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CREATION OF A VIRTUAL RIDE ENVIRONMENT THROUGH THE USE OF CAE MODEL DATA AND THE FORD VEHICLE VIBRATION SIMULATOR

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ABSTRACT

Many aspects of modern automobile design influence a driver's (or passenger's) perception of vehicle performance and quality. This is especially true in the evaluation of Noise Vibration and Harshness (NVH). Formal, juried evaluations of vehicle performance are essential for final vehicle design approval but, to be efficient, engineers need design guidance before prototype hardware has been built. To augment the design process, Ford has developed a high-bandwidth 11-degree of freedom simulator called the Vehicle Vibration Simulator or VVS. The VVS is a human-rated, hydraulically powered device that can be driven from data collected in-vehicle or from computer simulations.

In this paper the output of a high fidelity vehicle CAE model was used to create a virtual ride evaluation using the VVS. A model for a small sub-compact vehicle was used in a paired comparison study to help understand the process of data acquisition and simulation, using computer generated data and the VVS. This study demonstrated the ability to predict small model parameter changes using the VVS along with robust subjective testing techniques. Two vehicle ride attributes were evaluated against changes in the model parameters for vehicle front and rear suspension damping rates using a paired comparison of preference testing technique. This study demonstrated the feasibility of using modeling data to create a virtual ride environment that can lead to a reduction in prototypes.

INTRODUCTION

Traditionally, vehicle engineers rely heavily on the building of engineering prototype vehicles and performing on-road tests to verify the ride quality of a new vehicle design. For many years, computer generated data has been available to help predict the ride quality for a new vehicle design. With the advancement of CAE tools and modeling software, engineers are capable of predicting not only the dynamic behavior of vehicle suspension systems, but can also predict NVH behavior through finite element body models. One difficulty with this type of analysis is that the output has been traditionally confined to simple ride metrics or graphical comparisons of predicted accelerations. The engineer can look at a graphical representation of the "physics", and make a "seat of the pants" guess about what will happen in the "real world", but the engineer cannot "feel" the outcome unless he is willing to spend the money to build an engineering prototype vehicle. The current virtual ride process is depicted graphically in Figure 1.

With the advent of motion simulation systems like the Vehicle Vibration Simulation, we now have the capability through the use of modern control systems and hydraulic actuators to provide a simulated environment to realistically reproduce real vehicle dynamic behavior. The VVS has been shown in several research studies to be an effective tool for the vibration engineer in looking at vibration quality issues and to investigate basic vibration psychophysics [7,8,9]. However, it has always been our belief that the VVS can be used effectively as a replacement for several early level prototype vehicles. This study specifically focused on the use of a low-frequency non-linear ride modeling computer software. This software enables the development engineer to investigate the dynamic behavior of a vehicle up to about 20 Hz. The model includes body, powertrain, 4 wheels, and up to 2 seats. The body can be rigid (6 degrees of freedom (DOF)) or torsional flexible (7 DOF). The powertrain can be rigidly attached to the body (0 DOF) or elastically suspended by an arbitrary number of mounts (6 DOF).

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Available suspension models are:

- kinematic model (2 DOF, including wheel rotation)
- kinematic model with longitudinal compliance (3 DOF) or
- Parametric model (1,2,3 . . . DOF)

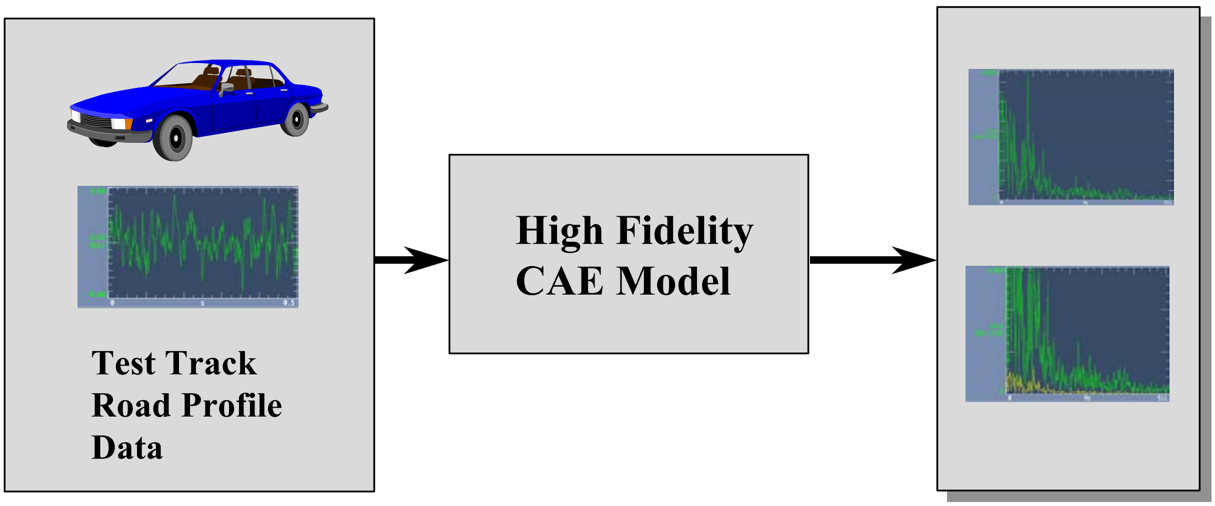

Figure 1 - Virtual Ride Process (pre – VVS)

Dry friction in the suspension is considered for all of these options. Components like tires and engine mounts can be described by:

- Characteristic curves or
- Detailed simulation models.

In this particular study a small sub-compact vehicle was used. This model was verified in Europe with four-poster hydraulic system measurements. The virtual ride process using the VVS is shown in Figure 2.

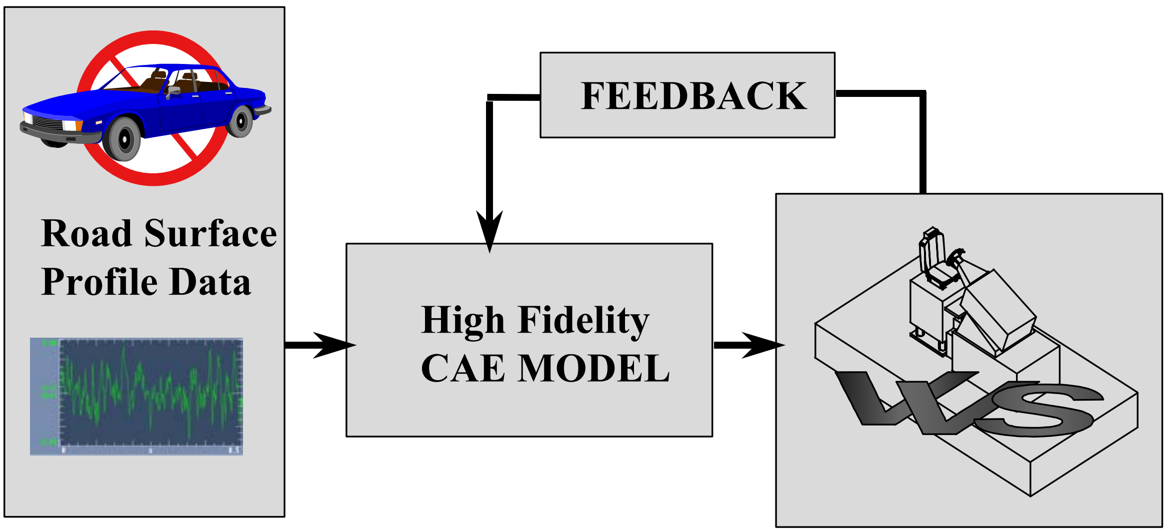

Figure 2 - Virtual Ride Process (with VVS)

BACKGROUND

The sound quality process has been widely accepted and applied in the automotive industry [1,2,3]. This process begins with the gathering of in-vehicle sound data through the use of a binaural recording head. The recordings are then used for "playback" to obtain subjective ratings as well as analyzed for objective measures. A statistical analysis is performed to determine the correlation between the subjective and objective measures. This method has provided an accurate solution to the complex problem of translating customer "wants and needs" into actual engineering specifications, which can be applied in the vehicle development process. In order to apply the same process to vehicle vibration, an analogy to the recording head was created and developed at Ford Research and Advanced Engineering [4,5,6].

Figure 3 shows the major components for the original design of the Ford Vehicle Vibration Simulator (VVS). Man-rated hydraulic shaker systems were designed and developed to provide motion to the vehicles major points of human contact, namely, the vehicle seat, steering column, and a section of the floorpan underneath the drivers feet. A common industrial hydraulic actuator provides a single degree of freedom motion (vertical only) for the floorpan section. However, both the seat and steering wheel hydraulic modules are unique and were created by an outside vendor (Team Corporation of Burlington, Washington) specifically for this application. In fact, the seat hydraulic module is actually prototype number one of a hydraulic system known as the "CUBE" ™ that Team Corporation is now marketing commercially. Team Corporation holds a patent on the hydraulic actuator design and Ford Motor Company has a patent on the overall concept of the Vehicle Vibration Simulator.

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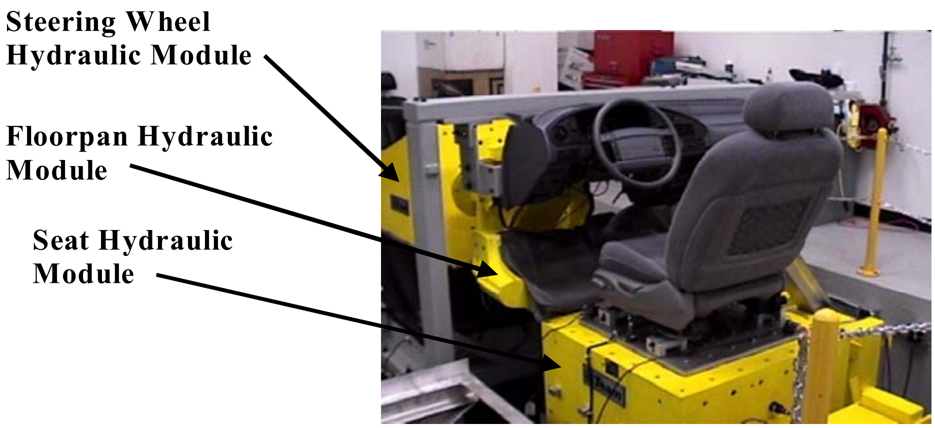

Figure 3 - Major Components of the VVS as Originally Designed

Six degrees of motion are achieved by using 3 pairs of hydraulic actuators assembled inside a hollow "cube" or block. The actuators combine to produce translation along the X, Y, and Z axis as well as the primary rotational motions of Yaw, Pitch, and Roll. The steering wheel hydraulic module is a variation of the seat module. Four actuators were combined with a stationary hydraulic "pivot point" inside of a rectangular shaped block to provide 4 DOF motion. Vertical, Lateral, and Longitudinal linear motion of the wheel as well as rotation about the center of the vehicle steering wheel.

The VVS was created to solve a number of problems, which result from trying to do subjective assessments of vehicle vibration by driving vehicles on the test track or actual city road surfaces. These include the following:

- Weather related problems
- Subject bias influencing rating results.
- Limited repeatability and controllability.
- The transient nature of human vibration event memory.
- The high cost of engineering prototype vehicles used to evaluate early product design alternatives.

Weather related effects are somewhat obvious. Many test track evaluations have been canceled or postponed due to weather conditions. The VVS is unaffected by weather conditions. The problem of subjective bias results from the difficulty of trying to prevent other attributes of the rating experience from influencing the desired or "measured" attribute. It is difficult to effectively disguise which brand or model of vehicle is being rated during a test track evaluation, and a subject's preconceived opinion of that vehicle may bias the rating. As shown in Figure 3, the configuration of the VVS provides total blind testing; the customer has no idea what vehicle make or model that is being evaluated and is forced to concentrate on the vibration stimulus only. The problem of limited repeatability refers to the difficulty of driving at the same speed over exactly the same part of the road surface each time a vehicle is rated by a customer on a road surface. With the VVS, the vibration signal for a specific road condition is recorded in the vehicle and reproduced by the simulator's control system exactly the same (<10% error) each time it is presented to the customer. Limited controllability is the inability in a vehicle test track evaluation to do such things as restrict the subjective vibration stimulus to just the vertical axis or just the seat or steering wheel location. This feature is important when diagnosing vibration related vehicle problems and provides the capability to "disconnect" interactive effects. With the VVS each axis can be played alone or in combination and the vibration stimulus can also be synthesized, which would be virtually impossible or extremely costly in a test track vehicle evaluation. Experiments conducted on the VVS have also clearly demonstrated that the vibration memory of humans is extremely short (within 10 sec). This means that during a test track evaluation where the time length between the evaluations of different vehicles is often 5 to 10 minutes or more, the customer has forgotten what the first evaluation vehicle felt like making it virtually impossible to make accurate comparative judgments with test track evaluations. Vibration stimulus can be "played" back- to –back within 1 or 2 seconds for direct customer comparisons on the VVS. One of the greatest potential uses for the VVS is to be able to "play back" vibration data from a CAE model to simulate the steady-state ride of a new vehicle proposal.

Since the installation of the original VVS design in 1994, many significant and innovative technological improvements have been made to the VVS. Figure 4, shows the current configuration of the Vehicle Vibration Simulator and depicts some of the improvements that have been implemented.

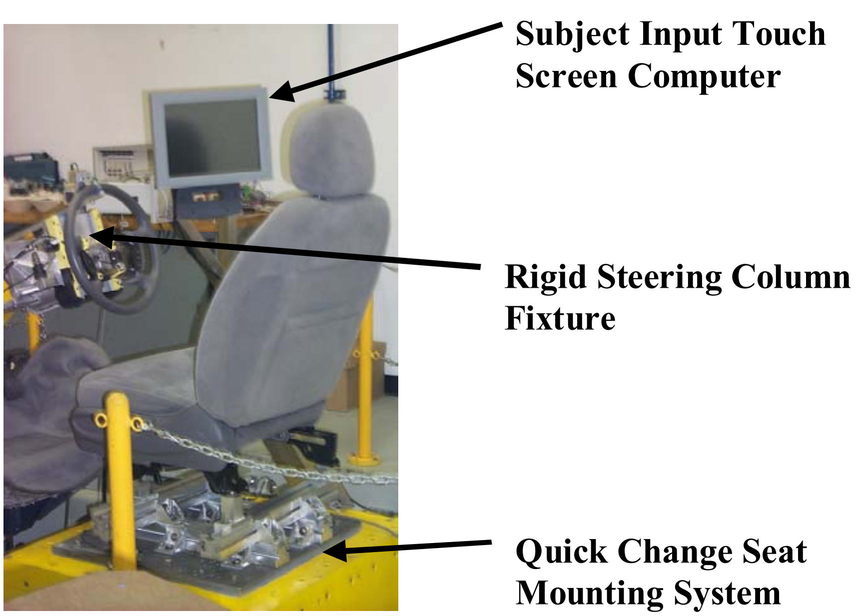

Figure 4 - VVS Current Configuration

The significant technological improvements that have been made to the VVS include:

- Developed a completely automated system for implementation of subject data input and analysis for several psychophysical tests methods such as, semantic differential, paired comparisons, and Levitt procedures.
- Developed software, instrumentation procedures, specialized mounting hardware, and unique test procedures to implement seat transmissibility testing.
- Created, developed and applied the rigid steering column test fixture and the semi-rigid seat test fixture to facilitate research of whole body and hand vibration threshold levels.
- Development of specialized vibration signal analysis and filtering techniques to assist vehicle programs in resolving "fire-fighting" issues.

DATA ACQUISITION

The initial vehicle parameter that was varied for the purposes of this study was Front / Rear suspension damping rates. The road profile that was used in this study was for the Basic durability road at Ford Motor Company's test track. Initially, 85 second time histories of acceleration for the driver's outboard front seat track bolt (vertical, lateral, longitudinal), the inboard front seat track bolt (vertical and longitudinal), and the rear inboard seat track bolt (vertical) were generated with the model at vehicle speeds of 80 KPH (49.7 MPH) and 40 KPH (24.9 MPH) for the following cases of vehicle suspension damping rates:

- Baseline vehicle
- 10 % decrease in front / rear damping
- 10% increase in front damping and 10% decrease in rear damping
- 5 % increase in front / rear damping

A plot of PSD (power spectral density) vs. frequency for this initial set of data is shown in Figure 5.

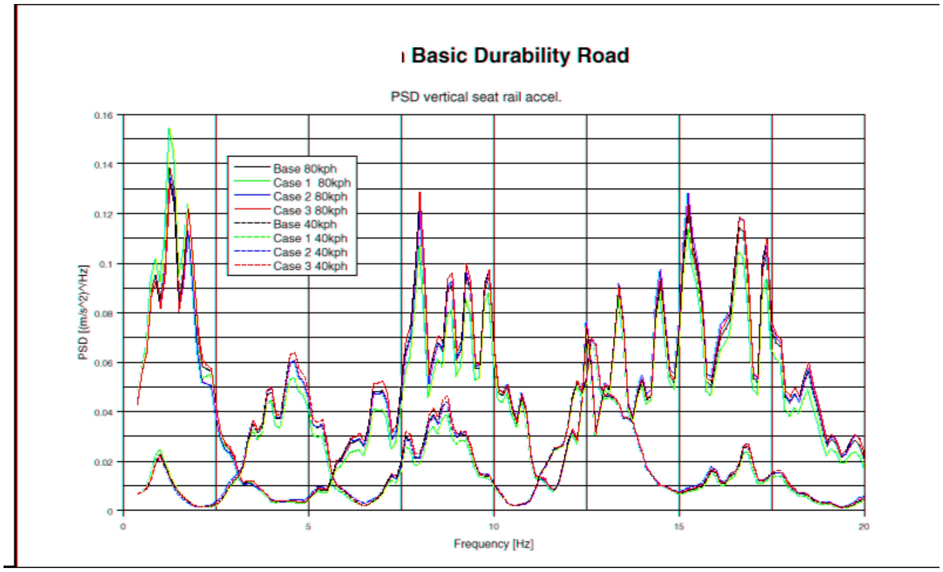

Figure 5 - PSD Plot for Initial Data from CAE model

STIMULI PREPARATION

The initial concern for preparing the model data set for replication on the VVS system was the high amplitude content of the 80 KPH data at low frequency (< 2 Hz) as shown in Figure 5. Large accelerations at low frequencies usually result in very large displacements and could exceed the simulators +/- one inch displacement limits. The VVS uses an iterative control process to achieve the desired target data. The time history output of the CAE ride model is used as the target data in an iterative control process on the VVS. Once the initial system identification is performed, the inputs to the VVS hydraulic actuators are iteratively adjusted to produce the target accelerations at the simulator seat track that are representative of those for the model output. The iteration process continues until the error between the simulation and model output accelerations is minimized. For this experiment, the seat accelerations were converged to a point where the RMS acceleration error was 10% or less. While attempting to converge the 80 KPH data, a system displacement limit for the vertical hydraulic actuators was exceeded on the second iteration. The VVS system has a maximum displacement limit of +/- 25.4 mm in the vertical, lateral, and longitudinal directions. Therefore, a decision was made to eliminate the 80KPH data from this study.

Another problem was encountered while attempting to extend the lower end of the frequency range (0.7 to 30 Hz) from 1.5 Hz down to 0.7 Hz. It was discovered that the system identification process plays a very critical role in determining the ultimate success in the ability to converge to less than 10% RMS error at low frequency. Starting with a high quality system identification (low noise in the system transfer function plots) increases the convergence capabilities. A high quality transfer function was eventually achieved by lowering the border frequency parameter of the White/Pink noise signal used by the control system software for system identification from an initial value of 5 Hz to a value of 1.0 Hz. This produces more characterization signal energy at lower frequencies, which increases signal coherence and produces less noise in the system transfer function. By changing this parameter, we were able to achieve less than a 10 % RMS convergence error for all channels within the usable frequency range of 0.7 to 30 Hz. The VVS normally has the capability to converge data up to 200 Hz. But since the bandwidth of the non-linear ride model was limited to approximately 20 Hz, we limited the upper frequency range to 30 Hz.

After converging the initial data, we had expert ride evaluator's sit on the VVS and "feel" the initial results. All of the evaluators felt the simulation was very accurate and based on their experience matched closely to what they would expect from the "real" vehicle performance on the test track. Most evaluators felt that ride differences were relatively small, probable close to the minimum perceptible levels, and 25 MPH was too low of a speed to perform ride evaluations of shock absorber rate changes. Since we were also concerned about exceeding the displacement limits of the VVS, we generated more time histories at an intermediate vehicle speed of 60 KPH (37.3 MPH) with a wider range of shock absorber damping rates:

- Baseline vehicle
- 15% increased damping at Front and Rear suspension
- 30% increased damping at Front and Rear suspension.
- 50% increased damping at Front and Rear suspension.
- 75% increased damping at Front and Rear suspension.
- 100% increased damping at Front and Rear suspension.
- 150% increased damping at Front and Rear suspension.
- 200% increased damping at Front and Rear suspension.

By only using increased damping rates, we could be relatively sure that we would not exceed our displacement limits on the VVS. The expert evaluators also commented that the 85-second time histories contained two distinct characteristics that are commonly evaluated during typical vehicle test procedures. The consensus of opinion was that the attributes of "abruptness" (quickness in changes of acceleration) and "bounce displacement" (low frequency body motion in the vertical direction) would be good candidates.

EVALUATION METHOD AND DATA PREPARATION

Paired comparison (PC) was the method used for this evaluation. This method is one that we have used successfully in vibration and sound quality experiments in a large number of applications. In this method, subjects make relative judgments on samples presented to them in pairs. This process is repeated until all possible pairs have been evaluated. Since judgments are relative, not absolute, as in rating scales, subjects never have to worry about previous or future judgments. The PC method is very natural and easy for non-expert subjects to use because it reflects something they do in everyday life, make comparisons. One disadvantage of the paired comparison method is that the number of pairs can be quite large since they grow as the square of the number of samples. This is one reason the sample time length is generally kept to less than 4 to 7 seconds. Initially, a short 8.5-second time sample was taken from each of the 85-second time histories for each of the 8 samples. An 8.5 second window was used to aid in selecting a portion of the total time history that had a medium level of acceleration (.55 RMS from a .4 to .8 RMS range) and contained both the abruptness and bounce displacement characteristic. As it turned out, we were able to "cut out" a section containing an initial 4.0-second portion that had primarily the abruptness characteristic and an ending 4.0-second time segment that contained mostly the bounce displacement characteristic. We then performed a small PC study with the 8.5-second time history. In this small study, we asked the subjects to first rate the pairs against the attribute abruptness and on the second run of the same set of pairs to evaluate against the attribute bounce displacement. All subjects commented that having both characteristics in the same time history made the evaluation very difficult. We then decided to edit the 8.5-second time history and divide it into two 4.0-second time histories, thus separating the two attributes into two different time histories. This demonstrates the power of the VVS as an evaluation tool. By using the editing functions provided in the simulator software tools, we have the capability to separate different characteristics so that separate evaluations can be performed. This type of evaluation would be virtually impossible to perform in an actual vehicle.

For this study, if we use 8 total samples, we have N (N-1)/2 or 28 number of pairs in a full paired comparison for each attribute. Since we generate all orders with the paired comparison software for a Bradley Terry Model [10] the total number of pairs would be 56. The data was arranged in 4 blocks of 14 pairs per block per sheet for each attribute (abruptness and bounce displacement) with one practice block to acclimate the subjects to marking the evaluation sheets. In the first part of this study, the subjects (total of 25) were exposed to the first set of pairs constructed from the first set (8) of 4.0-second vibration stimuli and asked to mark the pair with the greatest abruptness. In the second part of the study, the subjects (same 25) were exposed to a second set of pairs constructed from the second set (8) of 4.0-second stimuli and asked to mark the pair with the greatest bounce displacement. Table 1 shows the samples used for this study.

Table 1 - Sample Description for Paired Comparison Study

Sample #	Abruptness	Bounce Disp.	Description
0	X	X	Baseline vehicle
1	X	X	15% increased Front and Rear Suspension Damping
2	X	X	30% increased Front and Rear Suspension Damping
3	X	X	50% increased Front and Rear Suspension Damping
4	X	X	75% increased Front and Rear Suspension Damping
5	X	X	100% increased Front and Rear Suspension Damping
6	X	X	150% increased Front and Rear Suspension Damping
7	X	X	200% increased Front and Rear Suspension Damping

SUMMARY OF SUBJECTIVE RESULTS

For the purpose of grading or ranking stimulus in this paired comparison study, we assigned merit values based on a seven point scale from +3 to –3, +3 being a strong preference and –3 being no preference. Merit values and correlation results for the abruptness part of the paired comparison study are shown in Figure 6. As shown in this figure, the regression line slope was +0.03 with an R Square of 0.7922, indicating good correlation. The positive slope is expected, since increasing suspension damping rates should increase abruptness.

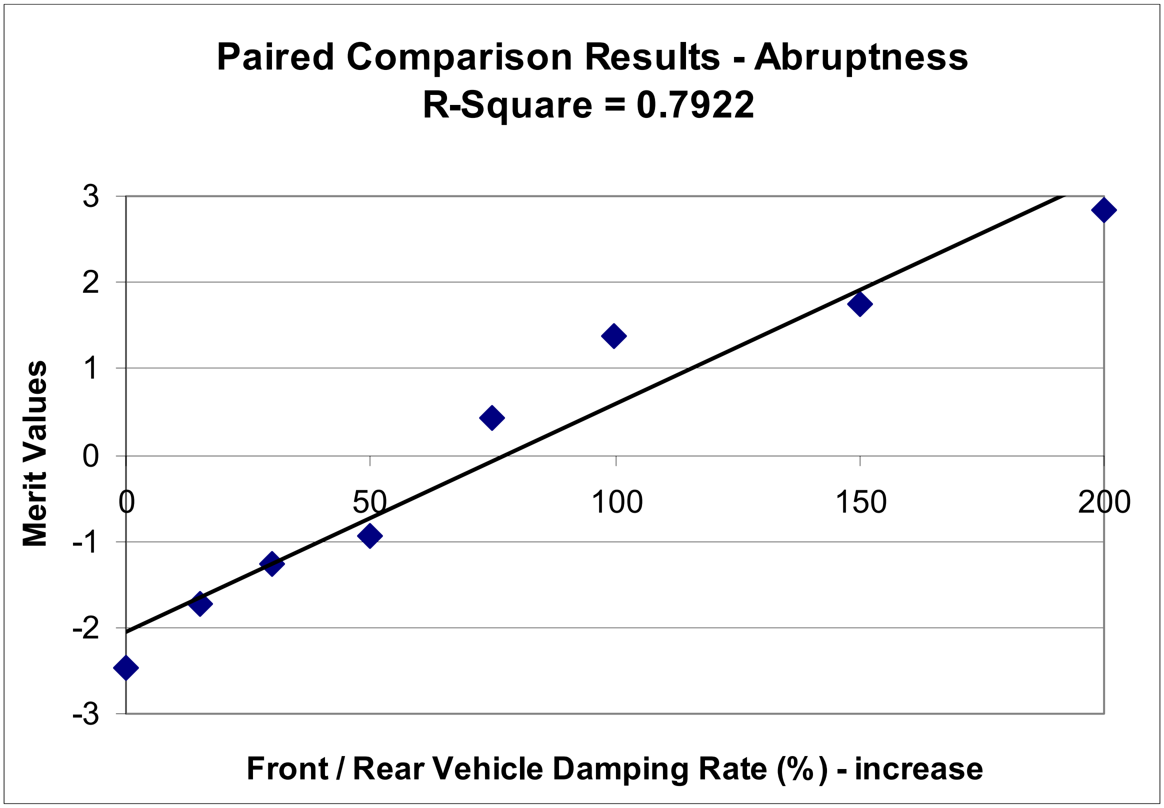

Figure 6 - Paired Comparison Results for the Attribute of Abruptness

The preference count and critical values at the 99% confidence level are plotted in Figure 7 for abruptness. Preference count for a paired comparison study is simply the number of times that stimulus was "preferred" or chosen across all subjects (total of 25) and stimulus (total of 8). If the difference between the preference counts of any two stimuli is greater than the critical value, then these two stimuli are statistically different at the 0.99 significance level. As shown in this figure, stimuli pairs 0-1, 1-2, and 2-3, were not statistically different at the 99% confidence level. This tends to indicate that the subjects had more difficulty identifying changes in damping rate at the lower levels of damping (<50%) for the ride attribute of abruptness.

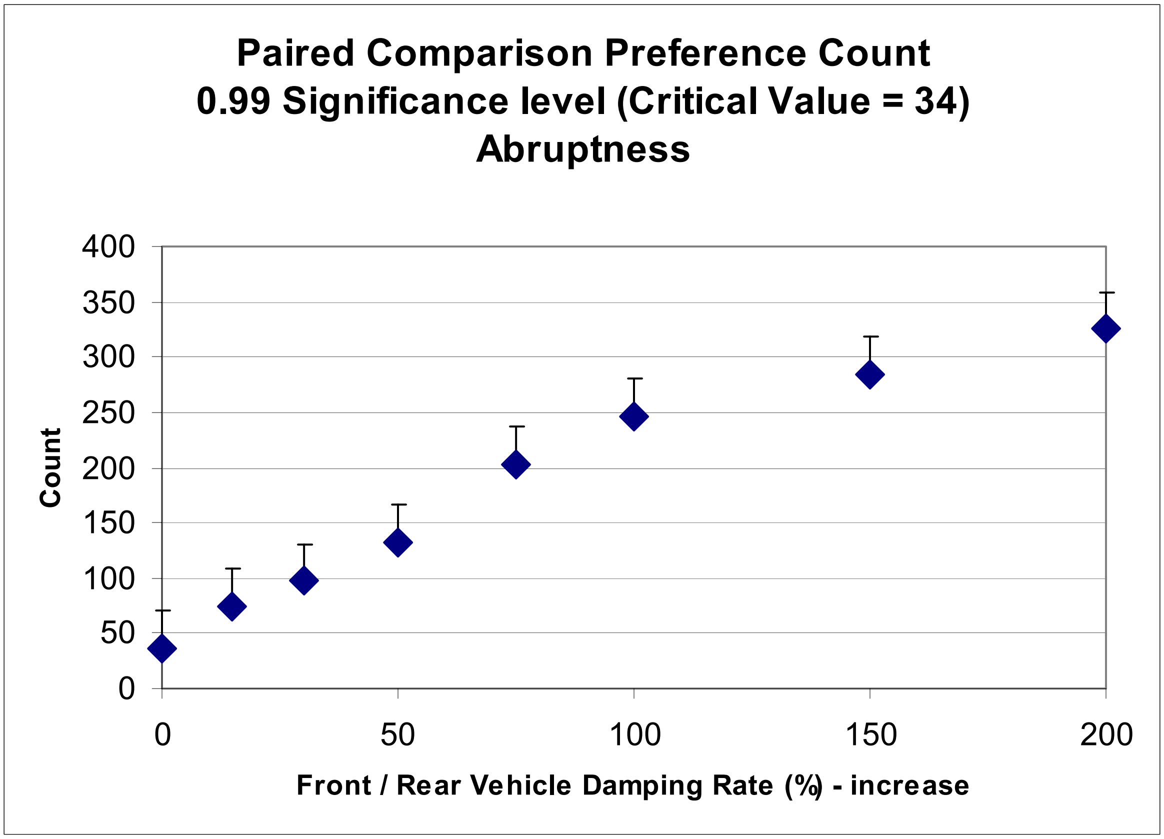

Figure 7 - Paired Comparison Preference Count for the Attribute Abruptness

Merit values and correlation results for the bounce displacement part of the paired comparison of preference study is shown in Figure 8. As shown in this figure, the regression line slope was –0.005 with an R square of 0.81, indicating good correlation. In this case the line slope was negative, since increasing the suspension stiffness should produce a reduction in the overall suspension travel, which would be judged as a reduction in the attribute of bounce displacement. As indicated by the smaller slope in the regression line (-0.005 vs. +0.03) the subjects were generally less sensitive to the attribute of bounce displacement. Subjects commented on several occasions during the course of this study that bounce displacement was much more difficult to judge compared to abruptness. Several subjects also made the comment that judging abruptness was somewhat of a "gut" feeling, while judging bounce displacement required the much more difficult task of judging relative motion.

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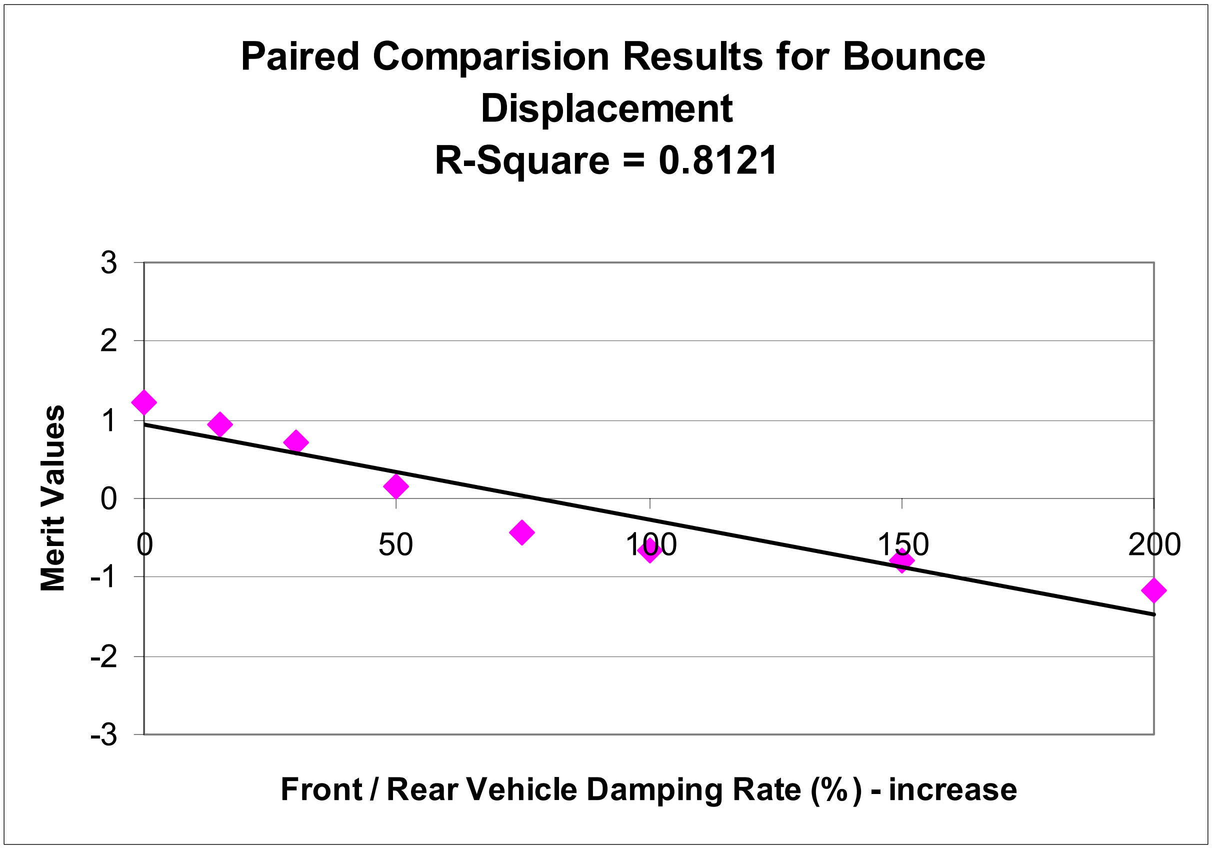

Figure 8 - Paired Comparison Results for the Attribute Bounce Displacement

The preference count and critical value at the 99% confidence level are plotted in Figure 9 for bounce displacement. As shown in this figure, stimuli pairs 0-1, 0-2, 1-2, 4-5, 4-6, 5-6, and 6-7 were not statistically different at the 99% confidence level. This data supports the previous conclusion, that bounce displacement was much harder to subjectively assess than the attribute of abruptness.

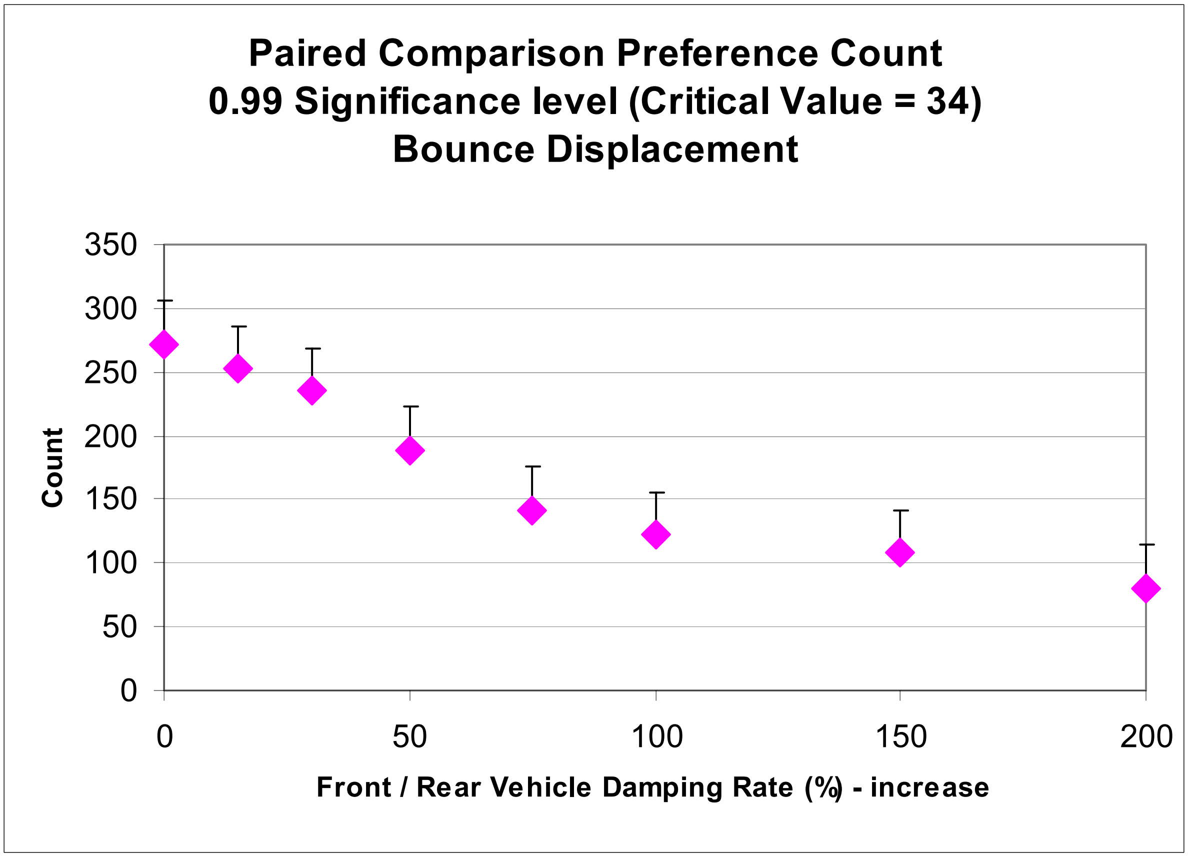

Figure 9 - Paired Comparison Preference Count for the Attribute Bounce Displacement

SUMMARY AND CONCLUSIONS

This small paired comparison study provided the opportunity to understand the overall process and develop the necessary techniques for using computer generated data and the VVS to create a virtual ride environment. An interesting result of the paired comparison study indicates that the subjects were less sensitive to suspension changes that affected bounce displacement than the attribute of abruptness. This result could be useful in future vehicle programs if a trade-off decision was required between tuning the vehicle suspension for more abruptness or more bounce displacement. Further correlation studies must be performed to demonstrate that a decision of an engineering design change made with the virtual ride process would be identical to that made in the actual vehicle on the test track.

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