

# In-Vehicle Tire Sound Quality Prediction from Tire Noise Data

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## ABSTRACT

Tire Sound Quality is an increasingly important factor for customer satisfaction within the replacement tire market. Manufacturers who compete in this market must be capable of predicting a driver's perception of tire noise as early in the design process as possible in order to reduce development time and cost. Typical methods for tire noise evaluation each have limitations that require improvement. Subjective in-vehicle testing is generally an effective method for predicting driver perception, but it is vehicle specific, time consuming, and requires complete sets of tires for testing. Traditional single tire (component level) test methods measure overall tire noise levels, but do not always provide information relevant to a driver's perception of tire noise in a vehicle. Detailed noise path analysis techniques are cost prohibitive due to the amount of time and effort required to characterize each vehicle and the multitude of vehicles that exist. Replacement tires must be designed to work well when fitted to multiple vehicle platforms. Because of this, there exists a need for a robust sound quality based test that can be performed at the component level and used to predict a driver's perception of noise that is relevant for entire classes of vehicles. In order to meet these requirements, replacement market tire manufacturers must implement innovative technologies and improve their processes by employing the following strategies:

- Develop better component test procedures
- Implement a simplified procedure for measuring vehicle sensitivity functions
- Define metrics for in-vehicle tire sound quality that correlate with subjective perception

This paper describes the experimental activities conducted by a major tire manufacturer to achieve these

objectives. All three strategies listed above must be integrated together such that the component level test results can be filtered based on the vehicle sensitivity function and then quantified utilizing a sound quality metric. Each test method must be as efficient as possible to reduce testing time and cost. Several known procedures were compared and the methods that best satisfied the given objectives are described within this paper.

## INTRODUCTION

The traditional method to evaluate tire noise is subjective evaluation of a given tire design equipped on a given vehicle. Not only does this present the problem of subjective difference from person-to-person, but it limits a tire manufacturer to a trial-and-error approach in design. This presents the need for a method to objectively quantify tire noise as it exists from on-road excitation, as well as a tool to predict this noise (and therefore driver perception) from a component-level test. The first need can be satisfied with appropriate data analysis and correlation to subjective perception of the noise. The latter issue will depend on a method by which the noise is decomposed into source, path(s) and receiver elements. The component level test should be designed to quantify the tire as a noise and vibration source, which can be tracked through various stages of system decomposition to result in a predicted sound as it would be heard in a given vehicle on the road. To achieve this, the system should be decomposed into sound as it is perceived in the vehicle on the road, in the vehicle on a chassis dynamometer, in the vehicle on a chassis dynamometer with a SINGLE tire rolling, and finally, a single tire mounted to a test fixture rolling on a chassis dynamometer. The flow of the system decomposition and synthesis can be represented as follows in Figure 1:

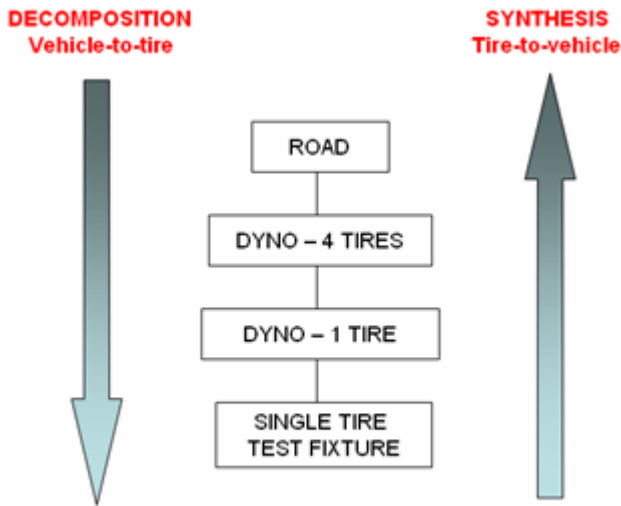


FIGURE 1

Figure 1: General process of decomposing and recomposing in-vehicle tire noise

Each of the steps in this process will include subjective and objective analyses of each of the baseline sounds which result in transfer functions (in time, order, and/or frequency domains) to create a synthesized sound which contains fundamental tire sound levels similar to those caused by the true road excitation. This synthesized sound should therefore yield the same subjective rating as the baseline road-induced sound. To standardize the subjective rating system, a Jury Evaluation Study was conducted. The products of this Jury study were:

- an understanding of objectionable tire noise as perceived by typical drivers
- a Sound Quality preference equation based on various metrics regressed against the juror's rankings of the sounds

The main objective is to predict airborne tire noise in the vehicle's interior as it would be perceived on the road. To achieve this and to validate the end result, it will be necessary to decompose the overall sound into airborne and structureborne contributions.

## ROAD TESTING

All tests were conducted using 8 sets of tires of various design and purpose, mounted 4 at a time on a given mid-sized sedan. To correlate with the tire manufactures traditional testing and initial subjective ratings, the tests were all performed on the same smooth stretch of highway (newly finished black top surface), with the following drive conditions:

- Coast w/ vehicle in neutral (from 60 – 45 mph)
- Light Drive (from 0 – 60 mph)
- Constant Speed - 50 mph
- Constant Speed - 60 mph
- Constant Speed - 70 mph

Each of these conditions was repeated three times to evaluate repeatability and ensure high-quality recordings.

The test vehicle was equipped with the following instrumentation:

- a binaural head in the passenger's seat
- two microphones near each tire
- triaxial accelerometers at the spindle of each tire
- 1 pulse-per-rev tach on the crank pulley
- 1024 pulse-per-rev encoder on 1 wheel

The eight sets of tires which were tested on the road were of various subjective ratings (from "A" being the best, to "D" being the worst), as judged by an experienced tire evaluator. The data was processed into frequency and order domains to establish correlation to the original subjective ratings and to determine, objectively, what qualifies tire noise as "good" or "bad". Figure 2 shows the color spectrogram of a good tire and bad tire. Initial analysis shows spectral differences in the 500 – 1200Hz frequency range, as well as fundamental tire orders due to pitch sequence.

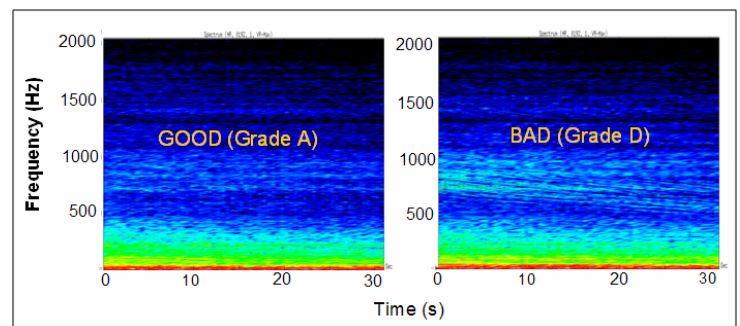


Figure 2: Spectrogram of sound recorded at the passenger's left ear (PLE) on the road during coast down condition. The two plots represent a recording with low tire noise and high tire noise, respectively.

## JURY TESTS

Sounds collected during the road acquisition were analyzed and used to construct a Jury Analysis test. Each of the three repeats for each drive condition was listened to and scrutinized for consistent ambient sound level (wind noise), passing traffic, and miscellaneous transient noises. The best of three repeats was used as a baseline sound in the Jury study. These sounds were trimmed to have consistent length and deceleration rate (for coast condition), so as to be judged fairly by the jurors. In an effort to design an efficient Jury test, the coast and 50mph conditions were chosen (because of their impact on subjective rating and consistency).

The subsequent "coast" and "50mph" sound files were analyzed in frequency and order domains for each of the eight tire sets. The results of this analysis, combined with the preliminary analysis from road acquisition and subjective ratings determined the impact of various characteristics, or dimensions, of tire noise. From these

eight sounds, it was hypothesized that the subjective rating of tire noise depends heavily on the following parameters:

- Sound level and content in the 500 – 1200Hz range (as it is widely known, see ref. 1)
- Deviation of various octave bands from ambient sound level
- The presence of discrete tire orders due to pitch sequence

This hypothesis was tested by synthesizing two sounds which were also included in the Jury study:

- The mid-frequency level of a “good” tire sound was increased, to make the tire noise worse
- The discrete tire orders of a “bad” sound were decreased, to make the tire noise better

An unforced Paired Comparison Jury Test was created to evaluate the preference of the 10 sounds in coast and 50mph conditions. Forty-five jurors of various gender and occupation were polled to determine the preference between various combinations of the 10 sounds. The sounds were presented in “A versus B” fashion, with an option to select “Neither” in the event of a subjective tie. The results from the various jurors were screened to assess the repeatability and consistency of each, while monitoring voting and timing errors. One of the products of this study was a preference ranking of the 10 sounds presented.

The ten sounds and their rankings were compared to their original subjective ratings and were found to correlate very closely. The synthesized sounds were also ranked by the jurors as intended. These conclusions confirmed the hypothesis that tire noise can be quantified by calculating the following dimensions:

- **LOUDNESS:** a measure of the overall sound level produced during the test
- **SPECTRAL BALANCE:** how much the mid frequency content deviates from low and high frequency
- **TONAL COMPONENT:** the presence of order-related noise due to the tread pitch sequencing

Various metrics were calculated to quantify each of these dimensions along with psychoacoustic metrics such as Fluctuation Strength, Roughness, Tonality, and others, to develop a Sound Quality Preference equation. During this process, each of the various metrics was regressed against the preference merits to evaluate their statistical impact. The most significant in each dimension were combined to create a preference equation. This equation can therefore be used to predict the empirical rating of a sound with respect to tire noise. Figure 3 compares the original preference rankings as produced by the Jury Study and the predicted rankings created by using metrics calculated for each sound in the Sound Quality Preference Equation.

$$SQ\ Pref = [(-c1)(M1)] + [(-c2)(M2)] + [(-c3)(M3)]$$

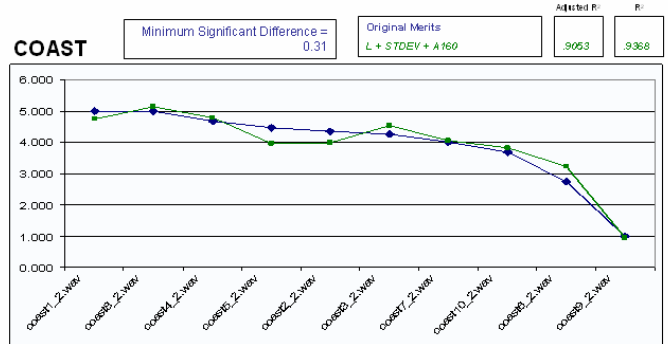


Figure 3: Preference ranking results from Jury Study (blue), compared to merits calculated from the developed Sound Quality Preference Equation (green)

The “c” terms represent coefficients and the “M” terms represent specific metrics. It should be noted that all metrics used in the equation are uncorrelated, and are of negative value. That is, a higher value of any of these metrics yields a lower sound quality ranking.

## LAB TESTS – CHARACTERIZATION OF SOURCES

To characterize the sources which contribute to tire noise, the vehicle was tested on a 4-wheel chassis dynamometer for each of the eight sets of tires, with the same drive conditions as the road. To correlate with the road measurements as closely as possible, a pressure spectrum of the tire’s contact patch was evaluated on normal ground, and mounted on the dyno (to ensure that the vehicle restraints induced minimal vertical load). Realizing that the road surface would be fundamentally different than any dyno surface available to test, the dyno rolls were fit with abrasive paper. This also ensured uniformity among facilities so that the same dynamometer facility was not critical in future testing. The data acquisition and instrumentation were identical to those during road acquisition, with the exception that all four wheels were instrumented with 1024-pulse encoders. The sound spectrum of the road and dyno are inherently different, yet possess similar characteristics, as seen in Figure 4.

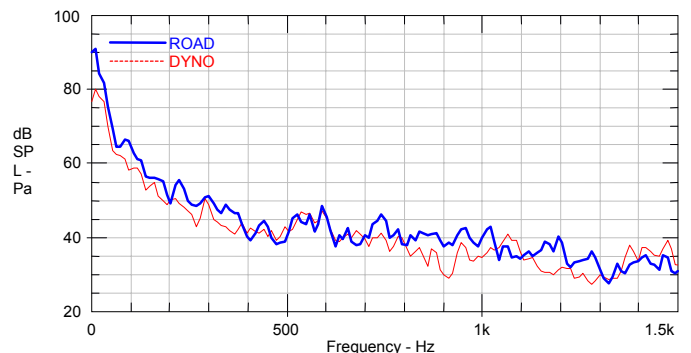


Figure 4: Spectral difference of sound recorded at the passenger’s left ear on the road (blue, solid) and chassis dynamometer (red, dash)

The vehicle was also tested on the 4-wheel chassis dynamometer for each of the eight sets of tires with a single tire rolling at a time. This was achieved by removing the non-critical tire, supporting the vehicle with airbags, and only running front or rear dyno drums as necessary for each test. The vehicle's ride height was maintained and the pressure spectrum was compared for single tire, and all 4 tires as restrained on the dyno to ensure similar loading. Similar to the road / dyno comparison, the spectral and dominant noise sources would be compared to develop a transfer function between 4 and 1 tire.

### LAB TESTS – CHARACTERIZATION OF PATHS

To characterize the airborne paths contributing to tire noise, the Noise Reduction (NR) of the test vehicle was measured with various methods of artificial excitation. These various methods all evaluated the vehicle transmission loss by using and measuring a broadband noise source at the tire patch and comparing the sound recorded at the vehicle's interior (a variation of this method was tested reciprocally where the noise source was placed inside the vehicle and response measured at the tire patch). The various NR functions were applied to the operating response from the microphones local to each tire to predict the airborne contribution. These tests and the resulting data are described in detail in the companion paper 2007-1-2252. Partial coherence (PCOH) analysis of the operating data was used as the control in evaluating the various airborne contribution methods. In this analysis, sounds and acceleration measurements from each tire were used as inputs and the passenger's left ear response was used as output. The Partial Coherence method calculates the partial power from each input after having removed the effects of the other inputs<sup>(2)</sup>. The best NR function (within the context of the project described in this paper) was identified based on the similarity of synthesized noise (using the NR various functions) and measured interior vehicle noise. Figure 5 shows an example of the measured interior airborne noise (from PCOH method) compared to five different iterations of predicted interior noise from various NR methods which are described in detail in the accompanying paper 07NVC-253.

The structureborne paths were characterized by measuring the sensitivity of sound due to input force at each location (P/F). This sensitivity function was applied to the operating acceleration measurements from the same locations to predict the structureborne contribution of sound.

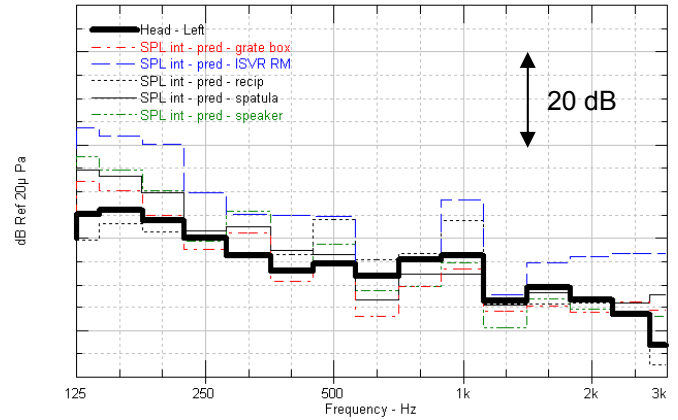


Figure 5: Third-octave Autospectra of interior airborne noise from PCOH (bold) compared to the various methods.

### LAB TESTS – TIRE TEST FIXTURE

A test fixture was designed to quantify a given tire as an acoustic source, which can then be applied to various acoustic transfer functions (to account for boundary conditions, microphone locations, and vehicle attenuation) to predict in-vehicle tire noise from airborne paths. The tire can be mounted to the fixture, which is lowered onto a single dynamometer roll with adjustable force. Force is adjusted to achieve a similar footprint to that of the same tire when mounted on the vehicle (with other 3 tires) as determined by using the same surface pressure transducer as previously mentioned. The tire is then back-driven by the dynamometer in the same drive conditions as were evaluated during the vehicle dyno testing. Again, the dyno roll was covered in abrasive paper for consistency among rolling surfaces.

An example of the result of this single tire test is compared to that of the single tire while mounted and driven on the vehicle in Figure 6.

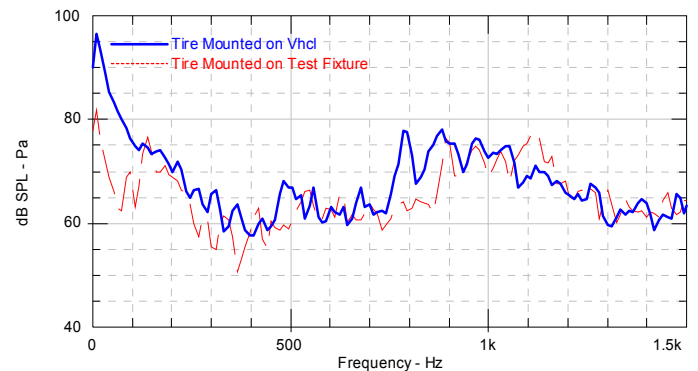


Figure 6: Spectral difference between sound recorded local to a tire mounted on a vehicle (blue, solid) and mounted on a tire test fixture (red, dash)

The resulting time recording of tire noise is used as the input to the Tire Noise Synthesis process.

## IN-VEHICLE TIRE NOISE SYNTHESIS

The synthesis of airborne tire noise for each tire/vehicle combination is summarized by the following conceptual relation:

$$SPL(tire)_{interior} = Tire(t) * NR_{vehicle}(f) \quad (1)$$

Where  $tire(t)$  is the time history of the sound pressure characterizing the tire and  $NR_{vehicle}(f)$  is the Noise Reduction (attenuation in decibels) offered by the vehicle in the frequency domain. In this case, the NR function is used as a digital filter through which the recorded tire is passed, in other words, the time history of tire noise is convolved with the NF function<sup>(4)</sup>.

In reference to the Tire Noise,  $Tire(t)$ , the various steps in the process (tire noise on the road, dyno with four tires rolling, dyno with one tire rolling, and tire test fixture) produce different sounds inherent to each test and therefore different averaged spectra. However, each sound has the same fundamental components: tire noise, engine noise (where applicable), and masking noise (that is, everything left in the noise after engine and tire orders have been removed). It is therefore possible to decompose each sound during the various tests to derive these dominant sounds which can be used not only to create transfer functions between steps, but also as input components during the synthesis of the predicted in-vehicle sound. This process is illustrated in Figure 7.

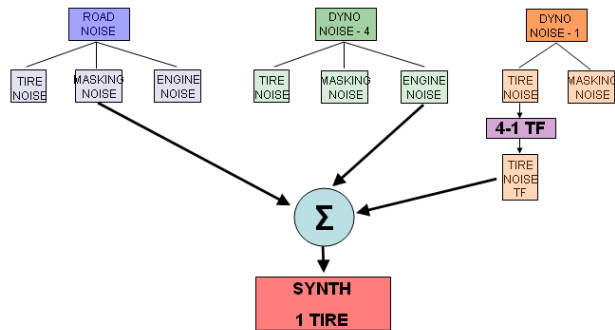


Figure 7: Block diagram of sound synthesis process to synthesize in-vehicle noise from data collected on a chassis dynamometer

For example, when the vehicle is tested on the road in coast condition, the dominant sounds present at the passengers' ear are tire noise, engine noise, and masking noise, which is composed of wind, and other non-critical components. Considering that the drive-train is under minimal load during coast condition all other drive train noises can normally be considered negligible. This is also the reason that tire noise is typically evaluated during coast down. Since the masking noise is derived by subtracting tire and engine noises, any additional drivetrain noises (axle, transmission, imbalance, etc) would still be present in the masking

noise and would therefore be accounted for in this synthesis process.

The decomposition of the dominant sounds was achieved by using time averaging synchronous to the wheel encoder and engine tachometer. By extracting each of these dominant noises from the original noise, the remainder can be considered masking noise. Since the noises directly attributed to the tire and engine are the only ones of interest during the dynamometer testing, they can be combined with the road masking noise to synthesize vehicle interior noise.

The Sound Quality Preference equation can then be applied to the synthesized sounds and the results compared to the original regression model, as shown in Figure 8.

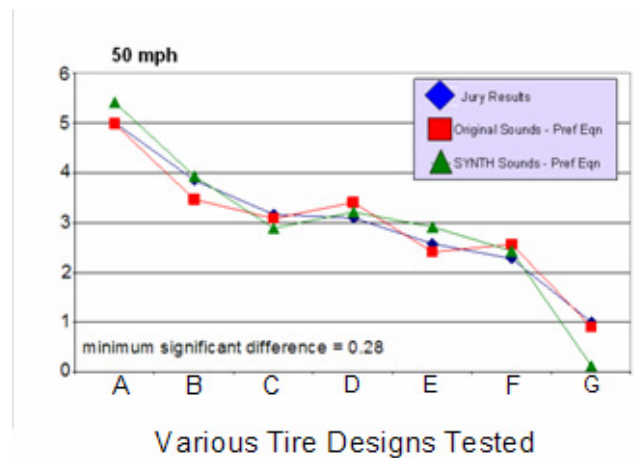


Figure 8: Preference ranking results from Jury Study (blue), compared to merits calculated on the same sounds (green) and merits calculated from synthesized sounds (red) (merits calculated on the latter two sounds by employing the developed Sound Quality Preference Equation)

The similarity of the predicted results to the original ranking proves the validity of this method. This same process can then be expanded to include the tire noise recorded on the fixture as the source input to the synthesis process. Additional transfer functions should be applied (as digital filters) to the recorded sound to account for boundary conditions, microphone proximity to the tire patch, and vehicle NR.

To accurately predict the tire noise in the vehicle while operating on the road, it is also necessary to account for the sound as it would propagate from all four tire locations simultaneously. This was achieved by analyzing the phase difference from all four tires as they operated simultaneously on the chassis dyno, applying these phase differences to the input sound (by shifting the time response in the time domain), and summing the various phase-shifted sounds.

This synthesized tire noise can then be combined with engine noise and road masking noise to predict interior vehicle noise.

## CONCLUSIONS

The method for predicting tire noise in the vehicle as described in the preceding paper proved to be very robust by subjective and objective comparison.

This process can be considered valid for all tire-types applied to this mid-sized sedan. It was designed such that the tire OEM can apply the procedure to predict the airborne tire noise from different tires on the same vehicle. Given the similarity in Noise Reduction among vehicles in the same class, it is assumed that the same procedure applies. The airborne / structureborne contributions of a different vehicle within the same class should be analyzed to validate.

The same process applies for different vehicle classes (trucks, full sized sedans, etc), but the Noise Reduction should also be accounted for, as it would be fundamentally different from that of a mid-sized sedan. To improve the process, a database of masking noise should be created. The spectra of masking noises from the various sound decompositions should be very similar and would account for variations in wind, road surface, and other variations specific to the recorded data. Based on these spectra, an average masking noise, or shaped random noise could be created to apply during the synthesis process. In this case, it would also be necessary to account for any non-transient noises attributed to the tire, as well as any other drivetrain noises that would be present in the masking noise under the normal subtraction method.

This process yielded an evaluation of various methods to predict airborne noise (process and results detailed in the companion paper 2007-01-2252). This analysis showed that the airborne contribution predicted from the vehicle's Noise Reduction is very similar to that derived from the Partial Coherence Method, and is therefore suitable for use in the overall process.

## ACKNOWLEDGMENTS

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