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Evaluation of Different Vehicle Noise Reduction Test Methods for Tire Sound Quality Synthesis

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ABSTRACT

For vehicle Original Equipment Manufactures (OEMs), road noise inside the vehicle is an important aspect that contributes to the comfort and the sound quality image of the vehicle. Road noise inside a vehicle is a function of the source (tire design interacting with road surface) and of vehicle sensitivity functions. Road noise targets and tire targets are typically developed by characterizing the tire as a noise and/or vibration source and by characterizing the vehicle as a matrix of acoustic or structural paths[(1)] . This paper focuses on the development of a simplified procedure for measurement of Noise Reduction (or acoustic vehicle sensitivity function) from tire patch to vehicle interior. Several procedures are available from either literature, vehicle manufacturers or software providers, which exhibit important differences regarding sound production, number and position of source and receiver microphones, or measured parameters [(2)] . The objective of the investigation described in this paper was to evaluate these different procedures and identify the simplest one that can provide data that can be used to simulate, with a reasonable accuracy, the noise reduction effect of a vehicle. Tests of Noise Reduction were conducted in a hemi-anechoic chamber on a production vehicle with the following methods: point source, reciprocity with volume velocity source, ad-hoc tire-patch speaker (grate box) and off-the-shelf loudspeakers. The averaged Noise Reduction (NR) functions between a binaural head inside the vehicle and each of the four tires were computed using each method. These functions were applied to time data acquired in vehicle, on a chassis dynamometer, to validate the prediction of interior noise by comparison to measured noise. The paper describes the test methods, their comparison and includes the authors' recommendations for best method.

INTRODUCTION

Noise Reduction is defined as the difference between the average sound pressure level at the source side L_1 and the average sound pressure level at the receiver side L_2.

$$L_{NR} = L_1 - L_2 \quad \text{(dB)} \qquad (1)$$

In a vehicle, it represents the acoustic attenuation provided by vehicle body and panels to exterior noise sources (powertrain, driveline, tires, road, wind). As described in the companion paper SAE 2007-01-2253, this parameter is needed to predict the contribution of different sources to the interior noise, as represented by the following equation:

$$SPL_{\text{int}} = \sum_i \left(Source_i * \sum_j Path_{ij} \right) \qquad (2)$$

NR can be directly measured or can be predicted by applying CAE models. As part of a project aimed at establishing a procedure to synthesize tire/road noise inside the vehicle, the NR of a current production sedan was tested using different methods. This paper compares the results of NR measurements conducted with different methods and the criteria used to compare them.

NOISE REDUCTION TEST SETUP

Noise Reduction (and other parameters quantifying the acoustic performance of elements of a system) is typically measured using artificial excitation, which, in the case of acoustic sources and paths, is made of one or more loudspeakers. There are two basic approaches to this type of measurement:

- The precise method: Volume Velocity
- The approximate one: Average Sound Pressure

Both rely on the use of loudspeakers. The difference between the two methods is that, in the Volume Velocity one, the source is designed to approximate as closely as possible a point source so that the Source Strength is known, while in the approximate method the sound source is simply characterized by an average sound pressure around it (or by its Sound Power). The Volume Velocity method requires a specifically designed and calibrated source, while the approximate method uses generic loudspeakers.

The purpose of this study was to identify the best approach that could give reasonably accurate results with the minimum investment. Therefore the NR of a vehicle was measured with the following methods:

1. Point Source with Spatula.
2. Point Source Direct
3. Point Source reciprocal
4. Average sound pressure with Loudspeakers
5. Average sound pressure with "Tire Grate Box"

These tests were repeated at each of the four corners of the vehicle (front left and right, rear left and right). In the interest of brevity only the results of the front left corner are summarized in this paper.

A total of 10 microphones were used with common placements for all methods tested. A binaural head was placed on the passenger seat of the vehicle, six microphones were placed around the tire patch area, as shown in Figure 1, and two microphones were placed in road measurement (operating) locations, mounted to the vehicle body in front of and behind the wheel, as shown in Figure 2. .

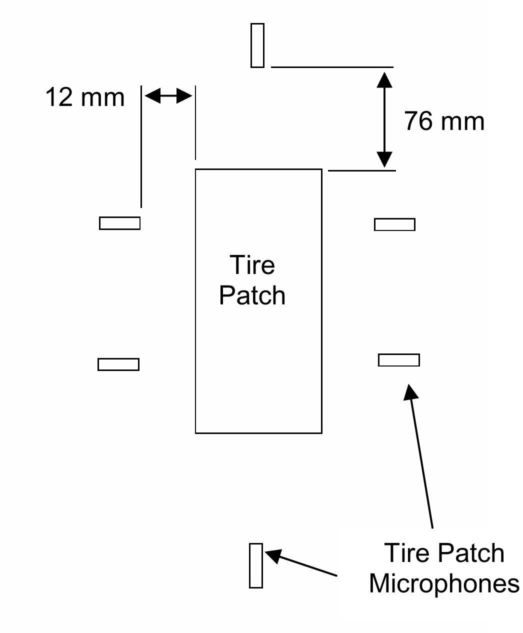

Figure 1: Tire Patch microphone locations

In all cases the logarithmic average of the six "tire patch" microphones were used to approximate the source strength for use in estimating the NR function. This means that even when the term "point source" is used, the reference source strength was approximated by averaging multiple microphone measurements around the noise emitting holes representing the point source.

The "road microphones" were used to estimate the sound pressure level at the tire patch, during implementation of the NR functions, in synthesizing the air borne contribution in the passenger cabin. This is explained in greater detail in a later section titled "Interior Tire Noise Synthesis".

POINT SOURCE WITH SPATULA

This test utilizes a calibrated volume velocity source with a fitted nozzle (which looks like a "spatula") to reproduce a pattern similar to the sound radiation from a tire (see Figure 2). This is a test devised by some vehicle OEMs and it has become popular in most test labs. During the test, the "spatula" is positioned between the tire and the floor surface, and noise is injected into it and radiated from its lateral and front holes. Depending on the OEM specification, one or more microphones are positioned in close proximity of the spatula and their average sound pressure level used as L_1 (source level). One or more microphones positioned inside the passenger cabin are used to compute L_2.

In our test, a binaural head was positioned at the front passenger's position and L_2 was represented by left and right sound pressures. L_1 was estimated by averaging the six "tire patch" microphones during measurements taken with the "spatula" oriented in each of the four principle directions.

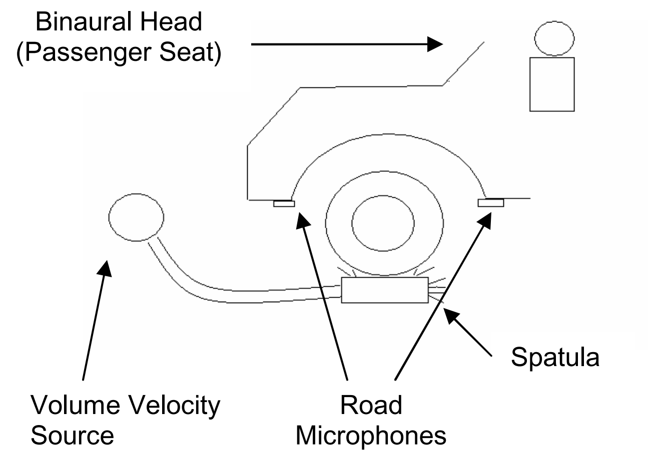

Figure 2: Spatula test setup

POINT SOURCE DIRECT

A calibrated volume velocity source was positioned in the wheel well, at the "road microphones" positions where operating noise data had been taken during on road and dynamometer testing (see Figure 3). The NR function was estimated between the binaural head at front passenger position and the wheel well point source, "road microphone" locations.

Again L_2 was left and right binaural head measurements, but L_1 was the average of the "road microphone" measurements.

This test was also used to estimate the transfer functions between the "road microphones" and the "tire patch" microphones, which are used to predict the tire patch sound pressure level, or source strength, during operating conditions, such as dynamometer or on road testing.

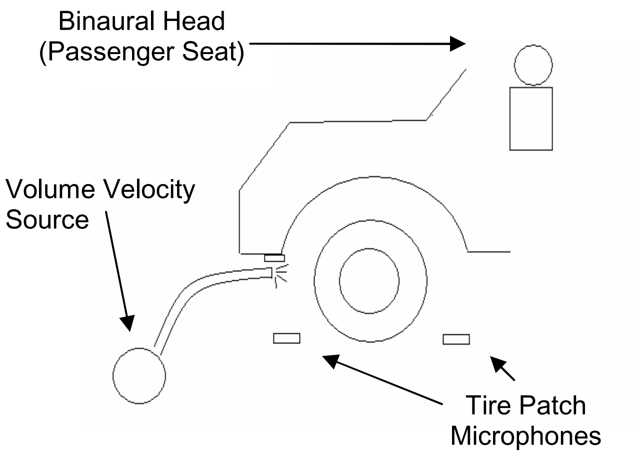

Figure 3: Point Source Direct test setup

POINT SOURCE RECIPROCAL

A volume velocity source was positioned at the passenger seat, in proximity of the left ear of the binaural head as the source, and the “tire patch” microphones, or receiver, were used to quantify the response, as shown in Figure 4.

During this test L_2 was the average of the six “tire patch” microphones and L_1 was the average of the binaural head left and right. The NR function was estimated as the average of six iterations, with the Volume Velocity Source pointed in the six principle directions, up, down, left, right, forward and backward to account for directionality within the vehicle’s diffuse interior field.

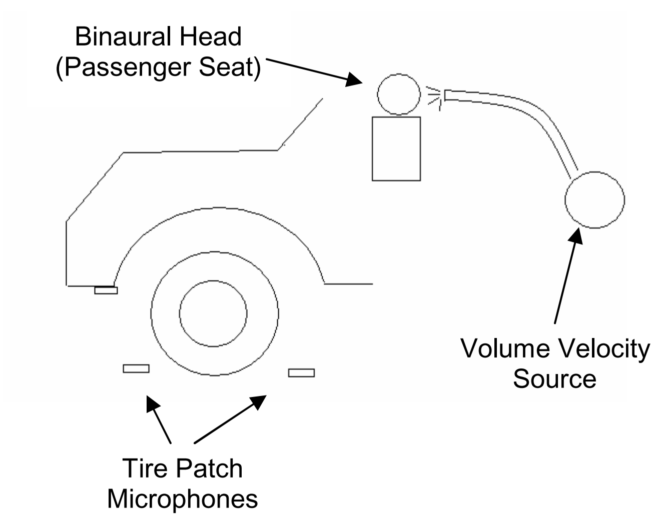

Figure 4: Point Source Reciprocal test setup

LOUDSPEAKERS

Generic, off-the-shelf loudspeakers were positioned in proximity of the tire with the generated noise directed into the tire patch area, shown in Figure 5. The six “tire patch” microphones were averaged together to represent the source, L_1, with the binaural head at the front passenger seat representing the receiver, L_2. This method was used to represent a classic lab set-up to determine the general transmission loss of a vehicle.

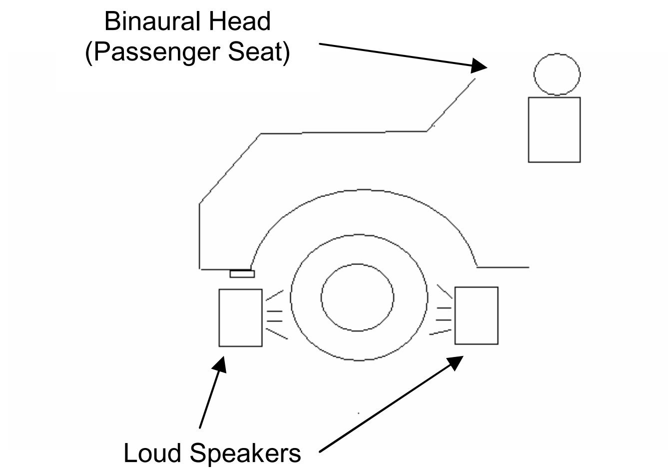

Figure 5: Loudspeakers test setup

LOUDSPEAKERS (“GRATE BOX”)

A box was constructed with a top made of steel plate strong enough to support the weight of the vehicle. The box was then mounted below grade, in such a way that the top of the box was even with the surrounding floor. Slots were then cut into the top of the box in locations that would surround the tire patch area**,** Figure 6 and Figure 7. Generic loudspeakers were then placed in the box, with the intent of creating a reverberant field that would let sound escape only through the slots surrounding the tire patch. This sound approximates the acoustic radiation of the tire patch with minimal structural excitation.

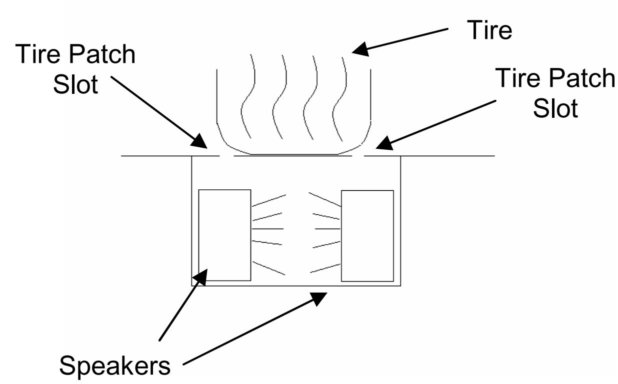

Figure 6: Front view of "Grate Box" tire patch area

The NR function is estimated using the average of the “tire patch” microphones as the source, L_1, and the binaural head left and right microphones as the receiver, L_2.

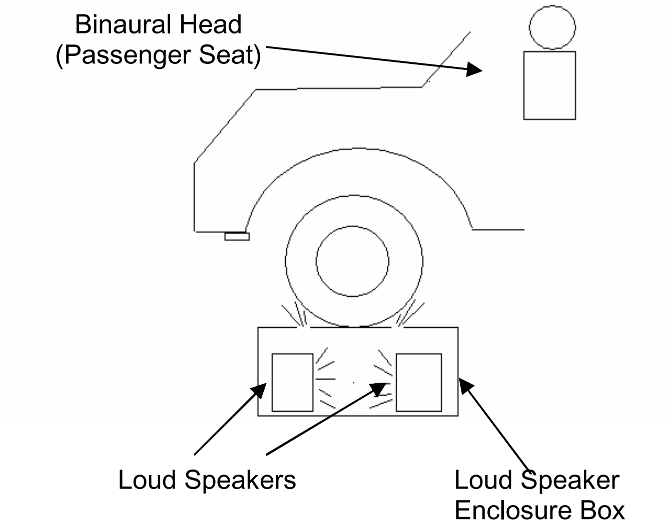

Figure 7: "Grate Box" test setup

It is interesting to note that, while researching literature for this paper, the authors found that a similar method had been used previously and described in reference [3]. This supports the validity of the method (at the expense of our originality claim).

TEST RESULTS COMPARISONS

The various methods used to measure the NR functions were evaluated in two different ways, ease of implementation and validity of the results.

EASE OF IMPLEMENTATION

The ease of implementation is evaluated by considering the special equipment and time required to conduct the test. Of the five methods three of them; Point Source Direct, Point Source Reciprocal and Spatula require the use of a point source. Of these three, the Point Source Direct method, labeled ISVR RM in the Figures following, is the easiest to conduct as it requires two measurements, one at each of the two "road microphone" locations. The "Spatula" method requires four measurements to be taken, one in each of the four tire patch directions. The "Reciprocal" method requires measurements be taken in six directions in the vehicle cabin.

The remaining two methods, "Grate Box" and "Speaker", involve using standard "off the shelf" speakers, rather than a specially designed point source. Of the two methods, the "Grate Box" is more difficult to implement as it requires a loud speaker enclosure box to be built and installed below grade, and a custom slots to be cut to the size of the tire patch.

The easiest method to implement is "Speaker" method which uses two standard loud speakers with no custom fixture required.

VALIDITY OF RESULTS

The Noise Reduction data resulting from the tests were compared objectively and subjectively. First, the NR functions were directly compared to check the effect of test setup and boundary conditions. For the sake of comparing data to historical results from various vehicle OEM's, the NR function measured with the spatula method was considered as a reference for the comparison. Next, each of the measured NR functions was used to predict the airborne tire noise contribution inside the vehicle and the result compared to the measured interior tire noise. The comparison between predicted and measured interior noise was done objectively, on the basis of autospectra and sound quality metrics, and subjectively, by informal listening of a few engineers. The best NR test method within the context of this project (described in the companion paper SAE 2007-01-2253) was identified as the one that provided the predicted interior sound which was closest to the measured one. All calculations and comparisons were done using narrow band spectra, but for ease of comparison are presented in this paper as 1/3rd octave spectra.

NOISE REDUCTION FUNCTIONS COMPARISON

The measured NR functions are shown in Figure 8, the bold trace being the reference, i.e. the function measured using the "spatula" method. Relative to the "spatula" method, the point source direct method underestimates the air borne NR into the vehicle. This is a result of the source being located nearly 0.5 meters from the tire patch area and closer to the passenger cabin. The reciprocal method over estimates the vehicle NR relative to the "spatula" method at lower frequencies (below 250 Hz) and underestimates the NR between 500 and 2000 Hz. It is believed that the error in the "reciprocal" method is due in large part to not having enough microphones in the passenger cabin to fully represent the source level and distribution.

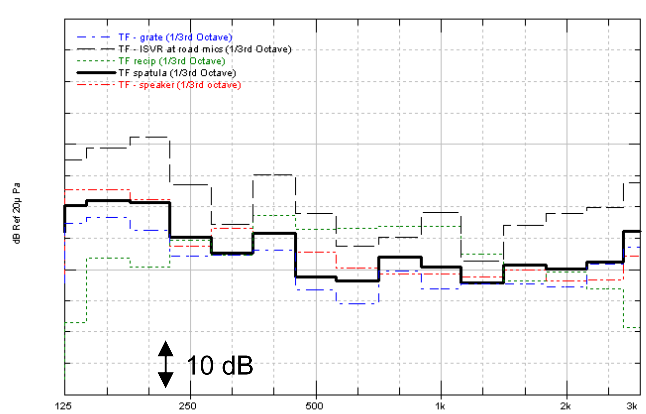

Figure 8: NR functions for the five methods

INTERIOR TIRE NOISE SYNTHESIS

Operating tests were performed with the vehicle on the dyno (explained in detail in the companion paper 2007-01-2253), one of which was performed with only one wheel of the vehicle rolling at 50 mph (other three wheels not rotating). During this test, microphones were placed at the “road microphone” locations, described earlier, and a binaural head was placed on the passenger seat. This test was repeated for eight different types of tires for each of the four tire positions. In the interest of brevity, the data presented in this report was acquired using two of these different tire types.

The interior tire noise was predicted by convolving the tire patch sound pressure time history with the NR functions (see Equation 3). The tire patch sound pressure was indirectly estimated by convolving the “road microphone” measured time histories with the transfer function between the “road microphones” and the “tire patch” microphones (“Local TF”) .

$$SPL_{\text{int},pred} = SPL_{tire\_patch,meas} * NR_{meas} \qquad (3)$$

The Local TF and the NR functions were applied stepwise to the “road microphone” time data through the use of FIR filters with frequency response functions that match the Local TF and NR functions respectively. The implementation of the FIR filters in processing the road microphone time data allow the Local TF and NR functions to be applied without losing the temporal aspects of the tire patch noise.

This procedure was repeated for the 5 different NR functions. The $1/3^{rd}$ octave band autospectra of the 5 interior noise predictions (one for each measured NR) are displayed in Figures 9, again the “spatula” method is displayed as a bold line.

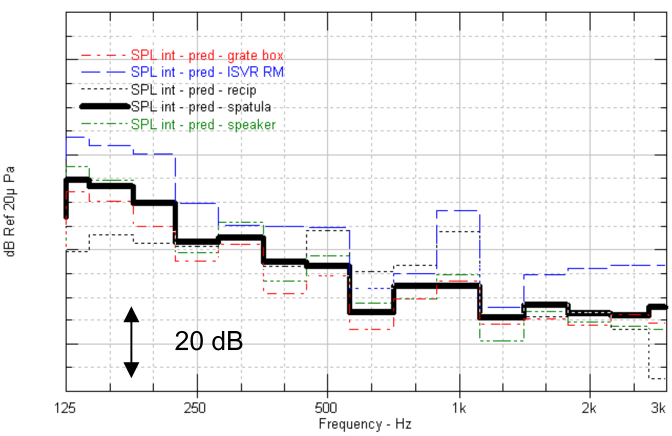

Figure 9: Third-octave Autospectra of interior predicted noise for the five methods, with the “spatula” method in bold.

VALIDATION OF SYNTHESIZED SOUNDS

To determine the validity of the various test methods, each of the five synthesized sounds was compared to the interior noise measured with the vehicle on the dynamometer with a single tire rolling. The measured interior noise however contained contributions other than the single tire noise (i.e. noise from the dyno and structureborne from the tire), and this needed to be extracted from the total measured noise. The tire-vehicle system was modeled as a Multiple Input Single Output system and the airborne tire contribution was extracted from the overall noise at the passenger’s ear using the Partial Coherence method [4]. Road microphone sound pressures (2) and spindle acceleration (X, Y, Z) were used as input to the Partial Coherence, with the passenger’s left ear as output.

The autospectra of the synthesized interior noise is compared to the measured interior noise in Figure 10, the measured interior tire noise is displayed with a bold line.

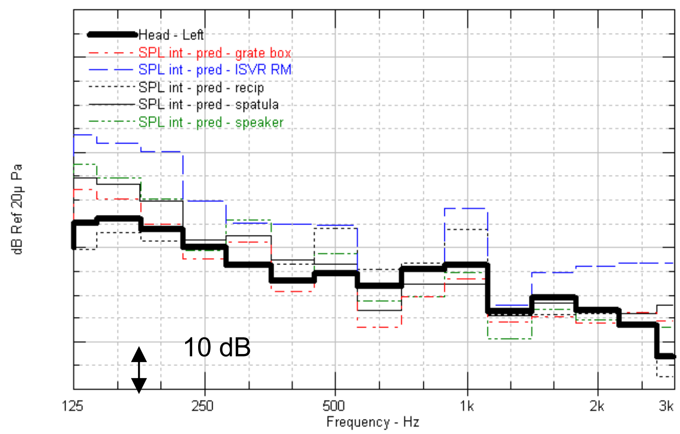

Figure 10: Third-octave Autospectra of interior airborne noise from PCOH (bold) compared to the various methods.

The synthesized interior tire noise was also compared objectively to the measured interior noise by using Sound Quality metrics (see companion paper SAE 2007-01-2253). The metrics describe three separate dimensions of tire noise: loudness, tonality and spectral envelope (discussed in detail in the companion paper SAE 2007-01-2253). These metrics were computed for each of the synthesized sounds and their deviation from the corresponding value for the measured airborne tire noise is listed in Table 1. These results show that the NR function measured using the “Grate Box” method most closely predicts the interior noise according to these metrics.

	Metric 1 % Deviation	Metric 2 % Deviation	Metric 3 % Deviation
Grate Box	2.9	1.0	7.3
Spatula	32.4	15.8	82.6
Speaker	23.5	151.5	181.8
Reciprical	11.8	5.0	373.7
Direct	164.7	10.5	415.8

Table 1: Deviation of the metric values for the predicted interior noise from the measured interior noise

Finally the five synthesized sounds were subjectively compared through an informal jury of three engineers. This confirmed that the sound synthesized using the NR from the "grate box" method provided the best match to the measured noise.

In addition to the "Grate Box" method, which matches the measured interior tire noise most closely, the "Spatula" and "Speaker" methods were considered satisfactory. The satisfactory grade was determined through a subjective evaluation done with the informal jury, as well as the sound quality metrics developed to describe tire noise.

CONCLUSION

This paper describes different methods that can be used to estimate vehicle noise reduction (NR) functions and compares ease of implementation and validity of results. Of the five methods that were explored, three were deemed acceptable when applied to tire noise. The method referred to as the "spatula" method is most often used by current OEMs for its ease of implementation and accurate estimate of the NR functions. Of the three satisfactory methods the "grate box" resulted in the most accurate synthesized interior noise, but requires a specially built box to be mounted below grade and slots cut to fit the tire patch of the vehicle under test. The "speaker" method is the easiest to implement, as it only requires off the shelf loud speakers to be placed close to the tire patch area.

The choice of the NR estimation method should be based on the expected use of the functions. In the case of this tire noise synthesis project (described in detail in SAE 2007-01-2253), the goal was to develop NR functions that describe a specific vehicle class, and use them to predict the performance of various tread patterns in that class of vehicle to catch unacceptable tire-vehicle combinations as early as possible in the tire development cycle. For this reason the NR functions do not have to be precise estimates of the Noise Reduction of the individual vehicle, but rather approximations of all vehicles in the class. Therefore an inexpensive, easy-to-apply NR estimation method with reasonably accurate results is sufficient.

If the objective of the project is the measurement of the most accurate NR functions for a specific vehicle (i.e. to establish/validate vehicle NR targets), the authors agree with the findings of reference 1 and recommend the "Grate Box" method as the first choice . The "Spatula" method could also be used, as commonly described in OEM specifications, although the results presented in this paper suggest that the NR function estimated using the "Spatula" method would be slightly less accurate.

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