



## Idle Vibration Analysis and Evaluation Utilizing a Full-Vehicle NVH Simulator

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### Abstract

Realistically experiencing the sound and vibration data through actually listening to and feeling the data in a full-vehicle NVH simulator remarkably aids the understanding of the NVH phenomena and speeds up the decision-making process. In the case of idle vibration, the sound and vibration of the idle condition are perceived simultaneously, and both need to be accurately reproduced simultaneously in a simulated environment in order to be properly evaluated and understood.

In this work, a case is examined in which a perceived idle quality of a vehicle is addressed. In this case, two very similar vehicles, with the same powertrain but somewhat different body structures, are compared. One has a lower subjective idle quality rating than the other, despite the vehicles being so similar. An NVH vehicle simulator was used to compare the sound and vibration characteristics of the two vehicles back-to-back in a realistic vehicle environment in order to understand the difference in the subjective rating. With the ability to control the various specific sound and vibration stimuli, the reason for the difference of subjective rating between the vehicles became apparent rapidly.

Further, the interaction of sound and vibration and the resulting effect on human subjective perception is explored, which emphasizes the importance of having both sound and vibration accurately reproduced and controlled for such simulations.

### Introduction

Accurate objective measurement and reporting of sound and vibration levels is commonplace. However, understanding these objective quantities in terms of human experience is not always easily performed or accomplished, especially with complex phenomena

involving simultaneous sound and multi-axial, multi-point vibration components. This is especially true when comparing two or more vehicles, conditions or configurations.

In the example discussed herein, there are 2 vehicles of very similar architecture with identical powertrains. One vehicle (Vehicle A) is deemed to have potentially unsatisfactory idle vibration quality, while the other vehicle (Vehicle B) is deemed to have average, acceptable idle vibration quality. The engine used in these vehicles is a 4 cylinder engine.

Utilizing a full-vehicle NVH simulator, the sound and vibration levels of the two vehicles could be compared back-to-back, and perceived differences in the idle characteristics of the two vehicle could be isolated precisely.

### Approach

The approach consisted first of measuring the sound and vibration levels of both vehicles. These objective measurements were then resynthesized and evaluated by expert assessors using an NVH vehicle simulator, in order to isolate various components of the sound and vibration experienced while comparing the two vehicles.

### Objective Measurements

Sound and vibration measurements were acquired on both vehicles under several operating conditions.

Vibration measurements were acquired utilizing seat-pad accelerometers on the seat base and seat back, and also at two locations on the steering wheel. Acceleration was also measured at the floor-pan/heel point. Tri-axial acceleration was measured at all locations. The accelerometers on the steering wheel were located such that both translational and rotational vibration could be resolved.



Figure 1. Typical Seat Pad Accelerometer positioning on base of a seat

In addition to the seat pad vibration measurements on the seat, seat bolt locations were also measured in order to correlate to and confirm previous measurements on these vehicles.

Sound was acquired utilizing a wearable binaural microphone worn by the driver/operator. The driver/operator sat in the instrumented driver's seat for the measurements, with both hands placed upon the steering wheel at the 10 o'clock and 2 o'clock positions.

For each vehicle, four separate steady-state operating conditions were measured from combinations of transmission selection (Park-idle or Drive-idle), and "consumers" on/off. For this series of measurements, the "consumers" consisted of headlights, electric defrosters and A/C. For the "consumers on" condition, all were turned on. For "consumers off" condition, all were off. Additionally, an "idle sweep" was performed for each condition, covering a relatively wide RPM range from approximately 600RPM to 900RPM. The purpose of the "idle sweep" measurements was to enable a driver-in-the-loop interactive experience in the NVH simulator, giving the assessor control over the engine speed whilst evaluating in the NVH simulator.

An initial observation of the data shows the strong 2<sup>nd</sup>-order vibration peak (as expected with a 4-cylinder engine) at approximately 26Hz (see Figure 2). Here, data is shown as RSS values (Root Sum of Squares utilizing X, Y and Z direction vibration levels).

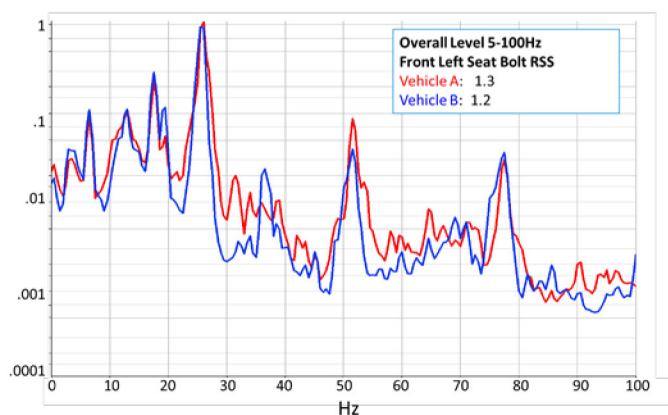


Figure 2. Front Left Seat Bolt, Vehicle A (Red) vs. Vehicle B (Blue) - Idle Drive Consumers On Condition, RSS

### Utilization of a Full-Vehicle NVH Simulator

A full-vehicle NVH simulator can provide highly accurate multi-axial, multi-point vibration together with calibrated sound reproduction in a realistic environment of a vehicle body.

The key attributes of the full-vehicle simulator are a) simultaneous, accurate, real-time sound and vibration generation, b) interactivity and c) context. Inherent in these attributes is the ability to play sound and vibration signatures from different vehicles back to back. The full-vehicle NVH simulator used for this study is comprised of a mid-size sedan vehicle body, a projector and large screen for road visuals, a seat/floorpan/steering wheel vibration generation assembly, high-quality open-back electrostatic headphones and a calibrated subwoofer.



Figure 3. Full-vehicle NVH Simulator Interior



Figure 4. Full-vehicle NVH Simulator Exterior

For this project, 6 independent degrees of freedom were utilized in providing the vibration to the assessor. These included seat back X (fore-aft), seat base Y (cross-car/lateral) and Z (vertical), floor pan Z, and steering wheel Y and Z. Sound was provided through the electrostatic headphones and a subwoofer.

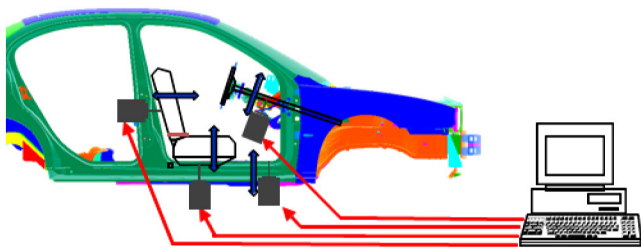


Figure 5. Full-Vehicle Simulator Diagram

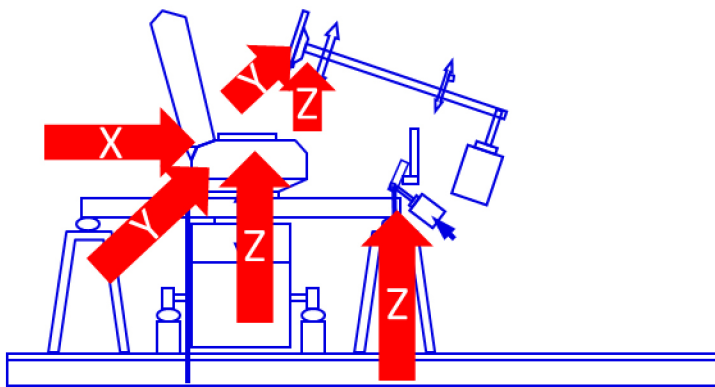


Figure 6. Full Vehicle Simulator - excitation points and directions used

As each vibration and sound channel is independent from all others, each can be enabled, disabled or modified independently. One telling procedure is to enable all vibration playback, but no sound; then play the opposite (sound only, no vibration), and then play both sound and vibration together. This exercise in itself demonstrates how humans perceive sound and vibration together, and how important each (both individually and together) is to the assessment of vehicle NVH.

For each condition, an NVH simulator model was created to replicate that condition. There are 2 basic methods of interaction with the simulator. One is through an engineering interface displaying all component parts of the sound and vibration being played, and enabling the modification of each part of the sound. The other is an evaluation interface (Figure 7), which presents a simplified view to the assessor and provides a means for collecting subjective preference.

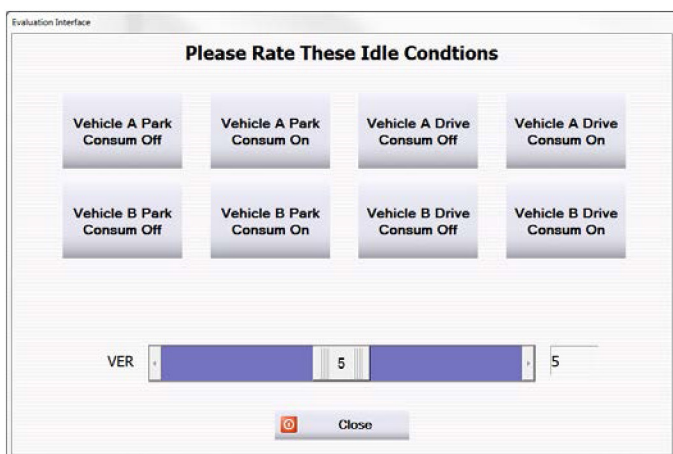


Figure 7. Evaluation Interface for NVH Simulator, with the models for each steady-state condition

There are 3 basic modes of operation of the NVH simulator. Free-driving mode is an interactive mode which allows the driver to control the vehicle exactly as if driving an actual car. In Free-driving mode, the sound and vibration signals are re-synthesized in real-time from decomposed component parts of the recorded sounds, and respond instantly to driver input to pedals, gear shift, etc. Fixed-replay mode replicates recorded files exactly. Fixed-driving mode essentially combines these two first modes, utilizing the Free-driving interactive models, but playing them with a prescribed scenario or profile.

For this study, primarily the fixed-replay mode was utilized, as the typical fixed-speed idle conditions lent themselves well to this type of playback. However, the free-driving mode was also employed, utilizing the component parts of the sound and vibration decomposed from original measurements. The decomposed parts for each sound and vibration channel included order-levels for all orders and half-orders as one sound object, and the random (non-harmonic) portions as a separate sound object. The exact methods for decomposing and recombining the sound and vibration signals and creating NVH simulator models will not be covered in this paper, as they are adequately addressed by other publications listed in the references.

In this study, a small group of expert assessors and NVH engineers were used to evaluate the sound and vibration of the two vehicles in an informal assessment using the NVH simulator.

From subjective evaluations, it was determined that the “Drive-Idle Consumers On” condition showed the most noticeable difference between the two vehicles, and was also the condition with the lowest subjective rating, with Vehicle A having a significantly lower subjective rating than Vehicle B. This is the condition most of the in-depth analysis was focused on. The “Park-Idle Consumers Off” condition also had significant differences between the two vehicles, with Vehicle A again having a lower subjective rating than Vehicle B.

## Results

The two vehicles were known to have similar 2<sup>nd</sup> order levels for vibration at the seat track location, when assessed with a standard RSS calculation. (Figure 2). Therefore, it was surprising that the two vehicles had a significantly different subjective rating for “idle vibration”.

The models of the two vehicles were compared in the NVH simulator back to back, and the differences in perception of idle vibration quality between the two vehicles was confirmed.

One advantage of using the NVH simulator is that it was possible to play the vibration of Vehicle A with the sound of Vehicle B, and vice versa (Figure 8). When this exercise was done, it was found that the subjective rating followed the sound, i.e. the combination with the “Vehicle A” sound (regardless of which vehicle's vibration it was paired with) received a lower subjective rating for idle vibration. Given that this was specifically an assessment of idle “vibration”, this was an interesting result.

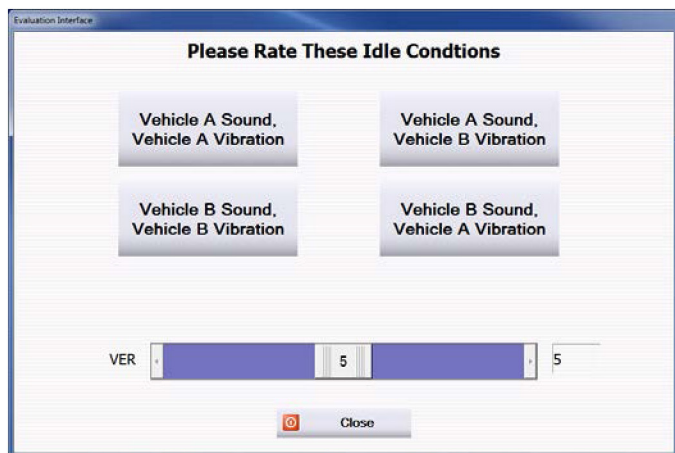


Figure 8. Evaluation Interface, with models for sound/vibration swap for Drive-idle Consumers On condition

Looking at the objective data, it can be seen that vibration levels of the two vehicles are very close, with Vehicle B being somewhat higher than Vehicle A. Figure 9 shows the seat pad vibration, with Vehicle B actually be slightly higher in overall level and at 2<sup>nd</sup> order (26Hz) peak. Figure 10 shows similar results for the steering wheel vibration.

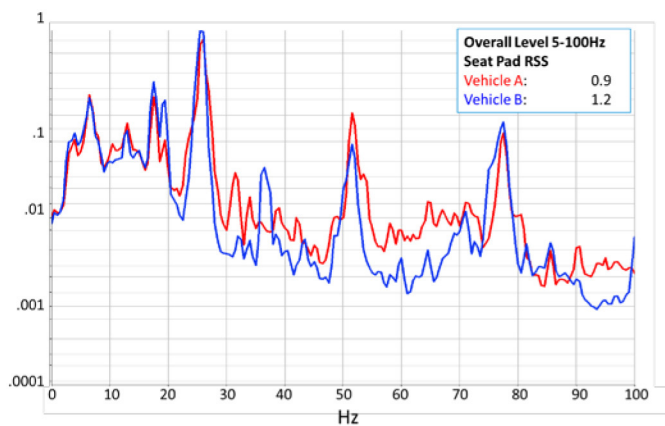


Figure 9. Seat Pad Vibration, Drive-idle Consumers On condition

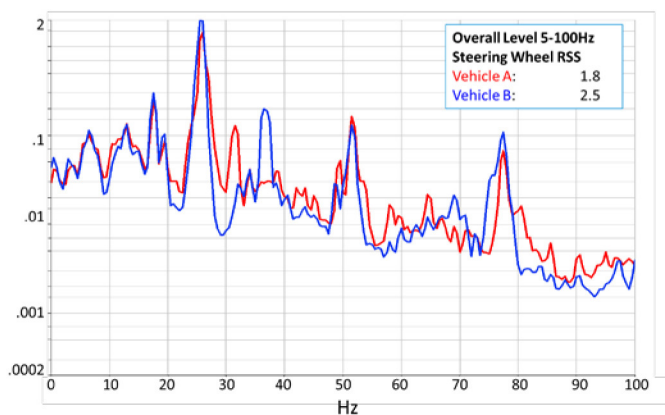


Figure 10. Steering Wheel Vibration, Drive-idle Consumers On condition

However, observing the sound levels in Figure 11, an interesting point is brought to light. The 2<sup>nd</sup> order sound levels at 26 Hz are, remarkably identical between the two vehicles. The 4<sup>th</sup>, 6<sup>th</sup>, and 8<sup>th</sup> order levels at 52, 78 and 104 Hz are quite different, with Vehicle A

having significantly higher sound levels for these orders. 4<sup>th</sup> order (56 Hz) is 7.2dB higher in Vehicle A than Vehicle B, and 10dB higher at 8<sup>th</sup> Order (104 Hz).

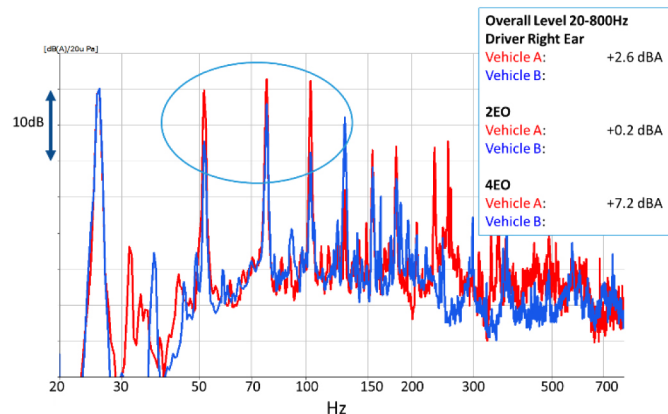


Figure 11. Driver's Right Ear Sound Pressure, Drive-idle Consumers On condition

Given that the sound was identified as a key factor, the sound levels were modified by reducing the 4<sup>th</sup> order (56 Hz), 6<sup>th</sup> Order and 8<sup>th</sup> Order sound level of Vehicle A, while leaving all other sound and vibration the same. This was compared to the original Vehicle A as well as Vehicle B. It was further possible to reduce each order individually and determine which order/frequency affected the perception of idle vibration quality the most, and which needed to be reduced to bring the subjective rating of Vehicle A into alignment and on par with Vehicle B for this condition.

By using this interactive subjective/objective approach, it was possible to isolate the factors causing the subjective difference in the two vehicles and instantly confirm this by experiencing the sound and vibration in the full-vehicle NVH simulator. It is noteworthy that the issue driving the perceived "idle vibration" issue in this case was not 2<sup>nd</sup> order as was initially supposed, but was actually higher-order sound components. This would of course mean that a different approach to handling this in the vehicle design would be taken to improve the perception of idle quality, with different types of countermeasures or design changes targeted at the higher orders/frequencies.

For another condition, the "Park-Idle Hot Consumers Off" condition, a different set of factors was isolated as being the differentiator between the two vehicles

In this case it was a time-varying characteristic of the idle which caused a difference in subjective perception. The overall levels were similar when viewed using a typical 30-second average of the data. But, as shown in Figure 12 and Figure 13, Vehicle A had considerable variation in the level over time compared to Vehicle B. This resulted in a different subjective perception, one where Vehicle B was perceived to be smoother than Vehicle A.

In addition the specific changes noted here that were performed on the data, mixing sound from one vehicle with vibration from the other, and adjusting the sound level of the primary orders, several other modifications were also done. These included various modifications to the vibration levels and sound levels of both

vehicles. All of the modifications and assessments were conducted over a period of approximately 4 hours, with most modifications taking only a few minutes.

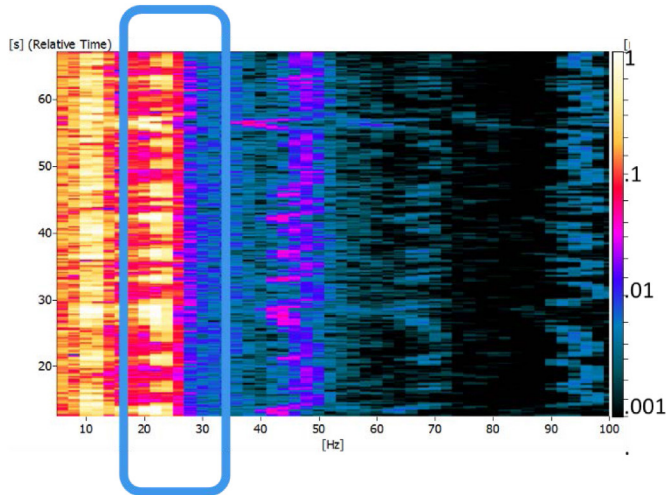


Figure 12. Spectrum vs. time - Park-idle Consumers Off condition, Vehicle A

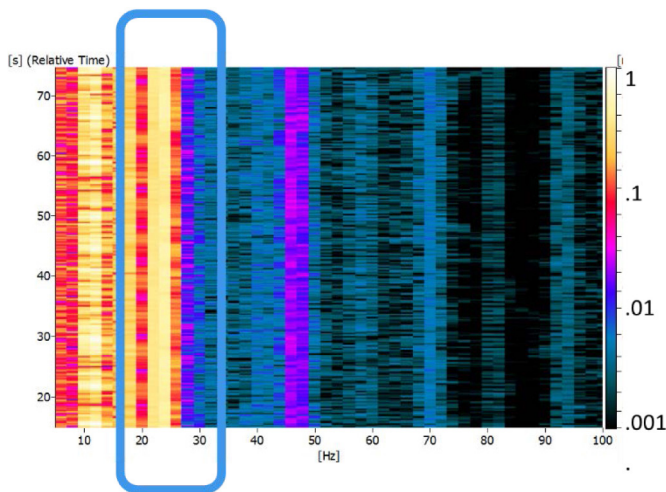


Figure 13. Spectrum vs. time - Park-idle Consumers On condition, Vehicle B

In the case of playing “sound only” and “vibration only” cases, and comparing these to the “sound + vibration” case, it was quite evident that for a phenomenon like idle quality, both sound and vibration were required to make an accurate assessment. Neither component, by itself, would subjectively seem to add up to the sum of both sound and vibration.

## Future Work

This work was focused on a very specific case with representative vehicles available for testing. However, similar assessments utilizing data generated from CAE models is also possible and should be explored for idle quality and similar issues. In such a way idle quality could be assessed well in advance of having actual physical prototypes. This would enable target setting and status assessment, and would be especially useful as the trends of vehicle light-weighting and alternative, smaller engines with fewer cylinders progress.

This also shows that there is a need to better understand the relationship between sound and vibration for lower-frequency phenomena. In this work, the interaction of the sound and vibration

were made evident, but it is obvious that there is still much to learn about the interaction of sound and vibration together as it impacts human subjective perception.

## Summary/Conclusions

In this work a case is shown where the subjective idle vibration quality between two vehicles is significantly different, but the idle vibration levels, including the primary firing order frequency peak, are essentially identical.

The main difference was shown to be not the idle vibration levels, but the sound levels for the 4<sup>th</sup>, 6<sup>th</sup> and 8<sup>th</sup> orders.

Experiencing the vibration and sound from each vehicle in the full-vehicle NVH simulator rapidly demonstrated that the vibration levels between the two vehicles were very similar, that the sound levels were higher for Vehicle A, and decreasing the sound levels for the 4<sup>th</sup>, 6<sup>th</sup> and 8<sup>th</sup> orders improved the “idle vibration quality”.

Using the full-vehicle simulator in this case provided several benefits. It was very easy to compare levels of sound and vibration of the two vehicles back-to-back directly. Transient or time-varying content of idle vibration was very apparent. The Full “human perception” experience is possible, combining the effects of sound and vibration. Making changes, “What-if’s?”, such as lowering sound level of specific orders or frequency ranges, isolating sound from vibration for playback, changing levels of vibration for specific channels, etc. are very easy to perform and provide instant insight and experiential understanding of the data.

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