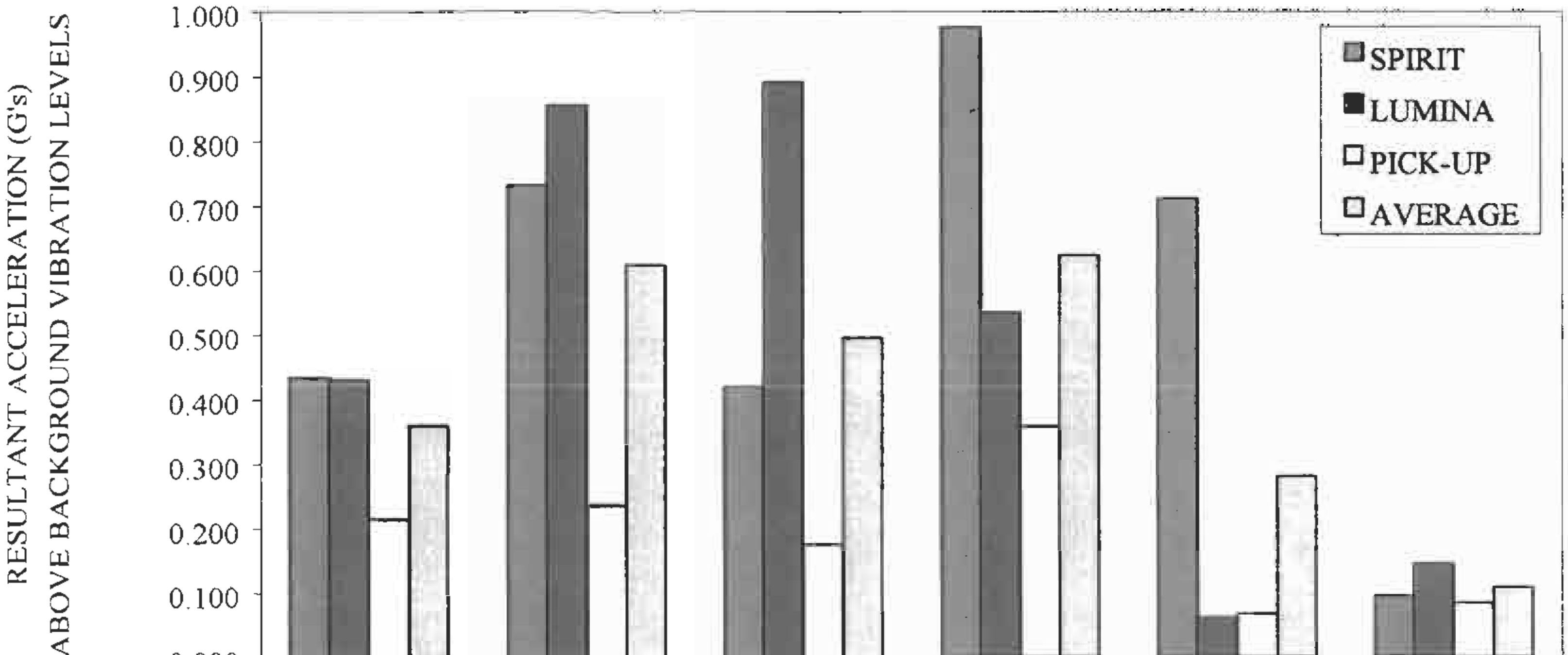


	6	7	8	9	10	11
80 KPH	0.359	0.608	0.495	0.623	0.280	0.108
100 KPH	0.252	0.625	0.578	0.824	0.197	0.091
AVERAGE	0.306	0.617	0.537	0.724	0.238	0.100

RUMBLE STRIP SEGMENT NUMBER

FIGURE C10

RAISED RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES AT 80 KPH

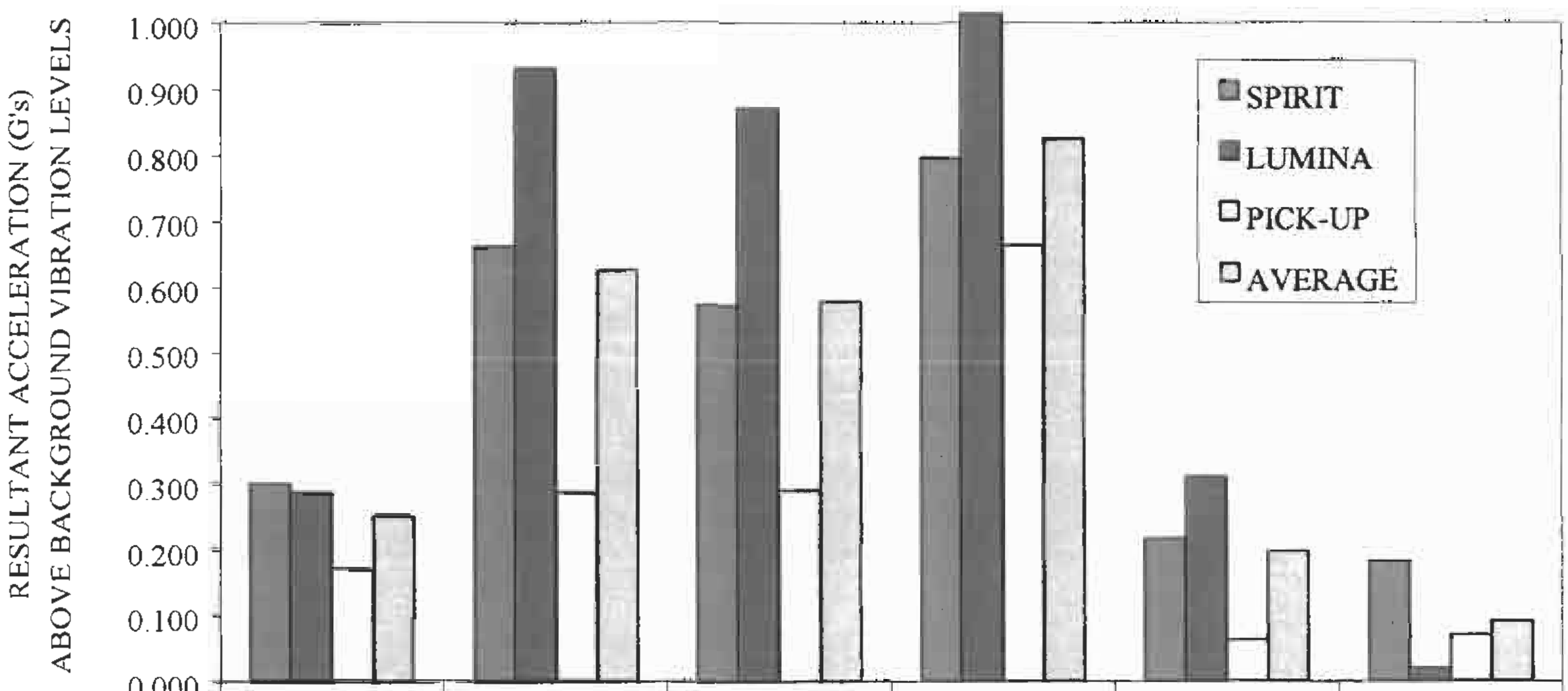


	6	7	8	9	10	11
SPIRIT	0.433	0.732	0.420	0.976	0.711	0.095
LUMINA	0.429	0.856	0.890	0.534	0.062	0.145
PICK-UP	0.215	0.236	0.176	0.358	0.068	0.085
AVERAGE	0.359	0.608	0.495	0.623	0.280	0.108

RUMBLE STRIP SEGMENT NUMBER

FIGURE C11

RAISED RUMBLE STRIP VIBRATION MEASUREMENTS
LIGHT VEHICLES AT 100 KPH

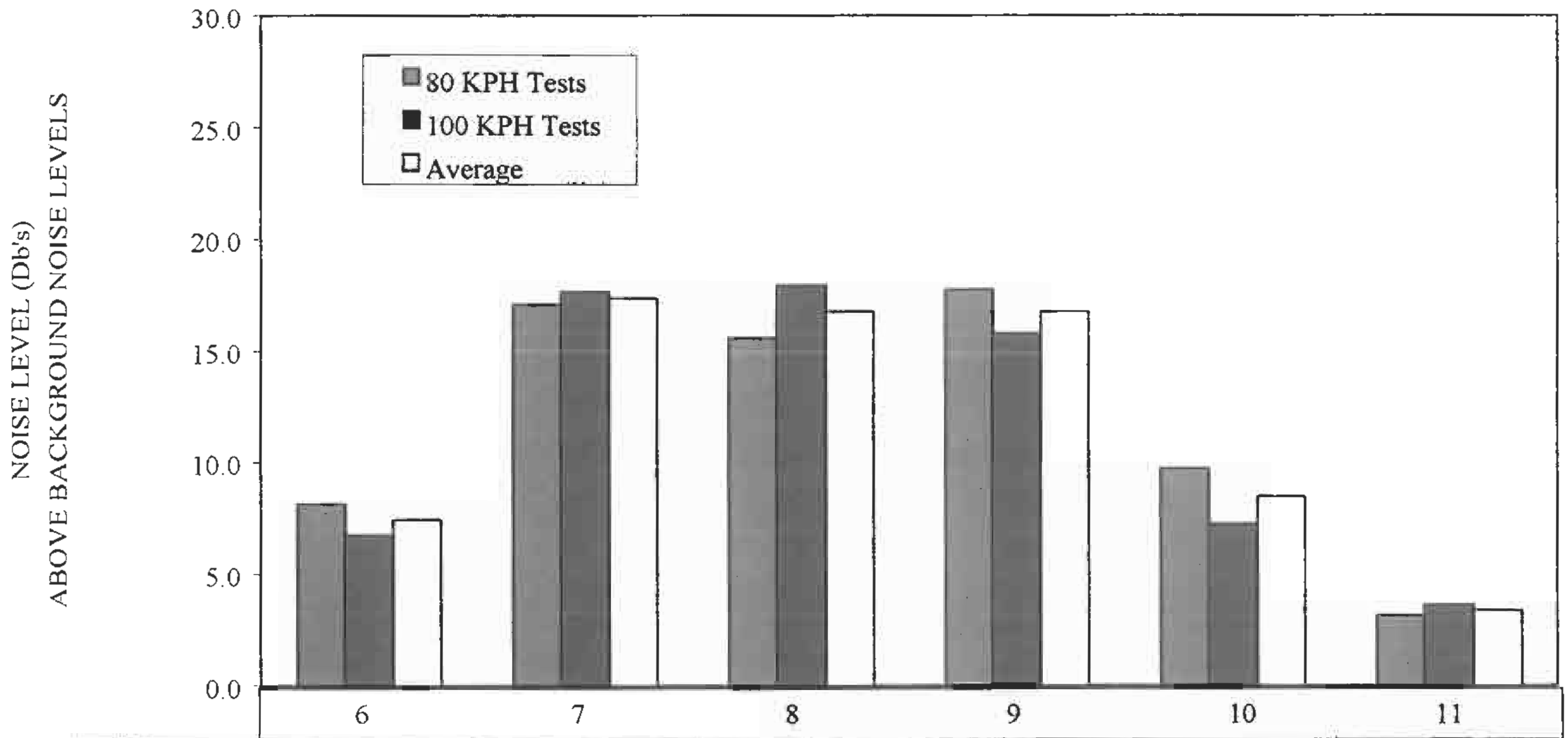


	6	7	8	9	10	11
SPIRIT	0.299	0.660	0.571	0.795	0.217	0.181
LUMINA	0.286	0.931	0.871	1.015	0.310	0.020
PICK-UP	0.171	0.286	0.291	0.663	0.063	0.071
AVERAGE	0.252	0.625	0.578	0.824	0.197	0.091

RUMBLE STRIP SEGMENT NUMBER

FIGURE C12

RAISED RUMBLE STRIP NOISE MEASUREMENTS
LIGHT VEHICLES

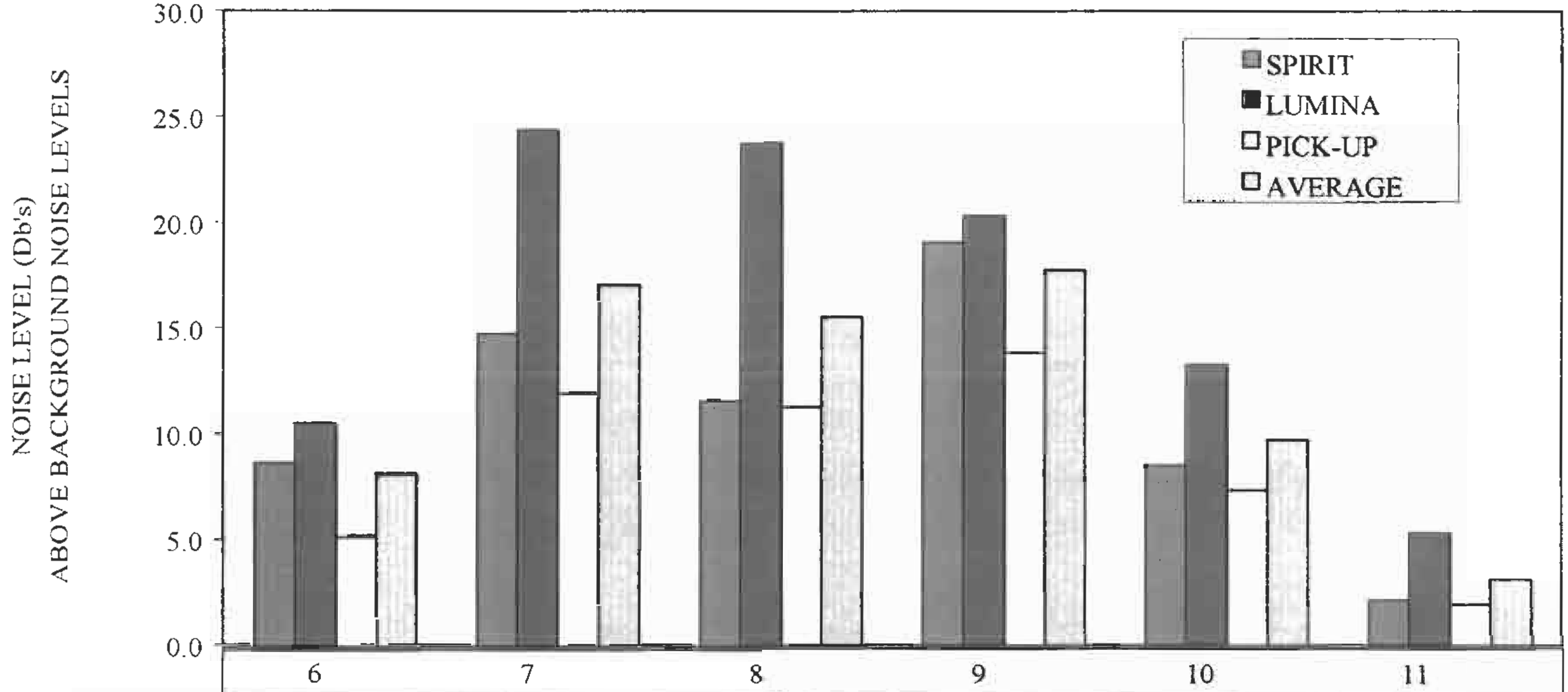


	6	7	8	9	10	11
80 KPH Tests	8.1	17.1	15.6	17.8	9.7	3.1
100 KPH Tests	6.7	17.6	17.9	15.8	7.2	3.6
Average	7.4	17.4	16.8	16.8	8.5	3.4

RUMBLE STRIP SEGMENT NUMBER

FIGURE C13

RAISED RUMBLE STRIP NOISE MEASUREMENTS
LIGHT VEHICLES AT 80 KPH

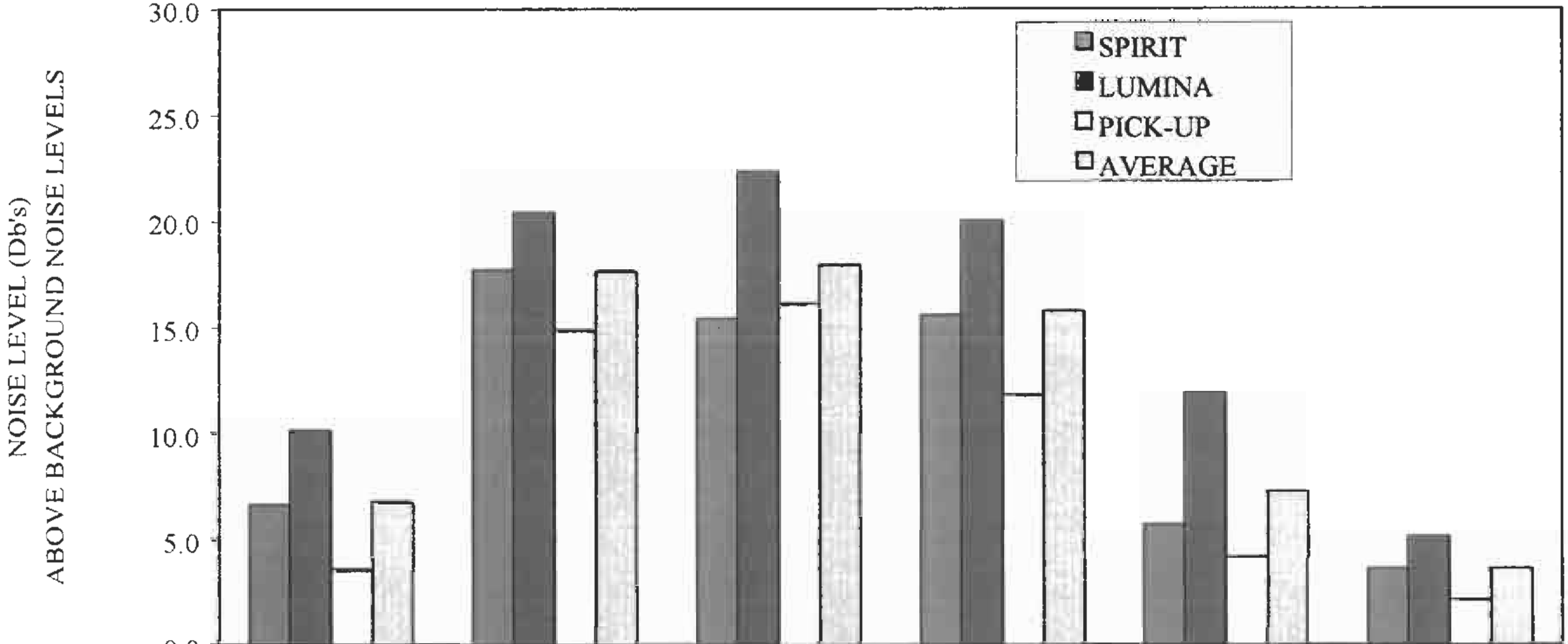


	6	7	8	9	10	11
SPIRIT	8.7	14.8	11.6	19.1	8.5	2.1
LUMINA	10.5	24.4	23.8	20.3	13.3	5.3
PICK-UP	5.2	12.0	11.3	13.9	7.3	1.9
AVERAGE	8.1	17.1	15.6	17.8	9.7	3.1

RUMBLE STRIP SEGMENT NUMBER

FIGURE C14

RAISED RUMBLE STRIP NOISE MEASUREMENTS
LIGHT VEHICLES AT 100 KPH

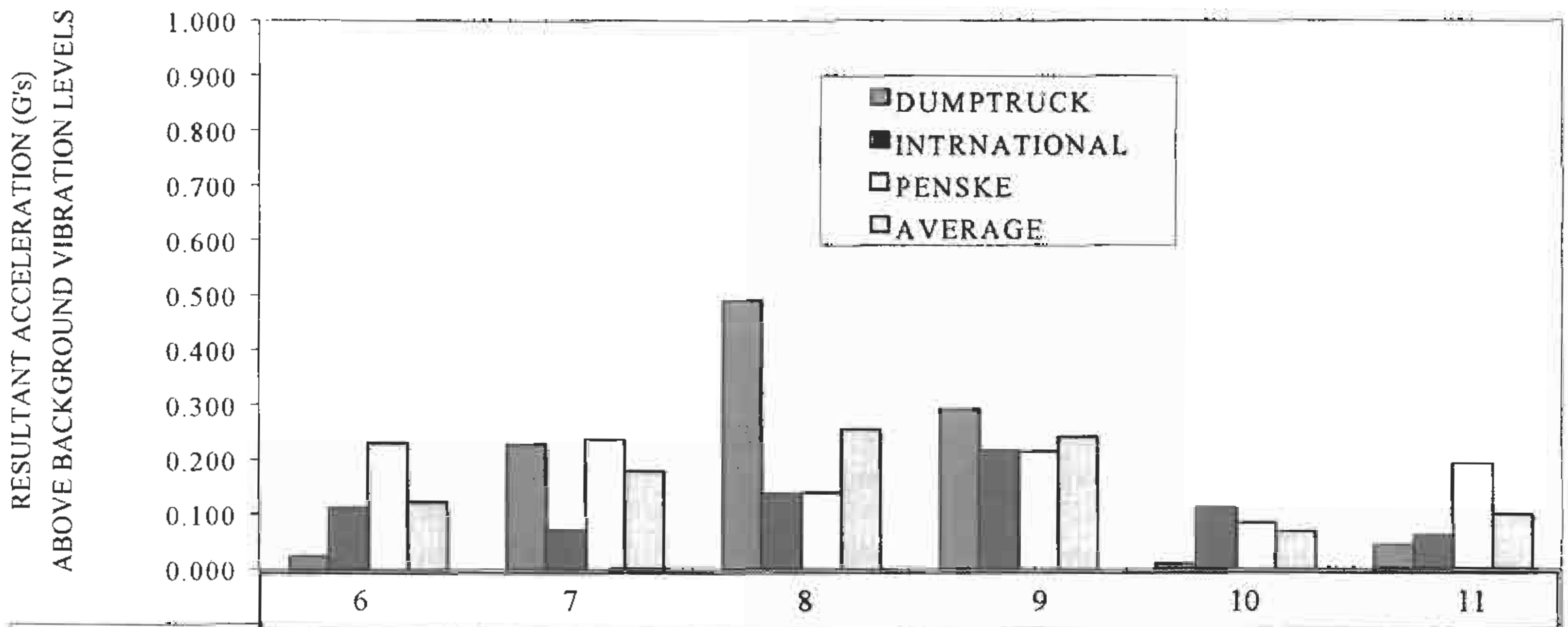


	6	7	8	9	10	11
SPIRIT	6.6	17.7	15.4	15.6	5.7	3.6
LUMINA	10.1	20.4	22.3	20.0	11.9	5.1
PICK-UP	3.5	14.9	16.1	11.8	4.2	2.1
AVERAGE	6.7	17.6	17.9	15.8	7.2	3.6

RUMBLE STRIP SEGMENT NUMBER

FIGURE C15

RAISED RUMBLE STRIP VIBRATION MEASUREMENTS
COMMERCIAL VEHICLES AT 80 KPH

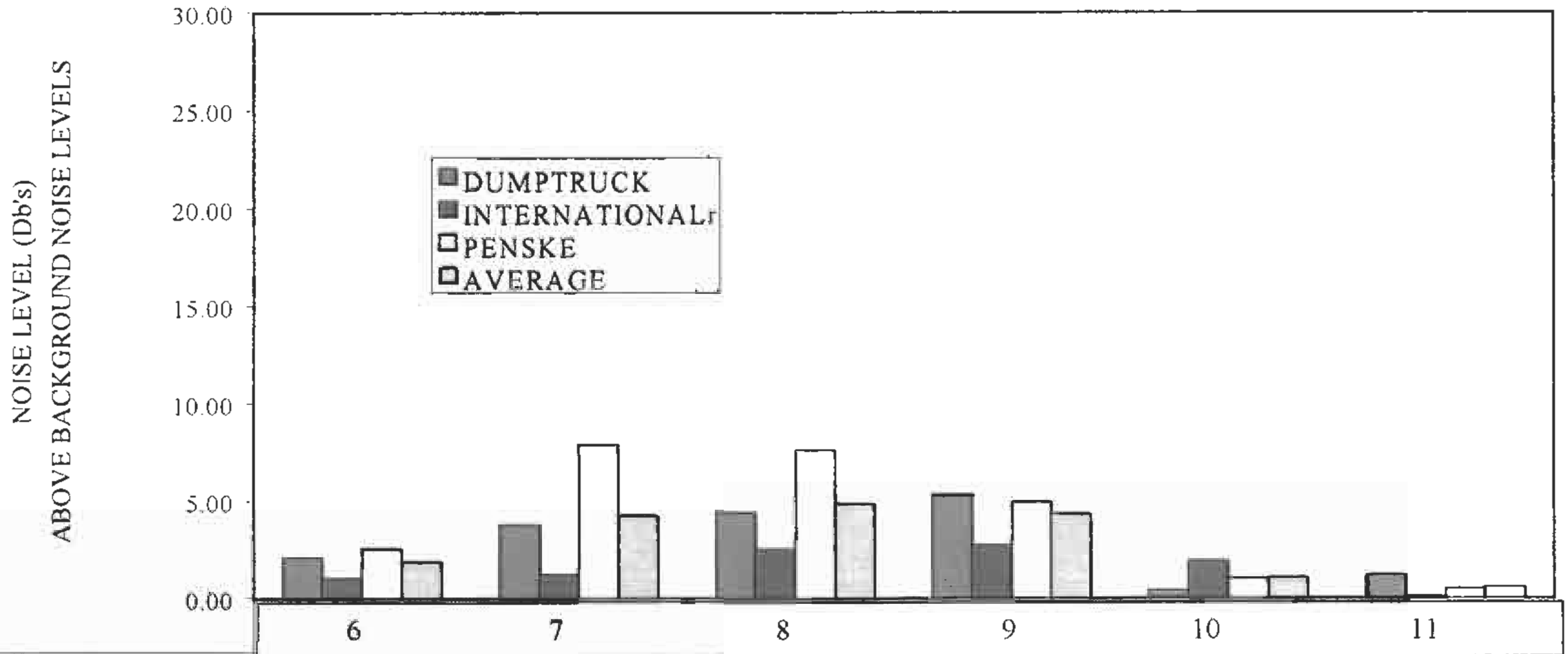


	6	7	8	9	10	11
DUMPTRUCK	0.024	0.228	0.489	0.292	0.009	0.044
INTRNATIONAL	0.113	0.072	0.138	0.218	0.113	0.062
PENSKE	0.230	0.236	0.139	0.215	0.085	0.192
AVERAGE	0.122	0.179	0.256	0.242	0.069	0.099

RUMBLE STRIP SEGMENT NUMBER

FIGURE C16

RAISED RUMBLE STRIP NOISE MEASUREMENTS
COMMERCIAL VECHICLES AT 80 KPH



	6	7	8	9	10	11
DUMPTRUCK	2.05	3.72	4.44	5.32	0.35	1.19
INTERNATIONALr	1.03	1.18	2.53	2.73	1.91	0.08
PENSKE	2.56	7.90	7.63	4.94	1.00	0.47
AVERAGE	1.88	4.27	4.87	4.33	1.09	0.58

RUMBLE STRIP SEGMENT NUMBER

APPENDIX D

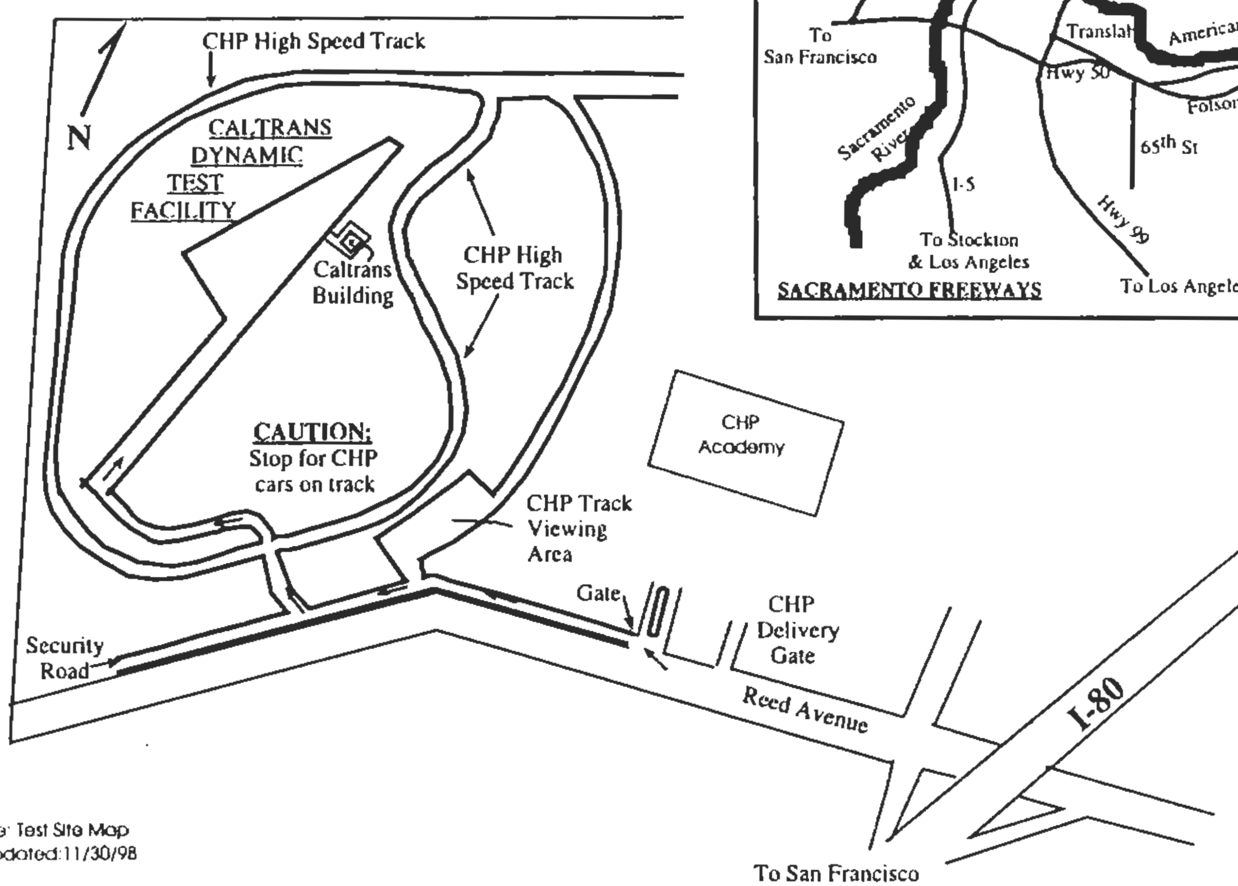
APPENDIX D: Dynamic Test Facility

CALTRANS DYNAMIC TEST FACILITY

Directions: From Interstate 80 take the Reed Avenue off ramp. Turn West on Reed Ave. Turn right at the SECOND gate for the CHP Academy and immediately turn left through the open gate. Follow the signs to the test facility. STOP and LOOK before crossing the high speed track.

CHP vehicles may be traveling in excess of 100 mph!

DO NOT drive on the CHP High Speed Track or Training Areas



File: Test Site Map
Updated:11/30/98

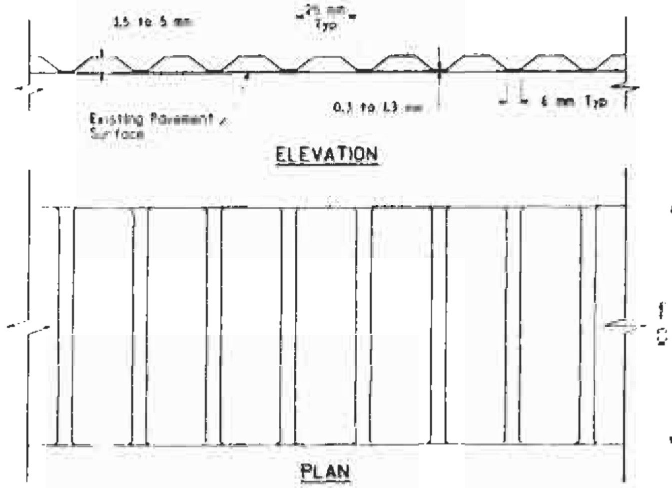
Questionnaire to gather background information	1	2	3	4	
May I have your name please? Last	Don Biava	Craig Conduff	Mike Cardoza	Mike Brock	**AVG**
Your phone number? (Optional)					
Please estimate the number of miles you ride per year.					
<1,000					
1,000-5,000					
5,000-10,000					
10,000-15,000					
15,000-20,000					
>20,000	x	x	x	x	
Years of Motorcycle Riding Experience					
1-5					
6-10	x				
11-15					
16-20		x			
>20			x	x	
What percentage of your riding is "off road"					
0-25	x	x	x	x	
26-50					
51-75					
76-100					
What is your age range?					
15-19					
20-25					
26-30					
31-35	x	x	x		
35-40					
41-45				x	
45-50					
51-55					
56-60					
<60					
Do you consider yourself a novice, intermediate or advanced rider?					
Novice					
Intermediate					
Advanced	x	x	x	x	
What is your sex?					
Male	x	x	x	x	
Female					

	1	2	3	4
Approximately how much do you weigh? (Lbs)				
<100				
100-116				
117-130				
131-145				
146-160				
161-175	x			
176-190		x		
191-205			x	
206-220				
221-235				x
236-250				
How tall are you?	6'	5'10"	6'	6'4"
Do you have any health problems?				
Yes				
No	x	x	x	x
Do you have pain in any of the following body parts or areas:				
Wrists/fingers/elbows?				
Yes				
No	x	x	x	x
Shoulders/neck?				
Yes				
No	x	x	x	x
Back?				
Yes				
No	x	x	x	x
Seat area?				
Yes				
No	x	x	x	x
Knee/ankle/foot?				
Yes				
No	x	x	x	x
Do you know what a shoulder rumble strip is?				
Yes	x	x	x	x
No				
Have you ever ridden your motorcycle over rumble strips?				
Yes	x	x	x	x
No				

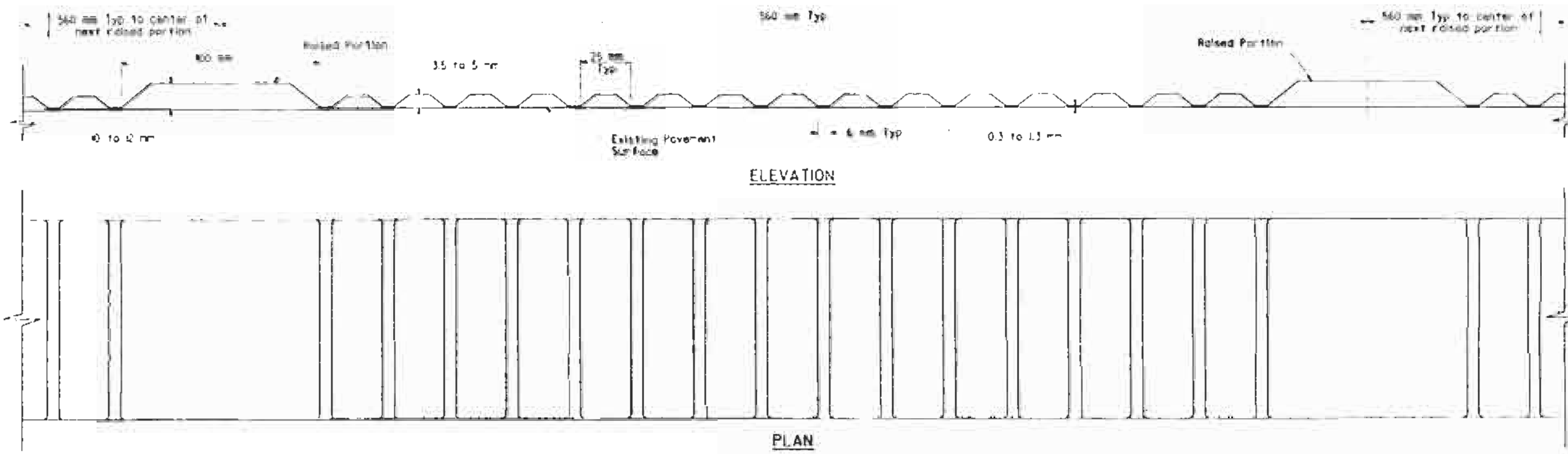
	1	2	3	4	
Subjective rider comfort and control questionnaire:					
Trial Characteristics					
RIDER COMFORT AND CONTROL RATING					
Wrist/Fingers/Elbows	4	5	5	5	4.75
Shoulder/Neck	4	5	5	5	4.75
Back	4	5	5	5	4.75
Seat area	4	5	5	5	4.75
Knee/Ankle/Foot	4	5	5	5	4.75
Overall	4	5	5	5	4.75
Control Level	4	5	5	5	4.75
Ground-In Section B					
Wrist/Fingers/Elbows	5	5	5	5	5
Shoulder/Neck	5	5	5	5	5
Back	5	5	5	5	5
Seat area	5	5	5	5	5
Knee/Ankle/Foot	5	5	5	5	5
Overall	5	5	5	5	5
Control Level	5	5	5	5	5
Ground-In Section C					
Wrist/Fingers/Elbows	4	5	4	5	4.5
Shoulder/Neck	4	5	4	5	4.5
Back	4	5	4	5	4.5
Seat area	4	5	4	5	4.5
Knee/Ankle/Foot	4	5	4	5	4.5
Overall	4	5	4	5	4.5
Control Level	4	5	5	5	4.75
Ground-In Section D					
Wrist/Fingers/Elbows	3	5	3	4	3.75
Shoulder/Neck	3	5	3	4	3.75
Back	3	5	3	4	3.75
Seat area	3	5	3	4	3.75
Knee/Ankle/Foot	3	5	3	4	3.75
Overall	3	5	3	4	3.75
Control Level	3	5	5	5	4.5
Ground-In Section E					
Wrist/Fingers/Elbows	3	5	2	4	3.5
Shoulder/Neck	3	5	2	4	3.5
Back	3	5	2	4	3.5
Seat area	3	5	2	4	3.5
Knee/Ankle/Foot	3	5	2	4	3.5
Overall	3	5	2	4	3.5
Control Level	3	5	5	5	4.5

	1	2	3	4	
Chip Seal Section 1					
Wrist/Fingers/Elbows	5	5	5	5	5
Shoulder/Neck	5	5	5	5	5
Back	5	5	5	5	5
Seat area	5	5	5	5	5
Knee/Ankle/Foot	5	5	5	5	5
Overall	5	5	5	5	5
Control Level	5	5	5	5	5
Raised Pavement Marker Section 2					
Wrist/Fingers/Elbows	5	5	3	4	4.25
Shoulder/Neck	5	5	3	4	4.25
Back	5	5	3	4	4.25
Seat area	5	5	3	4	4.25
Knee/Ankle/Foot	5	5	3	4	4.25
Overall	5	5	3	4	4.25
Control Level	5	5	4	4	4.5
Double Raises Pavement Marker Section 3					
Wrist/Fingers/Elbows	4	5	3	2	3.5
Shoulder/Neck	4	5	3	2	3.5
Back	4	5	3	2	3.5
Seat area	4	5	3	2	3.5
Knee/Ankle/Foot	4	5	3	2	3.5
Overall	4	5	3	2	3.5
Control Level	4	5	3	4	4
Carsonite Product Section 4					
Wrist/Fingers/Elbows	4	5	3	3	3.75
Shoulder/Neck	4	5	3	3	3.75
Back	4	5	3	3	3.75
Seat area	4	5	3	3	3.75
Knee/Ankle/Foot	4	5	3	3	3.75
Overall	4	5	3	3	3.75
Control Level	4	5	3	4	4
Raised Profile Thermoplastic Section 5					
Wrist/Fingers/Elbows	5	5	5	4	4.75
Shoulder/Neck	5	5	5	4	4.75
Back	5	5	5	4	4.75
Seat area	5	5	5	4	4.75
Knee/Ankle/Foot	5	5	5	4	4.75
Overall	5	5	5	4	4.75
Control Level	5	5	5	4	4.75

APPENDIX F



INVERTED PROFILE THERMOPLASTIC STRIPE



RAISED AND INVERTED PROFILE THERMOPLASTIC STRIPE

CONSTRUCTION DETAILS PROFILED THERMOPLASTIC TRAFFIC STRIPE

NO SCALE

ALL DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SHOWN

C-1

STATE OF CALIFORNIA - DEPARTMENT OF TRANSPORTATION

Caltrans

PROJECT ENGINEER

CALCULATED/DESIGNED BY

CHECKED BY

DATE REVISED BY

DATE REVISED

Caltrans Metric

ESC-DI LAST REVISED DATE 01 00

Profiled Thermoplastic is placed in either the inverted profile configuration or the raised & inverted profile (with a raised portion at 560 mm on center). Designate the type on the plans.

Profiled Thermoplastic Traffic Stripe shall not be used on pavement subject to snowplowing.

Profiled Thermoplastic Traffic Stripe may not be suitable for use on open-graded or seal coat surfaces or other roadway segments scheduled for preventative maintenance or rehabilitation work within 3 years.

Include Construction Detail sheet in the plans.

Use Contract Item Code:

840513 Profiled Thermoplastic Traffic Stripe

10-1.__ PROFILED THERMOPLASTIC TRAFFIC STRIPE

Profiled thermoplastic traffic stripe (traffic lines) shall conform to the provisions in Section 84, "Traffic Stripes and Pavement Markings," of the Standard Specifications and these special provisions.

2

Profiled thermoplastic material shall conform to the requirements of State Specification PTH 499A.

3

Profiled thermoplastic traffic stripe shall be inverted profile or raised and inverted profile, as designated on the plans.

4

During application of the thermoplastic material, the pavement shall be clean and completely dry, the temperature of the pavement shall be between 16°C and 60°C, and the temperature of the thermoplastic material shall be as recommended by the manufacturer. A primer of the type recommended by the thermoplastic manufacturer shall be applied whenever the pavement temperature is below 22°C and also when applying inverted profile thermoplastic to portland cement concrete pavements, asphalt concrete pavements over 6 months old, or over existing striping.

5

The thermoplastic material shall be applied at a minimum thickness of 2.8 mm before being profiled. The viscosity and thixotropy of the applied thermoplastic shall be such that the thermoplastic line shall retain its profile height and shape, and shall not flow or flatten while cooling or when bearing traffic.

6

Glass beads shall be applied to the surface of the molten thermoplastic material in 2 equal applications at a combined total rate of not less than 70 kg of glass beads per kilometer of 100 mm wide solid stripe.

7

At least 14 days prior to the scheduled start of production of profiled thermoplastic, the Contractor shall submit a written Quality Control Plan to the Engineer. At the request of the Engineer or the Contractor, the Contractor shall discuss details of the Quality Control Plan with the Engineer. The Engineer shall review and approve the Quality Control Plan in writing, prior to the placement of the test stripe.

8

The Quality Control Plan shall describe the organization and procedures that will be used to administer the quality control system, including the procedures used to control the production process, the procedures used to determine when changes to the production process are needed, and the procedures proposed to be used to implement the required changes.

9

Profiled thermoplastic production and placement shall not begin until the Engineer approves the Quality Control Plan in writing. Approval of the Quality Control Plan does not imply a warranty by the Engineer that adherence to the plan will result in production of acceptable profiled thermoplastic. It shall remain the responsibility of the Contractor to demonstrate such compliance.

10

The Quality Control Plan shall include the name and qualifications of a Quality Control Manager, experienced with the equipment, materials, and application of profiled thermoplastic traffic striping. The Quality Control Manager shall be responsible for the administration of the Quality Control Plan, including compliance with the plan and plan modifications. The Quality Control Manager shall be responsible to the Contractor and shall have the authority to make decisions concerning the quality of the work or product. Except in cases of emergency and with the written approval of the Engineer, the Quality Control Manager cannot be a foreman, member of the production or striping crew, an inspector, or tester on the project during stripe production and placement.

11

The Quality Control Plan may be modified as work progresses. A supplement shall be submitted in writing to the Engineer whenever there are changes to quality control procedures or personnel. Profiled thermoplastic production and placement shall not resume or continue until the Engineer approves the revisions to the Quality Control Plan in writing.

12

Prior to application, and in the presence of the Quality Control Manager, the Contractor shall place a test stripe on roofing felt or other suitable material to demonstrate the Contractor's abilities to apply a stripe with the desired profile for a minimum length of 15 meters. The Contractor shall not place striping material on the roadway without the approval of the Engineer. The Engineer shall require the Contractor to delay installation of the material if, in the opinion of the Engineer, the Contractor does not have suitable equipment or skills to place the striping materials in a suitable manner. If the Contractor's initial test stripe is not approved, the Quality Control Manager shall work with the Contractor to perform the necessary training and adjustments to repeat the test stripe application to the satisfaction of the Engineer.

13

The Contractor shall provide a profile template or profile height gauge to the Engineer during application and inspection of the thermoplastic striping to determine if the applied thermoplastic line is profiled to match the plans.

14

The Quality Control Manager shall be present during placement of the test stripe, the initial application, the final application, and at selected intervals as outlined in the Quality Control Plan. The Quality Control Manager shall immediately alert the Contractor and the Engineer to anything that could affect the performance of the product. The Quality Control Manager shall ensure that materials are placed in conformance with accepted procedures.

15

Profiled thermoplastic traffic stripe will be measured and paid for in the same manner specified for thermoplastic traffic stripe in Section 84-2, "Thermoplastic Traffic Stripes and Pavement Markings," of the Standard Specifications.

APPENDIX G

State of California Business, Transportation and Housing Agency

Memorandum

To: DISTRICT DIVISION CHIEFS
Operations

Date: March 31, 1999

File: TS File 3.2.23

From: **DEPARTMENT OF TRANSPORTATION**
Traffic Operations
Office of Traffic Safety Program and Research
Mail Station 36

Subject: Ground In Rumble Strip Applications

The Office of Traffic Safety and Research recently called together a Rumble Strip Task Force to advise me on rumble strip issues and applications within the state. Various bicycling groups throughout the state have contacted our bicycle coordinator with regard to their concerns about ground in rumble strips that have been installed on a demonstration basis, primarily in response to public concerns about run off road or cross centerline accidents.

In response to the concerns voiced by the bicycle groups, the task force has recommended that the use of ground in shoulder rumble strips be suspended. This suspension affects only ground in shoulder rumble strips on routes where bicycles are allowed access, and does not affect the use of rumble strips on the majority of our limited access freeway system or centerline applications.

This suspension does not affect installations which use our current standard rolled in rumble strip. Our bicycle coordinator has informed the task force that this type of rumble strip has not created a concern with the bicycle groups.

Any PS & E projects that are 9 months out or less should not use the ground-in shoulder rumble strip. It is encouraged that the current standard rolled in rumble strip or an audible edge stripe such as raised thermoplastic or inverted profile that have been approved for use be reviewed for application in your specific cases. You should also be aware that we are in the process of revising our current standard rolled in strip from it's 900mm (3 feet) length to a 600mm (2 feet) length. It is expected that this revision will be incorporated into the next set of standard plans that will be released. Please plan on making revisions to your plans which include rolled in rumble strips as the new standards become available to you.

Over the next several months, the Office of Traffic Safety and Research will begin gathering resources to conduct a rumble strip test and evaluation using bicycles. The test and evaluation will include ground in rumble strips at varying depths, various types of audible edge stripe and possibly some variations to our current rolled in rumble strip standard. When this research is completed, a decision will be made on the appropriate use of rumble strips and the use of alternative materials, including audible edge stripe, for locations on our highway system where bicycles are allowed.

If you have any further questions, please contact Mr. Craig Copelan of my staff at (916) 654-4682, CALNET 8-464-4682.

KIM NYSTROM, Chief
Office of Traffic Safety Program
and Research

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