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I, Abigail K. Yee,

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Student Signature: ____________________

This work and its defense approved by:

Committee Chair: Dr. Randall J. Allemang

Dr. Allyn W. Phillips

Dr. Teik C. Lim

Approval of the electronic document:

I have reviewed the Thesis/Dissertation in its final electronic format and certify that it is an accurate copy of the document reviewed and approved by the committee.

Committee Chair signature: ____________________

Using Group Transmissibility Concepts to Compare Dissimilar Vehicle Platforms

A thesis submitted to the
Division of Research and Advanced Studies
of the University of Cincinnati
in partial fulfillment of the
requirements for the Degree of

MASTER OF SCIENCE

From the Department of Mechanical Engineering
of the College of Engineering
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by

Abigail K. Yee

Committee Chair: Dr. Randall J. Allemang

Committee Member: Dr. Allyn W. Phillips

Committee Member: Dr. Teik C. Lim

Abstract

In today's market, the average car manufacturer is trying to improve not only their car's functionality, but also its ride comfort. One way to do this is to refine the structural system of the vehicle from a vibration or acoustic standpoint. However, there is currently no simple way to compare different vehicles. This thesis addresses one method to do just that. This method uses transmissibility as an indicator between the vehicles, where transmissibility is an output acceleration divided by a reference displacement, instead of the typical frequency response function. In particular, group transmissibility, or an averaged transmissibility is used. This is an average of several response points obtained from a particular sub-structure common to all of the vehicles tested, with a focus on the cross body beam and the A-pillar. Four different vehicles were tested, one of which was the Best in Class vehicle which was used as a target baseline. This was part of a larger project to determine if squeak and rattles could be detected based on the structure of the vehicle. Three different group transmissibilites were calculated, one first averaged over the reference points, another averaged over the response or output points and the last averaged over both the reference and response points, with the latter two more extensively evaluated than the first. In the end, the Best in Class vehicle did have different group transmissibility characteristics for some frequency ranges compared to the other vehicles, although it did not indicate that it was radically different from the other vehicles tested. Perhaps with more testing a stronger baseline can be established and a simpler method for comparing vehicles ascertained.

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Chapter 1 Introduction

1.1 Motivation

In today's automotive industry there are many different types of vehicles on the market as well as different manufacturers producing various similar and dissimilar vehicles. Since ride comfort is such a big concern for the automotive market, many car manufacturers are trying to make their car as comfortable as it is functional. In doing this, the manufacturers need to keep ahead of the competition with new ways of improving their cars. One way to improve the vehicle comfort from a vibration and/or acoustic viewpoint is to refine the structural system of the car. However, there is currently no simple way to compare similar problems on different vehicles. The methods that are currently used are very complicated. Consequently, there needs to be an easier, common way to evaluate many different types of vehicles.

In order to compare several different types of vehicles, there is a necessity to create some kind of structural baseline which is similar for all vehicles. With this accomplished, if there is a vehicle that is deviating from the baseline, then the offending vehicle might be easily identified. The next step would be to locate and fix the contributing problems.

One possibility is to look at the structural dynamics of the system. Frequency response functions (FRF) are traditionally used to observe the deformation of a structure. A FRF is an output acceleration divided by an input force. However, there are times when the input force needed to obtain the FRF is not available or the test setup would be prohibitive. With this information absent, is there any way to look at a structure and compare structural deformations? If the reference displacements are known, then transmissibility can be used in a similar fashion to an FRF, since transmissibility is an output acceleration divided by a reference displacement. The reference displacement is typically from the wheel of the vehicle, although it can be from any point on the structure if the displacement is known.

In general, the transmissibility is only observed at one particular point on the structure with respect to a reference displacement at one wheel. Although this can be very useful, it might be more useful to understand the how response acts over a specific section of the structure or even the entire structure with respect to one wheel. This can be especially difficult to determine when there are multiple inputs and multiple outputs (MIMO) for the system. This form of transmissibility is the subject of another, parallel MS thesis in the University of Cincinnati - Structural Dynamics Research Lab (UC-SDRL).

1.2 Research Problem

The overall inspiration for this thesis project was the question of whether body structure deformation or flexibility plays a role in the squeak and rattle (S&R) problems in automotive systems excited by impulse events during operation, since many S&R occurrences can be attributed to structural deficiencies.[1] This is really a two part problem. First, whether or not a system has an S&R problem, needs to be defined, and second, if there is a problem, then whether there is a structural difference between the automobiles with and without problems needs to be identified. Additionally, the structural difference needs to be identified across many different vehicle platforms. Since this problem is industry wide, a specific vehicle should not be the main focus.

Ravi Mantrala researched the squeak and rattle detection side of this problem and his results can be found in his thesis, *Squeak and Rattle Detection: A Comparative Experimental Data Analysis*.[2] However, the following thesis is focused on the structural deformation side of the problem. Although structural deformation is not a new topic and has been examined extensively, the approach shown here is quite different than the traditional approach. Hopefully, using this method of an averaged group transmissibility, a baseline can be established and used to identify structural variations between vehicles with and without squeaks and rattles.

Since structural integrity plays a role in S&R occurrence, it is thought that further investigation is necessary. To obtain superior structural integrity, there needs to be adequate static and dynamic stiffness both globally and locally. It is generally thought that stiffer is better, but adding extreme stiffness can be very costly as well as change the natural modes of the system, which in many cases have already been carefully planned. [1]

1.3 Research Goals

It is known that one vehicle will produce a different transmissibility curve than another vehicle at various points along its structure. What is not known is whether a set of spatially averaged transmissibility curves from a specific structure on the vehicles will produce similar responses. This spatially averaged transmissibility is referred to as group transmissibility. If this is the case, then if a particular vehicle has a very different group transmissibility it will be seen as a variant. Obviously, the specific substructure or spatial group would have to be common to all vehicles, such as the cross body beam or the door frame.

The objective is to test several vehicles with different structural platforms to determine whether or not a variant can be detected. Due to time constraints and a limited number of cars available for testing, several vehicles, some of which were known to have problems with squeaks and rattles, were tested and compared to a "Best in Class" vehicle to determine if the structures were similar or different in the frequency range from 0 – 20 Hertz.

Chapter 2 Background and Theory

2.1 Transmissibility

As stated earlier, transmissibility is similar to a frequency response function in that it is a ratio between the output of the system and the references. This is a Multiple Input Multiple Output (MIMO) system and the transmissibility function estimation below is the model. X and Y are the corresponding inputs and outputs.[3]

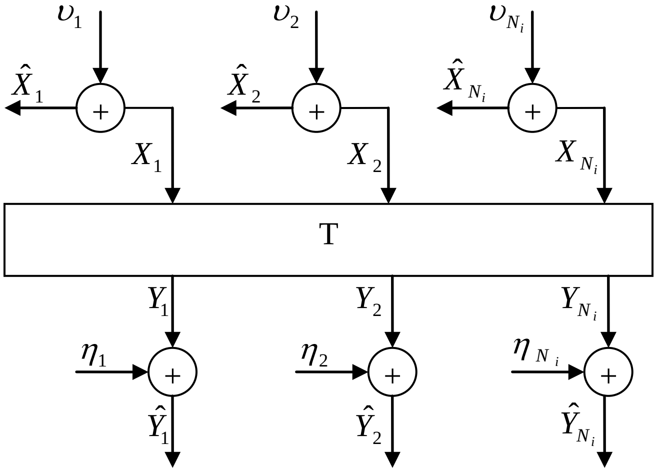


Figure 2-1 Transmissibility Function Estimation Model

The following equation represents the measurement case involving multiple inputs and a single given output (MISO) [3]:

$$\hat{Y}_p - \eta_p = \sum_{q=1}^{N_i} T_{pq} \times \left(\hat{X}_q - \upsilon_q\right)$$

Where:

- $X = \hat{X} - \upsilon$ Actual reference
- $Y = \hat{Y} - \eta$ Actual Output

- $\hat{Y}_p$ = Spectrum of the p-th output, measured
- $\hat{X}_q$ = Spectrum of the q=th reference, measured
- T_{pq} = Transmissibility function of output p with respect to reference q
- υ_q = Spectrum of the noise part of the reference
- η_p = Spectrum of the noise part of the output

Multiple Input Concept – Nomenclature [3]

$[GYX] = \{Y\}\{X\}^H$ = Output-input cross spectra matrix

$$[GYX] = \begin{Bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{N_o} \end{Bmatrix} \begin{bmatrix} X_1^* X_2^* \cdots & X_{N_i}^* \end{bmatrix}$$

$$[GYX] = \begin{bmatrix} GYX_{11} & \cdots & GYX_{1N_i} \\ \vdots & \ddots & \vdots \\ GYX_{N_o1} & \cdots & GYX_{N_oN_i} \end{bmatrix}$$

X^* = Complex conjugate

$[GXX] = \{X\}\{X\}^H$ = Input-input cross spectra matrix

$$[GXX] = \begin{Bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{N_o} \end{Bmatrix} \begin{bmatrix} X_1^* X_2^* \cdots & X_{N_i}^* \end{bmatrix}$$

$$[GXX] = \begin{bmatrix} GXX_{11} & \cdots & GxX_{1N_i} \\ \vdots & \ddots & \vdots \\ GXX_{N_o 1} & \cdots & GXX_{N_o N_i} \end{bmatrix}$$

$GXX_{ik} = GXX_{ki}^{*}$ (Hermitian matrix)

H$_1$ Technique*: Minimize Noise on Output (η) [3]

$$[T]_{N_o \times N_i} \{X\}_{N_i \times 1} = \{Y\}_{N_o \times 1} - \{\eta\}_{N_0 \times 1}$$

$$[T]\{X\}\{X\}^{H} = \{Y\}\{X\}^{H} - \{\eta\}\{X\}^{H}$$

$$[T]_{N_o \times N_i} \{X\}_{N_i \times 1} \{X\}_{1 \times N_i} = \{Y\}_{N_o \times 1} \{X^{H}_{1 \times N_i}\}$$

$$[T][GXX] = [GYX]$$

$$[T] = [GYX][GXX]^{-1}$$

Where:

- $[\ ]^{H}$ = Complex conjugate transpose (Hermitian)
- [T] = Transmissibility response function matrix

$$[T] = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1N_i} \\ T_{21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ T_{N_o 1} & \cdots & \cdots & T_{N_o N_i} \end{bmatrix}$$

* Similarly this can be applied to H$_2$ and H$_v$ techniques.

The references cannot be perfectly correlated or the $[GXX]^{-1}$ will not exist.

Response Group Transmissibility:

$$T_q = \sum_{p=1}^{N_o} T_{pq}$$

Reference Group Transmissibility:

$$T_p = \sum_{q=1}^{N_r} T_{pq}$$

2.2 Group Transmissibility Averaging

In order to explore whether a specific substructure or group of test points will have similar deformations between different vehicles, group transmissibility averaging needs to be defined. Since this is a MIMO system, there are several outputs as well as several references, so averaging can be set up a variety of ways. In this case, “response group transmissibility” is defined as taking the same reference and averaging it over several outputs. “Reference group transmissibility” is the opposite of group transmissibility, where the references are averaged for one output. The combination of these two is referred to as “reference-response transmissibility,” where both the references and outputs are averaged producing one curve for an entire structural piece. Since the reference group transmissibility does not consider the output over a vehicle substructure, it will only be briefly touched upon. The main focus will be the response group transmissibility and the reference-response group transmissibility.

Because the transmissibility data is in the form of a complex number at each frequency, obtaining a spatial average is not completely straight forward. For group transmissibility, there were two different techniques used to calculate the spatial average. The first was to take the each complex number and find the magnitude. Then take those magnitudes and add them up across the frequency range. At this point, the values were divided by the number of outputs to achieve the average. This method was a magnitude average and ignores the phase. The second method adds up the complex values first and then divides by the number of outputs. After that, the magnitude was calculated, which gave a similar value to the first method, but not quite the same. The second method was a straight average. Similar approaches were used to compute the reference group transmissibility and the reference-response group transmissibility, but for the reference transmissibility, the references (not the outputs) are averaged. Accordingly, for the reference-response group transmissibility, both the references and outputs are averaged. The formulas for the averages are shown below.

Magnitude Average (for response group transmissibility):

$$\overline{T_q} = \frac{\sum_{p=1}^{N_o} \left| T_{pq} \right|}{N_o}$$

Straight Average (for response group transmissibility):

$$\overline{T_q} = \frac{\left| \sum_{p=1}^{N_o} T_{pq} \right|}{N_o}$$

2.3 Frequency Range

There were some points to consider when choosing what frequency values to focus on. The first was looking at which frequencies, or range of frequencies, where the coherence was close to a value of one. Unity coherence means there is a linear relationship between the measurements made. [4] The figure below is an example of a coherence plot for a SISO transmissibility at a point in the center of the cross body beam. The coherence is close to unity until after 20 Hz.

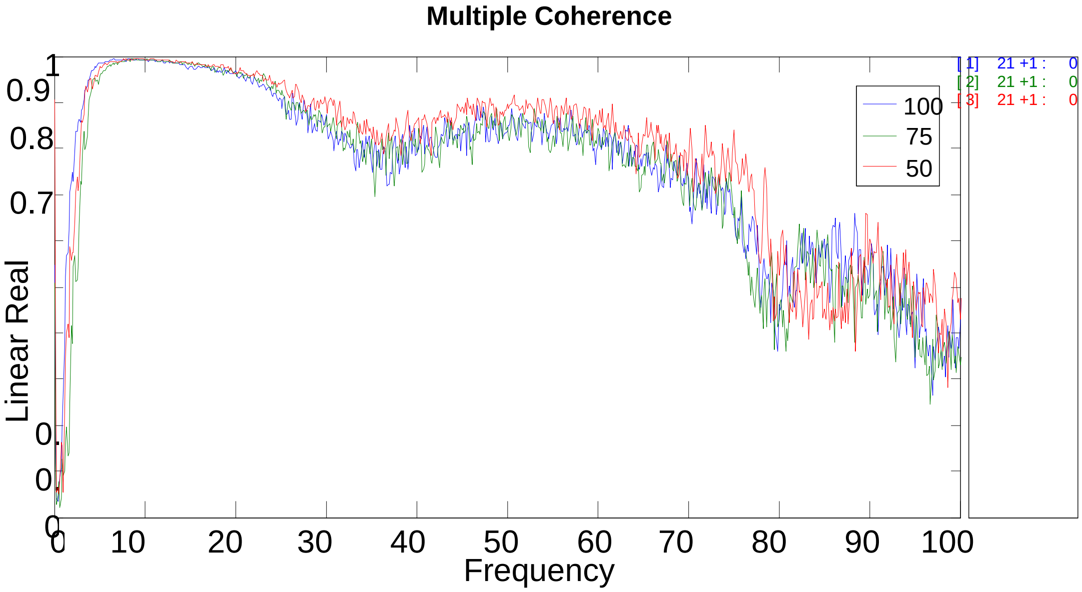


Figure 2-2 Coherence Plot for SISO Transmissibility

Also, since most deformation modes of automobiles start above 20 Hz and can vary greatly between various types of vehicles, it was established that a frequency range from about 5 – 20 Hz would be appropriate. The range was also limited due reasons which are proprietarily protected. This would give a good indication of structural integrity for the cars in question for this project.

Chapter 3 Testing, Data Acquisition and Processing

3.1 Testing

3.1.1 Test Setup

For this project, the MTS 320 Road Simulator System, which is located in the UC-SDRL high bay lab area, was used. The simulator basically consists of three components: the actuators, the hydraulic pump and the 320 Road Simulator Controller. There are four hydraulic actuators (Model 248.03) corresponding to each wheel. The input motion is delivered through the actuators to each wheel with a maximum vertical stroke of ±3 inches from the mean position. The actuators are operated by the MTS 506 Hydraulic Power Supply. The 320 Road Simulator Controller consists of the MTS 498.22 Test processor and the MTS 497.05 Hydraulic Control Unit. The test processer controls the testing rig, digitalizes the data, and allows the communication between the test rig and the data acquisition system. Flex Test, a user interface, allows the user to operate the test rig with a regular PC.[5]

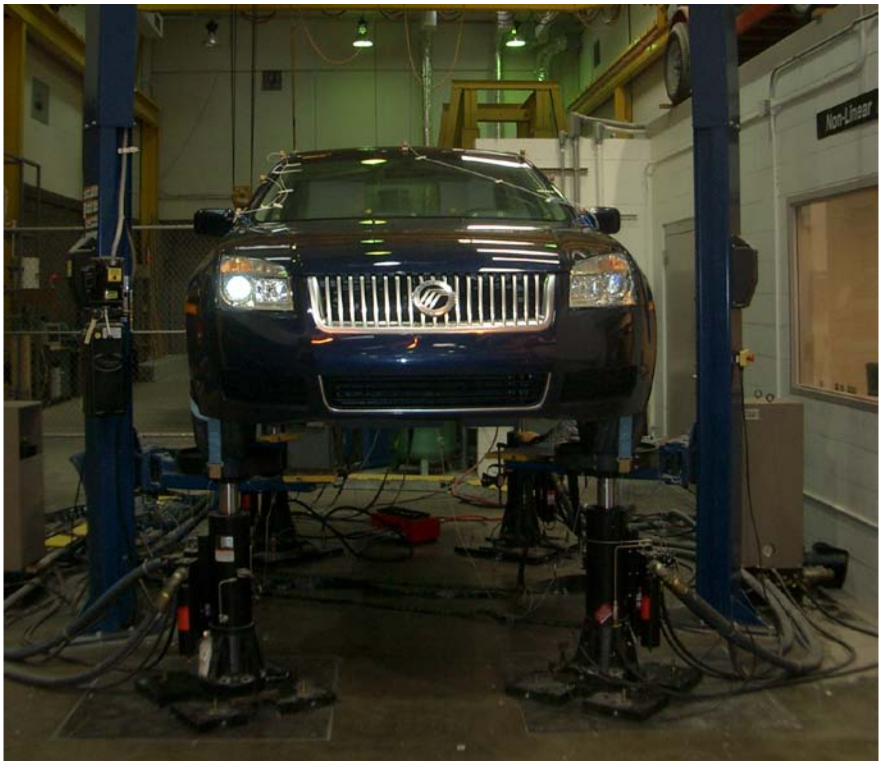


Figure 3-1 Typical Four Poster Shaker Setup

In order to move the car onto the actuators, a service lift was used to raise the car and then the actuators were moved under each wheel. The actuators were bolted town to steel plates embedded in the isolation mass; a poured 25x14x9 foot concrete block. Each wheel of the vehicle was strapped down to the wheel pan of the actuator with nylon ratchet straps. The actuators were numbered 1-4 with the front driver's side referred to as Shaker 1, the front passenger's side as Shaker 2, the rear driver's side as Shaker 3 and the rear passenger's side as Shaker 4. This can be seen in Figure 3-2.

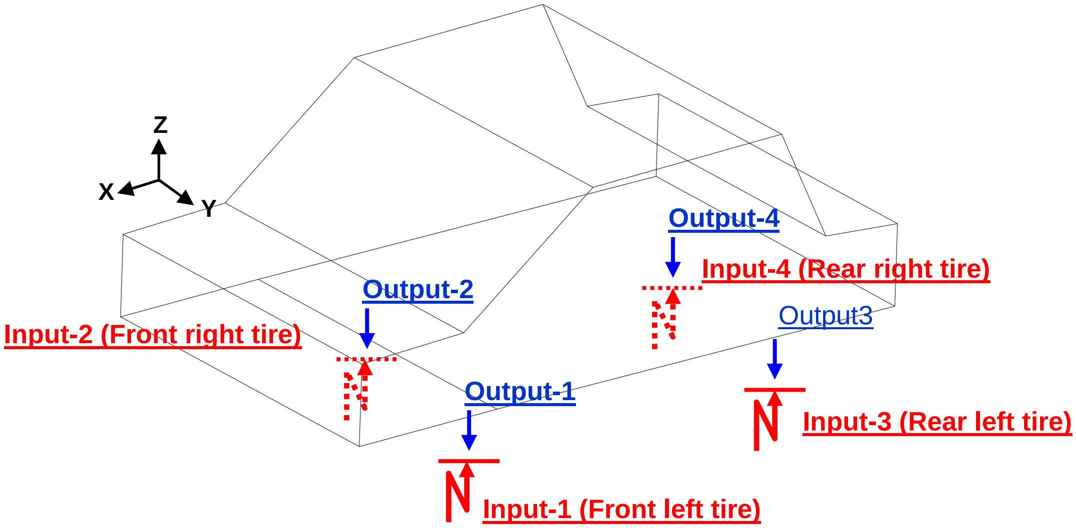


Figure 3-2 Orientation of Four Poster Setup

For the overall project, five fully trimmed vehicles were tested. Although for this particular aspect of the project, only four vehicles were used because the first vehicle was not tested to obtain the long MIMO transmissibility data due to time constraints. The vehicles were identified as Vehicles A, B, C, D and E, however, there will be no data for vehicle A in this thesis. Also note that Vehicle E is the "Best in Class" vehicle and is the basis for the standard "good measurement" or target baseline for this project.

For each vehicle, 40+ tri-axial accelerometers, 8 uni-axial accelerometers and 8 microphones were used. These accelerometers and microphones were placed in the same location, as close as possible, on each car. This insured comparable data from each vehicle. Although the data from the microphones was not used for any of the transmissibility analysis, it was used for the squeak and rattle detection, which offered additional insight into identifying more problematic vehicles. The orientation of the tri-axial accelerometers was x going in the fore/aft direction, y across the car and z in the vertical direction, seen in the Figure 3-2.

Table 3-1 shows the types of accelerometers and microphones which were used during the testing for this project.

Table 3-1 Accelerometer Information

Type	Sensitivity(nominal)	ICP powered	Model
Tri-axial accelerometer	1 volt/g	Yes	PCB XT356B18
Uni-axial accelerometer	1 volt/g	Yes	PCB UT333M07
Microphone	20 millivolt/pascal	Yes	PCB 130A10/P10

Because the transmissibility information was only a part of the overall project there were three main types of data collected for each vehicle. The first type was road response files. These were drive files generated for the vehicles and lasted 30-90 second. The second type was MIMO transmissibility data, which consisted of 100 averages. The last type was MIMO time response files which were acquired at three different sampling frequencies (25 KHz, 2.5 KHz and 200 Hz). Each of these was obtained at three different excitation levels of the simulator (50%, 75% and 100%). The MIMO transmissibility data was used for this thesis.

For all tests, the placement of the accelerometers was as close to the same location as possible. This aids in the direct structural response comparison of the vehicles using transmissibility. Also, the positioning of the accelerometers were concentrated in and around the instrumentation panel (IP), the A-pillar, the seat rails, the bulk head, the cross body beam, HVAC and the wheel spindles. A total of eight microphones were positioned using foam rubber mounting blocks in the front two seats, with microphones in the ear and torso areas. The microphones were used in the squeak and rattle detection. The following pictures show some of the locations of the accelerometers on an actual test vehicle.

Figure 3-3 Various Locations of Accelerometers on the Vehicles

In order to keep track of the accelerometers and microphone locations, the same numbering scheme was used for all vehicles. For the tri-axial accelerometers, the 100 and 200 DOF number series were located at the A-pillar, with 100 corresponding to the Input

1 (driver's) side and 200 corresponding to the Input 2 (passenger's) side. The 500 DOF number series was on the bulk head, under the structure of the vehicle and the 600 DOF number series was on the cross body bar and the HVAC. For the seat rails, the 700 DOF number series was used and the 900 DOF number series was in the instrumentation panel and the steering wheel. All microphones were the 800 DOF number series. The uni-axial had the 10 DOF number series on the 4-poster pans and the 20 DOF number series on the wheel spindles.

3.1.2 Strap Conditions

There were two different types of strap conditions analyzed during this project. The first was due to a problem that arose during testing in which the straps that were used during the first few vehicle tests were damaged and new straps were used for the rest of the vehicle testing. The second was to see how objective tightening of the straps would affect the results.

During testing the straps were changed due to wear damage. The initial straps used were a custom made basket-style strap which wrapped around the wheel and then was secured to the shaker. Although it would have been useful to acquire the same exact straps for strict adherence to maintaining consistent testing conditions, it was not feasible. A different type of strap had to be used for the remainder of the testing. The new straps were single straps that simply ran across the top of the tire and then connected to the shaker. The figure below shows the difference between the two different types of straps.

There was one car that was tested using both straps to show the effects of the straps on the transmissibility data.

Figure 3-4 Two Types of Straps used for Testing

As a check for consistency, various strap conditions were tested. The goal for this was to determine how much of a difference there was when the tie-down straps were loose or even off during testing. The idea behind this was to insure the best data results since there could be slight differences in the tightness of the straps for each vehicle. The conditions tested were: all straps tight; all not tight; rear off; front left and rear right on; front right and rear left on; left side on and right side on. The new, replacement straps were used for this test. A complete analysis of the use of the different straps on the measured data is reviewed in another MS thesis.

3.2 Transmissibility Data Processing

The input data for this thesis evaluation is the single input single output (SISO) transmissibility data. Matlab was used to process the raw time data and generate the SISO transmissibility data. Matlab was also used to generate the spatial averages compared and contrasted in the following sections. As stated previously, there were three main averages that were used in this process, which were: reference group transmissibility, response group transmissibility and reference-response group transmissibility. A few SISO transmissibility curves were also examined as a reference.

The group transmissibility was defined as the average of several output points on a specific area of the vehicle, e.g., the cross body beam, using only one reference. The reference group transmissibility was an average of single output point using all four references signals. The overall average reference-response group transmissibility was an average of both the references and outputs, creating a combination of reference group transmissibility and response group transmissibility.

Because the transmissibility data was complex, having both real and imaginary parts, averaging becomes a more complicated process. For this application the most relevant information was the magnitude of the transmissibility. As stated in the previous chapter, two methods were used to determine the average. They are typically referred to either as magnitude average or the straight average.

To serve as a check for consistency, the SISO transmissibility data (acceleration/displacement) was evaluated at the driving point to insure that the data was being processed correctly. The figure below shows the driving point corresponding to Shaker 1, which shows the ω^2 curve as expected.

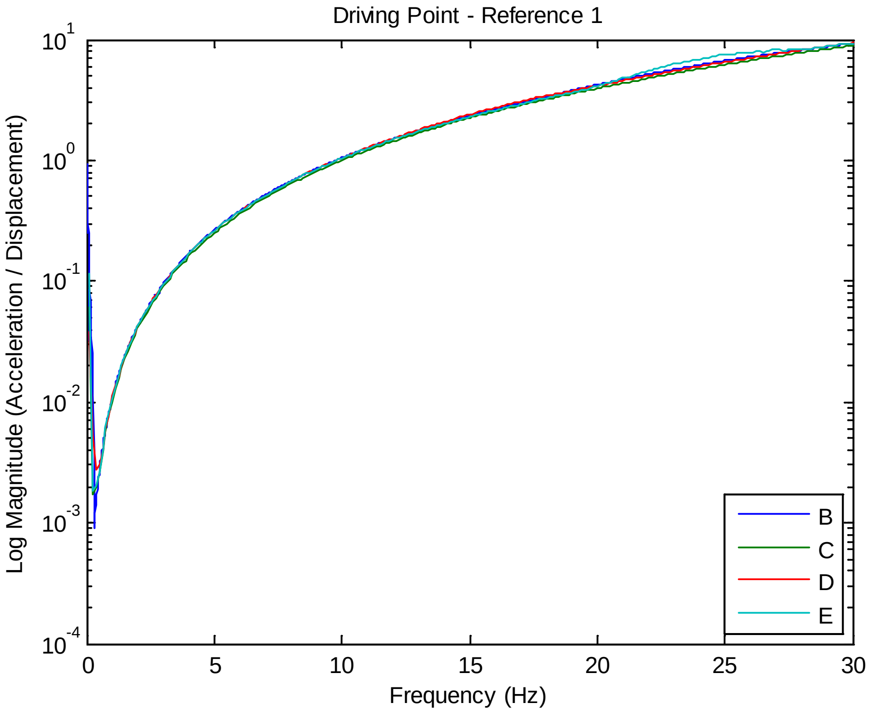


Figure 3-5 Driving Point Measurement at Shaker 1

Chapter 4 Results

4.1 Level Comparison

One of the first data processing items was to analyze how the various shaker output levels (inputs to the vehicle) affected the acceleration outputs. The levels used were 50%, 75%, and 100% of the actuators' maximum stroke distance. Figure 4-1 shows an example of the effect of these levels on the response group transmissibility. Additional level graphs can be seen in Appendix A. Noticing only slight differences between the different level percentages, it was concluded that varying the levels did not affect the transmissibility data very much, particularly below 30 Hz., and that the trend between the three levels was very similar.

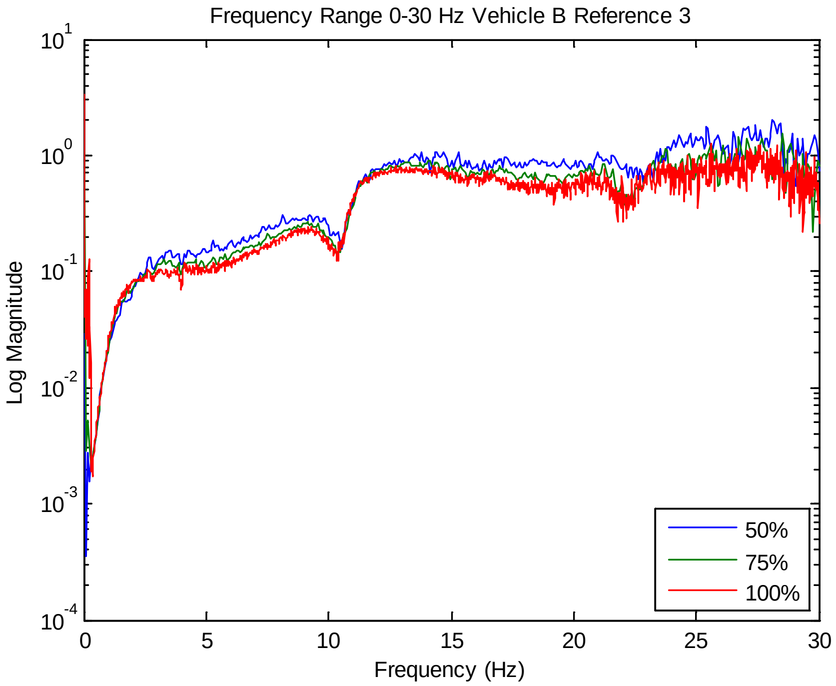


Figure 4-1 Level Comparison for Vehicle B, Response Group Transmissibility

Another concern when dealing with frequency data is the coherence. From the initial SISO transmissibility graphs, the coherence was seen to only be good until about 20 Hz. Although data above this frequency was observed, most of the focus was on the data up to this frequency. This also corresponds with the significant frequency range identified earlier to determine structural integrity between vehicles.

4.2 Comparison Between Averaging Methods

Since the spatial averaging was complicated because of the complex data, a consistent method needed to be used throughout the data processing. The two methods that were evaluated during this project, were first taking the magnitude of each signal, then averaging that magnitude (magnitude average) and averaging the complex number and then taking the magnitude of that (straight average). In the end, these two methods generated very similar results and similar trends, which can be seen in Figure 4-2. One notable difference was that the second method, averaging the complex number and then obtaining the average, seemed to be have more noise on the output, but the values and curves were very similar. Because of this, the first method, finding the magnitude first and then averaging, was used for the main data processing.

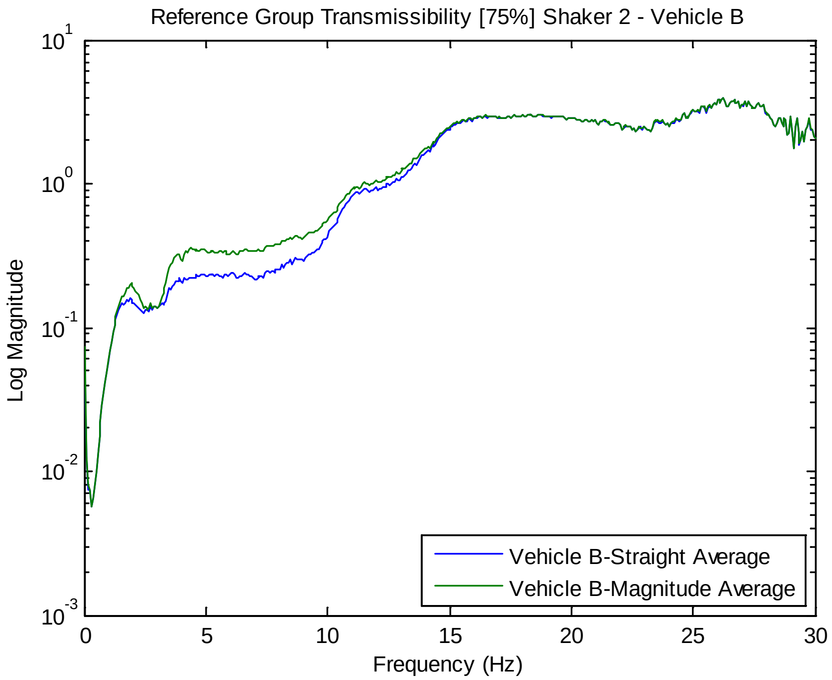


Figure 4-2 Comparison between Averaging Methods for Vehicle B, Response Group Transmissibility

As a second check, a comparison between the averaging methods for all vehicles was executed to insure that there were similar results for all vehicles. As can be seen in Figure 4-3, there are some slight differences in magnitude between the averaging techniques, however each of the vehicles follow similar trends. The main reason for this difference is probably because of the phase of the data in this frequency range. Usually when a magnitude is calculated, the phase angle is considered. If the phase angles are different, then the way the values are averaged will make a difference. For instance, if two complex numbers are added up first and the phase is 180 degrees from each other, they will cancel each other out. But if the magnitudes are taken first and the phase is not taken into account then the numbers will not cancel each other. In the 10-20 Hz frequency range, suspension modes are transitioning to deformation body modes at slightly different natural frequencies, vehicle by vehicle, resulting in a phase mismatch between vehicles. For the data used in this experiment, the different averaging techniques do not have a great difference in values, and this is probably because the phase angles are similar for the same frequency values.

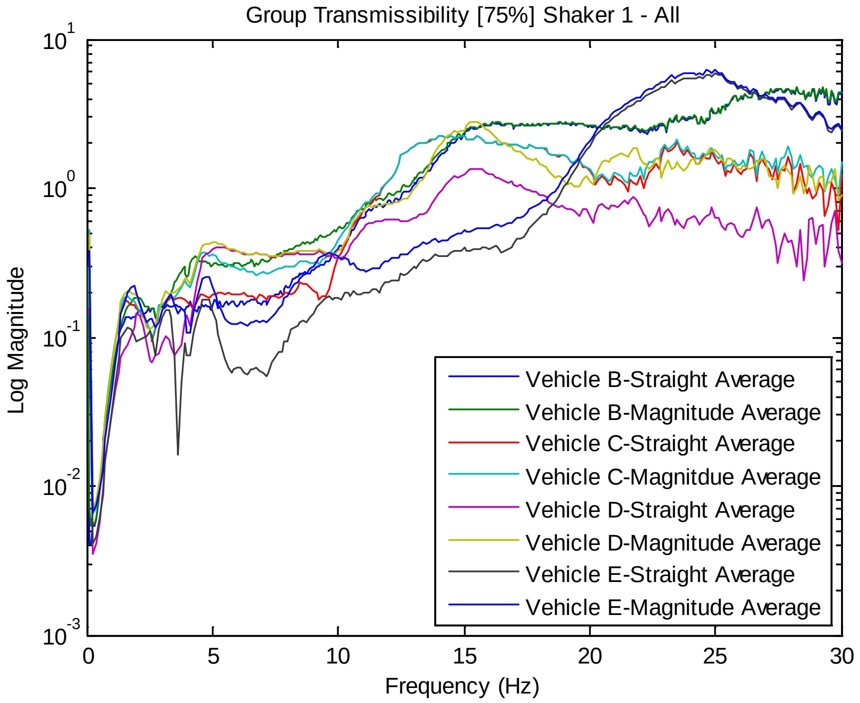


Figure 4-3 Comparison between Averaging Methods for All Vehicles

Figure 4-3 shows a comparison between the averaging methods for all of the vehicles in relation to Reference 1. This is an extension of Figure 4-2 where only one vehicle was shown. The additional averaging comparisons for each car can be found in Appendix A.

4.3 Comparison between Vehicles

4.3.1 Averaging Techniques

The response group transmissibility, reference group transmissibility, and the reference – response group transmissibility were taken for the four different vehicles for various parts of the structure. As stated earlier, the response group transmissibility averages the outputs over a single reference, reference group transmissibility averages the references over a single output and reference-response group transmissibility averages both the references and the outputs. All of the following graphs are of the cross body beam, unless stated otherwise.

4.3.2 Response Group Transmissibility

As noted, the response group transmissibility is an average of the outputs over a specific reference. Below is an example of the response group transmissibility plots. It displays the response group transmissibility for all vehicles for the cross body beam. The reason the cross body beam was used, is because the structure is similar on most vehicles. More plots can be found in Appendix A.

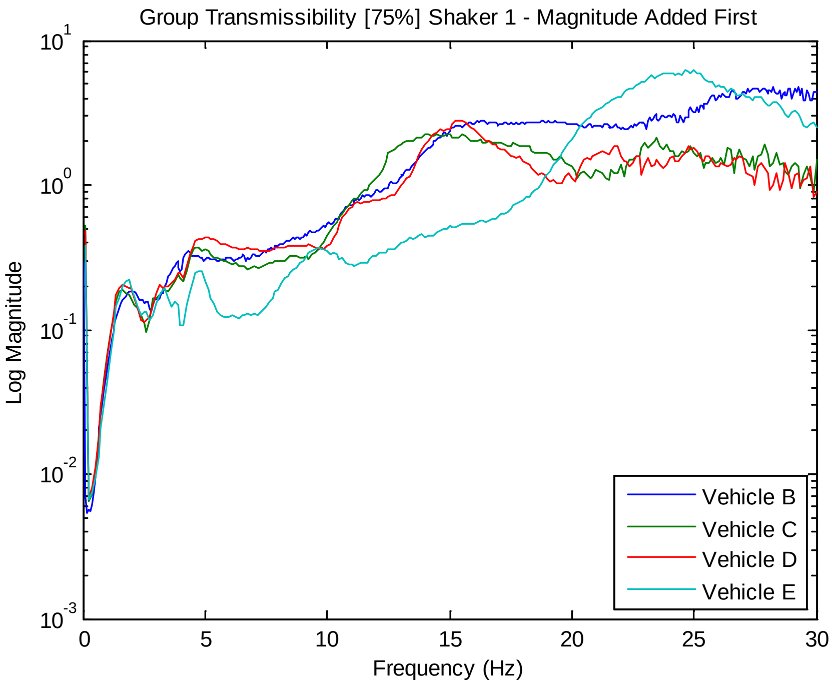


Figure 4-4 Response Group Transmissibility for All Vehicles

4.3.3 Reference Group Transmissibility

The following figure shows the reference group transmissibility at a point close to the center of the cross body beam. Although this method does take into account all of the references, it only considers one output. Since the objective of this project is to show how a specific substructure of a vehicle performs dynamically, there was not much emphasis in this direction.

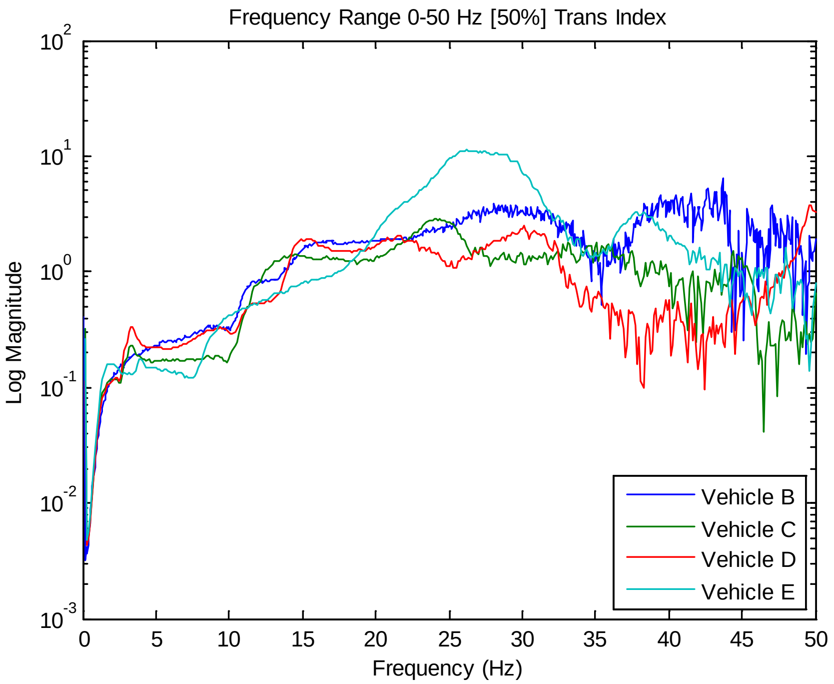


Figure 4-5 Reference Group Transmissibility for All Vehicles

4.3.4 Reference-Response Group Transmissibility

The reference-response group transmissibility is a good way to look at a MIMO system in a single curve, particularly for a vehicle with four common references (the tire patch at each of the four wheels). It takes into account both the references and outputs of the system and converts them into an overall average transmissibility.

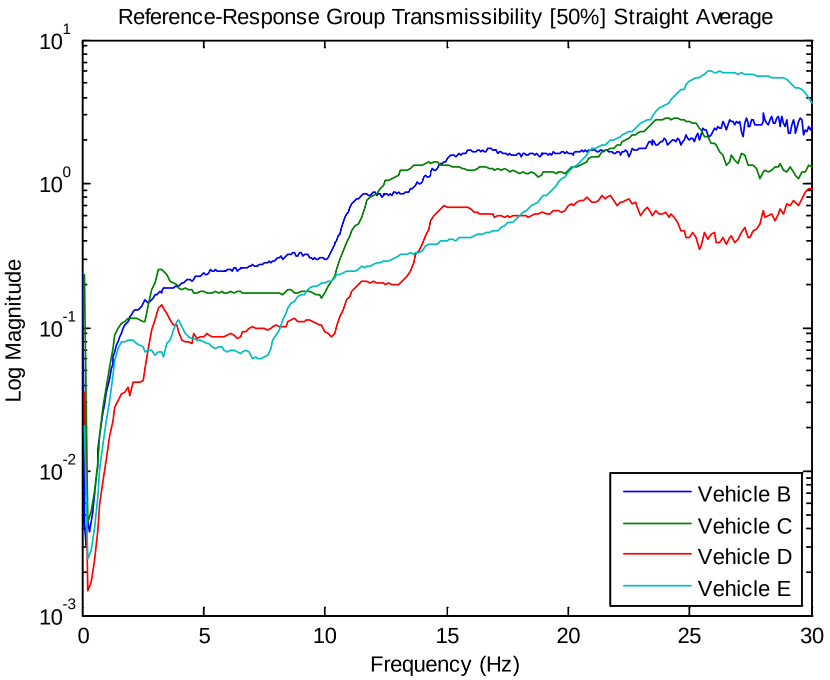


Figure 4-6 Reference-Response Group Transmissibility

The above figure shows the reference group transmissibility for all vehicles at the cross body beam in the z-direction. Since the structure of the car is quite different from the front to the rear, a reference-response group transmissibility for only the front and only the back references were made. These can be seen in the following figures.

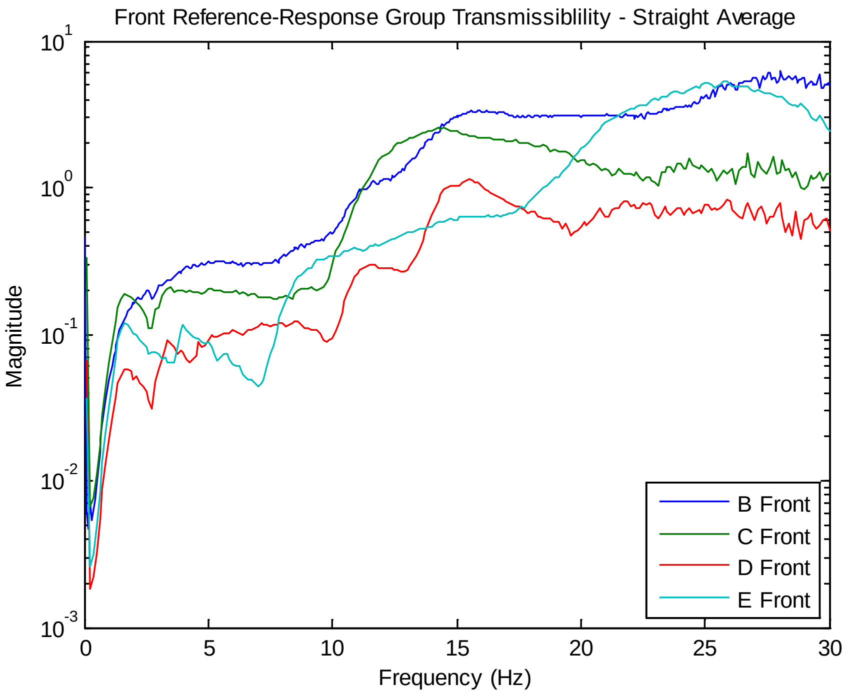


Figure 4-7 Reference-Response Group Transmissibility Using Only Front References

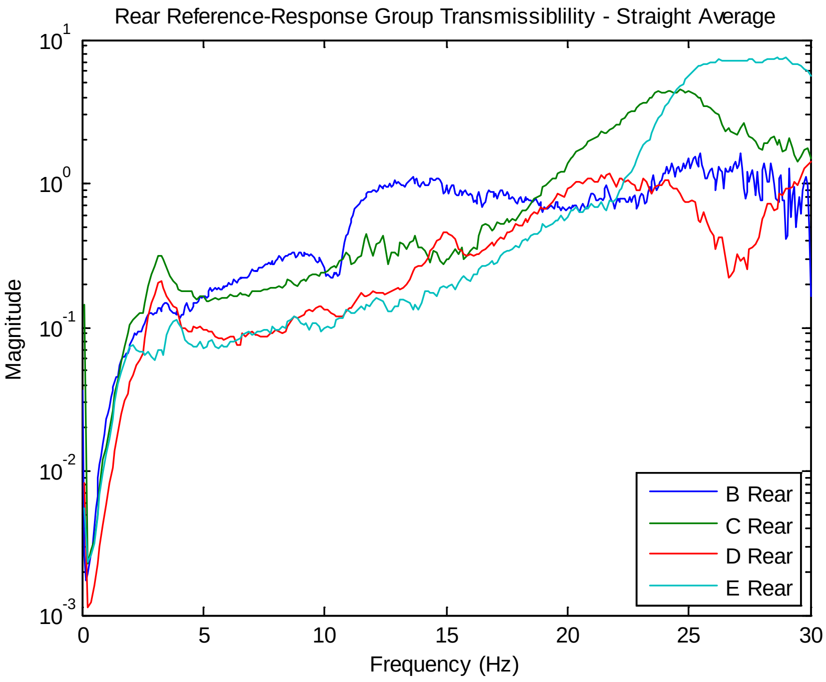


Figure 4-8 Reference-Response Group Transmissibility Using Only Rear Inputs

4.3.5 A-Pillar Data

Although the cross body beam was of great interest when looking at the transmissibility of the vehicles, another common significant location is the A-Pillar and door frame. This can be a problematic area because, if the door frame is flexing excessively compared to the door, the likelihood of a squeak occurring between the two is greatly increased. The figures below are all of the A-Pillar reference-response group transmissibility results in the vertical direction.

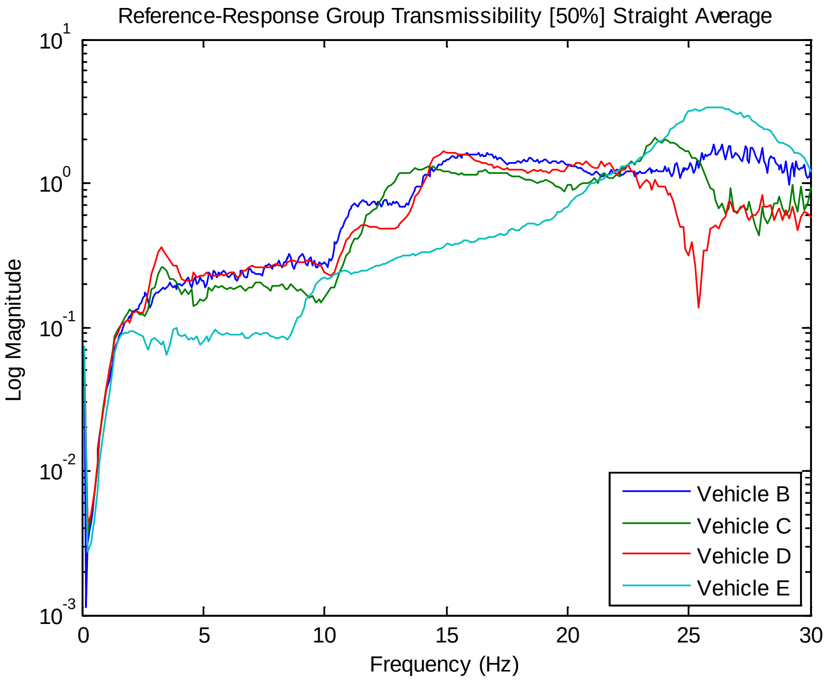


Figure 4-9 Reference-Response Group Transmissibility for the Driver's Side A-Pillar, Vertical Direction

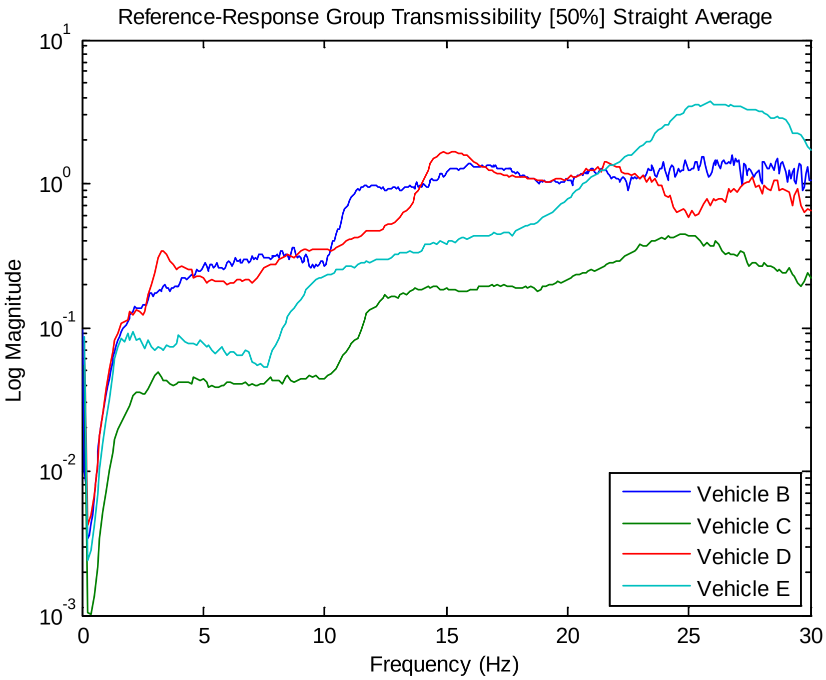


Figure 4-10 Reference-Response Group Transmissibility for the Passenger's Side A-Pillar, Vertical Direction

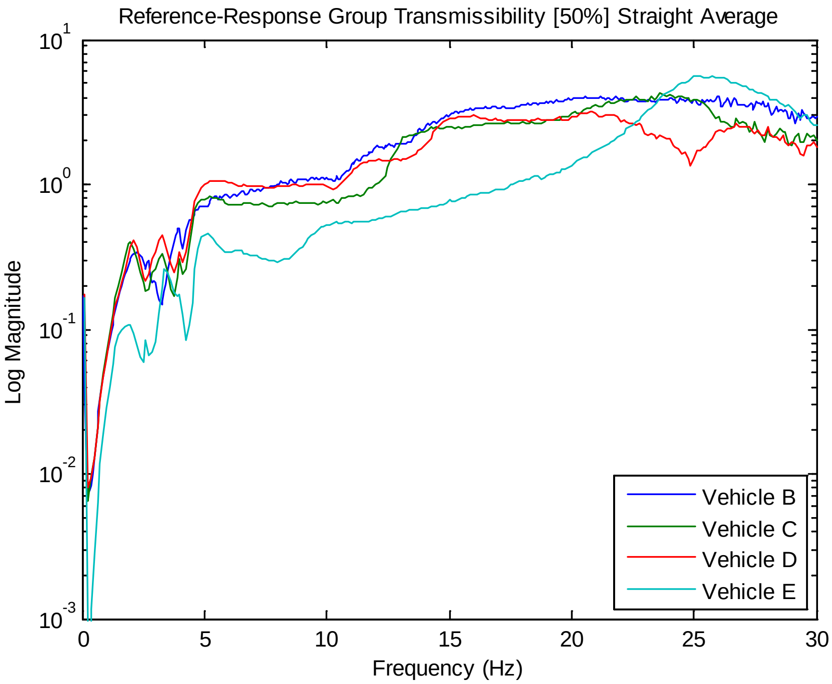


Figure 4-11 Reference-Resposne Group Transmissibility for Driver's Side A-Pillar Using References 1&3, Vertical Direction

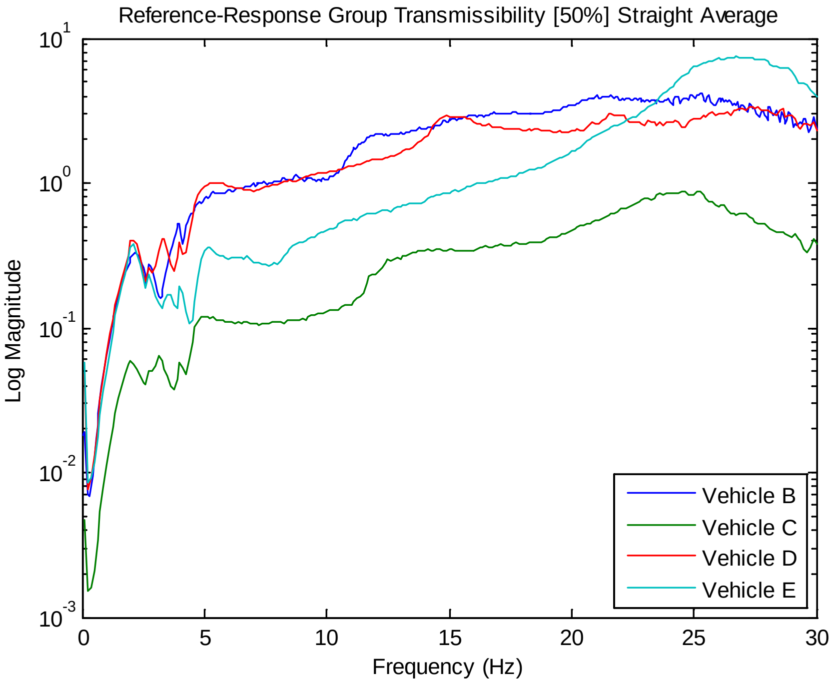


Figure 4-12 Reference-Response Group Transmissibility for the Passenger Side A-Pillar Using References 2&4, Vertical Direction

Figures 4-9 and 4-10 show the reference-response group transmissibility of the driver's side and passenger's side A-pillars averaged over all inputs. Figures 4-11 and 4-12 show the reference group transmissibility for the driver's side and passenger's side A-pillars when averaged only over the corresponding sides inputs. The differences between the plots show how the dynamics can vary greatly from side to side of the vehicles, although some of the vehicles barely differ at all. The cause for the side to side differences most likely depends on how major sub-components are position in each car. For instance, if the engine is oriented differently, it might cause a difference between the left and right sides.

4.4 Numeric Difference Metric

There was a need determine if the changes that were observed could be numerically represented. In order to compare the transmissibility data numerically instead of just visually, Matlab was used to create a best fit 5th degree polynomial function. These functions were created to fit the transmissibilities from 5-10 Hz, 5-15 Hz and 5-20 Hz. This is done by shifting all x-axis values 10 Hz lower, so that the data points were about the y-axis. This way the y-axis intercept reference point consistent between the different range fits, so those ranges could be easily compared. Below is a table of values for the coefficients for the polynomial function for Vehicle B, where C_0 is the constant value.

Table 4-1 Coefficients for Vehicle B

	C_5	C_4	C_3	C_2	C_1	C_0
A-pillar DS 5-10 Hz	0.00047	0.00510	0.01701	0.01376	-0.00016	0.20671
A-pillar DS 5-15 Hz	0.00034	0.00038	-0.00914	0.00152	0.12164	0.31798
A-pillar DS 5-20 Hz	0.00000	-0.00023	0.00048	0.01698	0.07333	0.27594
A-pillar DS ref 1&3 5-10 Hz	0.00010	-0.00026	-0.01224	-0.05752	-0.02698	0.79066
A-pillar DS ref 1&3 5-15 Hz	0.00013	-0.00013	-0.00215	0.02472	0.15502	0.87011
A-pillar DS ref 1&3 5-20 Hz	0.00002	-0.00057	0.00112	0.03620	0.14030	0.83856
A-pillar PS 5-10 Hz	0.00079	0.01033	0.04603	0.07203	0.01838	0.22758
A-pillar PS 5-15 Hz	0.00038	-0.00077	-0.01484	0.01933	0.20189	0.40061
A-pillar PS 5-20 Hz	0.00000	0.00011	-0.00212	0.00352	0.11716	0.42731
A-pillar PS ref 2&4 5-10 Hz	0.00081	0.01072	0.04617	0.06043	0.02084	0.79582
A-pillar PS ref 2&4 5-15 Hz	0.00036	-0.00124	-0.01454	0.03964	0.28848	1.00272
A-pillar PS ref 2&4 5-20 Hz	0.00002	-0.00013	-0.00268	0.01860	0.20603	1.04217
Cross Body Beam 5-10 Hz	0.00046	0.00521	0.01765	0.01109	-0.00890	0.23519
Cross Body Beam 5-15 Hz	0.00037	-0.00003	-0.01180	0.00788	0.15897	0.36864
Cross Body Beam 5-20 Hz	-0.00001	-0.00002	0.00005	0.01087	0.08949	0.35207
Cross Body Beam ref 1&2 5-10 Hz	0.00104	0.01292	0.05781	0.12609	0.19065	0.40539
Cross Body Beam ref 1&2 5-15 Hz	0.00028	0.00080	-0.00491	0.01351	0.17480	0.46652
Cross Body Beam ref 1&2 5-20 Hz	0.00004	-0.00100	0.00091	0.05509	0.16155	0.36393
Cross Body Beam ref 3&4 5-10 Hz	-0.00058	-0.00939	-0.05878	-0.17576	-0.20321	0.19918
Cross Body Beam ref 3&4 5-15 Hz	-0.00005	-0.00157	-0.00182	0.04142	0.13749	0.31368
Cross Body Beam ref 3&4 5-20 Hz	0.00006	-0.00045	-0.00392	0.01657	0.13702	0.37312

This was completed for all vehicles, with the thought that the coefficients might be different for each vehicle, especially the C_0 and C_1 coefficients. The additional coefficient tables can be found in Appendix B. These coefficients were graphed against each other and can be seen in Figures 4-13 and 4-14.

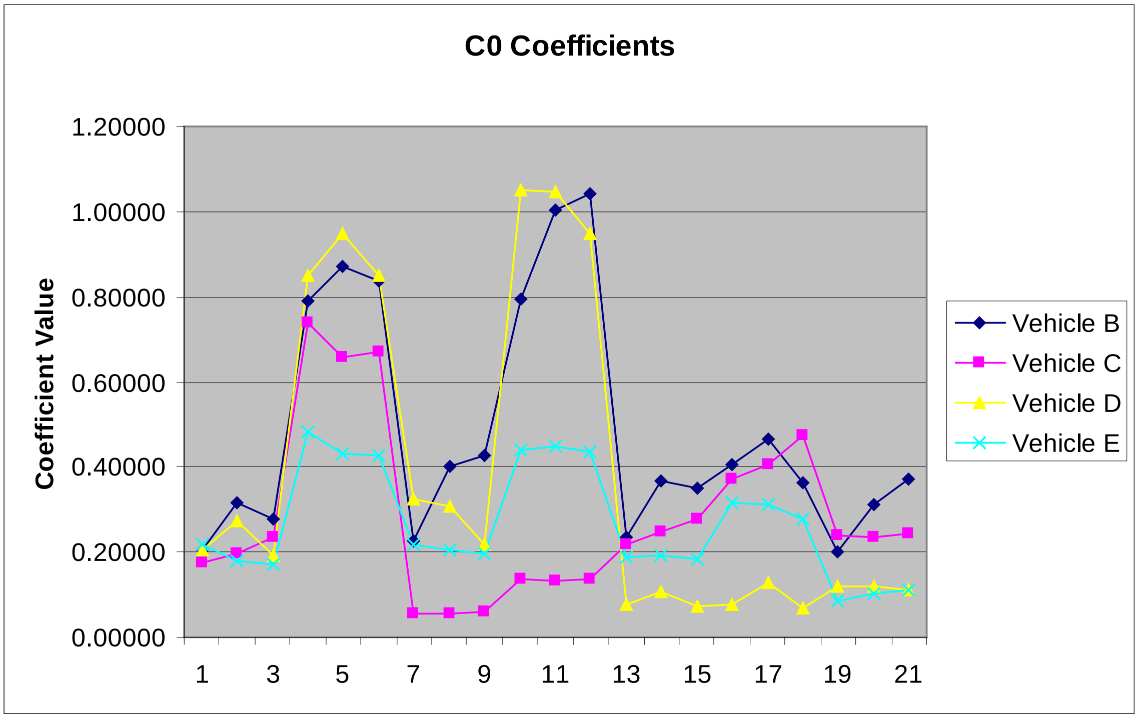


Figure 4-13 C_0 Coefficients for All Vehicles

Figure 4-3 looks like it might be indicative of something, and perhaps with more testing it will show a greater difference between Vehicle E and the other Vehicle platforms.

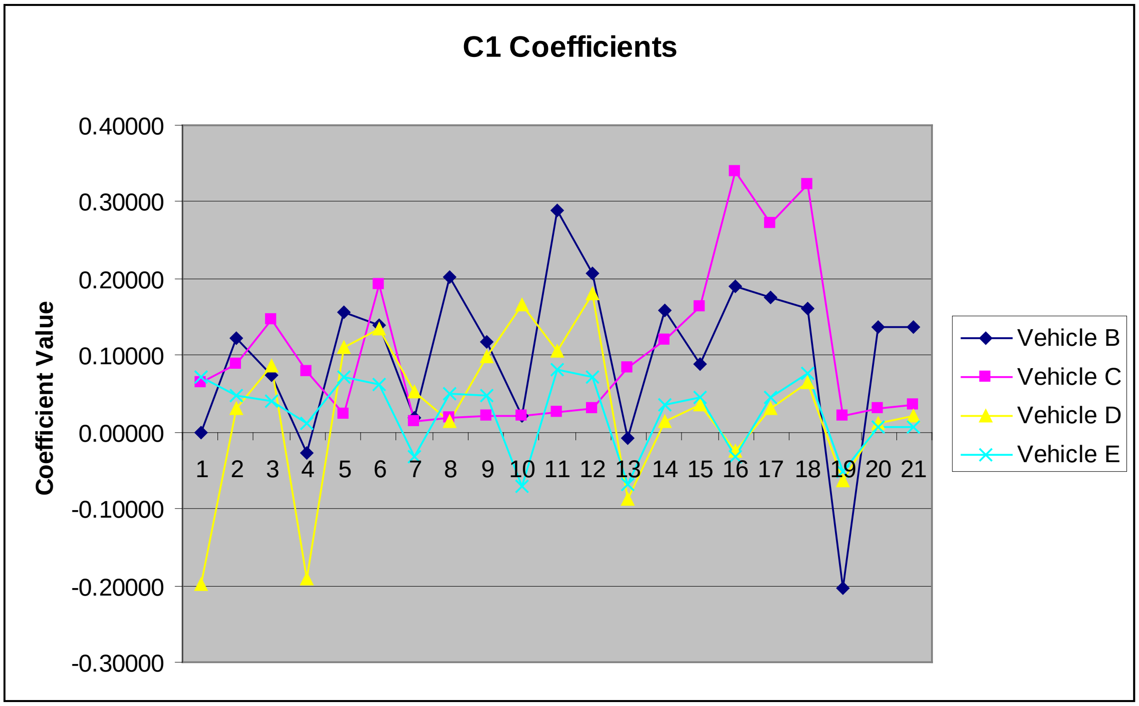


Figure 4-14 C_1 Coefficients for All Vehicles

As can be seen in Figure 4-13 the C_0 Coefficients vary somewhat between vehicles. There is also a difference depending on what group transmissibility was fitted. The graphs' points go in the same order as in Table 4-1 where left most point is the coefficient value for the driver's side A-Pillar in the 5-10 Hz range and the left most point is the value from the cross body beam transmissibility using only the rear references. It was observed that Vehicle E has an overall more consistent C_0 and even C_1 value than the rest of the vehicles.

4.5 Strap Conditions

4.5.1 New Straps vs. Old Straps

Because the old straps broke during testing, it was necessary to replace them. Unfortunately, the same type of strap could not be obtained, so they were replaced with a different strap, which would also have a different stiffness component when holding down the tires. Data was repeated using both straps for Vehicle D, so any difference between the two could be observed. The Figure below shows these results.

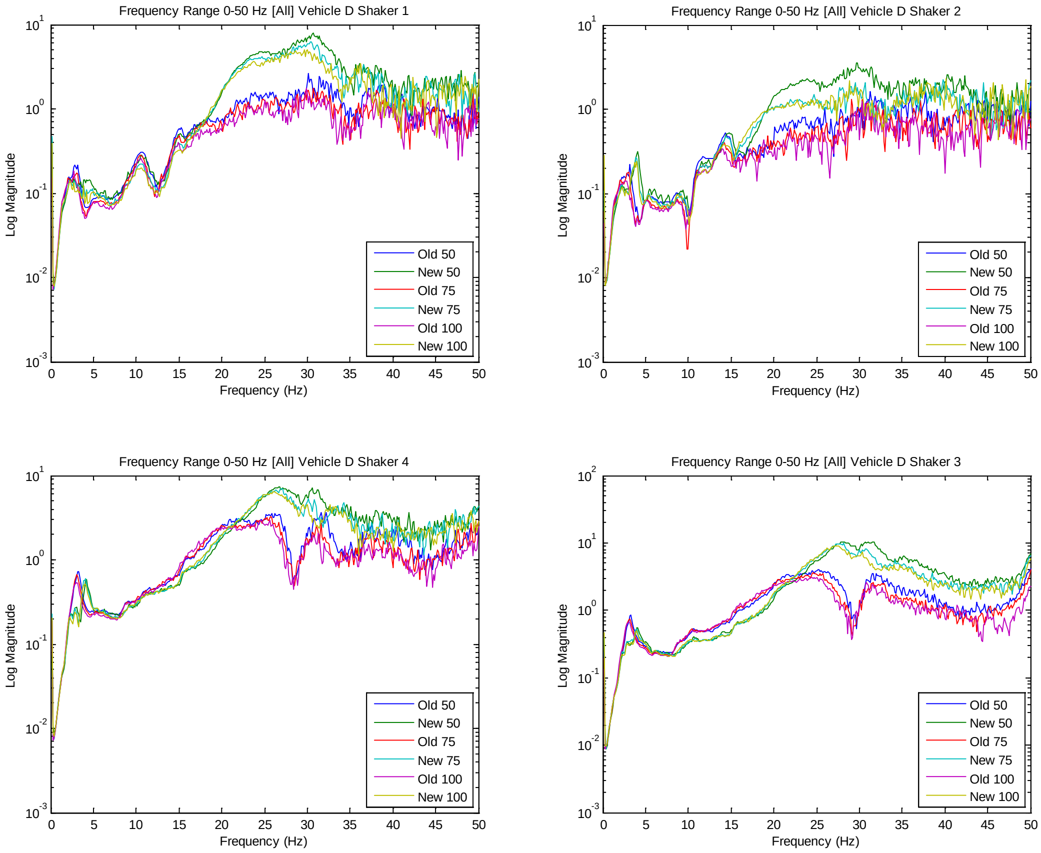
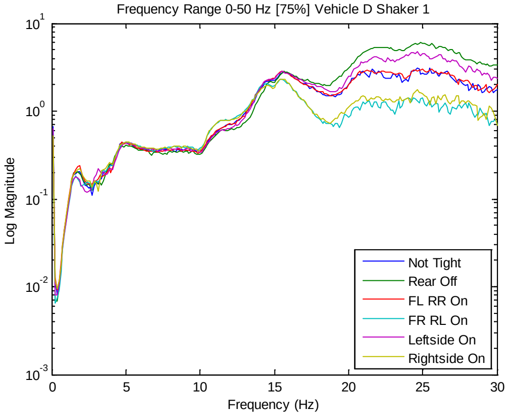


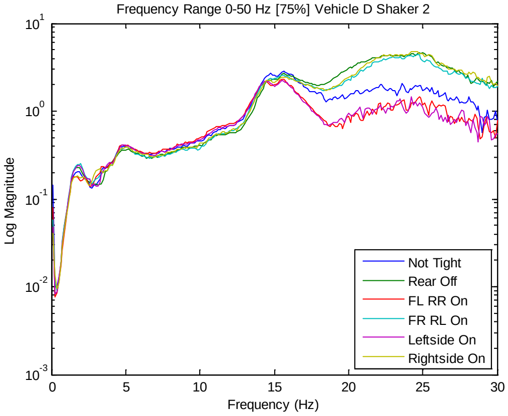
Figure 4-15 Group Transmissibility for New Straps vs. Old Straps for All Levels and Each Shaker

These figures show that there is almost no difference between the straps up to about 17 Hz. Since the focus range was from 5-20 Hz, it was determined that the new straps did not make a significant difference during testing.

4.5.2 Various Strap Tightening Criteria

To account for any variance that might have occurred during testing if the straps were not quite as tight from one vehicle to the next, various strap conditions were tested where some straps were tight and some were loose, while others were completely removed during the testing. The straps were loosened and then the vehicle was tested to see how the relative tightening affected the results. This testing was done on Vehicle D with the new straps. The results are shown below and reveal that even if the strap was very loose there is not an observably significant influence on the outcome and when there is deviation, it begins after approximately 15 Hz.


Frequency Range 0-50 Hz [75%] Vehicle D Shaker 1


Frequency Range 0-50 Hz [75%] Vehicle D Shaker 2

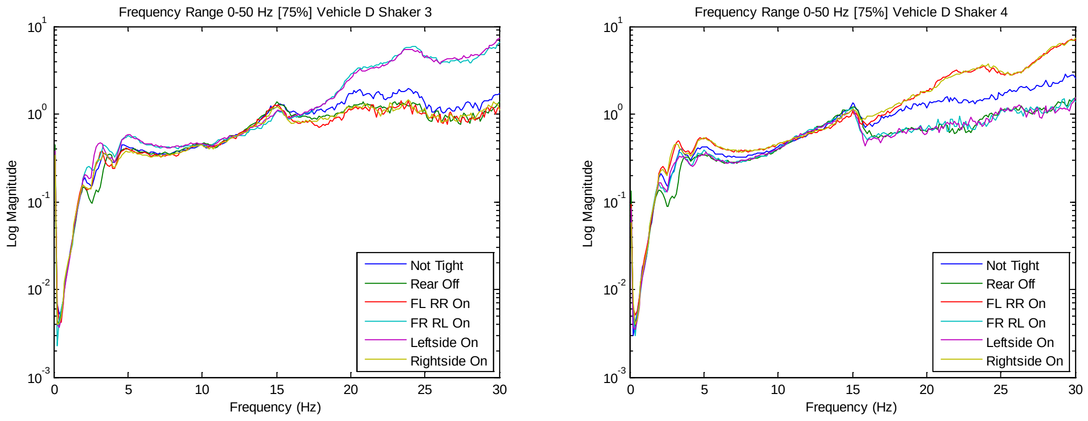


Figure 4-16 Group Transmissibility - Various Strap Conditions for Vehicle D for All Shakers

Chapter 5 Conclusions and Future Work

5.1 Overall Conclusions

The most significant conclusion for this thesis is that when looking at the response group transmissibility for the cross body beam, the Best in Class Vehicle E consistently has different group transmissibility characteristics in some frequency ranges compared to the other vehicles tested. However, when looking at the reference-response group transmissibility data, especially when the front and rear references are averaged separately, Vehicle E's group transmissibility characteristics are not as varied from the rest of the vehicles. In addition to this, the Best in Class Vehicle E also differs when looking at the A-Pillar reference-response group transmissibility, although Vehicle C differs even more than Vehicle E for the passenger's side A-Pillar. This is most likely due to transverse engine mounts or the spatial orientation of rear wheel drive versus front wheel drive for the vehicles. This does not mean that for all points Vehicle E has different group transmissibility characteristics and an example can be seen in Figure 4-5, displaying the reference group transmissibility.

There are a few practical issues when dealing with various vehicle structures and trying to compare them to each other. They mainly deal with how the car is actually put together. Although most of the sub-components are the same for all vehicles, they will vary slightly depending on the manufacturer. These sub-components could also be (and probably are) mounted differently from one model to another which could create problems while testing, preventing some of the response points from being accessible.

This was a problem for a couple of points on some of the vehicles tested. But considering that every point was slightly different for each vehicle, the response points were as similar as possible for all vehicles.

Also to be noted, is when the group transmissibility curves were fitted to a 5th order polynomial in the 5-10, 5-15 and 5-20 Hz ranges, Vehicle E had a more consistent C_0 value overall and it also tended to be lower than the rest of the vehicles. This means that the transmissibility values were overall lower for Vehicle E.

In the end, the group transmissibility data does not indicate that the Best in Class vehicle is radically different than the other vehicles tested. But, since Vehicle E has slightly lower response group transmissibility characteristics, one recommendation would be to try to lower the stiffness for the vehicle through the 5-20 Hz range. Perhaps with more testing, a more distinct baseline could be found.

5.2 Future Work

The main suggestion for future work for this concept is to test more vehicles. Like any project, the more cases you have to study the more statistically sound the results would be. Specifically, if more Best in Class vehicles could be tested to obtain a better baseline value, then the deviants might be more identifiable. Since the focus is to compare dissimilar vehicles, if the Best in Class vehicles from several classes could be tested and compared, there might be quite different results. Although testing the same exact type of vehicle would also show if there are even slight differences between the same vehicle just due to testing procedures and human error.

Another idea is to obtain more cars from different manufactures to test. This would probably vary the results more due to the difference in how the cars are made, however the overall baseline might be more accurate when comparing dissimilar vehicles.

During testing, there were some vehicles which were not able to accommodate an accelerometer at the same location as the other vehicles. While every accelerometer was placed with the intention of being in the same exact location on each and every car, it was simply not possible. If the precise geometry was available for each and every car before testing for the accessible structure, then this might be avoided and then the measurements would be more exact.

One extension of this thesis would be to calculate a combined spatial average for all directions (x, y and z) at once. It would be a complete vector average. The work shown described only considers on direction at a time, but there could be many advantages to looking at the entire motion at once. Such as when observing the motion of the door frame, there might be small movements in a two directions, but when they are looked at together, the movement is very significant.

There is possibly a need to create a better numeric metric to determine the differences between the transmissibilities for the vehicles. The polynomial fit curves that were created did show some differences between the vehicles, however there are other iterations of this curve fitting that can be preformed which might give better results.

Also, it was known that a couple of the other vehicles might squeak or rattle, it was not assumed that they all were overtly bad. If some cars that were known to have severe problems could also be tested, a larger variance might be identified.

References

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3. Structural Measurements: Lecture Notes – Part I. UC-SDRL Experimental Techniques Seminar Series. Structural Dynamics Research Laboratory, University of Cincinnati 2004: 6-26 – 6-35.
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6. Worden K, Manson G, Allman D. Experimental Validation of a Structural Health Monitoring Methodology: Part I. Novelty Detection on a Laboratory Structure. Journal of Sound and Vibration 2003 259(2): 323-343.
7. Haroon M, Adams, D E, Luk Y W. A Technique for Estimating Linear Parameters Using Nonlinear Restoring Force Extraction in the Absence of an Input Measurement. Journal of Vibration and Acoustics Oct 2005 Vol 127-1.
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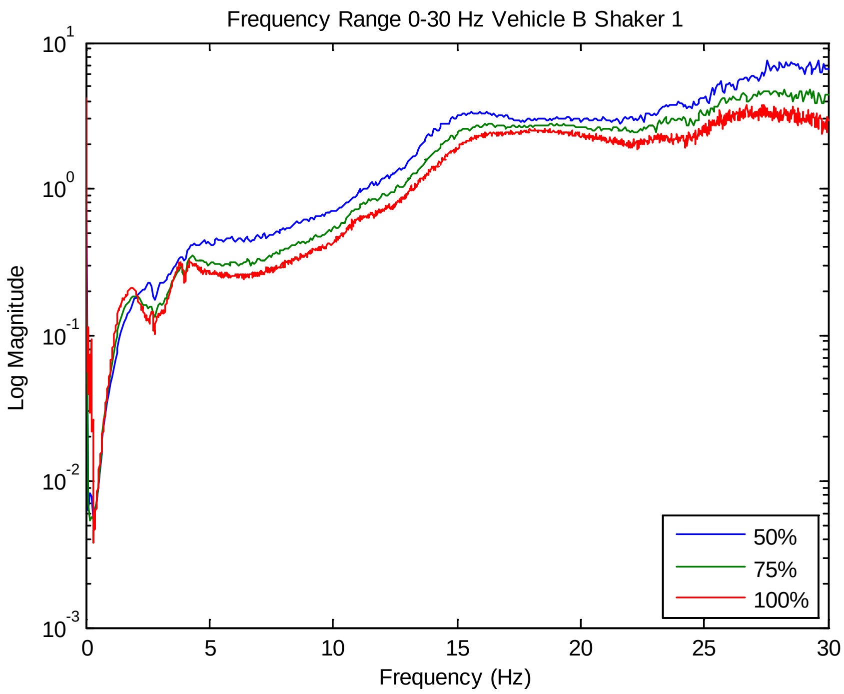
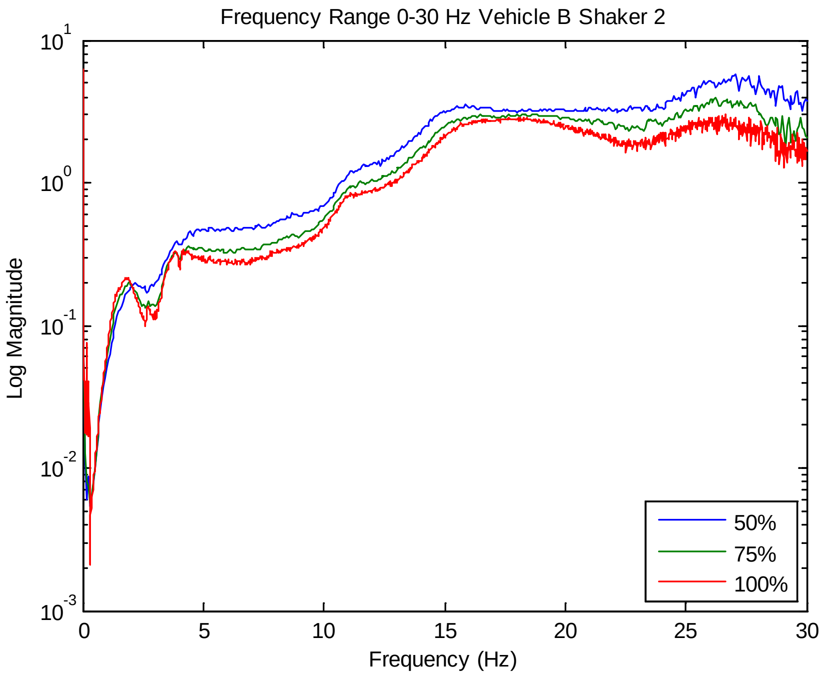
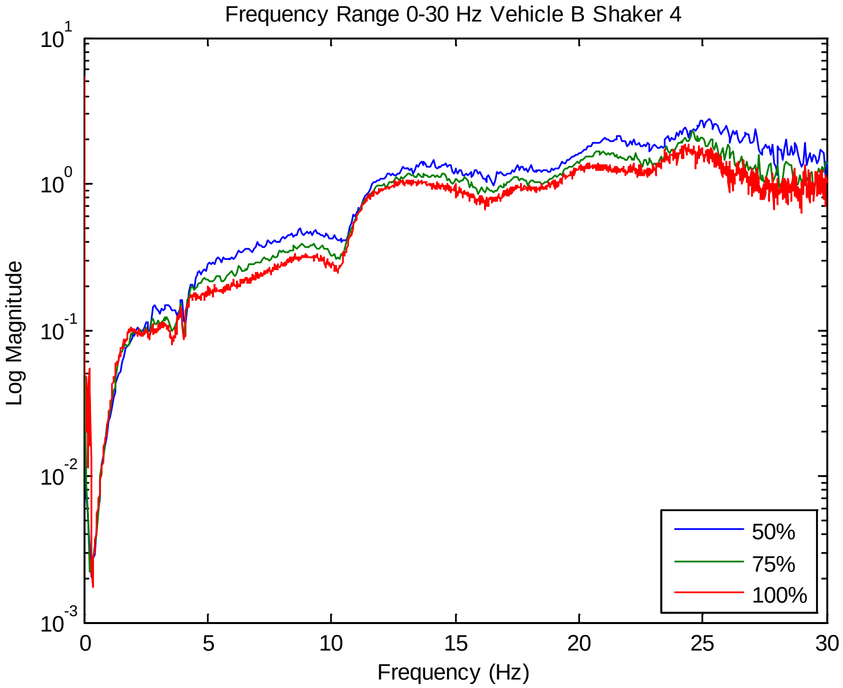
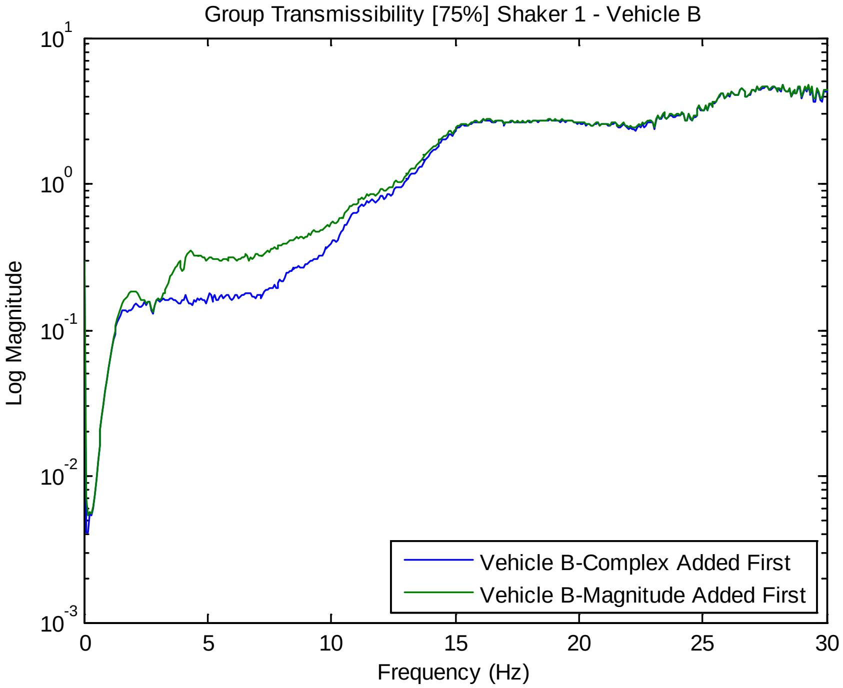
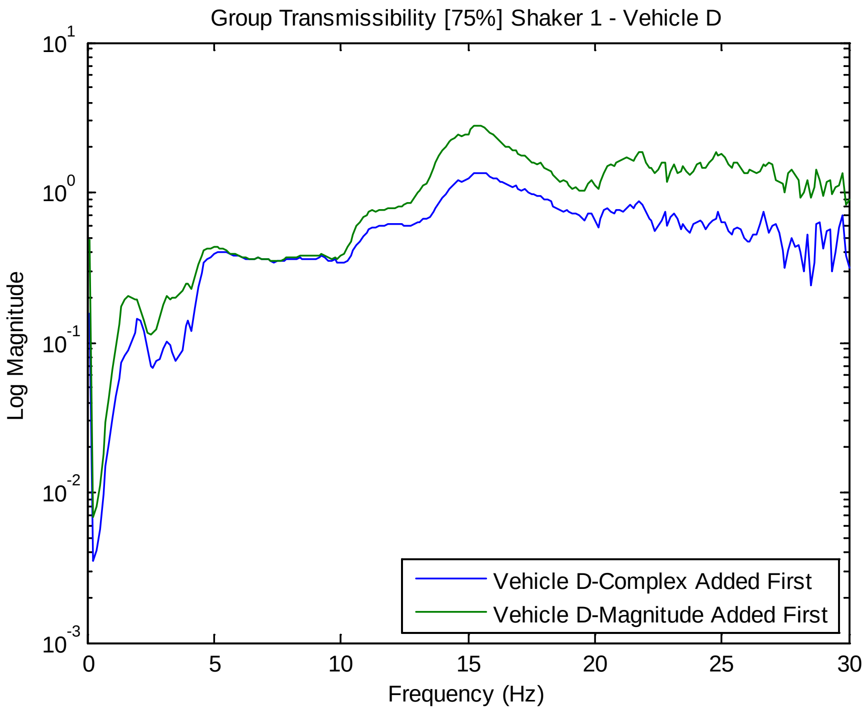
Appendix A – Additional Graphs

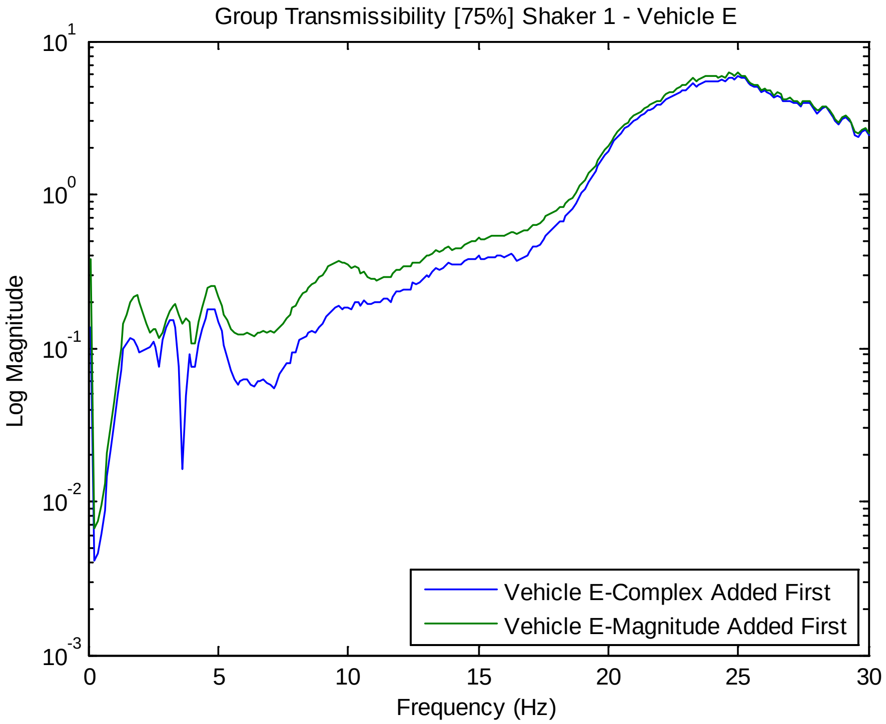


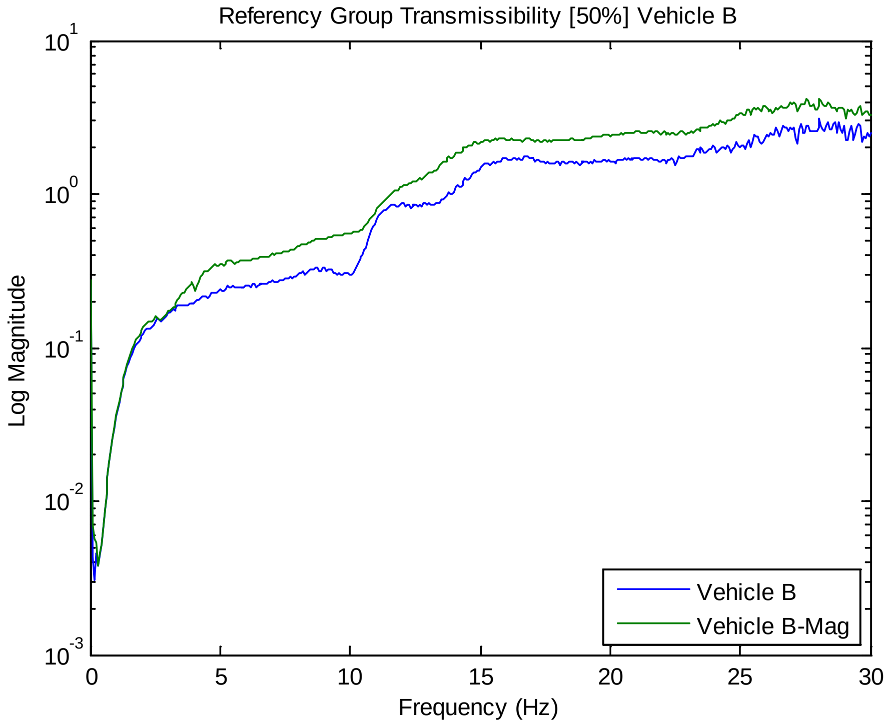


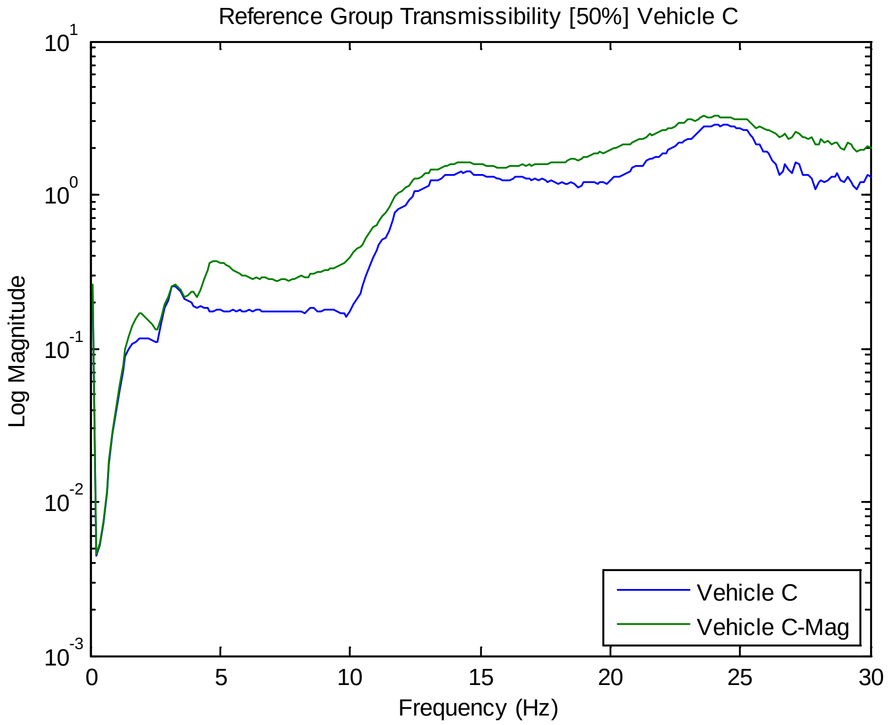

Frequency Range 0-30 Hz Vehicle B Shaker 4
Log Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
50%
75%
100%

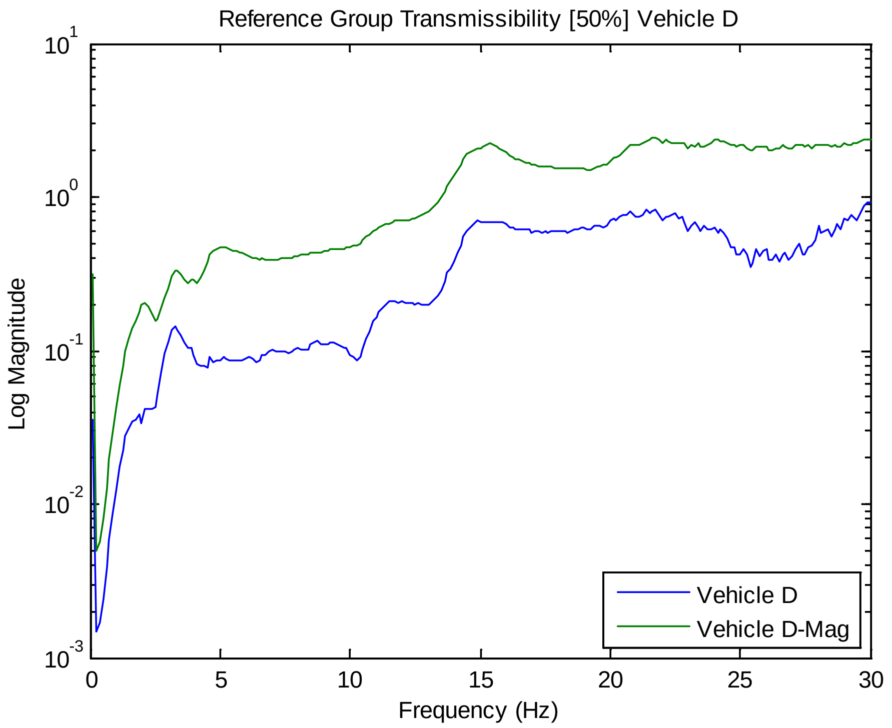

Group Transmissibility [75%] Shaker 1 - Vehicle B
Log Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
Vehicle B-Complex Added First
Vehicle B-Magnitude Added First

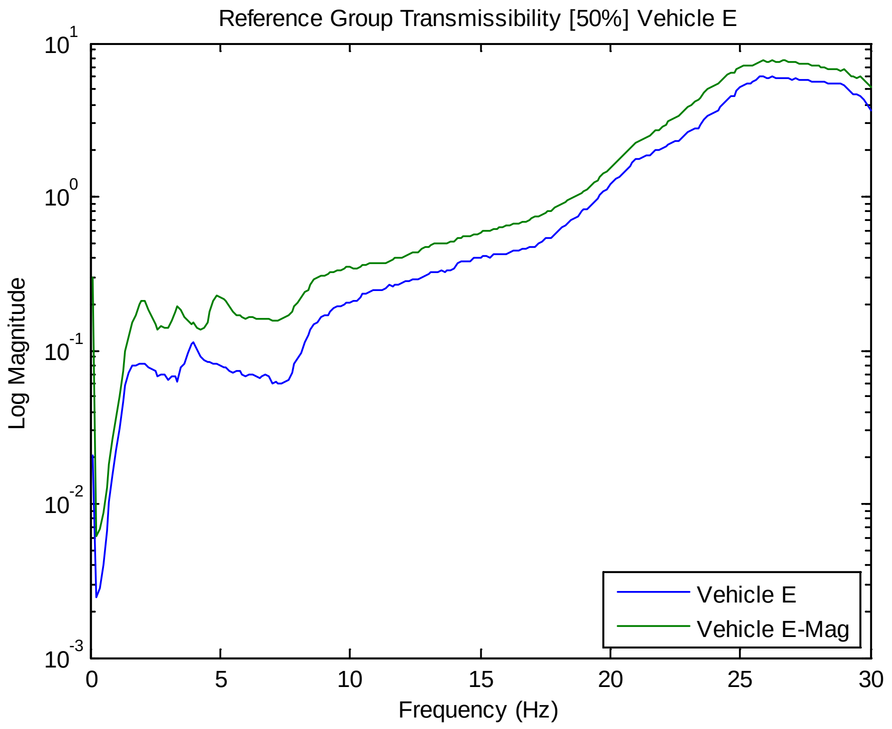

Group Transmissibility [75%] Shaker 1 - Vehicle D
Log Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
Vehicle D-Complex Added First
Vehicle D-Magnitude Added First

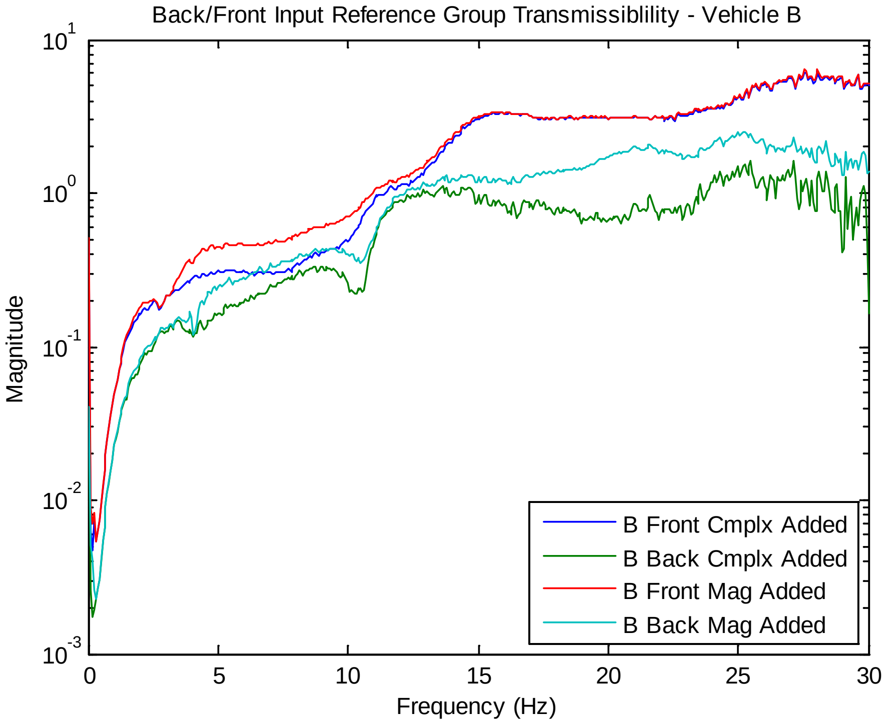

Group Transmissibility [75%] Shaker 1 - Vehicle E
Log Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
Vehicle E-Complex Added First
Vehicle E-Magnitude Added First

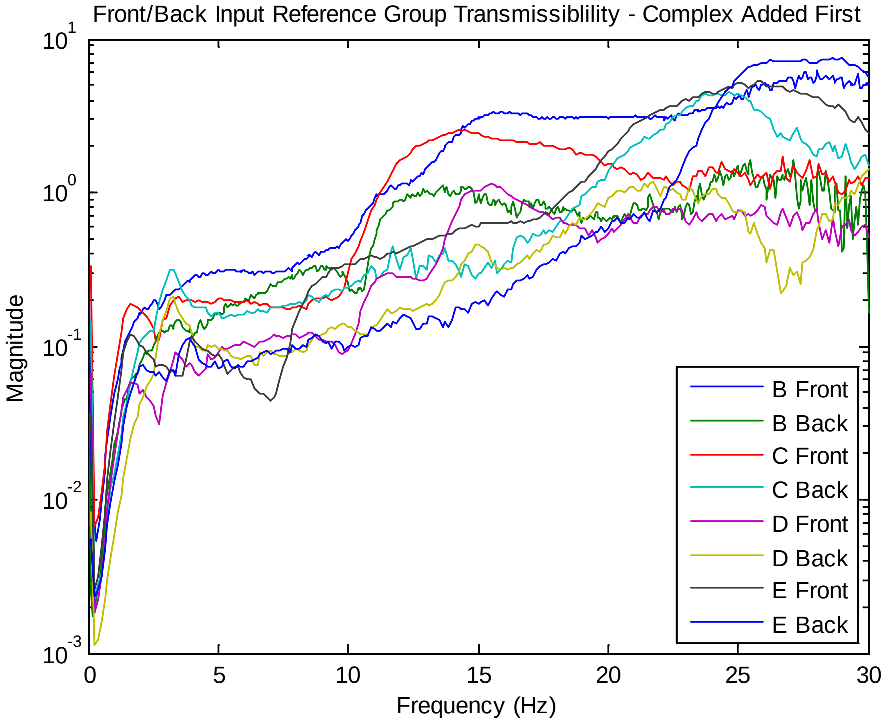

Referency Group Transmissibility [50%] Vehicle B

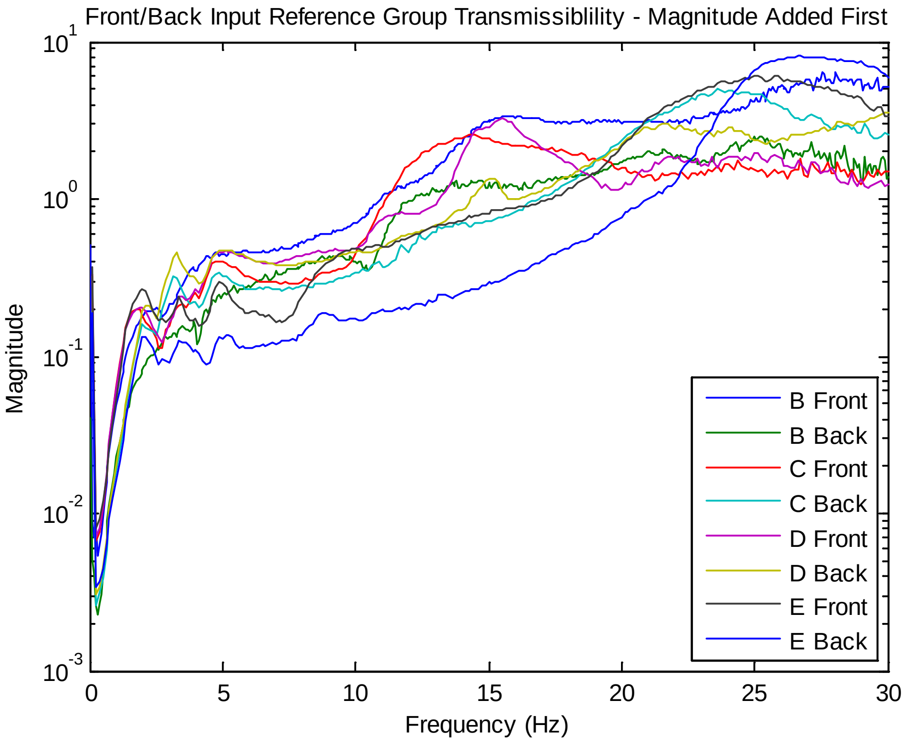

Reference Group Transmissibility [50%] Vehicle C


Reference Group Transmissibility [50%] Vehicle D
Log Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
Vehicle D
Vehicle D-Mag


Reference Group Transmissibility [50%] Vehicle E
Log Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
Vehicle E
Vehicle E-Mag


Back/Front Input Reference Group Transmissiblility - Vehicle B
Magnitude
Frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-3
0
5
10
15
20
25
30
B Front Cmplx Added
B Back Cmplx Added
B Front Mag Added
B Back Mag Added


Front/Back Input Reference Group Transmissiblility - Complex Added First
Magnitude
Frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-3
0
5
10
15
20
25
30
B Front
B Back
C Front
C Back
D Front
D Back
E Front
E Back


Front/Back Input Reference Group Transmissiblility - Magnitude Added First
Magnitude
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
Frequency (Hz)
B Front
B Back
C Front
C Back
D Front
D Back
E Front
E Back

Appendix B – Additional Tables

Polynomial Coefficients for Vehicle C

	C_5	C_4	C_3	C_2	C_1	C_0
A-pillar DS 5-10 Hz	0.00087	0.01130	0.05141	0.09545	0.06364	0.17608
A-pillar DS 5-15 Hz	-0.00030	-0.00152	0.00743	0.05469	0.08778	0.19515
A-pillar DS 5-20 Hz	0.00009	-0.00095	-0.00369	0.04012	0.14564	0.23547
A-pillar DS ref 1&3 5-10 Hz	0.00073	0.00975	0.04235	0.07665	0.08015	0.74014
A-pillar DS ref 1&3 5-15 Hz	-0.00080	-0.00169	0.02470	0.07854	0.02305	0.65787
A-pillar DS ref 1&3 5-20 Hz	0.00016	-0.00187	-0.00426	0.07842	0.19251	0.67137
A-pillar PS 5-10 Hz	0.00002	0.00027	0.00156	0.00567	0.01336	0.05457
A-pillar PS 5-15 Hz	-0.00001	-0.00014	0.00008	0.00530	0.01759	0.05661
A-pillar PS 5-20 Hz	0.00001	-0.00009	-0.00044	0.00413	0.01998	0.05954
A-pillar PS ref 2&4 5-10 Hz	-0.00011	-0.00135	-0.00562	-0.00467	0.02014	0.13718
A-pillar PS ref 2&4 5-15 Hz	-0.00003	-0.00016	0.00054	0.00725	0.02481	0.13329
A-pillar PS ref 2&4 5-20 Hz	0.00001	-0.00011	-0.00065	0.00598	0.03115	0.13686
Cross Body Beam 5-10 Hz	0.00066	0.00830	0.03715	0.07553	0.08307	0.21936
Cross Body Beam 5-15 Hz	-0.00019	-0.00131	0.00419	0.05010	0.11937	0.24558
Cross Body Beam 5-20 Hz	0.00009	-0.00092	-0.00418	0.03960	0.16391	0.27599
Cross Body Beam ref 1&2 5-10 Hz	0.00207	0.02701	0.12958	0.29160	0.34014	0.36947
Cross Body Beam ref 1&2 5-15 Hz	-0.00021	-0.00227	0.00208	0.08516	0.27212	0.40613
Cross Body Beam ref 1&2 5-20 Hz	0.00013	-0.00130	-0.00801	0.06046	0.32206	0.47504
Cross Body Beam ref 3&4 5-10 Hz	-0.00011	-0.00139	-0.00672	-0.01161	0.02119	0.23756
Cross Body Beam ref 3&4 5-15 Hz	-0.00004	-0.00017	0.00056	0.00435	0.02950	0.23393
Cross Body Beam ref 3&4 5-20 Hz	0.00001	0.00003	-0.00082	0.00002	0.03450	0.24356

Polynomial Coefficients for Vehicle D

	C_5	C_4	C_3	C_2	C_1	C_0
A-pillar DS 5-10 Hz	-0.00150	-0.02045	-0.10218	-0.22682	-0.19877	0.20418
A-pillar DS 5-15 Hz	0.00002	0.00049	0.00386	0.01246	0.03144	0.27230
A-pillar DS 5-20 Hz	0.00010	-0.00138	-0.00126	0.05095	0.08615	0.19035
A-pillar DS ref 1&3 5-10 Hz	-0.00057	-0.01141	-0.07880	-0.21416	-0.19185	0.84804
A-pillar DS ref 1&3 5-15 Hz	0.00019	0.00067	-0.00215	0.01820	0.11155	0.94938
A-pillar DS ref 1&3 5-20 Hz	0.00009	-0.00136	-0.00166	0.06211	0.13460	0.84928
A-pillar PS 5-10 Hz	0.00091	0.01049	0.03798	0.04641	0.05127	0.32363
A-pillar PS 5-15 Hz	-0.00013	0.00072	0.00813	0.00683	0.01311	0.30731
A-pillar PS 5-20 Hz	0.00010	-0.00136	-0.00181	0.04904	0.09843	0.21946
A-pillar PS ref 2&4 5-10 Hz	0.00239	0.02659	0.09364	0.13095	0.16650	1.05144
A-pillar PS ref 2&4 5-15 Hz	-0.00003	0.00104	0.00380	0.00802	0.10443	1.04440
A-pillar PS ref 2&4 5-20 Hz	0.00010	-0.00126	-0.00375	0.05457	0.17995	0.94813
Cross Body Beam 5-10 Hz	-0.00065	-0.00900	-0.04530	-0.10084	-0.08724	0.07888
Cross Body Beam 5-15 Hz	0.00002	0.00024	0.00126	0.00441	0.01485	0.10862
Cross Body Beam 5-20 Hz	0.00004	-0.00054	-0.00034	0.02051	0.03443	0.07388
Cross Body Beam ref 1&2 5-10 Hz	0.00005	0.00040	-0.00014	-0.00932	-0.02579	0.07772
Cross Body Beam ref 1&2 5-15 Hz	0.00004	0.00029	0.00146	0.00898	0.03143	0.12814

Cross Body Beam ref 1&2 5-20 Hz	0.00007	-0.00101	-0.00123	0.03649	0.06354	0.06702
Cross Body Beam ref 3&4 5-10 Hz	-0.00098	-0.01300	-0.06155	-0.11977	-0.06413	0.12120
Cross Body Beam ref 3&4 5-15 Hz	0.00001	0.00022	0.00072	-0.00004	0.01138	0.12006
Cross Body Beam ref 3&4 5-20 Hz	0.00001	-0.00011	-0.00018	0.00573	0.02216	0.11077

Polynomial Coefficients for Vehicle E

	C_5	C_4	C_3	C_2	C_1	C_0
A-pillar DS 5-10 Hz	-0.00133	-0.01664	-0.06808	-0.08237	0.07061	0.21849
A-pillar DS 5-15 Hz	0.00006	0.00018	-0.00226	-0.00254	0.04849	0.17759
A-pillar DS 5-20 Hz	0.00000	0.00010	-0.00062	-0.00061	0.04008	0.17262
A-pillar DS ref 1&3 5-10 Hz	-0.00340	-0.04174	-0.17607	-0.26113	0.01188	0.48211
A-pillar DS ref 1&3 5-15 Hz	0.00004	0.00041	-0.00276	-0.00412	0.07149	0.43156
A-pillar DS ref 1&3 5-20 Hz	-0.00002	0.00033	-0.00104	-0.00217	0.06266	0.42654
A-pillar PS 5-10 Hz	-0.00078	-0.01252	-0.06997	-0.14755	-0.03312	0.21613
A-pillar PS 5-15 Hz	0.00002	0.00031	-0.00133	-0.00644	0.04905	0.20629
A-pillar PS 5-20 Hz	0.00000	0.00012	-0.00075	-0.00221	0.04790	0.19611
A-pillar PS ref 2&4 5-10 Hz	-0.00173	-0.02420	-0.12144	-0.23652	-0.07145	0.44170
A-pillar PS ref 2&4 5-15 Hz	0.00006	0.00038	-0.00286	-0.00386	0.08164	0.45017
A-pillar PS ref 2&4 5-20 Hz	-0.00001	0.00018	-0.00093	0.00107	0.07254	0.43710
Cross Body Beam 5-10 Hz	-0.00016	-0.00527	-0.04343	-0.12447	-0.06727	0.18711
Cross Body Beam 5-15 Hz	-0.00002	0.00026	0.00016	-0.00444	0.03664	0.19389
Cross Body Beam 5-20 Hz	0.00001	0.00003	-0.00090	0.00051	0.04546	0.18272
Cross Body Beam ref 1&2 5-10 Hz	0.00144	0.01278	0.01956	-0.05869	-0.03299	0.31490
Cross Body Beam ref 1&2 5-15 Hz	-0.00010	0.00057	0.00245	-0.01231	0.04516	0.31290
Cross Body Beam ref 1&2 5-20 Hz	0.00003	-0.00011	-0.00193	0.00261	0.07735	0.27776
Cross Body Beam ref 3&4 5-10 Hz	-0.00024	-0.00331	-0.01783	-0.04749	-0.05151	0.08509
Cross Body Beam ref 3&4 5-15 Hz	-0.00001	-0.00004	0.00048	0.00173	0.00731	0.10425
Cross Body Beam ref 3&4 5-20 Hz	-0.00001	0.00009	0.00031	-0.00144	0.00743	0.11301