



Procedure to Measure Vehicle Vibration Sensitivities to Corner System Forces

1 Introduction

Note: Nothing in this standard supercedes applicable laws and regulations.

Note: In the event of conflict between the English and domestic language, the English language shall take precedence.

1.1 Purpose. The purpose of this test procedure is to objectively measure the sensitivity of a vehicle to periodic excitation of the corners predominately at the 1st harmonic of the wheel rotation rate. Results are used to infer ride performance when operated on a smooth road at highway speeds.

1.2 Applicability. This test procedure applies to passenger vehicles and light and medium duty trucks operated on a continuous and smooth paved road with vibratory content that is predominately periodic in the wheel rate. The smooth road shake fitted models are typically used to predict performance of populations of vehicles equipped with statistically varying corners based on expectations of populations of tires, wheels, rotors, etc. The measure represents a quantification of the Path in the Source-Path-Receiver Model. The test results are used to quantify overall vehicle ride performance to facilitate vehicle-to-vehicle comparisons.

1.3 Remarks. This test procedure describes a method to measure a vehicle's vibration sensitivities to first order corner force inputs. These first order inputs can be readily induced using tire/wheel assembly inboard or outboard imbalances (i.e., force and moment inputs), couple imbalances (i.e., pure moment inputs), or split imbalances (i.e., pure force inputs). Each statistically derived mathematical model, based on the test results, describes the relationship between the vibration environment experienced by the driver and the corner system forces. Although the test strictly determines sensitivities to the superimposed imbalance states at the corners, the intention of the test is to quantify the sensitivity to total 1st harmonic corner force and moment systems. Since imbalance offers a convenient means of superimposing a controlled excitation, it is the predominate means for quantifying these sensitivities to corner force systems.

2 References

Note: Only the latest approved standards are applicable unless otherwise specified.

2.1 External Standards/Specifications.

None

2.2 GM Standards/Specifications.

None

2.3 Additional References. The following are supplemental readings, if required:

- Griffin, M. J. (1990). Handbook of Human Vibration London, Academic Press, pp. 479-480
- Michael J. Griffin, University of South Hampton, England, Evaluation of Vibration with Respect to Human Response, SAE Paper 860047
- VTS Reference Section 3.2.1.3.6.1 "Ride: Customer - Level Requirements"

3 Resources

3.1 Facilities. Test conditions are defined for the Milford Proving Grounds North/South Straightaway, the Desert Proving Ground East Straightaway, the Dudenhofen Circle Track, and any other track that provides a minimum

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of road vibration input, and enables the vehicle to be operated at the maximum required constant speed for the maximum amount of required time with a minimum amount of steering input needed from the driver.

3.1.1 Calibration. The test facilities and equipment shall be in good working order and shall have a valid calibration label.

3.1.2 Alternatives. Alternative test facilities and equipment may also be used. However, all measuring variables as specified in this standard shall be determined correctly with respect to their physical definition.

3.2 Equipment.

3.2.1 Data Acquisition Hardware. The Smooth Road Shake data acquisition hardware must be able to acquire at least 36 accelerometer and four (4) strobe (tach) channels simultaneously at a sample frequency of 256 samples/s/channel. The hardware must also provide anti-aliasing on all channels with a corner frequency of 100 Hz. Very high over sampling frequencies and digital filtering may be used for alias protection if the sampling frequency exceeds expectations of the bandwidth of the mechanical response. Considerations for such acquisition systems should accommodate the need to quantify responses at approximately 10 Hz to 25 Hz in the presence of realistic vehicular vibrations.

3.2.2 Accelerometers. The accelerometers used must be able to measure three orthogonal axes simultaneously. They must have a minimum dynamic range from 2 Hz to 500 Hz. They must have a maximum measurement range of at least 50G. They must have a temperature operating range from -54 °C to 250 °C (-65 °F to 250 °F). They should be no larger than a 2.5 cm (1 in) cube. The exterior accelerometers, and their connectors, must also be resistant to adverse weather conditions.

3.2.3 Strobes/1 pulse per revolution (ppr) Tachometers. The strobe/tach must be able to provide at least a 5 V signal each time it is triggered. The operating base frequencies of the pulses will range from 5 Hz to 30 Hz. The strobe must be resistant to adverse weather conditions and it should be able to be cleaned in the field easily enough to maintain functionality. Inputs to the acquisition system must be short duration pulses so that the 1st six (6) harmonics of the rotation rate are distinguishable in the spectrum of the periodic signal. The strobe must also be impervious to external light sources such as sunlight.

3.3 Test Vehicle/Test Piece.

3.3.1 Test Vehicle Type. The test vehicle may be any passenger vehicle, light, or medium duty truck. The Smooth Road Shake analysis currently defined has not been validated for heavy duty trucks or nonautomotive vehicles.

3.3.2 Test Vehicle Qualification. The test vehicle should be qualified to insure that it represents design intent. Deviations should either be corrected or noted. This is also subject to the specification of the test requester. The requester should fully describe the condition of the test vehicle if it is nonstandard or if more than one (1) suspension level is available. The vehicle should also be qualified to insure that there are no worn tires, leaky shocks, system groundouts or tire force variations exceeding specification limits. The base state level of vibration of the vehicle should be free of any shake or other unusual vibratory conditions. Although the post processing methods are able to detect superimposed excitation states, vehicular systems are typically nonlinear and may be improperly characterized by testing vehicles with noticeable vibrations. Wheel alignment should also be within specification limits. The engine and transmission must be operating properly.

3.4 Test Time.

Calendar time:	Approximately 2 days
Test hours:	Approximately 12 hours
Coordination hours:	Approximately 4 hours

3.5 Test Required Information. Not applicable.

3.6 Personnel/Skills.

3.6.1 General Skills. To complete these tests, one (1) technician skilled in noise and vibration data acquisition is required. The technician must be approved to drive on the test road system. Furthermore, specialized training in evasive driving or extensive experience driving on the test road system is recommended.

3.6.2 Technician. The technician should be trained in the use of the Smooth Road Shake Measurement System. Users must have a working knowledge of how to properly use and handle various adhesives (e.g., hot glue, dental cement, epoxy, etc.) in order to instrument and de-instrument a vehicle. Users must also understand the

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required instrumentation, which includes accelerometers, strobes, various cables and connectors, seat fixtures, floor fixtures, data acquisition system, monitor, keyboard, and power supply. Performing an in-lab instrumentation checkout requires familiarity with instrumenting a vehicle as well as root cause analysis of instrumentation malfunctions, and computer skills working with various operating system functions; specifically, copying, moving, and renaming files; creating and renaming directories, etc. Although not required, it is very beneficial for a driver to be able to supplement the objective test data with subjective. The driver must, however, be able to judge the level of vibration present in the baseline state of the vehicle; tests are only to be completed on vehicles that are free of vibration (especially shake) in their base state.

4 Procedure

4.1 Preparation.

4.1.1 Methodology. This document details the methods to objectively determine vehicle vibration sensitivities to first order corner force inputs. These first order inputs can be induced using tire/wheel assembly inboard or outboard imbalances (i.e., force and moment inputs), couple imbalances (i.e., pure moment inputs), or split imbalances (i.e., pure force inputs). Sensitivity tests are conducted using a Taguchi L9 orthogonal array design of experiments (DOE), which allows evaluation of multiple vehicle corner inputs (i.e., estimation of four (4) main effects – no interactions – with nine (9) experiments). The controlled variable is the corner excitation level, and there are three (3) levels: low (**L**), mid (**M**), and high (**H**) (see Table 2). In keeping with Taguchi philosophy, the levels of input need to be sufficiently high so that the effects can be clearly visible even in the presence of road noise and uncontrollable vehicle inputs. At the same time, the input levels must not be too high and overdrive the corners causing a highly nonlinear and non-representative response. The amount of applied corner excitation will depend upon the vehicle. A guideline for L9 input levels can be found in Table 1 (the responsible engineer may modify the levels as appropriate).

Table 1: Orthogonal Test Condition Matrix

Test Condition	Applied Imbalance Input			
	LF	RF	RR	LR
L91	L	L	L	L
L92	L	M	M	M
L93	L	H	H	H
L94	M	L	H	M
L95	M	M	L	H
L96	M	H	M	L
L97	H	L	M	H
L98	H	M	H	L
L99	H	H	L	M

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Table 2: Imbalance Input Levels

Design Level	Imbalance Input Level	
	Inboard/Outboard/Split	Couple
L = Low	Base Condition: Zero Imbalance	Base Condition: Zero Imbalance
M = Mid	30 g (1 oz) typical for small and some mid-size vehicles 55 g (2 oz) typical for larger vehicles and light trucks	55 g (2 oz) typical for small and some mid-size vehicles 85 g (3 oz) typical for larger vehicles and light truck
H = High	2 times the Mid-Level Imbalance: 55 g (2 oz) for 30 g (1 oz) Mid DOE 115 g (4 oz) for 55 g (2 oz) Mid DOE	2 times the Mid-Level Imbalance: 115 g (4 oz) for 55 g (2 oz) Mid DOE 170 g (6 oz) for 85 g (3 oz) Mid DOE

A typical test involves eight (8) measurements for each condition of the L9 DOE. These measurements correspond to the following vehicle speeds: 89 km/h, 97 km/h, 105 km/h, 113 km/h, 121 km/h, 129 km/h, 137 km/h, and 145 km/h (55 mph, 60 mph, 65 mph, 70 mph, 75 mph, 80 mph, 85 mph, and 90 mph). A sensitivity test, however, may be conducted at any set of vehicle speeds.

Vehicle vibration sensitivity is determined by relating the outputs (i.e., vibration measurements at select points) to the corner inputs using Multiple Input, Multiple Output (MIMO) data analysis techniques.

4.1.2 Vehicle Preparation.

4.1.2.1 Preparation of Stock Tire/Wheel Test Assemblies. The preferred option for performing the smooth road shake (SRS) test is to use production tire/wheel assemblies. These assemblies must be dynamically balanced to manufacturer's specifications. If the Low Speed Uniformity R1H values of all four tire/wheel assemblies are below 55 N (P-P), and if the static balances of all assemblies are below 10 g ($\frac{3}{8}$ oz) then a single 0 degree test may be performed to obtain accurate SRS results. If, however, the assemblies do not meet these uniformity/balance specifications, or the conditions of the assemblies are unknown, then it is recommended that two sets of test data (a 0 degree test and a 180 degree test) be acquired. The 0 degree test is performed by placing the imbalance weight at the valve stem. The 180 degree test is performed by placing the imbalance weight 180 degrees from the valve stem.

4.1.2.2 Preparation of Screened Tire/Wheel Test Assemblies.

4.1.2.2.1 Building Screened Tire/Wheel Assembly Test Set. Vehicle vibration sensitivity tests can also be performed using a test set of tire/wheel assemblies that are screened for assembly force variations. If these test assemblies do not exist but are requested by the responsible engineer, the appropriate tires and/or wheels must be ordered according to the requirements specified by the engineer.

4.1.2.2.2 Remove/Install Screened Tire/Wheel Test Assemblies. Label each tire/wheel assembly on the vehicle as received with its current location (e.g., RF – right front) and vehicle identification number (VIN). Locate the orientation of the assemblies on the hubs by marking the studs corresponding to the tire valve locations (i.e., mark the stud that is in-line with the valve stem or mark both of the studs that the valve stem is located between). Check the test sheet for the first required tire/wheel test assemblies. If the required assemblies are different than those on the vehicle, remove those on the vehicle; label and store the original assemblies. Find the required assemblies and check dynamic balance. Balance the assemblies as required. If possible, weights used to dynamically balance the assemblies should not be located in areas where weights will be used for imbalance sensitivity tests. Place the test set on the vehicle according to the specified corner positions written on the assemblies and/or on the test sheet, and orient the assemblies on each hub according to the stud(s). If the test assemblies are not available, cannot be found, or do not have positions marked, contact the responsible engineer and/or the test coordinator.

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4.1.2.3 Ballast Condition. Although not standard, if test conditions require loading other than standard (i.e., driver and equipment weight only), install appropriate ballast and secure.

4.1.3 Steering Column/Wheel Preparation.

4.1.3.1 Steering Column Angle. Adjust tilt steering columns to eliminate any relative angle between the lower and upper steering column. If the vehicle has a rake type column adjustment, locate it near the midpoint of its travel, but allowing driver to see critical instruments such as the Speedometer.

4.1.3.2 Telescoping Column. For a vehicle with a telescoping column, locate the column at the middle of its travel.

4.1.3.3 Steering Wheel Alignment. Insure that the steering wheel is aligned while the vehicle is traveling straight down the road. If the steering wheel is not aligned, note the steering wheel position when the vehicle is traveling straight. This will be the steering wheel position used when the steering wheel accelerometers are installed.

4.1.4 Instrumentation Calibration. Smooth Road Shake Measurement System calibration should be checked periodically, according to component manufacturer's specifications.

Note: If accelerometers are replaced, the calibration file must be updated to track the Serial Number (S/N) of the accelerometers used in the data acquisition hardware package. All transducers are precision, high cost instrumentation. They must be handled with extreme care.

4.1.5 Instrument Test Vehicle. Only use instrumentation that is in calibration. If none are available, contact the responsible engineer.

4.1.5.1 Standard Instrumentation Setup. The following subsections show the standard instrumentation setup. See the responsible engineer for any atypical instrumentation requirements.

The standard channel names used in SRS testing are as follows:

- **Interior Vehicle Interfaces:**

- SH: Steering Wheel at 12 o'clock
- SH2: Steering Wheel at 6 o'clock
- SB: Driver Seat Back
- BT: Driver Seat Bottom
- LOBST: Driver Front Left Outboard Seat Track
- FF: Driver Floor/Feet

- **Exterior Vehicle Locations:**

- LF: Left Front Spindle
- RF: Right Front Spindle
- LR: Left Rear Spindle
- RR: Right Rear Spindle
- TR: Left Side Tie Rod
- FL: Driver Floor Pan

- **Measurement Directions:**

- X: Fore and Aft, Forward is Positive
- Y: Lateral, Right is Positive
- Z: Vertical, Downward is Positive

- **Corner Strobe Sensors:**

- LFS: Left Front Strobe
- RFS: Right Front Strobe
- LRS: Left Rear Strobe
- RRS: Right Rear Strobe

4.1.5.1.1 Install Interior Instrumentation.

4.1.5.1.1.1 Steering Wheel Accelerometers. Attach triaxial accelerometers to the steering wheel at the 12 o'clock and 6 o'clock positions. Each steering wheel accelerometer is mounted to a bracket, which can be attached to the steering wheel with tie straps. These accelerometers should be oriented so that they are aligned

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with the vehicle's coordinate system and not the plane of the steering wheel rim. Ensure that there is enough slack in the cables to allow the steering wheel to make full turns freely. Always make sure the cables fall toward the driver to ensure that the cables do not get wound around the steering wheel. See Figure 1.

Figure 1: Steering Wheel Accelerometers



4.1.5.1.1.2 Left Outboard Seat Track (LOBST). Attach a triaxial accelerometer to the left front outboard seat track. Route the accelerometer cable to the data acquisition system and connect it to the port labeled LOBST. This accelerometer should not interfere with seat position adjustments. See Figure 2.

Figure 2: Seat Track Accelerometer



4.1.5.1.1.3 Driver Floor/Feet. Remove the driver's floor mat and place the floor/feet accelerometer pack as close to the center of the floor as possible without interfering with the pedals. Use tape to secure the accelerometer pack to the floor of the vehicle. Connect the driver floor/feet accelerometer pack cable to the FF port. See Figure 3.

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Figure 3: Floor/Feet Accelerometer Fixture



4.1.5.1.1.4 Driver's Seat Back. Use a seat jig (see Appendix B, Figure B1) to set the seat back angle and to locate the Seat Back and Seat Bottom accelerometer packs. Secure the seat back accelerometer pack to the seat with tape (preferably masking tape). (Never use duck/duct tape on leather seats!) Route the seat back pack cable to the data acquisition computer and connect to the port labeled SB. See Figure 4.

Figure 4: Seat Back Accelerometer Fixture



4.1.5.1.1.5 Driver Seat Bottom. Place the seat bottom accelerometer pack in the center of the driver seat bottom. Use the seat jig (see Appendix B, Figure B1) to locate the pack in the fore and aft direction. With the beveled surface down into the seat and the accelerometer pack cable exiting toward the rear of the vehicle secure the pack down with tape. Masking tape is preferred. Never use duck/duct tape on leather seats. Connect the seat bottom accelerometer pack cable to the port labeled BT. See Figure 5 and Figure 6.

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