On Single Event Measurements of Heavy Road Vehicles in Freely Flowing Traffic

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Summary
The validity of statistical pass-by measurements of road vehicles is usually checked by the 6 dB down criterion. It ensures that the sound pressure level drops down at least 6 dB before and after the maximum is reached. In dense traffic situations the percentage of valid events decreases strongly due to interfering effects with neighbour vehicles. The probability that a measurement is considered valid depends on the emission strength of the vehicle. This leads to a systematic overestimation of the average vehicle level. A method is proposed to correct for the effect of disturbing vehicles and thus to evaluate maximum levels of passing vehicles even in case where the 6 dB down rule is violated. The applicability of the method is demonstrated for a 24 days measurement campaign where more than 40’000 heavy vehicles were evaluated.

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1. Introduction
Classical source strength descriptions of roads were based on measures like the equivalent sound pressure level at 1 m distance. However in the last decade it become more and more popular to use the sound power of a vehicle as a descriptor instead. The consideration of each vehicle as a single point source is more consistent from a physical point of view and allows for more detailed investigations of road traffic noise [1]. The determination of a vehicle’s sound power is usually based on a measurement of the maximum pass-by sound pressure level, recorded at a distance of 7.5 m. In freely flowing and dense traffic the difficulty arises that a measurement of the wanted vehicle is often disturbed by neighbour vehicles. The relevance of the contributions of unwanted vehicles can be checked by investigation of the measured level time curve. Following ISO 11819-1 [2] a measured maximum value is valid if the level drops down for at least 6 dB before and after the maximum is reached. In addition one has to ensure that no other disturbing vehicle passes the microphone at the time the wanted vehicle produces the maximum level.

An elementary difficulty with the above mentioned strategy is that a noisy vehicle is more likely to fulfill the 6 dB down criterion. On the other hand there is a high probability that a silent vehicle with a low maximum level will violate the criterion and will thus be excluded from further analysis. Consequently the average pass-by level becomes dependent on traffic density and is overestimated systematically.

Within the Eureka project Footprint [3] ideas are developed to raise individual road access charges for heavy vehicles. Such a charge would be higher for trucks that have bigger effect to the infrastructure and the environment. The sum of these impacts is called “footprint” of the vehicle [4, 5]. The noise labelling of such a footprint should be based on an acoustical pass-by measurement for each single truck. To increase the probability of a valid measurement and to reduce the above mentioned systematic error of the average, it would be desirable to have a strategy to evaluate pass-by events even if the 6 dB down criterion is not fulfilled. In the next section the consequences of the 6 dB down criterion are investigated in more detail. Based on a priori knowledge of the pass-by level time history of a moving point source a recipe is developed to compensate for the effect of interfering noise from neighbour vehicles. Finally exemplary results are presented for a measurement campaign at a highway location in Switzerland where more than 40’000 heavy vehicles were gathered.

2. Statistics for the 6 dB down criterion
To estimate the consequences of the 6 dB down criterion in freely flowing traffic, measurements were performed at the highway A2 in Reiden, Switzerland. The road has four lanes and an extra breakdown lane on both sides. The allowed maximum speed is 120 km/h for passenger cars and 80 km/h for trucks. The microphone was installed on the east side of the road with a geometry based on the ISO 11819-1 standard. However the distance and the height of the microphone had to be slightly adjusted (6.5 m and 3.0 m) to avoid significant shielding of the guard rail. The microphone signal was fed to a Norsonic 121 sound...
level analyzer which evaluated and recorded the \( A \text{,Fast-weighted sound pressure level with a time resolution of 100 ms. Furthermore traffic was counted by two induction loops. The counter delivered an event list indicating "event time", "traffic lane on which the vehicle passed the measurement site", "category of the vehicle according to the SWISS 10 scheme" (see below) and "speed of the vehicle".}

Based on the traffic list those events were selected where a truck passed the microphone on the nearest lane. Then the sound level time history was inspected to evaluate at which passed the microphone on the nearest lane. Then the sound level time history was inspected to evaluate the maximum level. The 6 dB down criterion was tested by following the monotonic decrease (with a tolerance of 0.1 dB) on both sides of the maximum until the minimum was reached. The dependency of the percentage of events fulfilling the 6 dB down criterion from traffic density was evaluated on an hourly basis for a time period of 1 month (Figure 1).

As can be seen for a traffic density of 500 vehicles per hour about 85% of the heavy vehicles fulfilled the criterion. If the density increases to 2500 vehicles per hour the percentage of valid events drops to about 45%. As a first order approximation the percentage of valid events \( \eta \) can be estimated for a highway with two lanes in one direction as a function of traffic density \( \gamma \) in vehicles per hour,

\[
\eta \approx 100 - 0.0217 \cdot \gamma \quad \text{[\%]}
\]  

3. Basics of the pass-by level time history for a moving point source

If ground reflections are ignored the momentary sound pressure level \( L(t) \) for an omnidirectional point source that passes with speed \( v \) a microphone at shortest distance \( d \) is given according to

\[
L(t) = L_{\text{max}} + 10 \log \left( \frac{d^2}{d^2 + (vt)^2} \right). \tag{2}
\]

In equation (2) time zero \( t = 0 \) is for the source at the shortest distance. \( L_{\text{max}} \) is the maximum level with \( L_{\text{max}} = L(0) \).

With the substitution

\[
s = \frac{d^2}{v^2} \tag{3}
\]

the level time history from equation (2) can be described by \( s \) and \( L_{\text{max}} \) alone,

\[
L(t) = L_{\text{max}} + 10 \log \left( \frac{s}{s + t^2} \right). \tag{4}
\]

If the maximum level \( L_{\text{max}} \) and the level \( L(t_x) \) at time \( t_x \) are known, \( s \) can be calculated with

\[
s = \frac{A \cdot t_x^2}{1 - A}, \quad \text{where} \quad A = 10^{\frac{t_{x} - t_{x_{\text{max}}}}{10}}. \tag{5}
\]

A road vehicle differs from the ideal omnidirectional point source discussed above in two respects. As the axles are responsible for the tire noise the resulting source is no longer concentrated at one position but is distributed over two or more separate locations. Secondly, tire noise shows a horn effect which favors radiation along the direction of propagation. These effects can be summarized in a horizontal directivity \( \Delta L_H(\phi) \) which is given in [6] for the frequency range between 800 and 6300 Hz by equation (6). For lower and higher frequencies the directivity is 0.

\[
\Delta L_H(\phi) = -2.5 + 4 \cdot \text{abs}(\cos(\phi)) \quad \text{[dB]}. \tag{6}
\]

Assuming a typical road traffic source spectrum [7] the directivity for \( A \)-levels can be deduced according to

\[
\Delta L_H(\phi) = -2.1 + 3.4 \cdot \text{abs}(\cos(\phi)) \quad \text{[dB(A)]}. \tag{7}
\]

Compared to an omnidirectional point source the pass-by level time curve of a real vehicle with a horizontal directivity according to equation (7) shows less steep slopes. This broadening can be approximated by modifying equation (4),

\[
L(t) \approx L_{\text{max}} + 7.6 \log \left( \frac{s}{s + t^2} \right). \tag{8}
\]

The approximation in equation (8) is better than 0.3 dB in the range from \( L_{\text{max}} \) down to \(-10 \text{ dB} \). Taking into account the uncertainty of the directivity itself this accuracy appears good enough. The solution for the slope parameter \( s \) in equation (5) from the maximum level and level \( L(t_x) \) at time \( t_x \) reads now

\[
s = \frac{A \cdot t_x^2}{1 - A}, \quad \text{where} \quad A = 10^{\frac{t_{x} - t_{x_{\text{max}}}}{10}}. \tag{9}
\]

In addition to geometrical spreading sound propagation from the vehicle to the microphone is influenced by ground reflection. As the source-receiver distance varies while a vehicle drives by, the ground effect interference pattern for the superposition of direct and ground reflected sound changes. At high vehicle speeds the rolling noise dominates. The corresponding source height is close (50...100 mm) to the road surface [8], resulting in ground effect dips at very high frequencies. To demonstrate the
The compensation procedure is explained with the help of Figure 3. The level time curve $L_s$ denotes the sound pressure stemming from the wanted vehicle, $L_n$ is the contribution of a disturbing vehicle. At the microphone only the total sound pressure level $L_t$ can be observed.

Starting point is the maximum level $L_{00}$ which is identified as belonging to the vehicle under consideration. The analysis of the 6 dB down criterion yields that the minimum level $L_{01}$ at time $t_1$ is less than 6 dB below $L_{00}$. Thus $L_{00}$ significantly overestimates the true maximum value for the wanted vehicle ($L_{00}$) and has to be corrected for by the following procedure:

1. Estimate the slope parameter $s_x$ for the wanted vehicle pass-by. With good accuracy it can be assumed that at time $t_1$ the level of the wanted vehicle and the level of the disturbing vehicle are equal. From that follows

$$s_x = \frac{A_x(t_0 - t_1)^2}{1 - A_x}, \quad \text{where} \quad A_x = 10^{\frac{L_{00} - L_{01}}{10}}. \quad (10)$$

2. Identify time $t_2$ and level $L_{n2}$ for the pass-by of the disturbing vehicle.

3. Estimate $L_{n2}$ by subtracting the contribution of the wanted vehicle,

$$L_{n2} = 10 \log \left(10^{0.1L_n} - 10^{0.1L_x}\right), \quad (11)$$

where $L_{n2} = L_{n0} + 7.6 \log \left(\frac{s_n}{s_x + (t_0 - t_2)^2}\right)$.

4. Estimate the slope parameter $s_n$ for the disturbing vehicle pass-by:

$$s_n = \frac{A_n(t_1 - t_2)^2}{1 - A_n}, \quad \text{where} \quad A_n = 10^{\frac{L_{n0} - L_{n1}}{10}}. \quad (12)$$

5. Estimate $L_{00}$ by subtracting the contribution of the disturbing vehicle:

$$L_{00} = 10 \log \left(10^{0.1L_n} - 10^{0.1L_x}\right), \quad (13)$$

where $L_{00} = L_{n0} + 7.6 \log \left(\frac{s_n}{s_x + (t_0 - t_2)^2}\right)$.

In step 1) the level time curve for the wanted vehicle is based as a first guess on the maximum level of the total sound pressure. At the end of step 5) a better estimate is available and thus the procedure could be repeated iteratively. However numerical experiments have shown that the final result for $L_{00}$ after a second and a third run alters only by 0.1 to 0.3 dB.

5. Results

In this section results are shown for a measurement campaign conducted in September 2005 at the Footprint site A1 near Lenzburg in Switzerland. In difference to the location Reiden mentioned in section 2 this site was equipped with a Linesic weigh in motion (WIM) sensor from Kistler Instruments, Winterthur, Switzerland. This allowed for correlations between noise and weight data. The highway
in Lenzburg has two lanes in each direction, the maximum allowed speed is 120 km/h for passenger cars and light vehicles and 80 km/h for heavy vehicles and trucks. During the measurement period of 24 days a total of 43'000 heavy vehicles were acquired. All levels are corrected for possible interference with neighbour vehicles according to the strategy described above.

5.1. Vehicle categories

The vehicle classification used in the next sections follows the Swiss10 scheme. The categories can be translated into COST 323 [11] classes according to Table I.

5.2. Speed dependency

For a given site and vehicle category the most important parameter influencing sound emission is vehicle speed. Figure 4 to 6 show the measured and corrected maximum pass-by levels in different speed classes. The tilted line is the expected speed dependency for heavy vehicles according to the Swiss road traffic noise model SonRoad [7].

Table I. Equivalence between Swiss10 categories and COST 323 vehicle classes.

<table>
<thead>
<tr>
<th>SWISS10 category</th>
<th>COST 323 class</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (Lastwagen)</td>
<td>class 4</td>
</tr>
<tr>
<td>9 (Lastenzug)</td>
<td>class 6</td>
</tr>
<tr>
<td>10 (Sattelzug)</td>
<td>class 5</td>
</tr>
</tbody>
</table>

Up to 90 km/h the measured speed dependency coincides with the calculation model. Surprisingly enough for category ”8” and ”10” vehicles emission seems to decrease for speeds higher than 90 km/h. For speeds higher than about 100 km/h the speed dependency vanishes. The explanation for this behaviour is the error in classification. Vehicles with speeds above 90 km/h are vans and medium heavy vehicles which produce less sound emission. There are almost no category ”9” vehicles with speeds above 90 km/h. Category ”9” vehicles are trucks with a trailer. Obviously these can be classified with almost no error.

5.3. Influence of weight

After normalising all measurements to a reference speed of 80 km/h (speed dependency according to [7]) further factors influencing sound emission can be investigated. Figure 7 to 9 show the measured maximum pass-by levels in different weight classes. The influence of weight on sound emission is relatively small. For category ”8” (COST4) vehicles the level increases by 0.12 dB(A) per ton. In category ”9” (COST6) emission grows with 0.06 dB per ton. For category ”10” (COST5) vehicles the gradient is only 0.03 dB per ton.

5.4. Correlation of maximum pass-by level and correction

In the introduction it was postulated that silent vehicles have a lower probability to fulfill the 6 dB down criterion compared to noisy vehicles. This is demonstrated by Figure 10 to 12. After normalisation for speed, maximum pass-by levels are evaluated as a function of correction. As
expected it turns out that vehicles without any correction are loudest while larger corrections are connected (in a statistical sense) to more silent vehicles. In dense traffic situations where more than 50% percent of the heavy vehicles need a correction the average maximum pass-by value for the sample with correction 0 is about 1.5 dB higher compared to the average of the complete sample.

The span between the lowest and highest level becomes smaller for higher correction values. This simply depicts the fact that the number of events in a certain correction class correlates negatively with the height of correction. On the other hand the 50% range is independent of the correction up to 2 dB. This indicates the reliability of the correction algorithm.
6. Conclusions

Statistical pass-by measurements of road vehicles are usually validated by checking the 6 dB down criterion. Comprehensive measurements have shown that the percentage of valid measurements decreases strongly with increasing traffic density. For dense traffic a percentage of only about 45% of the heavy vehicles can be expected to be valid. As the probability for a valid pass-by event is higher for a noisy vehicle the emission of the average vehicle is over-estimated by about 1.5 dB.

A simple and robust method is proposed to loosen the 6 dB down criterion by correcting for the interfering effects of unwanted neighbour vehicles. To do so knowledge of the level time history is sufficient. The successful application of the method is demonstrated for measurements of heavy vehicles. The advantages are a higher probability for a valid single vehicle measurement and the usage of an adequate sample.

Acknowledgement

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References