Evaluation of SPC and BSS for indoor pass-by noise contribution analysis

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Abstract

The indoor vehicle pass-by test is a simulation of a field pass-by noise measurement in a controlled environment allowing repeatable measurements independent of weather conditions. During vehicle development modifications can be tested out in a fast manner to see the immediate influence on the overall vehicle noise levels produced during a pass-by acceleration test. Besides performing the standard pass-by noise test, vehicle improvement work requires knowledge about the noise contribution from the different vehicle sources during the pass-by test. A source path contribution (SPC) concept involving modelling the main vehicle noise sources contributing to the pass-by noise will be presented. A special feature of this approach is that it processes entirely in the time-domain to produce source strength estimates for the considered noise sources followed by a synthesis to produce pass-by noise estimates for the vehicle and for individual noise sources based on indicator microphone near-field data and acoustic transfer functions. As a result major pass-by noise contributors are identified at a given vehicle position during the pass-by test. Results produced by this method will be compared to a blind source separation (BSS) methodology applied to the operational dataset only for extracting source signals related to the different noise processes during vehicle operation. Extracted source signals are correlated with far-field measurements to estimate pass-by noise contributions. The BSS methodology is verified using a speaker setup showing excellent separation of tyre and engine noise contributions. Data from indoor pass-by noise measurements with a vehicle on a chassis-dynamometer is finally used to test and evaluate the two methods.

1 Introduction

Indoor vehicle pass-by noise applications deal with measuring the exterior noise from a vehicle which is fixed on a chassis dynamometer (dyno) inside a large semi-anechoic room. During a standardised acceleration test, the noise is measured with an array of microphones placed in the vehicle far-field, and the overall noise level versus vehicle position can be determined. As such the indoor test is a simulated pass-by noise measurement. Since the indoor facilities allow controlled and repeatable measurements independent of weather this test is popular during development stage of vehicle design allowing modifications being tested out in a fast manner.

In addition to performing the indoor pass-by noise test there is a growing need for vehicle noise source contribution analysis. A source path contribution (SPC) concept is presented involving modelling the main vehicle noise sources contributing to the pass-by noise. The SPC methodology presented here processes entirely in the time-domain, working on measured time recordings during the fast acceleration test. Initially near-field microphone recordings are filtered to produce source strength estimates for the considered noise sources followed by another set of synthesis filters to produce pass-by noise estimates for the vehicle and for individual noise sources. As a result we may identify major noise source contributions at a given vehicle position during the pass-by test.

For testing and validating the proposed methodology indoor pass-by noise measurements were carried out with a passenger car on a chassis dyno. In addition to the pass-by array of microphones in the far-field extra indicator microphones were located close to the noise sources during the test. Indicator microphone data recorded during the acceleration test and transfer function data measured using a small volume velocity source are combined to form the vehicle source model. A further synthesis process allows predicting exterior pass-by noise from the vehicle source model. The predicted pass-by result from the complete vehicle SPC model is compared with the indoor pass-by result obtained directly from the pass-by array of microphones for validation of the chosen SPC model setup.

Individual component source contributions are however more difficult to validate for an operating vehicle. In this study a new operational source separation methodology based on blind source separation (BSS) is introduced briefly and verified for a simple setup using speaker signals. Next, the BSS approach will be tested on the data taken with the car on the chassis dyno for separating tyre noise from engine related noise and finally perform the pass-by contribution analysis. Results from the SPC and BSS approach are compared and discussed.

2 Indoor simulated pass-by noise measurement

A pass-by noise measurement is defined as the method of measuring the noise emission of a road vehicle under acceleration conditions, with various gear positions in a certain measurement range. These measurements are mandatory for automotive manufacturers in terms of product certification. For this reason, ISO (International Organization for Standardization) regulates the measurement and analysis procedures, as well as the reporting format [1].

In some cases, however, pass-by noise measurements cannot be taken out in the field because of bad weather or poor test-track conditions. In such cases, the indoor simulated pass-by noise measurement is often used. The indoor simulated pass-by noise measurement does offer a number of advantages such as good repeatability, flexibility, ease of use and is being considered as the conformance test, together with the field pass-by test by ISO standard.

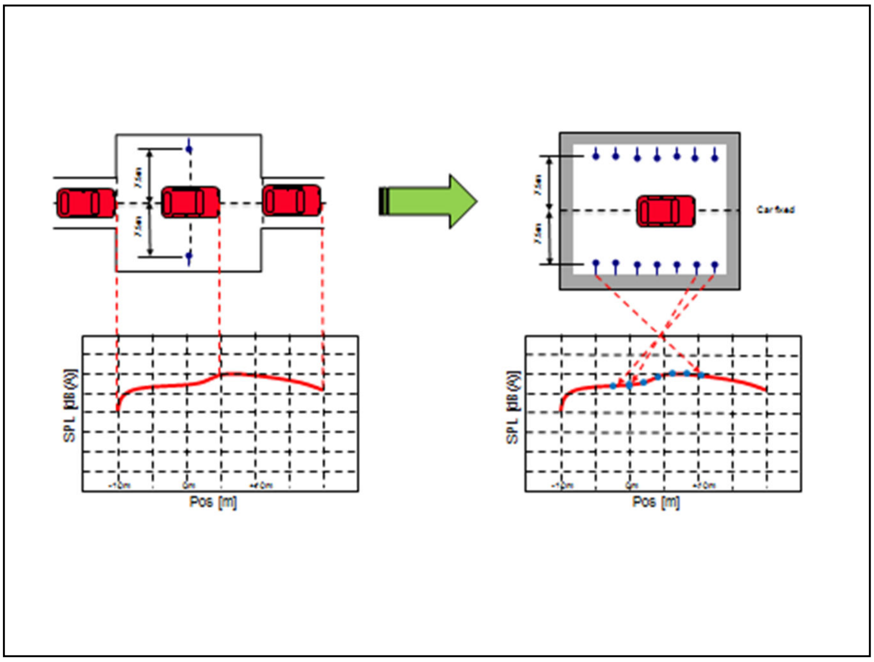

Figure 1: Field pass-by and indoor simulated pass-by noise measurement.

Instead of making the test vehicle pass two stationary microphones as being the standard in a field pass-by measurement, indoor pass-by setups use one or two rows of microphones placed alongside the vehicle. See figure 1 for a comparison of the field and indoor situation. The vehicle runs on a chassis dyno and is accelerated in the same way it would be for a field pass-by measurement. Time histories are measured by the microphones together with vehicle parameters and dyno drum speed. A sophisticated algorithm uses information from the dyno to calculate the vehicle's position relative to the microphones as a function of time. This is used to extract the contributing portions of the time histories that correspond to when the vehicle would have passed the standard microphone positions had it been moving. A synchronised single time history is created by stitching all of these time history sections together and interpolating across the segments' boundaries. This synchronised single time record combined with the dyno drum speed profile represents the vehicle noise emitted during a simulated pass-by measurement. The new time history is played back through the analysis section of the system, offering the option of applying various types of frequency analysis to the time history. It can also be previewed and listened to in order to determine whether it sounds right.

The indoor pass-by system described in this paper has been developed to allow for microphone positions closer than 7.5m from the vehicle while still providing correct results. This is extremely useful for situations where space is limited and is achieved assuming that the noise is emitted from one point (an acoustic center) as seen from the far-field. Individual acoustic centers can be chosen for the left and the right side of the vehicle. In addition, the array of microphones does not need to have full coverage of all vehicle positions since typically the room size is limited. Missing microphone positions close to the entrance or exit of the virtual pass-by track can simulated from the existing array microphones and the specified acoustic centers. This latter feature is employed in this study.

3 Contribution analysis methods

3.1 SPC modelling of noise sources

In order to estimate contributions from the different vehicle noise components some more effort is typically required. The classic approach is to apply acoustic transfer path analysis [2, 3] (called source-path-contribution here) which is based on a solid foundation. All relevant noise components are modelled using a set of acoustic point sources, their source strength during operation is calculated from near-field acoustic data and transfer functions. Finally, the source strengths are propagated to the receiver via other acoustic transfer functions. In the current context, the receivers would be the array of microphones for the indoor simulated pass-by test. The near-field data is measured using indicator microphones at selected positions close to any vehicle noise source, i.e. inside engine room, close to mufflers, exhaust and tyres. The classical approach has been extended to time-domain simply working directly on the recordings measured by the indicator microphones and applying time filters derived from the transfer functions. The procedure for performing such analysis has been reported earlier [4], but is briefly reviewed in the following.

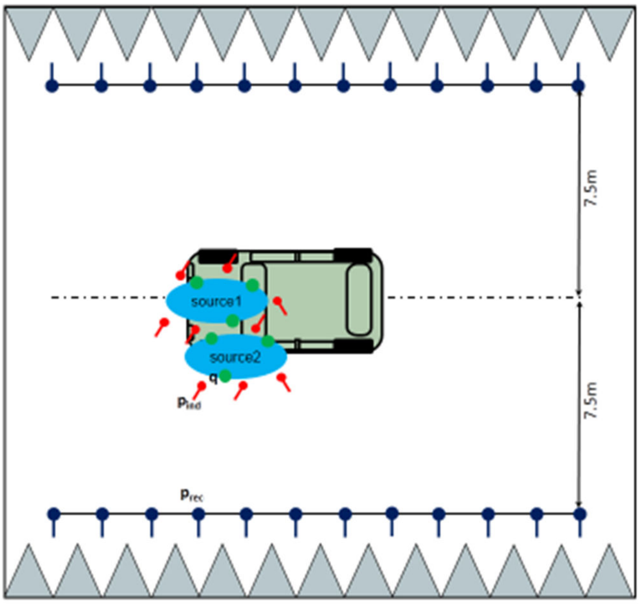

Figure 2: SPC modeling of vehicle noise sources for indoor pass-by contribution analysis.

In figure 2, a vehicle setup is shown involving two noise sources modelled by a set of distributed point sources. Indicator microphones are placed close to the chosen point sources and by measuring every acoustic transfer function between any point source and all indicator positions we may be able to deal with the problem of crosstalk, i.e. an indicator microphone close to source 2 measures a mixture of both source 1 and source 2 contributions. The cancellation of any crosstalk is however very dependent on the chosen point source models and the quality of the measured transfer functions. The transfer function matrix between point sources and indicators is inverted and turned into inverse filters. Indicator recordings during pass-by acceleration are filtered by the matrix of inverse filters to get source strength time histories for every point source in the model.

$$\boldsymbol{q}_{src}(t) = \boldsymbol{H}(t) * \boldsymbol{p}_{ind}(t) \tag{1}$$

Here $\boldsymbol{H}(t)$ is a n x m matrix of sufficiently long inverse filters, n is the number of point sources in the model and m is the number indicator microphones.

The contribution from each component source to one of the receiver microphones of the pass-by array is found by adding the corresponding point sources:

$$p_{rec}(t) = \sum g(t) * q_{src}(t) \tag{2}$$

Where $g(t)$ is another time filter from source to receiver made from the measured transfer function and the sum is taken over the set of point sources belonging to a component source. Repeating this for every component source and every receiver microphone results in predicted contributions all synchronized with the indicator recordings and the corresponding vehicle speed. Pass-by noise contributions are calculated using the indoor simulated pass-by algorithm on the contribution time data for the pass-by array.

As opposed to consider the full matrix $\boldsymbol{H}$ of all source positions and all indicator positions in the same matrix, and as such model all possible crosstalk between noise source components, a component submatrix solution approach can be used to model only the relevant crosstalk. For example, when engine noise is strong compared to front tyre noise, engine noise crosstalk will appear at the front tyre indicator microphones but very little front tyre noise contribution at the engine indicator microphones inside the engine room. In that situation we should only allow for removal of engine noise contribution at the front tyre indicators. This is controlled by solving a set of smaller submatrix problems in an appropriate sequence. Additionally, by considering only small component transfer function matrices numerical issues with matrix inversion becomes less severe since the matrix condition numbers are much smaller. The important thing though is to make the correct sequence of matrix solutions in order to remove relevant crosstalk only. Figure 3 shows one such sequence indicating that as a first step the source1 component source strengths are found from corresponding indicator microphone sound pressures $\boldsymbol{p}_{source1}(t)$ and the local transfer functions (FRF's) for that source only. Next, the source1 contributions are subtracted from source2 indicator sound pressures and with the modified source pressures $\tilde{\boldsymbol{p}}_{source2}(t)$ and the local transfer functions for that component source its source strengths are estimated. This is repeated until all component source strengths are estimated. The stronger noise sources should therefore appear at the beginning of the sequence. Pass-by noise contributions are obtained from the estimated component source strengths propagated to the pass-by array microphones and finally performing indoor simulated pass-by calculations.

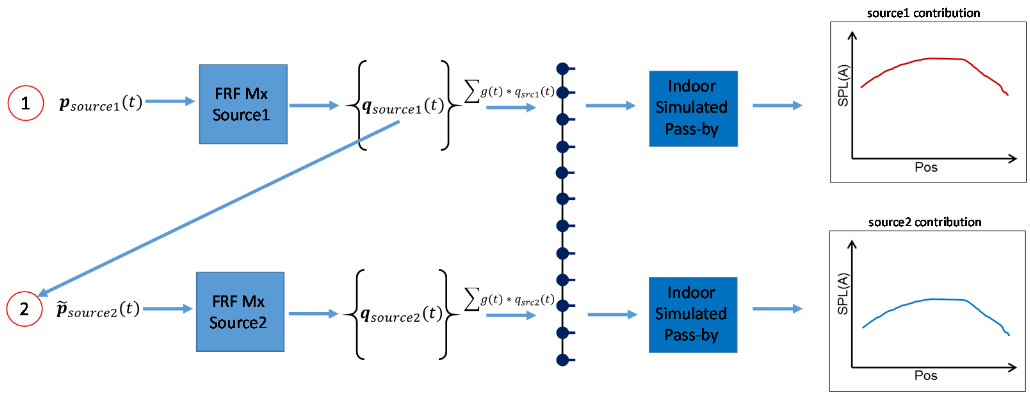

Figure 3: Example of submatrix solution sequence for estimating volume velocity source strengths for setup in figure 2 and eventually predict pass-by noise contributions.

3.2 Blind source separation approach

Blind source separation (BSS) refer to signal processing methods with the aim of separating different source signals from a mixture of sources using little information about the source signals and the mixing process. In acoustics the mixing process of different sources at sensors is complicated by the fact that the propagation is convolutive due to delays and reflections between sources and sensors. Many different methods have been proposed in the past to solve the separation problem at the sensors, most methods focused on music and speech related problems and algorithms working in either frequency domain or time domain are reported. BSS on industrial type of signals is however rarely found. Most methods make the assumption, that the source signals are independent and other signal properties like non-stationarity may also be exploited [5].

For the current problem of separating vehicle noise sources during a fast acceleration, a time domain method for separating microphone recordings into so-called independent components (IC) is employed. The basic principle of the selected separator is to make use of a linear prediction approach to model the time correlations of a set of recorded mixtures, here called reference signals $\boldsymbol{p}_{ref}(t)$. A matrix of whitening filters $\boldsymbol{W}(t)$ can be estimated from the correlations which ensures a set of whitened signals $\boldsymbol{u}(t)$ to be produced

$$\boldsymbol{u}(t) = \boldsymbol{W}(t) * \boldsymbol{p}_{ref}(t) \tag{3}$$

The feature of $\boldsymbol{u}(t)$ is that the samples of each signal $u_i(t)$ are now uncorrelated, and $u_i(t)$ and $u_j(t)$ are uncorrelated as well. Final step is to solve an instantaneous BSS problem looking for a matrix $\boldsymbol{B}$ which rotates the whitened data to find the most the independent time series, the independent components in the vector of time series $\boldsymbol{y}(t)$. Standard algorithms may be applied here using either higher-order or second-order statistics.

$$\boldsymbol{y}(t) = \boldsymbol{B} \cdot \boldsymbol{u}(t) \tag{4}$$

Such two-stage linear prediction approach for solving the convolutive BSS problem has been proposed for blind identification of communication channels [6] and other variants of this implementation for source separation are reported as well [7].

Having separated into independent components, contribution filters can be estimated using time recordings at the desired receiver microphones which had been measured together with the set of reference microphones.

3.2.1 Validation of BSS for engine and tyre noise separation

In order to demonstrate the capabilities of the chosen BSS strategy for noise source separation, a simple yet challenging experimental test setup was considered. A small vehicle located in a normal room served as scattering object and two speakers were positioned around the vehicle. One box loudspeaker on the floor at the right-hand side of the vehicle and a tyre structure with built-in speaker was positioned at the rear left-hand side of the vehicle. A set of 4 reference microphones were mounted on the floor in positions between the two considered speaker sources, in addition to an array of microphones placed along the vehicle left hand-side to represent a set of pass-by receivers. The setup is sketched in figure 4.

Real recordings from another measurement served as input for the two speaker sources, an engine signal consisting of engine orders only was sent to the box speaker to produce pure engine noise an another signal made by a recorded tyre signal with all engine orders removed was sent to the tyre speaker to represent pure tyre noise. Both recordings were originally taken during a pass-by acceleration test with and after modification they are considered as independent signals making them amenable for BSS analysis. All time recordings for this validation case were done using a sampling frequency of 32768 Hz and about 12 seconds of data was recorded.

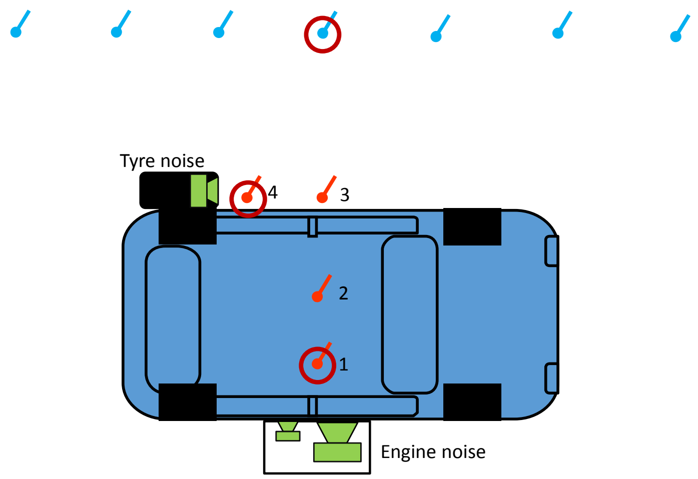

Figure 4: Two-speaker setup around small vehicle for evaluation of BSS separation. Reference microphones are placed close to the speakers and a set of far-field microphones serve as pass-by receivers. The microphones marked with a circle are used in the validation study presented here.

By playing the two signals simultaneously through the speakers mixtures are created at the microphones in the setup, as would be the case during a real vehicle operating. The advantage of the setup is that each speaker can play solo to create the true contributions at the microphones for validation purposes. The convolutive mixture of the tyre and engine signals as picked up by the two reference microphones closer to the speakers, i.e. reference #1 and reference #4 are used in the adaptive blind separation stage to generate two new signals which are independent. The independent signals are not associated with any particular position from the setup and the order in which they appear at the output of the unmixing process is arbitrary. So to make meaningfull use of the independent signals it is necessary to identify which noise source process each IC belongs to.

Before processing the measured reference microphone mixtures the data samples were down-sampled with a factor 2 to reduce the number of samples and possibly reduce the length of the unmixing filters. This so-called subband processing is a standard BSS procedure and after processing the time data can be up-sampled again [8]. Note, if the data is split into several subbands for processing, independent components belonging to different subbands must be combined to form the full-band signals again, but since the independent component order is unknown for each subband this associated permutation problem must be solved. In our case only one subband is considered so this permutation problem is not an issue. Next, the unmixing filters are learned using the 12 seconds of data, i.e. the whitening filters are constructed and the data whitened followed by solving an instantaneous problem. The only parameter set is the filter length of the whitening filters. The output of this procedure is two independent component time signals, which are filtered versions of the clean reference signals related to either of the two speakers. The independent components are now correlated with the input signals (reference #1 and reference #4) to calculate a set of time filters between IC's and the two reference microphones. Finally, we can transform each IC into a time-domain contribution at a reference microphone, which re-scales each independent component back to sound pressure at the physical microphone positions. Results for this procedure in the given case is shown in figure 5. The mixture of reference #4 close to the tyre speaker is shown as spectrogram, then the contribution of the two IC's at this reference microphone is shown next and for comparison, we include the true contributions from the engine speakers and the tyre speaker. We notice that IC1 represents the tyre signal and IC2 the engine signal, and furthermore we see impressive agreement between the BSS separated contributions and the true individually measured contributions. Only very little engine noise is left in the tyre noise estimations, and vice versa, suggesting that the separation problem has been solved.

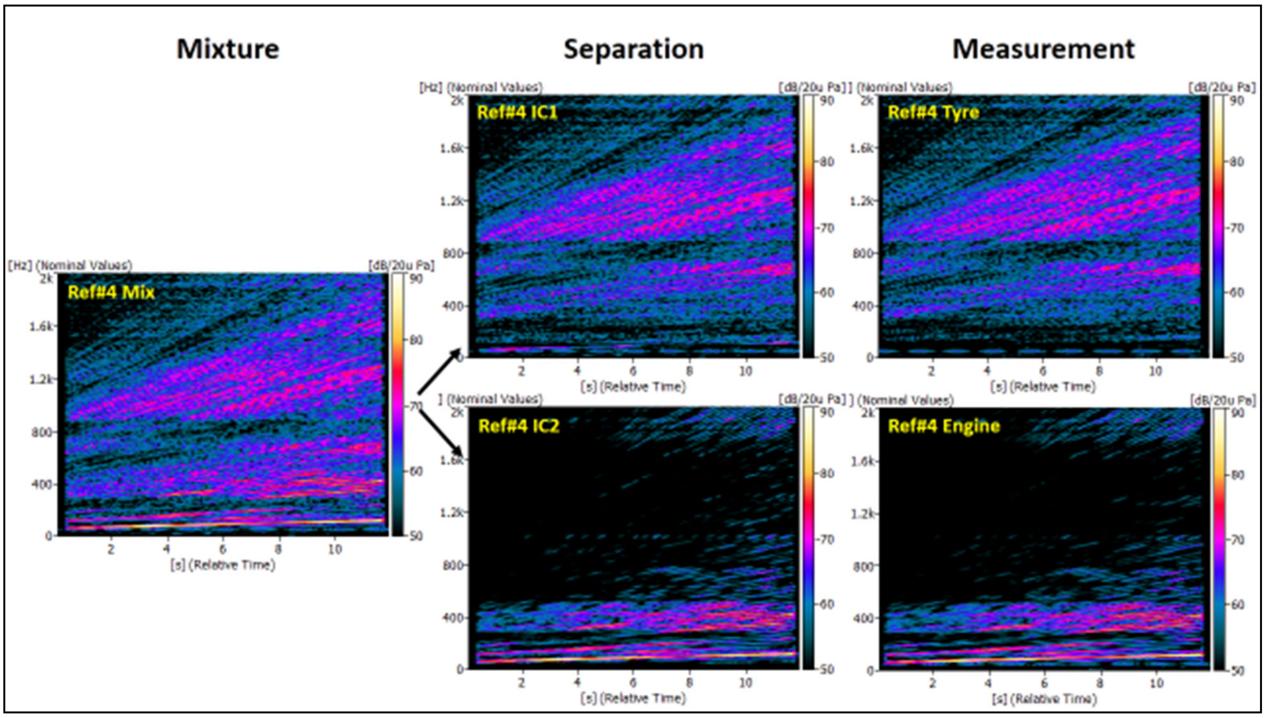

Figure 5: Spectrogram of engine/tyre mixture at reference #4 (left), contribution of separated independent components at reference #4 (center), true measured tyre and engine contributions at reference #4 (right).

The final step is to correlate the IC's found with the selected far-field receiver data measured simultaneously with the reference mixtures. Another set of filters are estimated from the IC's (input) to the receiver (output) and subsequently used to filter each IC to find the receiver contribution time signal. The average spectrum during the 12 seconds of measurement at receiver #4 is plotted together with the contribution from IC1 (tyre) and IC2 (engine). In figure 6, the average spectrum is shown for the measurement at receiver #4 and compared with the sum of the two contributions from the IC's. We observe excellent agreement between the two spectra, telling us that the two derived independent components fully describe the measured signal at the receiver. Moreover, in figure 7 we plot the true measured average spectrum from each speaker against the independent component contribution spectrum which is identified to represent the corresponding speaker. Again, near to perfect agreement is seen suggesting that the convolutive mixing problem has been solved satisfactory.

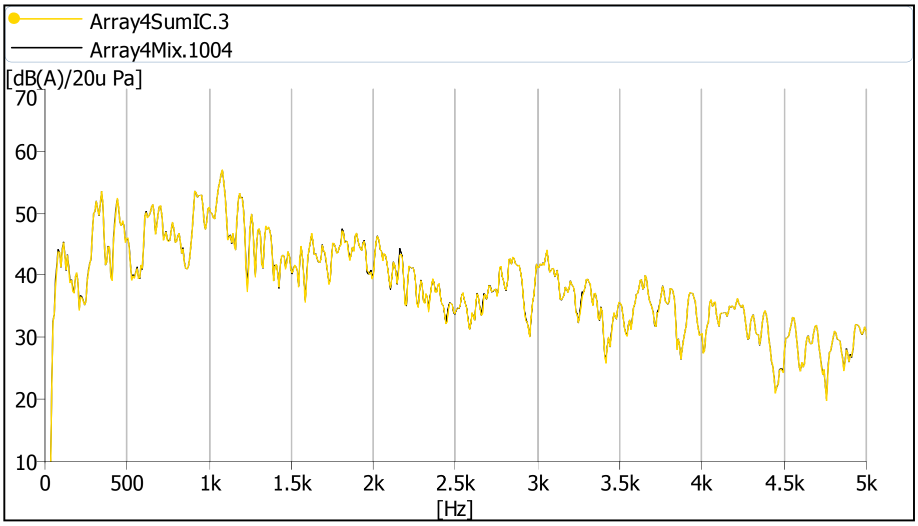

Figure 6: Average spectrum at receiver #4 for speaker mix measured (black) vs. sum of contributions from IC's (yellow).

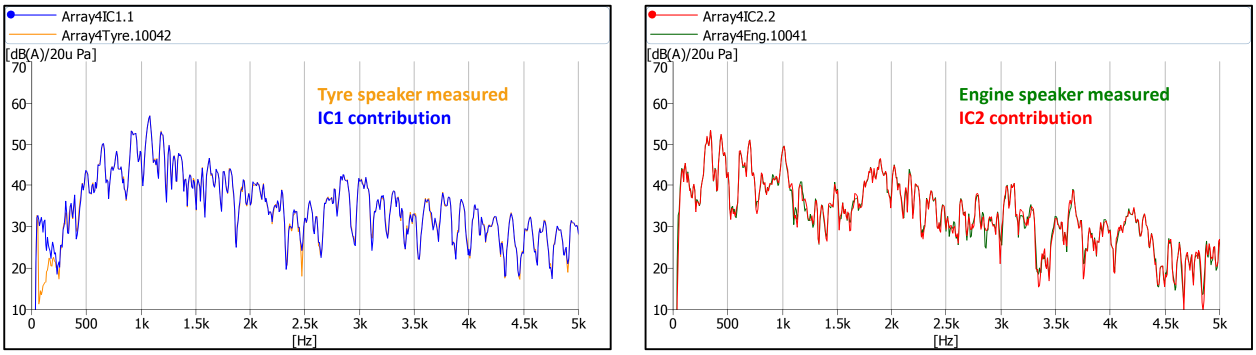

Figure 7: Average spectrum at receiver #4. Tyre speaker measured vs. contribution from IC1 (left). Engine speaker measured vs. contribution from IC2 (right).

4 Indoor pass-by measurement setup

A setup with a vehicle on a chassis dyno in an indoor pass-by test room is now considered. The test room could only accommodate a single-sided pass-by test with pass-by microphones at 7.5m, hence all results presented in the following refer to the left-hand side of the vehicle. The engine midsize passenger test vehicle was equipped with normal tyres making tyre contribution to pass-by noise significant. In total 25 indicator microphones were placed close to potential noise sources (engine, intake, mufflers, exhaust and tyres) of the vehicle and 20 source positions were distributed among these noise sources. The contribution from the right-hand side tyres to the left-hand side pass-by noise is neglected in this study, hence no indicator microphones were placed close to these tyres. 12 pass-by microphones covered the left hand-side of the vehicle. The spacing between the pass-by microphones was 1 m for the microphones closer to the vehicle whereas other microphones were spaced by 2 m. A picture of the single-sided indoor pass-by setup is shown in figure 8.

Figure 8: Single-side indoor pass-by measurement setup with additional indicator microphones for contribution analysis.

Two separate measurement tasks must be completed to do the indoor pass-by test including the additional contribution analysis. For different pass-by conditions (acceleration and constant speed test) time data of all microphones in the setup and the required tachometer pulses were recorded with a sampling rate of 16384 Hz. Following the operational measurements, a volume velocity source was used to measure acoustic transfer functions from a source position to all microphones in the setup. This was repeated for every source position of the vehicle SPC model. The frequency range considered for these tests was up to 6.4 kHz.

5 Pass-by acceleration results

An acceleration test in 3rd gear is analysed using a dataset performed as described previously. The synchronization condition chosen here is 50 km/h at the center (x=0 m) of the virtual pass-by track according to the new ISO 362 test procedure. From that condition the simulated pass-by time signal is constructed and turned into overall SPL(A) as a function of the vehicle position inside the virtual pass-by track. This process is carried out for the recordings made at the pass-by array microphones during the acceleration test and also for the source contributions resulting from the SPC analysis of the indicator microphone recordings and the corresponding transfer functions. From the initial set of source and indicator positions a subset was selected to avoid numerical problems during the calculation of source strengths. 24 indicator microphones and 15 source positions were used for the SPC contribution analysis and the component submatrix solution approach described earlier was adopted with an appropriate sequence to minimize the influence of crosstalk between source components. The result of summing all source contributions and compare with the indoor pass-by result can be used to verify that all pass-by noise contributors were picked up by the indicator microphones. Processing results for the acceleration operating condition are shown in figure 9. Notice, that the result is shown from vehicle position -10 m to +10 m although the pass-by microphones only covered the vehicle positions from roughly -4 m to +10 m, so the extrapolation capability of the indoor pass-by calculations has been used. We observe fine agreement between the indoor pass-by result and the sum of all contributors from the vehicle SPC model, i.e. all significant noise sources are included in the analysis. Individual contributions reveal dominating engine noise contribution to pass-by noise with intake and tyre noise contributing significantly as well. The exhaust outlet is a major contributor towards the exit of the pass-by track.

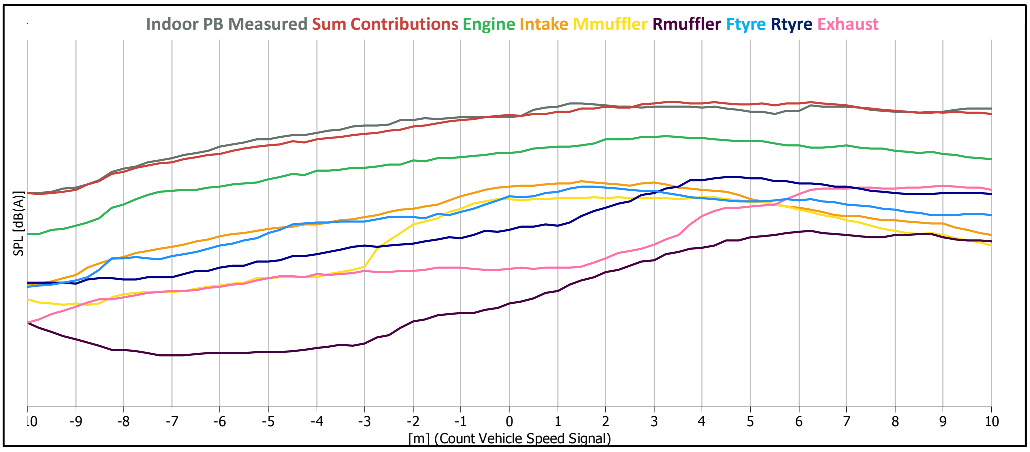

Figure 9: Overall SPL(A) vs. vehicle position for 3rd gear acceleration pass-by test. Indoor pass-by results and source contributions from SPC vehicle model.

For a given vehicle position the 1/3 octave band levels can be investigated to see how the peak overall SPL(A) is composed. Figure 10 provides the 1/3 octave contribution levels at vehicle position +4 m. Acceptable agreement between what is measured by the pass-by microphones and the model prediction (Sum Contributions) is found. Engine contribution is dominating most of the frequency bands with significant tyre contribution at higher frequencies in particular in the 1 kHz band.

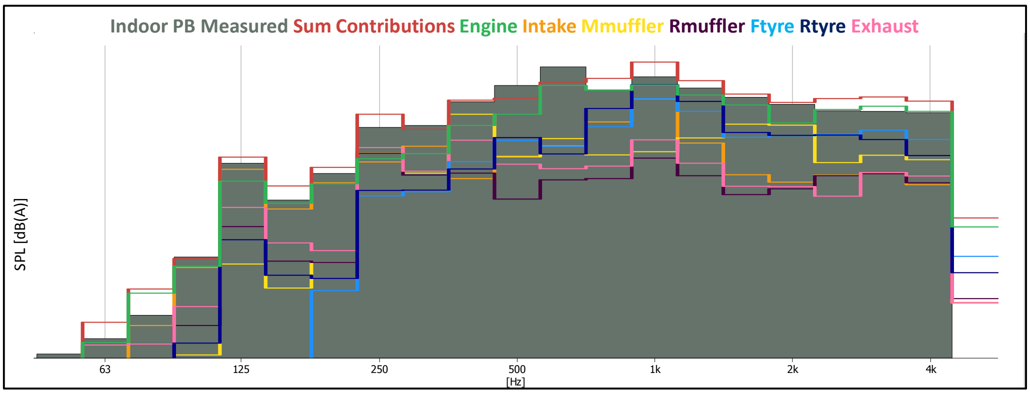

Figure 10: 1/3 octave contribution analysis corresponding to vehicle position +4 m during acceleration pass-by test. Indoor pass-by result and SPC source contributions.

The SPC modeling of the vehicle revealed fine agreement between the noise prediction and the direct result from the pass-by microphones however the individual source contributions are by nature more difficult to validate. The attempt taken here will be to make use of the described blind separation technique to estimate the pass-by noise contribution from the front and the rear tyre, respectively, and compare with the SPC prediction.

The measured set of indicator recordings can serve as input data to the blind separation process of identifying a set of independent components for the noise processes during vehicle operation. In this study 23 reference microphones were selected from the 25 available indicator microphones. 2 engine room indicator microphones were discarded. From the 3rd gear acceleration recordings, 12 seconds of data were picked representing the run-up and coast-down part, and this time data was down-sampled to 8192 Hz to reduce the amount of data. In effect, only the frequency content up to 4096 Hz is considered. The blind separation of the 23 reference microphone channels results in 23 independent component time signals which are sorted according to their power contribution at the 23 reference microphones thus making a labelling possible. 3 of the independent components were selected to represent noise processes caused by the front tyre and another 3 independent components represent the rear tyre. To understand if all the derived 23 independent components can represent the measured noise at the pass-by microphones the multiple input-multiple output problem between all independent component signals and all pass-by microphone signals is solved to obtain a matrix of time filters. All 23 independent components can be filtered and summed at one of the pass-by microphones and we can compare with the actual measured signals during the run-up and coast-down. The average spectrum comparison between the measurement and sum of all independent component contributions is performed for pass-by microphone #5, see figure 11. Below 1.6 kHz all of the noise measured by the pass-by microphone is accounted for by the independent components whereas at high frequencies there is a small gap between measured and reconstructed by the independent components, however the high frequencies are less important in the overall SPL(A).

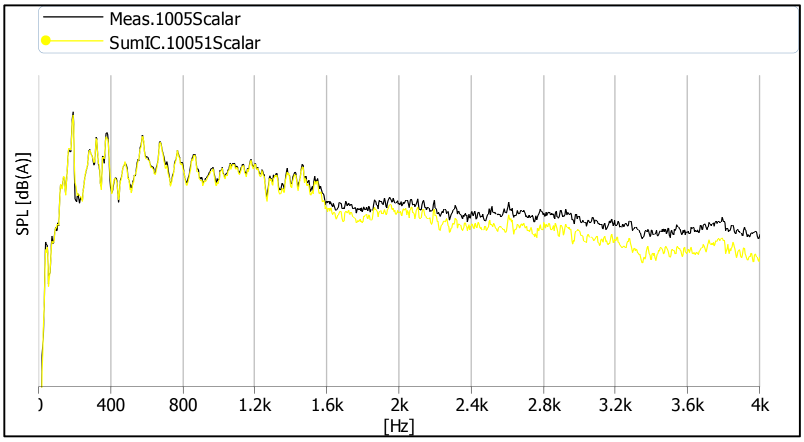

Figure 11: Average SPL(A) spectrum at pass-by microphone #5 during gear 3 acceleration. Measurement (black) and sum of all IC contributions (yellow).

Having established the matrix of filters between each independent component signal and each pass-by microphone, we can calculate and listen to the contribution from each independent component at a pass-by microphone. Furthermore, the contributions of the 3 identified independent components for each of the two tyres are summed at every pass-by microphone and the resulting time signals are combined with the original tacho signal recordings for indoor simulated pass-by evaluation. As a result we get an estimate of the front tyre and the rear tyre pass-by noise contribution provided by the BSS approach. A comparison of the predicted tyre contributions from the two methods considered is shown in figure 12.

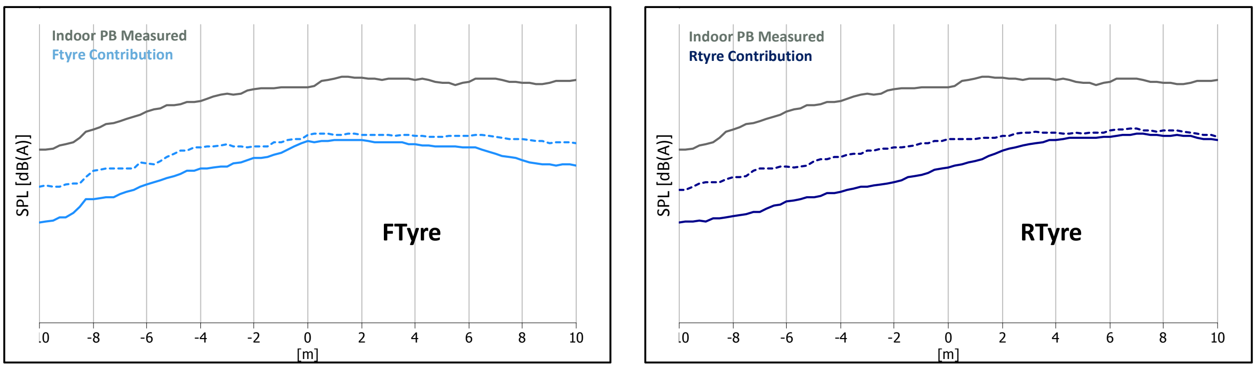

Figure 12: Overall SPL(A) vs vehicle position for gear 3 acceleration pass-by test. Indoor pass-by measured (grey) and tyre contributions estimated by SPC (solid) and BSS (dashed) methods for front and rear tyre.

At vehicle positions where the tyres contribute the most to the pass-by noise we have comparable levels from the SPC and the BSS approach, whereas BSS provides higher levels in general. Figure 13 compares the 1/3-octave levels at vehicle position +4 m for the two tyres. The front tyre contributions for SPC and BSS are similar above 800 Hz whereas BSS shows more pronounced low frequency content compared to SPC. The rear tyre contribution spectra are comparable.

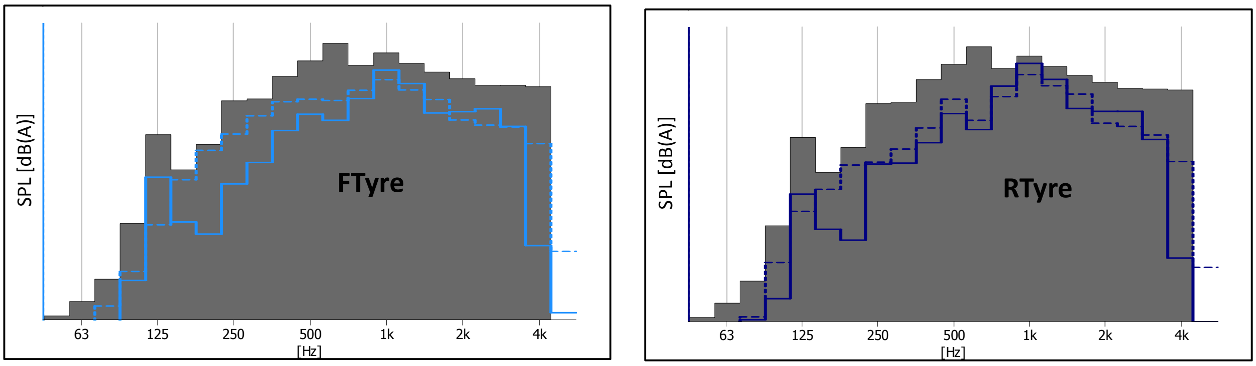

Figure 13: 1/3 octave spectrum at vehicle position +4 m during gear 3 acceleration pass-by test. Indoor PB measured (grey) and source contributions (SPC=solid, BSS=dashed).

6 Pass-by constant speed results

A 3rd gear constant speed test (50 km/h) was processed and analysed in a similar fashion using the same source positions and indicator microphones for the SPC model as for the acceleration case. The submatrix calculation was employed for estimating source strength time data with minimum crosstalk between noise source components. Here the submatrix solution sequence differed from the acceleration case since the crosstalk between components is different for each operating condition. The final SPC processing is though identical to the acceleration case and the obtained source contributions as overall SPL(A) during the pass-by test are plotted together with the indoor pass-by result in figure 14. Fine correspondence between indoor pass-by result and sum of all source contributions is observed. For this test condition the engine and the two tyres mainly contribute to the total measured pass-by noise.

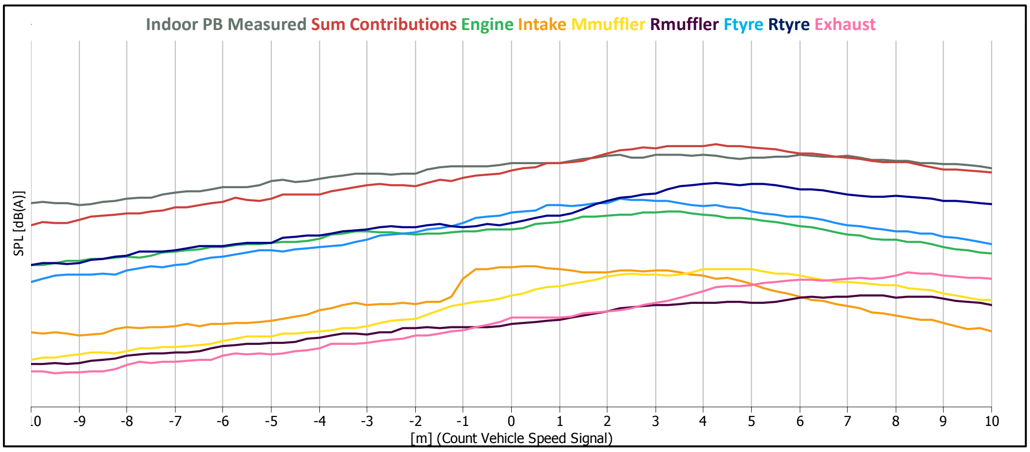

Figure 14: Overall SPL(A) vs vehicle position for gear 3 constant speed pass-by test. Indoor pass-by results and source contributions.

1/3-octave contribution results at vehicle position +4 m indicate that the pass-by noise at this position is dominated by the frequency content from 500 Hz to 2 kHz, and that the rear tyre is the main contributor, see figure 15.

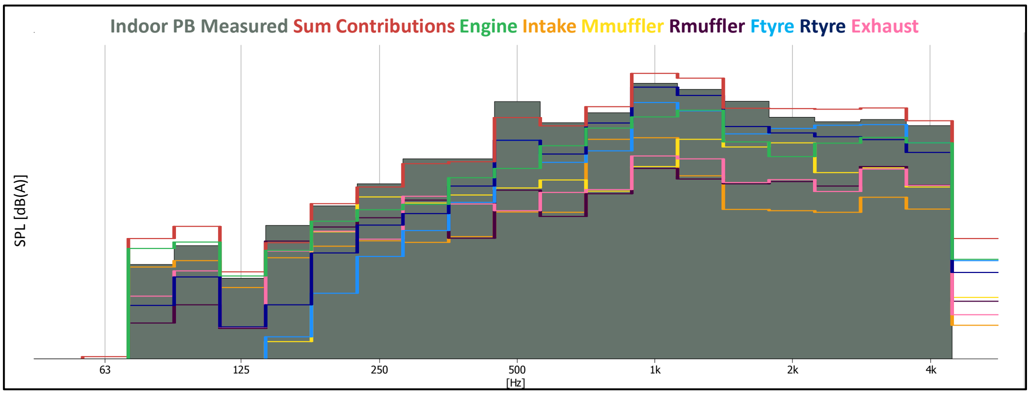

Figure 15: 1/3 octave contribution analysis corresponding to vehicle position +4m during constant speed pass-by test.

For verification, a blind separation of the operating time data at the same 23 reference microphones used for the acceleration case was performed using 12 seconds of data for each microphone. Down-sampling with a factor 2 was again performed before blind separation into independent components. A few independent components were seen to contribute almost exclusively to the noise measured with the indicator microphones close to each tyre, hence these independent components were selected to represent noise processes related to tyre noise generation. First of all it is examined if the 23 obtained independent components can represent the measured noise at the pass-by microphones, and compare the spectrum of pass-by microphone #5 with the sum of contributions from all 23 independent components. In figure 16 these two spectra are compared showing excellent agreement especially in the range between 400 Hz and 1.6 kHz where most of the signal power is present. Some low frequency harmonics are less well reproduced by the sum of independent contributions and at high frequencies we see a small gap between spectra indicating that more noise processes should be taken into account.

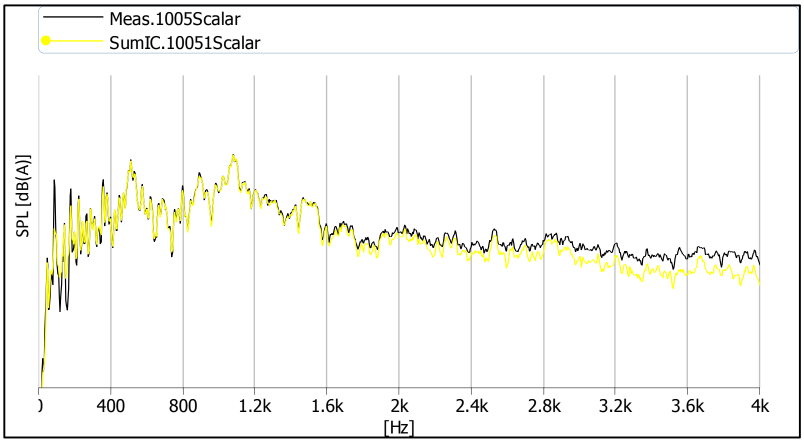

Figure 16: Average SPL(A) spectrum at pass-by array mic #5 during constant speed test. Measurement (black) and sum of all IC contributions (yellow).

The two sets of independent components representing each of the two tyres are processed to obtain an estimate of their pass-by noise contribution, see figure 17. For this condition we see a reasonably good agreement between tyre noise estimates from SPC and BSS approach over the whole pass-by track.

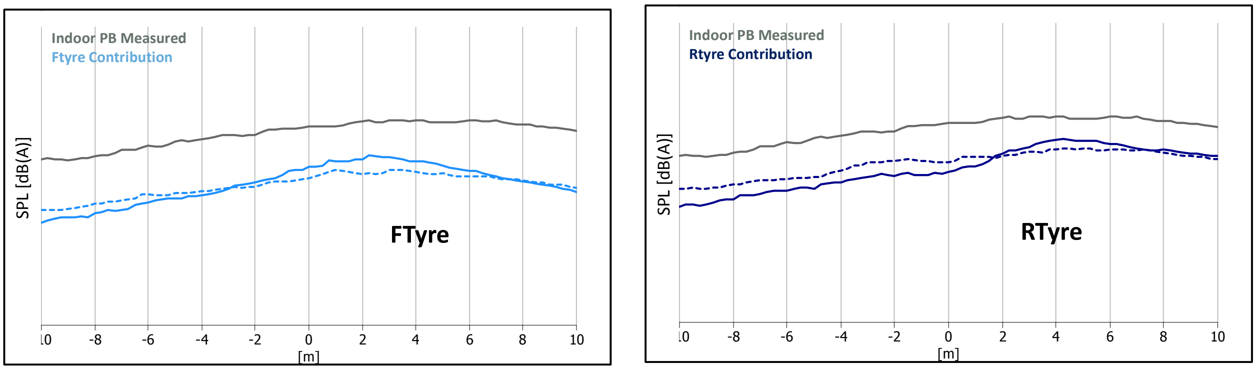

Figure 17: Overall SPL(A) vs vehicle position for constant speed pass-by test. Indoor pass-by measured (grey) and tyre contributions estimated by SPC (solid) and BSS (dashed) methods for front and rear tyre.

1/3 octave contribution spectra for vehicle position +4 m are compared in figure 18 showing good agreement between front tyre contribution spectra in particular in the range 500 Hz to 2 kHz which is dominating the overall SPL(A). For rear tyre contribution spectra, the SPC model estimates rather high levels around 1 kHz matching the total measured spectrum levels. Otherwise we have good correspondence between SPC and BSS 1/3 octave levels.

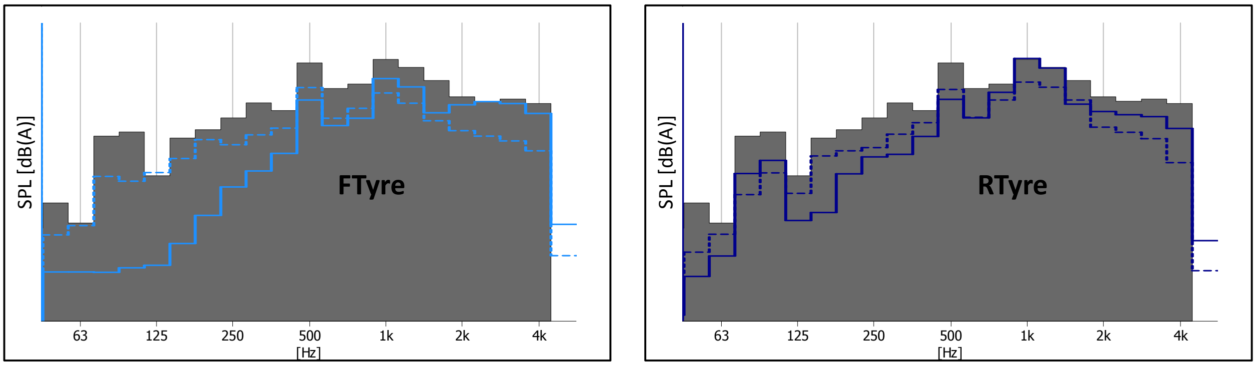

Figure 18: 1/3 octave spectrum at vehicle position +4m during constant speed pass-by test. Indoor PB measured (grey) and source contributions (SPC=solid, BSS=dashed).

7 Conclusion

This paper has dealt with indoor vehicle pass-by noise measurements for performing noise source contribution analysis in addition to the more conventional overall simulated pass-by evaluation. A vehicle SPC model approach was considered for separating noise source components using indicator microphone operating data and measured transfer functions. A component submatrix solution approach for estimating the source strengths of the vehicle SPC model was introduced. With this solution approach, relevant crosstalk between components is cancelled while the matrix inversion becomes more straightforward. The predicted pass-by noise from the vehicle SPC was compared with the indoor simulated pass-by result to verify the sum of all modelled contributions. Good correspondence was found for both the acceleration test and the constant speed test. Individual source contributions are harder to verify, the attempt described here was to use a new operational blind source separation technique for decomposing into at least individual tyre and engine-related noise contributions. Considering the assumptions in SPC and BSS, fine agreement between predicted tyre pass-by noise contributions were found. The BSS approach for noise source separation will be explored in more detail to determine how many reference microphones are needed to have adequate separation of vehicle noise sources. Further validations of both methods for accurate contribution analysis will be done.

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