DELIVERABLE 2.2

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	Evaluation of State of the Art Vehicles
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TABLE OF CONTENTS

0 EXECUTIVE SUMMARY 3
0.1 Objective of the deliverable 3
0.2 Strategy used and/or a description of the methods (techniques) used with the justification thereof 3
0.3 Background info available and the innovative elements which were developed 4
0.4 Problems encountered 4
0.5 Partners involved and their contribution 4
0.6 Conclusions 4
0.7 Relation with the other deliverables (input/output/timing) 5
1 Introduction 6
2 Principle of Component Synthesis 8
2.1 Component Measurements 8
2.2 SRTF 9
2.3 Synthesis 9
2.3.1 Radiation Filter 10
2.3.2 Extended Synthesis 10
2.4 Validation 11
3 Vehicle Setup 12
3.1 Power train 12
3.2 tires 13
4 Measurement 14
4.1 Input 14
4.2 SRTF 15
4.3 Real Pass-by 16
5 Synthesis 17
5.1 Hybrid Compact Class Car 19
5.1.1 acc50 20
5.1.2 const50 24
5.2 Commercial Van 31
5.2.1 acc50 31
5.2.2 const50 34
5.3 Public Transport Bus – Small 36
5.3.1 acc38 36
5.3.2 const38 38
5.4 Sub-Compact Class Car 40
5.4.1 *acc50* 40
5.4.2 const50 42
6 Conclusion and Outlook 44

0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The following report describes the work done and results gained in WP 2.1.2 during the first twelve months of the QCITY project. The main objective is the application of the quantitative component synthesis developed within the EU project SVEN by using SENSE[1] on selected vehicles of different transportation means. In this process, an extended synthesis approach will be implemented. The advantage of this approach is a simplified and more flexible measurement procedure using reciprocal measurements, radiation filters and avoiding a dependency on a semi anechoic chamber. This widens the range of measurable vehicles and improves synthesis results.

The data of the selected vehicles is recorded, synthesized and evaluated. The results are presented.

0.2 STRATEGY USED AND/OR A DESCRIPTION OF THE METHODS (TECHNIQUES) USED WITH THE JUSTIFICATION THEREOF

The selection of the vehicles aims on providing a wide range of acoustic characteristics. Different transportation means as well as specific concepts are considered.

The results of the measurements described in this deliverable should be a quantitative statement about the contribution of single noise sources of a vehicle to the overall exterior noise. An adequate method for gaining these results is represented by the component synthesis developed within the EU project SVEN and exploited in HAC software SENSE. Since the approach is not feasible for specific vehicles like a large public transport bus, the method and software is adapted to allow measurements without a semi anechoic chamber and a chassis dynamometer.

The evaluation of single vehicles contains the correlation of noise source contribution and overall noise to identify noise sources emitting specific patterns and/or dominating the overall noise. A comparison of the course of the SPL gives general insights about composition and relative importance regarding noise sources and overall noise.

The compiled data and results will be an essential input into WP2.2.2 to generate a tool for the calculation of perception quality of vehicle exterior noise and based on this a bonus-malus-sytem for vehicles and their noise sources. Regarding the traffic noise synthesizer (WP5.12) it will be possible to apply source specific mitigation measures properly only on the specific noise source, e.g. the effect of different road surfaces on rolling noise.

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[1] SENSE – software of HEAD acoustics, developed as an exploitation of the synthesis approach

0.3 BACKGROUND INFO AVAILABLE AND THE INNOVATIVE ELEMENTS WHICH WERE DEVELOPED

Within the EU project SVEN a method was developed, which allows the quantitative determination of single noise source contribution to the overall exterior noise in the time domain. This method was exploited for the HEAD acoustic software SENSE for commercial application. An extension of the original approach developed in SVEN was implemented, so the measurements of the transfer functions are performed reciprocally and if necessary without using a semi anechoic chamber. Radiation filters are introduced. This all widens the range of measurable vehicles and improves synthesis results.

0.4 PROBLEMS ENCOUNTERED

The implementation of the extended synthesis approach and the necessary adaptation of the analysis software SENSE were more time-consuming then expected. Therefore, the measurements and syntheses are still in progress and will be finished till the end of the work package in M18.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

The data acquisition serves not only the respective tasks in WP2.1 but generates also input to other work packages like WP2.2 and WP5.12. Further, the specific contribution of the different work package partners could not exactly be foreseen. Therefore the PM allocation between WP2.1.1 and WP2.1.2 is not restrained strictly.

HEAD acoustics (HAC) implemented the extended synthesis approach and adapted their SENSE software accordingly. The measurements and syntheses of the vehicles using the standard and the extended synthesis approach were performed by HEAD acoustics. Finally, the evaluation of the compiled data was performed by HEAD acoustics.

Goodyear (GOOD) supported several of the measurements.

STIB/MIVB (STIB) supported several of the measurements.

0.6 CONCLUSIONS

The application of the component synthesis procedure has been effective, especially the implementation of the extended synthesis approach into SENSE[2] using reciprocal measurements and avoiding a dependency on a semi anechoic chamber.

The data for the calculation of the source related transfer functions (SRTF) was previously recorded directly and in a semi anechoic chamber, which meant a high measuring effort concerning instrumentation and facilities. Further, the synthesis is a straight application of the SRTF on the input signals and therefore prone to errors from cross talking or wrong radiation models of the components.

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[2] SENSE – software of HEAD acoustics, developed as an exploitation of the synthesis approach

With the extended approach the SRTF measurements are performed reciprocally with a monopole sound source, leading to a simplified and faster instrumentation. A special recording and analysis technology has been used allowing sample-precise synchronous play-back and recording of pseudo noise signals. The advantages of this are the possibility to perform the measurements without a semi anechoic chamber and more precise SRTF, especially regarding the phase response.

The effect of errors in the radiation models on the synthesis result – which increases for the reciprocal measurements – is compensated by the implementation of radiation filters. These filters consider the radiation characteristics of functional component groups. The determination of these radiation filters requires a chassis dynamometer. Since this is not available for public transport busses, the software had to be adapted to allow synthesis calculation and reviewing using less or foreign radiation filters.

All this widens the range of measurable vehicles and lowers costs.

So far, data for various transportation means has been recorded, successfully synthesized and evaluated. This includes a hybrid car, two public transport busses, a commercial van and a sub-compact class car. Further measurements and syntheses will follow to complete the data acquisition phase. The data will provide input for future deliverables (D2.9) and several work packages (WP2.1, WP2.2, and WP5.12).

0.7 RELATION WITH THE OTHER DELIVERABLES (INPUT/OUTPUT/TIMING)

D2.9: Input of data and further evaluations

D2.8: Input of data

Auralizer (WP2.2.3): Input of data into sound library

Traffic noise synthesizer (WP5.12): Input of data and results on noise sources

1 INTRODUCTION

In WP2.1 data about different transportation means and their respective noise sources is collected and evaluated to rank the noise source elements (D.2.10 M18) and draw conclusions about the future potential of the noise sources (D2.9 M18). Two different approaches are chosen to collect the data. On the one hand, a comprehensive overview over a large number of vehicles and transportation means and their noise sources is needed to get an impression how the current urban traffic noise is composed – beginning from the single noise sources up to vehicle classes and groups. The measuring procedure for this overview cannot be very in-depth but rather qualitative due to the large number of vehicles to consider. On the other hand selected vehicles will be analyzed more thoroughly to determine quantitatively the contribution of single noise sources to the overall noise of a specific vehicle. The former method is subject of WP2.1.1 and its progress is described in D2.1. The latter is the objective of WP2.1.2 and the current status subject of this deliverable.

WP2.2.2 will rely on all the gathered time signals to carry out listening test and psychoacoustic analyses. The exterior noise of the various vehicles will be compared and the determined contributions of the noise sources will be evaluated. The qualitative results of listening tests will be used to define an algorithm using quantitative psychoacoustic parameters and to generate a bonus-malus-system for vehicles and their noise sources. Hereby, a tool for the calculation of the sound quality of pass-by noise is created and will be implemented in the Auralizer software (WP 2.2.3). This will be further enhanced and improved for traffic noise in WP5.12. Concerning WP2.2.3 the recorded data is a part of the sound library of the Auralizer software and therefore accessible for all the partners within QCITY. It can be subject to filtering and testing the effect of the screening techniques and mitigation measures developed within SP4.

All the topics mentioned above are strongly related to the development of the traffic noise synthesizer in WP5.12. The gained recordings of and information about single vehicles and their noise sources in specific driving situation will be combined for the auralization of a traffic flow at a specific road section with a specific vehicle fleet composition. Mitigation measures for specific noise sources can be auralized adequately, e.g. by applying road surface effects only on rolling noise. The synthesized traffic flow can then be analyzed concerning its perception quality using the results of the psychoacoustic analysis.

The following report describes the work done and results gained in WP 2.1.2 during the first twelve months of the QCITY project. The main objective is the application of the quantitative component synthesis developed within the EU project SVEN[3] on selected vehicles of different transportation means. In this process, an extended synthesis approach will be implemented. The advantage of this approach is a simplified and more flexible measurement procedure using reciprocal measurements, radiation filters

[3] using the HEAD acoustics software SENSE

and avoiding a dependency on a semi anechoic chamber. This widens the range of measurable vehicles and improves results.

The data of the selected vehicles is recorded, successfully synthesized and evaluated. The results are presented in the next chapters.

2 PRINCIPLE OF COMPONENT SYNTHESIS

The applied method bases on the exterior noise synthesis developed during the EU project SVEN. It is exploited for the HEAD acoustics software SENSE. The concept is universally applicable for the simulation of exterior noise. The calculation of vehicle pass-by noise is only one possible application.

The main idea is to compose the radiated noise of an object from the contributions of its single noise sources – called components. The influence of a single noise source on the overall noise at an arbitrary listener position in the far field is determined by the so-called transfer path.

Therefore, in the application the following steps are necessary:

1. Measurement of the single noise contributions of the components in the near field
2. Measurement of all transfer paths between the components und the listener positions
3. Simulation of a time signal in accordance to a real pass-by situation using component synthesis
4. Measurement of a real pass-by for later validation of the synthesis result (optional)

2.1 COMPONENT MEASUREMENTS

For the measurement of the input data the vehicle is run on a test track or a chassis dynamometer.

In principle, any driving situation can be considered. For QCITY two situations are chosen:

- pass-by with constant speed e.g. 50 km/h – *const50*
- pass-by with wide open throttle (WOT) e.g. from 50 km/h (following ISO 362) – *acc50*

All dominant noises sources – the components – are recorded by microphones placed in the respective near field (e.g. engine, tire, exhaust, see chapter 3). Additionally, the speed of the vehicle is recorded.

Most of the measurements are conducted on the chassis dynamometer at HEAD acoustics in Herzogenrath, Germany. The dynamometer is placed in a semi-acoustic chamber. Ideally the room should show the dimensions of the test track as defined in ISO 362 (approx. 26 x 15 m). Then it is possible to record the vehicle noise in the far field with a microphone array at a distance of 7.5 m on both sides of the vehicle. The length of the array should be 26 m (± 13 m). The recorded far field signals serve as a reference for the component synthesis.

Since the room at HEAD acoustics does not provide these dimensions the microphone array is placed at a distance of 4 m and the recorded signals are extrapolated to 7.5 m during the following synthesis.

For the input measurements on a test track the array recordings are omitted.

2.2 SRTF

The source related transfer functions (SRTF) are the airborne transfer functions between the near field microphones and any position in the far field. For the calculations of pass-by situations it is sufficient to determine the SRTF for the dimensions of the ISO test track (± 65° perpendicular to the driving direction).

Within the HAC software SENSE the determination of the SRTF is now done reciprocally with a monopole sound source. Therefore, the monopole sound source (with known radiation characteristic) is moved over the respective angular range (respectively placed on the positions of the microphone array of the input measurements). The radiated noise is recorded with all near field microphones simultaneously. Additionally, the input voltage of the monopole sound source is recorded.

The recordings should be carried out either in a semi-acoustic chamber or under free field conditions (e.g. parking lot) to avoid influences of the room acoustics in the recordings.

A dodecahedron system of the Institute of Technical Acoustic, Aachen University, Germany is used as monopole sound source. It consists of three single loudspeaker systems:

- a subwoofer for the frequency range of 20 Hz – 200 Hz (woofer)
- a dodecahedron for the frequency range of 200 Hz – 1,200 Hz (mid range)
- a dodecahedron for the frequency range of 1,200 Hz – 4,500 Hz (tweeter).

Beyond the stated frequency ranges the subsystems show a significant directivity. Nevertheless, the tweeter system is used also for the higher frequency range of 4,500 Hz – 16,000 Hz. This is done to complete the necessary frequency range for a good hearing impression after the auralization.

Due to the number of subsystems and frequency ranges respectively three to four measurements are required for each point, for which a SRTF shall be determined.

2.3 SYNTHESIS

For the synthesis of the far field signal at a certain far field position the SRTF between the components and this far field position are calculated. The respective far field signal is then gained by filtering the input measurements with the SRTF and adding them up.

Yet, the resulting far field signals show differences compared to the reference recordings of the microphone array, which are due to cross talking and errors in the radiation model. This effect is even amplified by using the reciprocal SRTF measurements.

For compensation it is possible to apply radiation filters within the HAC software SENSE.

2.3.1 Radiation Filter

A radiation filter is used to compensate possible errors due to the modeling of the component radiation characteristics (especially errors in the positioning of the near field microphones) or cross-talking.

Therefore, as much as possible components should be recorded separately. The vehicle is conducted in an appropriate way and the radiated noise is recorded simultaneously with the component microphones and the reference microphones in the far field. On the 4-wheel chassis dynamometer at HEAD acoustics it is possible to investigate three different component groups:

1. power train: the dynamometer is in standstill and the engine is running at a typical engine speed at idle mode
2. front tires: the dynamometer drives the front tires, the engine is turned off and the rear tires stand still
3. rear tires: the dynamometer drives the rear tires, the engine is turned off and the front tires stand still

For each measurement a synthesis is done for the reference positions using all component microphones, even the ones not belonging to the current active component group. An average radiation filter is calculated out of the difference between the synthesized signals and the measured far field signals at the reference positions for each component group.

Only the power train can be investigated as a separate group of components if the measurements are done without a chassis dynamometer.

2.3.2 Extended Synthesis

The synthesis algorithm is then extended by the radiation filters described above.

Consequently, the procedure of the synthesis involves three steps, which are carried out for each reference point in the far field:

1. The signals of all near field microphones are filtered with their respective SRTF.
2. The filtered signals of all components belonging to the same component group are added up.
3. The summed-up signals of each component group are filtered with their respective radiation function and finally the filtered signals of the component groups are added up to the overall sound.

If necessary, the signals will be interpolated and extrapolated using a monopole approach during this procedure. For instance, the reference for the measurements at the HAC chassis dynamometer is located at a distance of 4 m. Hence, the synthesized signals will be extrapolated from 4 m to 7.5 m.

The resulting signals correspond to a measurement with a far field microphone array at a distance of 7.5 m. Binaural and monaural pass-by noise can be calculated using these signals when the following information is available:

- positioning of the microphones of the microphone array (angle and distance from considered vehicle at a reference point)[4],
- position of the observer relative to the reference point,
- speed vs. time function of the vehicle.

A binaural signal is necessary for aurally accurate play-back and sound evaluation purposes. In this document diagrams of monaural signals are used for a better illustration.

2.4 VALIDATION

A comparison of the calculated pass-by noise with real far field recordings of the respective driving situation gives information about the quality of the reproduction. Therefore, the synthesized driving situations have to be conducted with the vehicle on a test track and recorded accordingly.

[4] This defines also the maximum track section which can be synthesized regarding the angle of observation.

3 VEHICLE SETUP

Each vehicle to be measured has to be examined for its dominant noise sources. The number and type of components to be considered and the instrumentation effort can vary strongly. Nevertheless, often three main component groups can be identified: the power train, the rear and front (or driven / undriven) tires[5]. All components, which are identified as relevant, are equipped with a sufficient number of microphones to acquire its radiation characteristic.

In the following, the instrumentation procedure is shown exemplarily for the Toyota Prius.

3.1 POWER TRAIN

Essential contributions to the overall noise derive from the following parts of the power train:

- intake,
- engine and
- exhaust.

The noise radiation of the engine is recorded by five microphones in the near field around the engine (engine top, oil pan, engine driver side (ds), engine co-driver side (cd), engine front). The intake and the exhaust are equipped with one microphone in the near field each. Four of these seven microphone positions are shown in Figure 1.

[5] Wind noise has only little relevance for the exterior noise at the considered speeds.

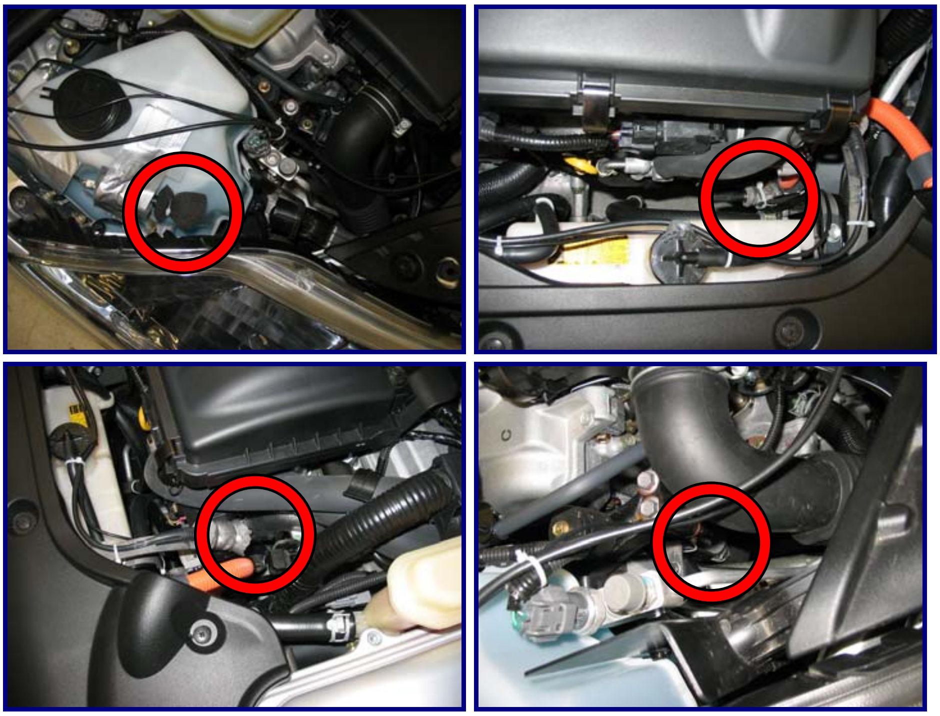

Figure 1: Examples for microphone positioning.
clockwise from upper left: intake, engine front, engine cd, engine ds

3.2 TIRES

Eight microphones in total detect the tire-road-noise. Every tire is equipped with two microphones – one at the leading edge, one at the trailing edge. By this, it is guaranteed that the different radiation characteristics of leading edge and trailing edge or driven and undriven tires respectively are considered. The microphones are positioned central to the tread and at a distance of 100 mm above the ground and 50 mm from the tire (Figure 2).

Figure 2: Positioning of microphones at the trailing edge of the right front tire (left) and at the leading edge of the right rear tire

All in all, the vehicle is equipped with 15 microphones for the measurement of the noise sources.

4 MEASUREMENT

Three measurements campaigns are necessary to get the required data base for the component synthesis:

- measurement of the input signals for the synthesis
- measurement of the SRTF
- measurement of a real pass-by for validation of the synthesis (optional)

Two pass-by situations are considered: a constant pass-by e.g. with 50 km/h – abbreviated with *const50* – and an accelerated pass-by e.g. from 50 km/h (following ISO 362) – abbreviated with *acc50*.

4.1 Selection of Vehicles

The selection of the vehicles aims on providing a wide range of acoustic characteristics. Different transportation means as well as specific concepts are considered.

The chosen vehicles include a hybrid car, a commercial van, two public transport busses (small and large), a sub-compact class car, a luxury class car and a all-wheel SUV. Thereby, different engine types, drive concepts and vehicle classes are considered.

Due to the small number of considered vehicles, it is not intended to make generalizations about certain vehicle classes. The results of the vehicle synthesis will rather present different acoustic characteristics of noise sources and exterior noise. On the one hand, they are analyzed in standard terms of spectra and SPL giving the component contribution in Hz and dB(A). On the other hand, an evaluation of the noise sources focusing on human perception will be performed in WP2.2.2. Using the results of this evaluation, the relevance of noise sources concerning their perception can be defined by analyzing their acoustic characteristics. The noise source potential derived from this procedure will be very effective and productive to choose measures for the improvement of the urban traffic soundscape.

The measurement of the SUV is not yet carried out, due to delays during the development of the extended synthesis approach and the necessary adaptation of the analysis software SENSE. It will be performed in February 2006.

4.2 Input

The input signals of the near field microphones are recorded either on a chassis dynamometer or on a test track (extended synthesis approach, Figure 3, Figure 4). A speed signal and – on the chassis dynamometer – reference signals of a microphone array (covering the necessary angular range) are recorded as well.

The two driving situations mentioned above are recorded. Either a light barrier (test track) or a manual trigger is used to mark the point of acceleration/WOT. By this, it is possible to determine the necessary time sequence for the synthesis.

For the radiation functions the sound of single component groups are recorded with the near field microphones and the microphone array. If no chassis dynamometer is available the power train is the only component group, which can be recorded separately in this way. A coast-by measurement can be performed for the assessment of the tire noise. Unfortunately, this is not possible for the measured public transport busses, since their engine cannot be turned off while rolling.

Figure 3: Toyota Prius on the chassis dynamomter, right: with microphone array

Figure 4: VanHool A308 on the test track

4.3 SRTF

The measurements are carried out in a semi anechoic chamber in the free field.

Beside the signals of the near field microphones, the input voltage of the dodecahedron is recorded. Together with a calibration curve of the dodecahedron (voltage to pressure) this serves as reference for the calculation of the transfer functions.

The monopole sound source is placed successively on the same positions as the reference microphones before (Figure 5). For each position the different frequency ranges are measured separately. A pseudo noise signal is used as excitation signal for the recordings. It is played back over a multiple of the period length of the pseudo noise. The respective pseudo noise and microphone signal is averaged for the later determination of the airborne transfer path between far field position and a specific component microphone.

Figure 5: Monopole sound source. left: tweeter dodecahedron, right: mid range dodecahedron mounted on the subwoofer (not scaled)

4.4 REAL PASS-BY

These measurements are carried out on a test track, which meets the demands of the ISO 362.

The recorded signals derive from the near field microphones, from far field microphones according to ISO 362 (left and right side, 7.5 m distance, 1.2m height) and a speed signal from an external radar or a sensor in the vehicle via telemetry.

The same driving situations as for the input measurements are carried out. If the input signals are also recorded on the test track, the input measurements and the real pass-by measurements are performed in parallel.

Figure 6: Measurement set-up on a test track

5 SYNTHESIS

The synthesis is performed using the HEAD acoustics software SENSE. To synthesize the exterior noise from the single contributions of a vehicle's components it is at first necessary to calculate the airborne transfer functions. The microphone signals and the input voltage recorded during the pseudo noise playback are averaged according to the period length to minimize disturbances and to maximize the signal-to-noise-ratio in the respective frequency range. These averaged signals are used to calculate the transfer functions of the components for the different frequency ranges. The *Source Related Transfer Function* (SRTF) of each component results from adding the transfer functions for one component and one far field position to cover the whole frequency range in one function.

The next step is the determination of the radiation functions and their integration in the model. This is necessary to compensate influences of the measuring environment, cross talk and errors in the radiation model[6]. In general, this is done by a comparison of the recorded far field signals of the microphone array and the far field signals calculated from the near field. The contributions of the components to each microphone array position are calculated using the before gained SRTF and summed up for each position. The result is compared to the separate measurements of the component groups. The averaged difference over all array positions gives the radiation function for the respective component group.

The synthesis is now calculated in the following way:

1. Filtering of the near field signals with the respective SRTF
2. Subsuming specific components into component groups and filtering the summed up signals of these groups with the respective radiation function
3. Summation of the time signals of the component groups.

[6] The radiation characteristics of the single noise sources are complex and to a large extent unknown. They are rarely monopoles as it would be required for the direct application of the SRTF measured with the monopole sound source.

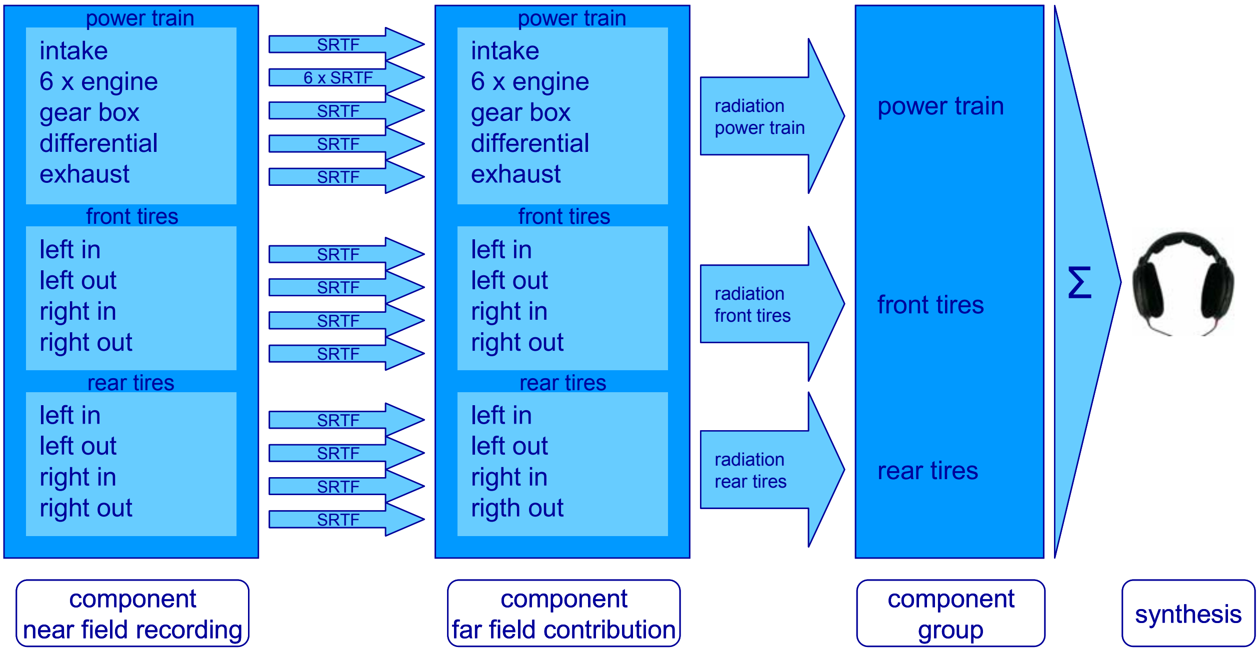

Figure 7: Scheme for the synthesis of a far field signal from component recordings (example of Toyota Prius)

The results of this procedure are time signals for the single reference points of a virtual microphone array. Binaural and monaural pass-by noise can be calculated using these signals when the following information is available:

- positioning of the microphones of the microphone array (angle and distance from considered vehicle at a reference point)[7],
- position of the observer relative to the reference point,
- speed vs. time function of the vehicle.

A binaural signal is necessary for aurally accurate play-back and sound evaluation purposes. In this document diagrams of monaural signals are used for a better illustration.

The exterior noise calculated from the signals of the microphone array serve as a reference for the exterior noise synthesized from the component recordings. If the two pass-by signals match, it can be assumed that the contributions of the component groups are determined correctly in level and frequency. Of course, this matching is only possible if the input data was recorded on a chassis dynamometer together with reference microphones.

The engine compartment acts as a pressure chamber especially regarding the low frequencies. This means, it exists a homogenous sound field and the recorded signals of the microphones in the engine compartment are not incoherent anymore. This can lead to an overestimation of the low frequency range of the engine compartment –

[7] This defines also the maximum track section which can be synthesized regarding the angle of observation.

e.g. main engine orders – during the synthesis. As a counter measure, the level of the input signals of the microphones in the engine compartment can by reduced accordingly. In turn, this can lead to an underestimation of the levels in the incoherent high frequency range.

Furthermore, it is often necessary to filter the signals of the tires with a high-pass. The lower frequencies are dominated by engine noise due to cross talk. This accounts of course more for the tires which are near by the engine than for the other tires. Since the typical frequency range for radiated tire noise lies in the mid and high frequency range a high-pass filter can compensate the crosstalk effect in a simple and sufficient way. The cut-off frequency has to be determined for each case and axle separately and can go up to 500 Hz.

The synthesis of the luxury class car and the second public transport bus is not yet finished, due to delays during the necessary adaptation of the analysis software SENSE. It will be performed till March 2006.

A comprehensive presentation of the results of the component synthesis for each measured vehicle would go beyond the scope of this deliverable. Therefore, an extensive overview is given exemplarily for the Toyota Prius in the following. The results for the other vehicles are presented as summaries including the main outcomes which are important for the QCITY project.

5.1 HYBRID COMPACT CLASS CAR

15 microphones are applied in and at the car for the input recordings:

- intake,
- 5 x engine,
- exhaust,
- 8 x tires.

The recorded driving situations include *acc50* and *const50*.

The measurements are carried out on the chassis dynamometer of HEAD acoustics and the test track of the IKA, Aachen University.

The comparison of the pass-by noise calculated from the array microphones and the one synthesized from the component shows a very good match (Figure 8). A general weakness of this method is the incorrect reproduction of frequencies below 35 Hz. Here the synthesized pass-by noise always underestimates the low frequency levels. This is due to the fact that the woofer cannot produce enough output level to generate a sufficient signal-to-noise-ratio in this frequency range.

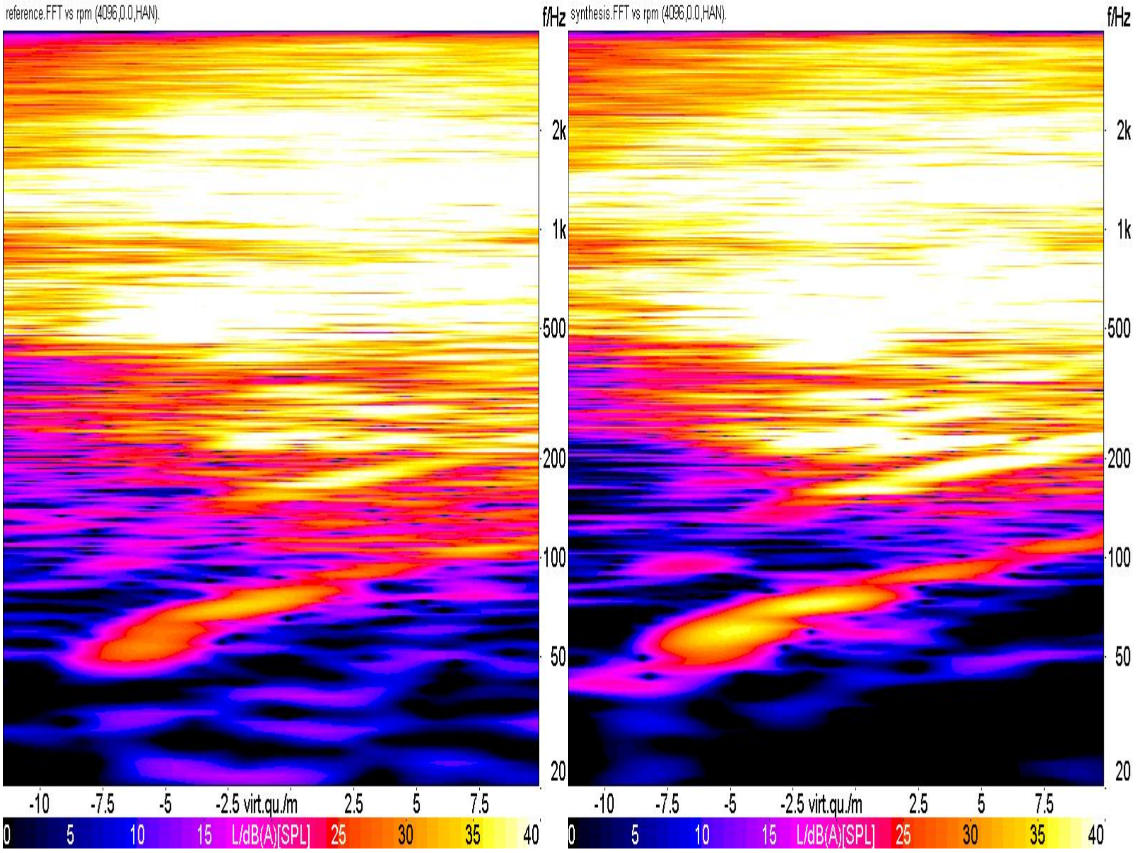

Figure 8: FFT vs. distance. Comparison of pass-by noise generated by calculation from the microphone array signals (left) and by component synthesis (right) for *acc50*

5.1.1 *acc50*

The contributions of the three component groups power train, front tires and rear tires are displayed in Figure 9.

The spectrum of the power train shows clearly the engine orders, and here particularly the dominating second engine order. Furthermore, resonances at about 230 Hz, 430 Hz and 830 Hz can be found.

The signals of the front tires are filtered with a high-pass at 300 Hz. The front tires are the dominating noise sources in the mid and high frequency range. High levels are reaches in the frequency range between 450 Hz and 750 Hz as well as 900 Hz and 1.6 kHz.

The signals of the rear tires are filtered with a high-pass at 150 Hz (the measured car owns a front engine). The overall sound pressure level is lower than the one of the front tires. This can be put down to the fact that the front axle is the driven axle. The dominating feature in the spectrogram of the rear tires are frequency contributions between 1.2 kHz and 1.45 kHz.

The rolling noise of the front tires dominates the frequency range above 450 Hz and also the overall sound pressure level.

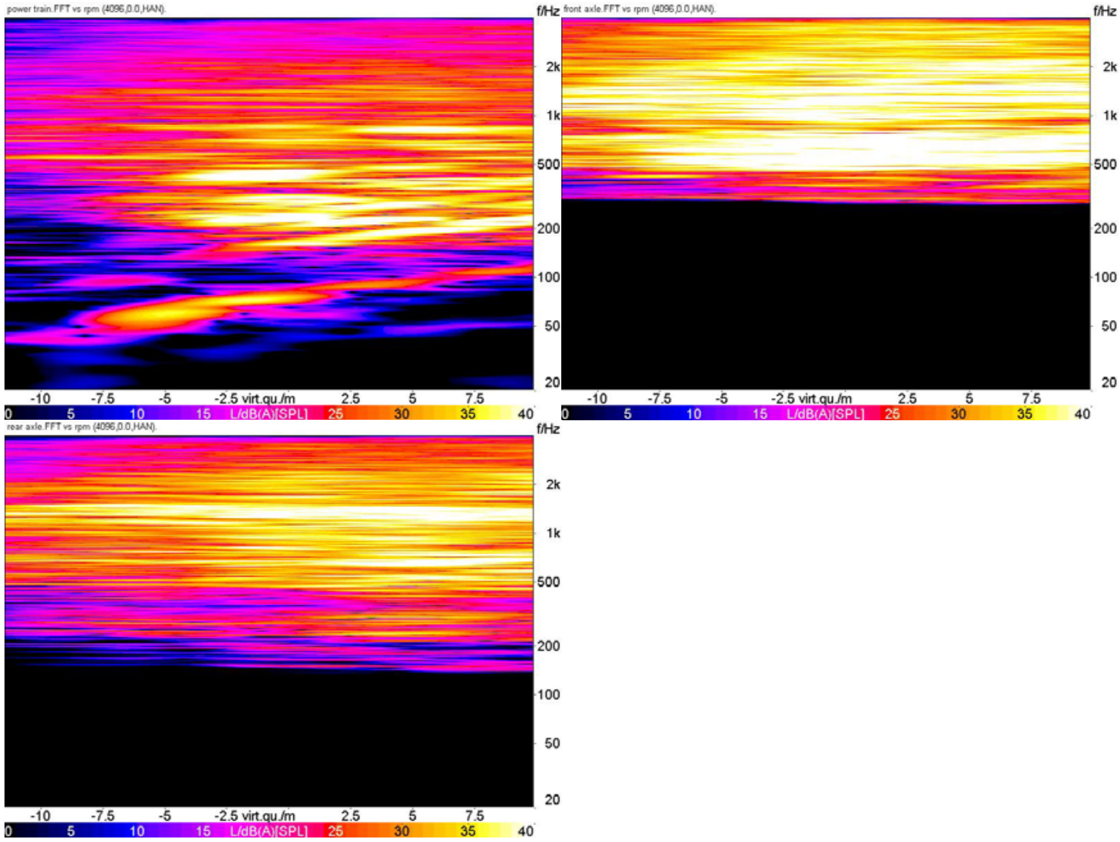

Figure 9: FFT vs. distance. Contributions of the component groups power train(top left), front tires (top right) and rear tires (bottom)

Figure 10 displays the spectra of the components of the power train. Intake and engine top are the components which define the level. At the beginning of the test track the second engine order is mainly radiated by the intake, later on by the top of the engine. These two components are also the main source for the resonance at 230 Hz. The resonance at 430 Hz is radiated by the top and driver side of the engine, the resonance at 830 Hz mainly by the intake.

The top of the engine radiates hardly any high frequencies.

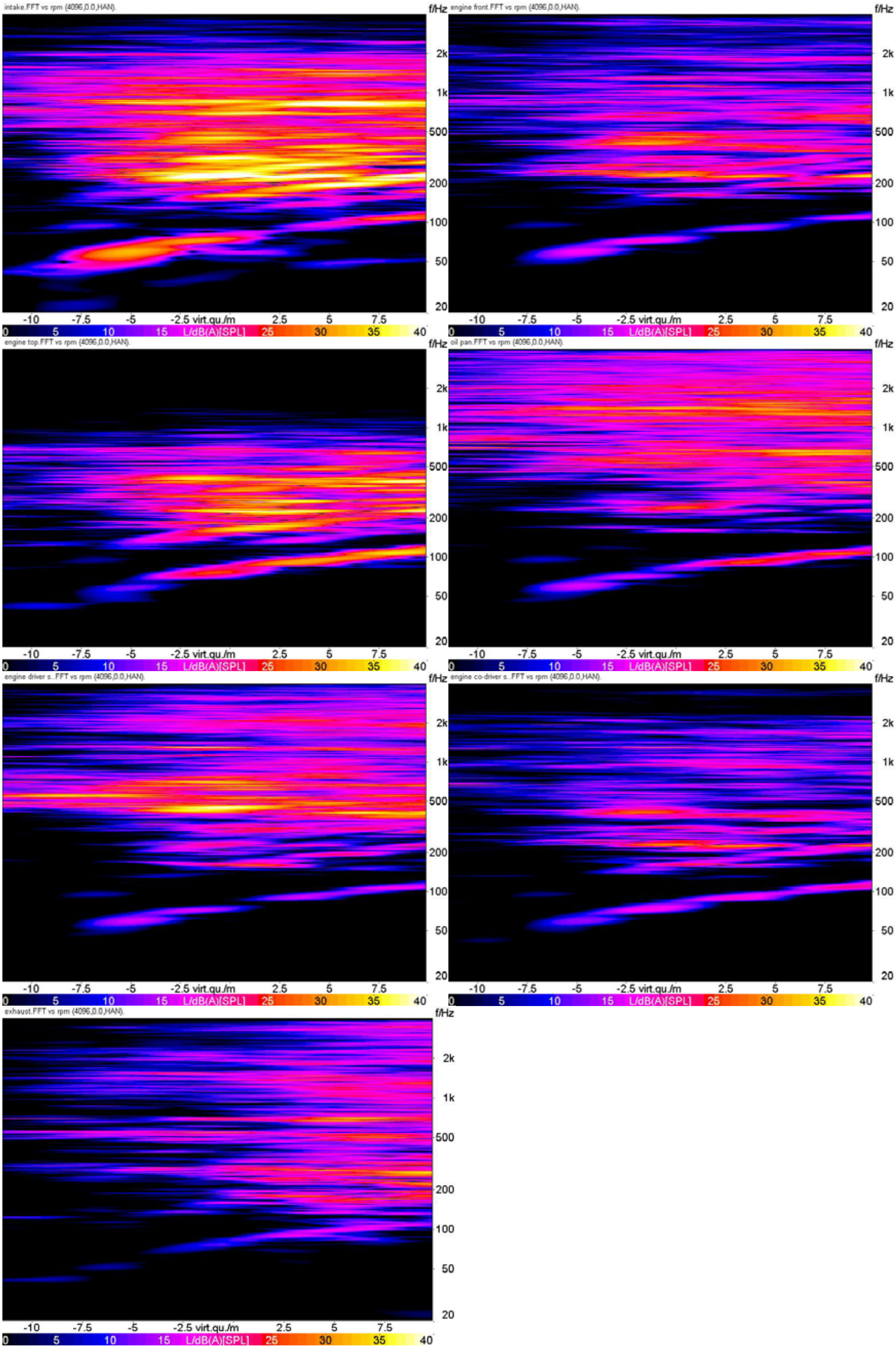

Figure 10: FFT vs. distance. Contributions of the power train components: from top left : intake, engine front, engine top, oil pan, engine ds, engine cd, exhaust

The single contributions of the front tires are shown in Figure 11. The left tire contributes mainly to the overall level of the front tires since a pass-by from left to right is simulated.

Furthermore it is apparent that first the leading edge is dominating but then the trailing edge at the end of the pass-by.

The frequency characteristics of the four components are quite similar. Beside the level difference between left and right tire the diagrams of the trailing edges show a slightly higher level share in the frequency range above 2.5 kHz.

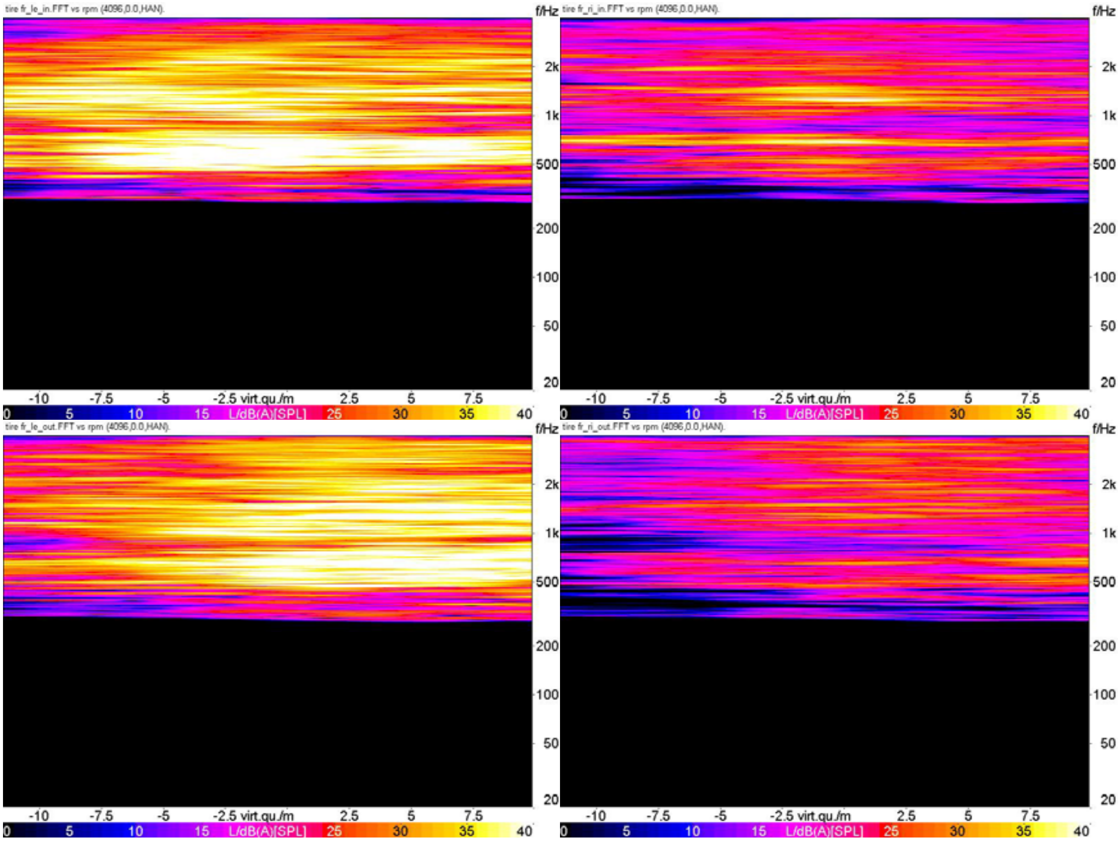

Figure 11: FFT vs. distance. Contributions of the components of the front tires: left tire leading edge (top left) and trailing edge (bottom left), right tire leading edge (top right) and trailing edge (bottom right)

The single contributions of the rear tires are shown in Figure 12. The spectrograms show relations analogue to the front tires.

The levels of the left tire are noticeably higher than the ones of the right tire. The frequency characteristics are comparable. However, the mentioned emphasis of the high frequency range concerning the front tires cannot be found at the rear tires.

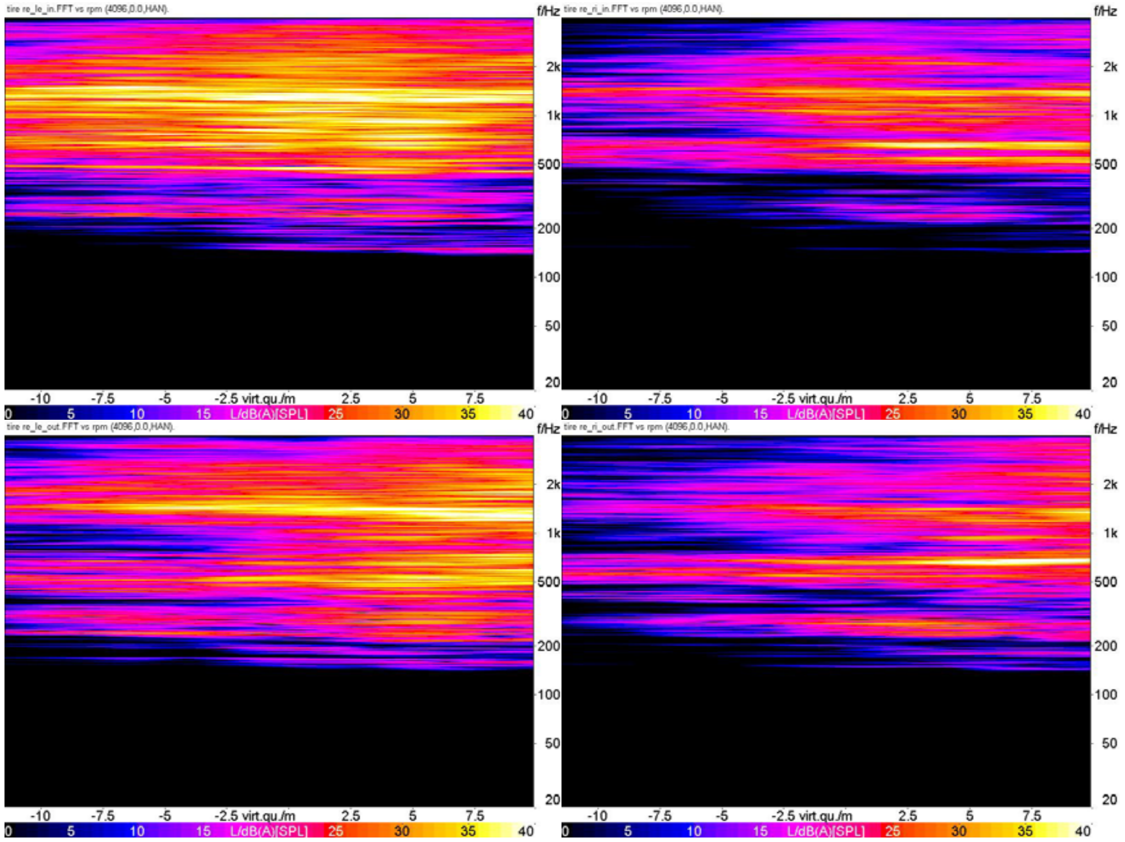

Figure 12: FFT vs. distance. Contributions of the components of the rear tires: left tire leading edge (top left) and trailing edge (bottom left), right tire leading edge (top right) and trailing edge (bottom right)

5.1.2 *const50*

In the following the results for the driving situation *const50* are presented.

The component synthesis reproduces the main sound characteristics of the microphone array calculation (Figure 13). Certain parts appear slightly blurred at the component synthesis (e.g. at 270 Hz in the second half of the test track). The levels below 200 Hz are lower than calculated out of the signals of the microphone array. Very good correspondence is reached at the mid and high frequency range, which are defining mainly the hearing impression.

In comparison to *acc50* the engine orders can hardly be perceived and the levels in the mid frequency range are much lower. This is due to the significantly reduced load of the engine.

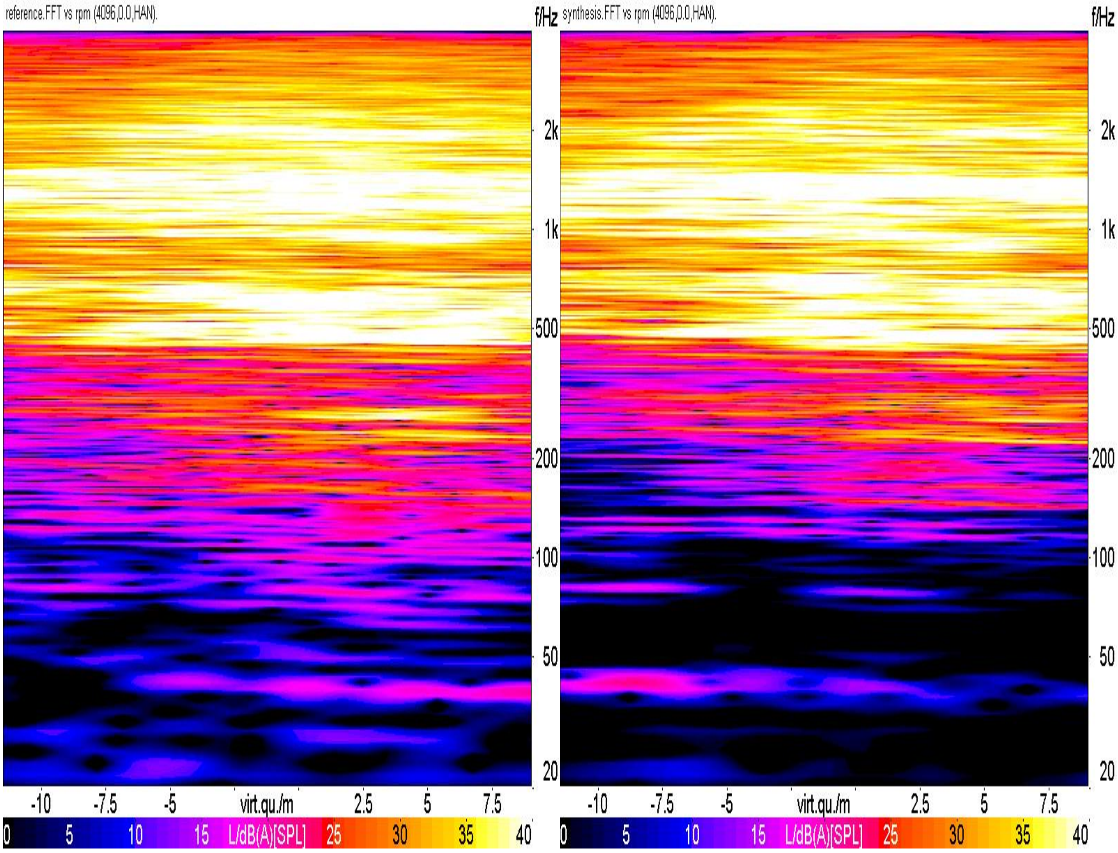

Figure 13: FFT vs. distance. Comparison of the pass-by noise generated by calculations using a microphone array (left) and component synthesis (right) for *const50*

The contributions of the single component groups are depicted in Figure 14.

As stated above the contribution of the power train is much lower compared to *acc50*. The rolling noise of the front tires is less noisy too, whereas the noise of the rear tires is very much the same. Hence, the speed influences hardly the rolling noise level (the deviation of the final speeds of the two driving situations is 7 km/h).

The differences between the front tires of *acc50* and *const50* can be ascribed to the different loads on the driven front tires. The spectral characteristics of the rolling noise are very similar in both driving situations.

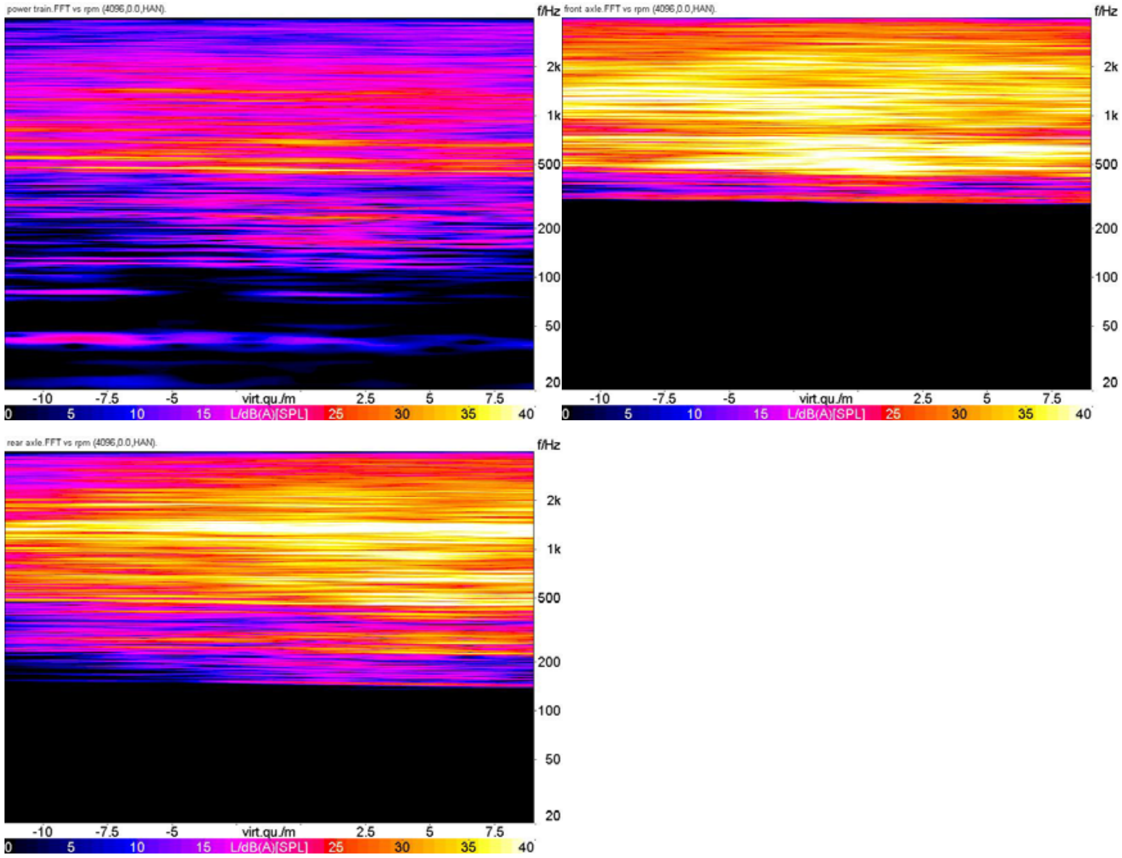

Figure 14: FFT vs. distance. Contributions of the component groups power train (top left), front tires (top right) and rear tires (bottom)

The contributions of the component groups to the overall level regarding the length of the test track is depicted in Figure 15. The different relevance of the front tires for *acc50* and *const50* is shown (especially in the second half of the test track) as well as the rising influence of the rear tires. Nevertheless, the front tires are the dominating noise source in both driving situations.

The noise level of the power train is negligible. At *acc50* it is about 10 dB(A) below the overall level, at *const50* even 15 dB(A).

The maximum level difference between reference (microphone array) and component synthesis is 0.86 dB(A) for *acc50* and 0.44 dB(A) for *const50*.

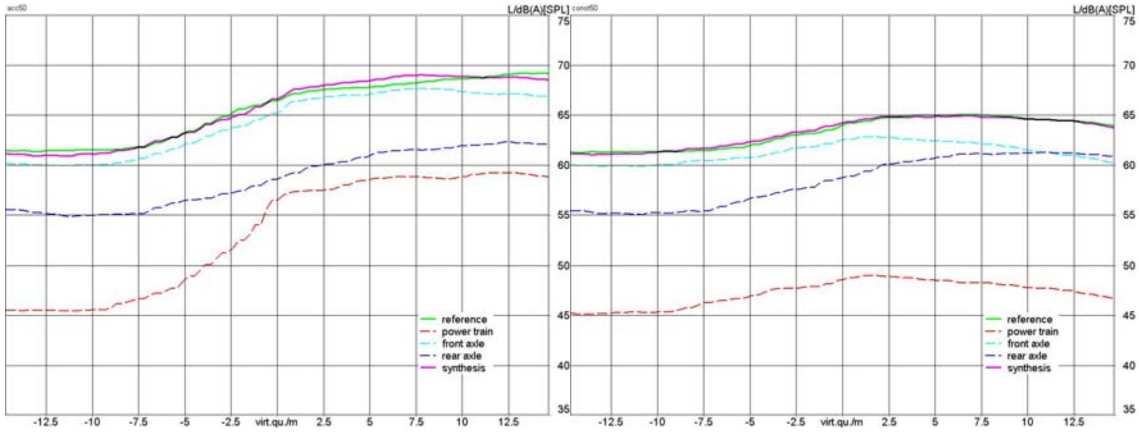

Figure 15: Level vs. distance. SPL of reference (microphone array) and component synthesis (overall and component groups) for *acc50* (left) and *const50* (right)

The single components of the power train are depicted in Figure 16. Certain noise characteristics (e.g. engine orders, resonances) are not as emphasized as at *acc50* and the contributions of the single components are more balanced. This can be accounted to the lesser load and engine speed (~ 1200 rpm).

The resonance at 230 Hz is radiated mainly by the intake and the top of the engine. A resonance at 460 Hz is recorded particularly at the oil pan and the driver side of the engine.

Approaching the end of the test track the exhaust has the highest level contribution.

Again, hardly any high frequencies are radiated from the top of the engine.

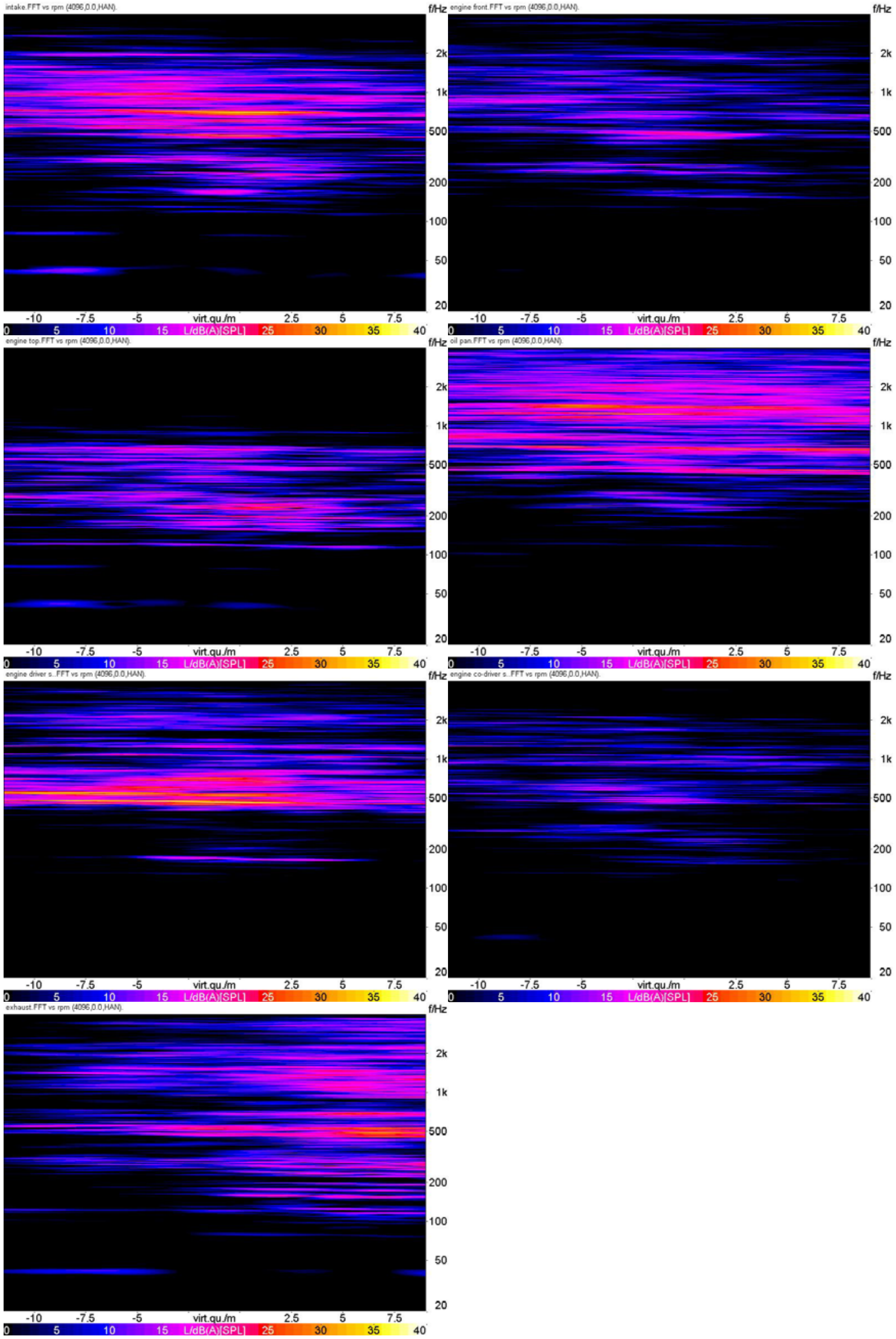

Figure 16: FFT vs. distance. Contributions of the power train components: from top left: intake, engine front, engine top, oil pan, engine ds, engine cd, exhaust

The component contributions to the noise of the front tires are shown in Figure 17. Basically the components show a similar behavior as at *acc50*. The left tire is dominating the overall noise due to the shorter and unobstructed way between tire and microphone position. The leading edge is more important during the first half of the test track, the trailing edge during the second half.

In comparison to *acc50* the sound pressure level is reduced, though the spectral composition of the two situations is very alike.

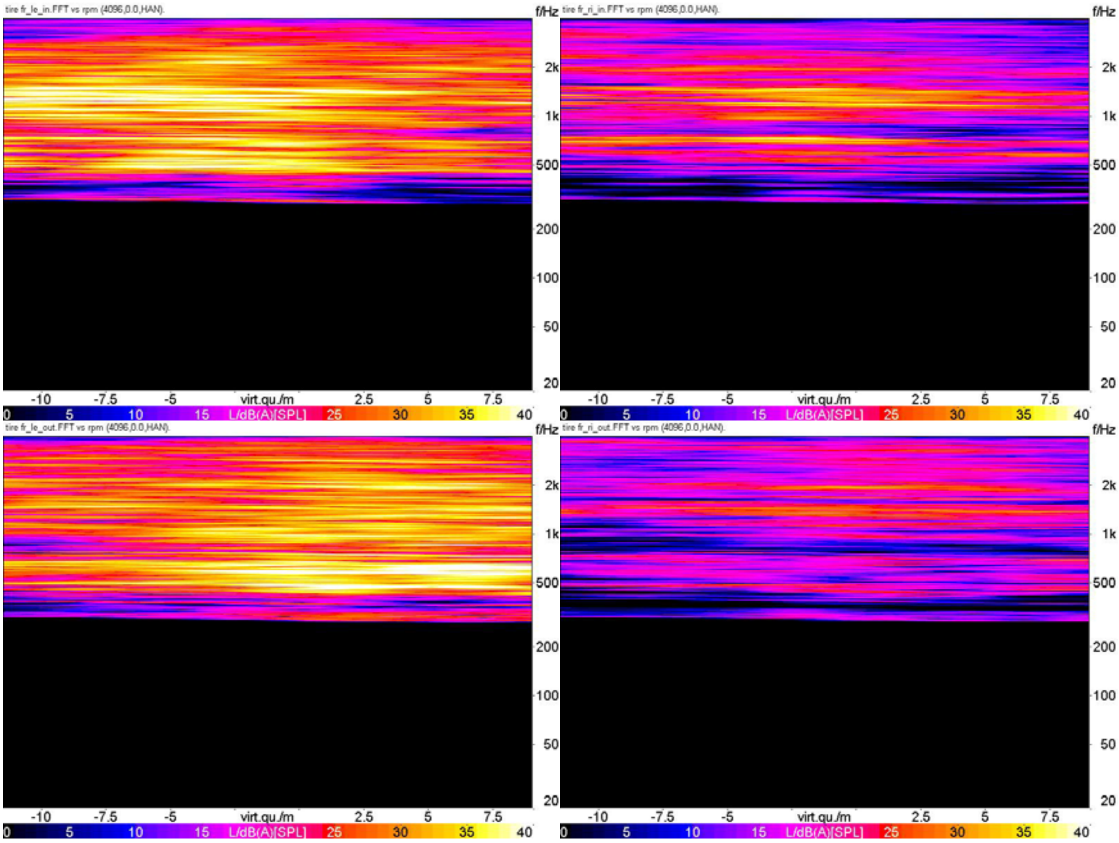

Figure 17: FFT vs. distance. Contributions of the components of the front tires: left tire leading edge (top left) and trailing edge (bottom left), right tire leading edge (top right) and trailing edge (bottom right)

Figure 18 is depicting the spectrograms of the components of the rear tires. These spectrograms resemble the ones of *acc50*. The reduced speed results only in an level difference of 1 dB(A) to 1.5 dB(A) at the highest speed difference (at the end of the track).

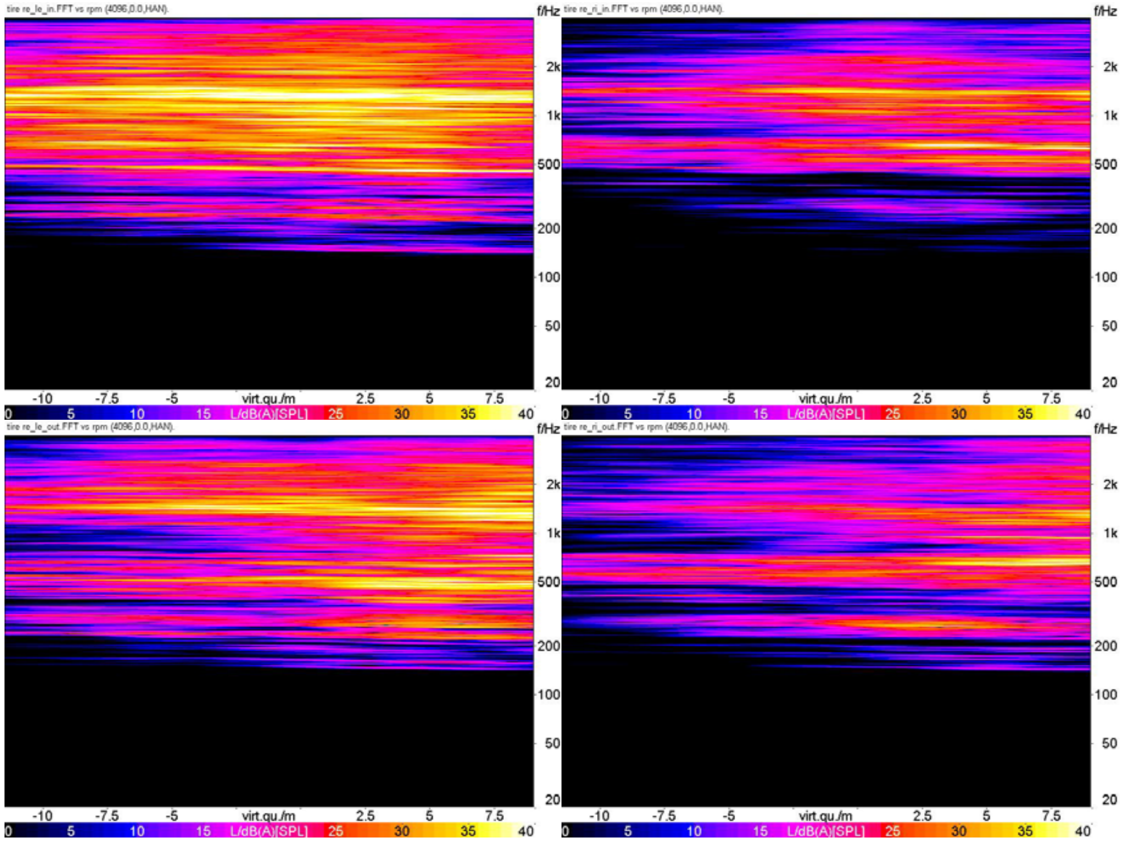

Figure 18: FFT vs. distance. Contributions of the components of the rear tires: left tire leading edge (top left) and trailing edge (bottom left), right tire leading edge (top right) and trailing edge (bottom right)

Validation

The conducted comparisons between component synthesis and microphone array gives information about the quality of the transfer functions and possible neglected noise components. How good the synthesis represents the reality can be judged by comparing a recording of a real pass-by with the component synthesis. Exemplarily this is depicted in Figure 19 using the respective spectrograms for *acc50*.

Above described sound characteristics appear also at the real pass-by. Apparent deficits exist in the frequency range below 200 Hz. Reasons for the underestimation of the low frequency range are stated already in the former paragraphs. Nevertheless, since the most sound energy is located in the frequency range above 200 Hz, the difference of the maximum SPL is 1.8 dB(A) and the maximum SPL difference is 2.4 dB(A).

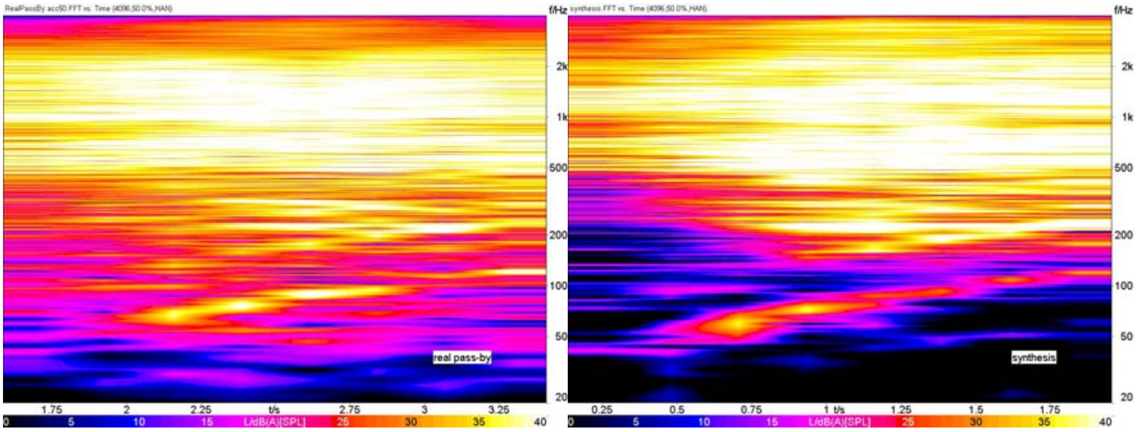

Figure 19: FFT vs. time. Comparison of a real pass-by noise (left) and the result of the component synthesis (right) for *acc50*

5.2 Commercial Van

18 microphones are applied in and at the car for the input recordings:

- intake,
- 6 x engine,
- gear box
- differential
- exhaust,
- 8 x tires.

The recorded driving situations include *acc50* and *const50* with and without an additional payload of 600 kg respectively.

The measurements are carried out on the chassis dynamometer of HEAD acoustics and the test track of the IKA, Aachen University.

5.2.1 *acc50*

The maximum level of the pass-by noise is defined by the noise emitted by the tires of the driven axle. Their level lies up to 10 dB(A) above the levels of the other component groups.

With additional payload (Figure 20)

The noise of the power train shows a dominating second engine order and increased levels above 1000 Hz. At the beginning of the pass-by the second engine order is emitted mainly from the top of the engine and the intake. At the end of the pass-by it is the exhaust. The high frequent emissions of the power train derive from the oil pan.

The noise of the front tires is concentrated in a frequency band between 750 Hz and 1 kHz.

The noise of the rear tires shows also high levels in the frequency band between 750 Hz and 1 kHz. Furthermore levels increase between 1.4 kHz and 2.7 kHz with rising speed. The rear tires belong to the driven axle. That causes the general higher levels compared to the front tires.

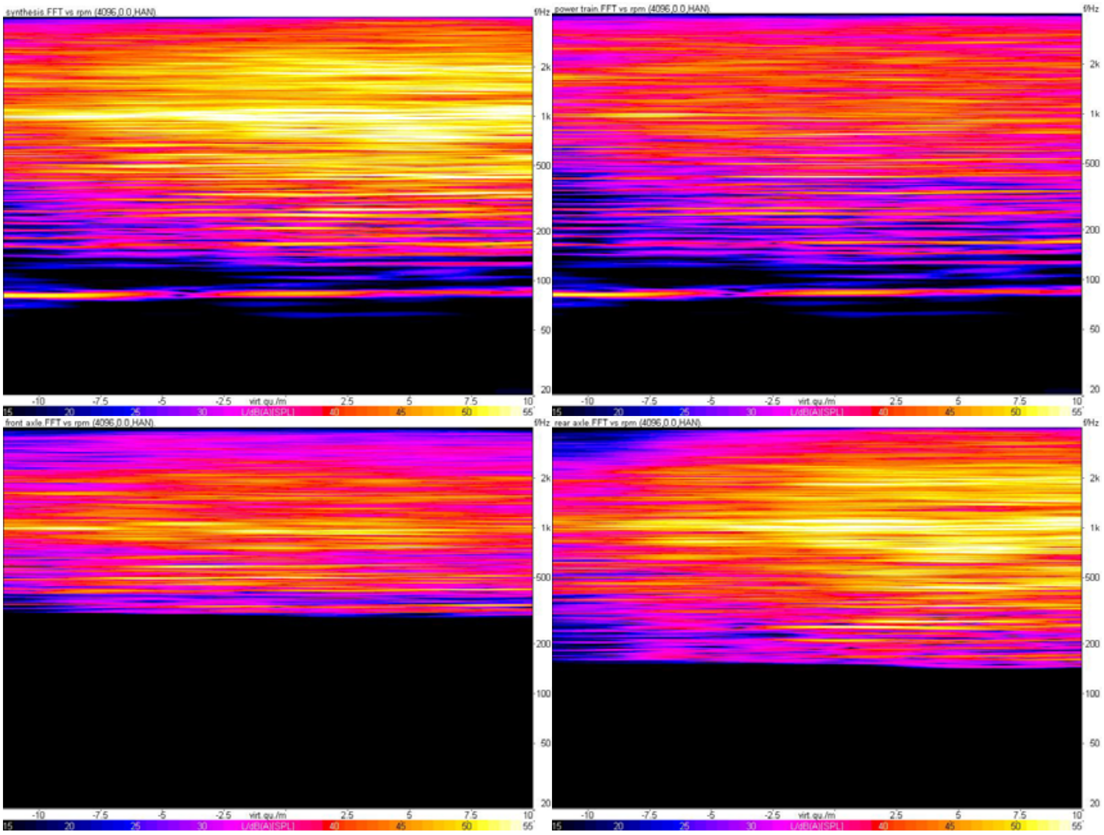

Figure 20: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Without additional payload (Figure 21)

For the power train, the engine orders are slightly less dominant as with the additional payload. Obviously the reduced load has barely an influence on the radiated power train noise.

A level reduction applies for the tires concerning the characteristic frequency band around 1 kHz. For the front tires the highest levels are reached in a broad frequency range around 500 Hz. The sound energy of the rear tire noise is spread over a broad frequency range. With rising speed this effect increases.

In general, the contributions of the component groups are more broadband. Specific narrow band noise components like resonances or engine orders are not so pronounced.

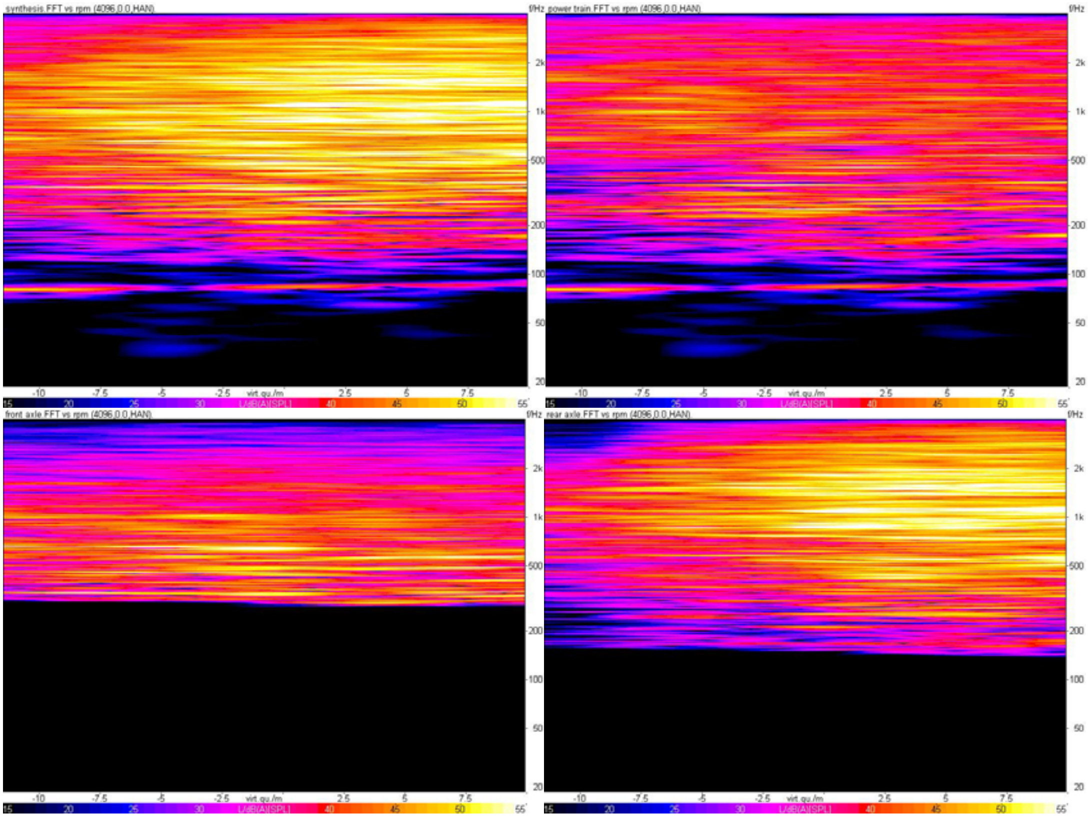

Figure 21: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 22 is depicting the contributions of the component groups to the overall level. The rear tires are obviously the dominating noise source, especially at the second half of the test rack where the maximum level is reached. At the beginning of the test track, the level seems to depend on the payload, whereas at the end of the track the speed (higher for the situation without additional payload) turns the balance. The additional payload barely influences the level of the front tires and power train.

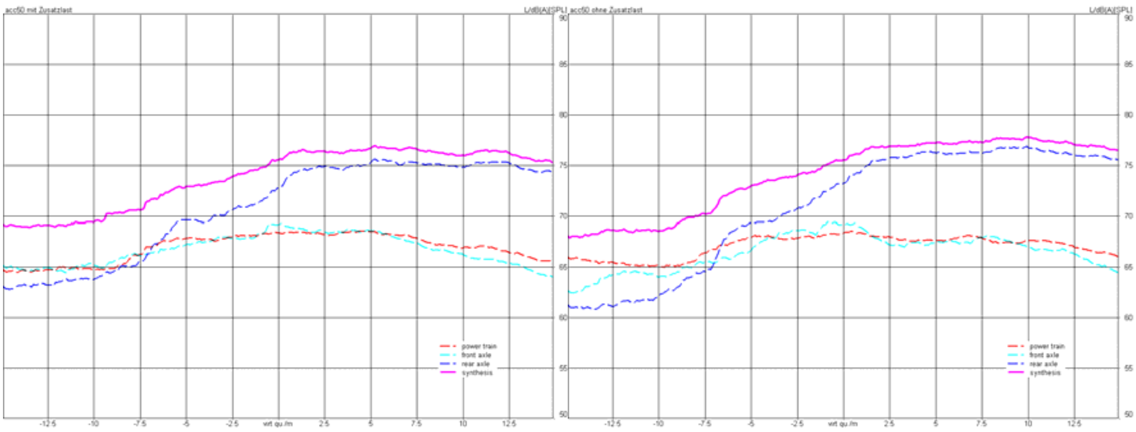

Figure 22: Level vs. distance. Level of the component synthesis and component groups with (left) and without (right) additional payload for *acc50*

5.2.2 *const50*

The influence of the power train on the pass-by noise is further reduced. The decreased load on the driven axle results in lower levels at the respective components. Therefore, the overall level is defined by the noise of front and rear tires. Concerning the tires the leading edges contribute significantly to the overall noise.

With additional payload (Figure 23)

In comparison to acc50, the power train and therefore the engine orders show lesser influence on the overall noise. This applies particularly for the components mainly emitting these orders, e.g. the exhaust.

The contributions of the tires are quite balanced between front and rear tires. The tires of the driven axle do not show significantly higher levels than the other tires. The radiated noise of all tires is dominated by a frequency band between 750 Hz and 1 kHz.

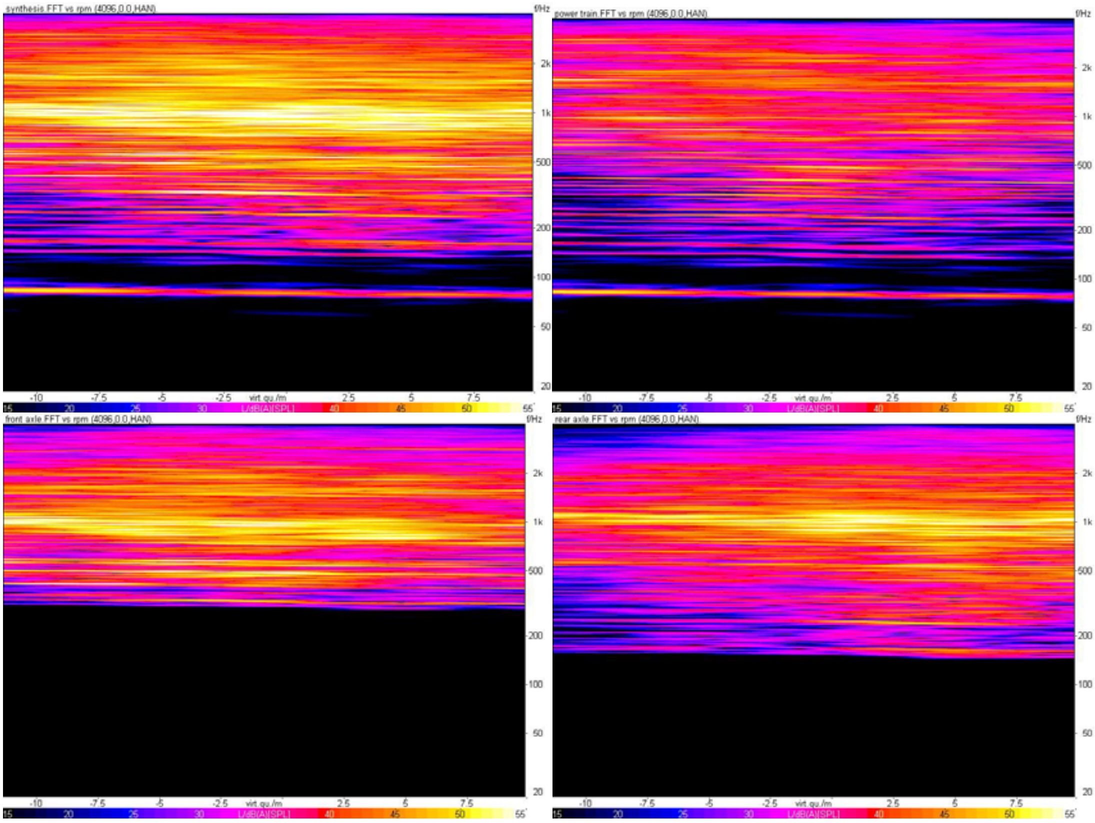

Figure 23: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Without additional payload (Figure 24)

The influence of the power train on the overall noise is again reduced compared to *const50* with additional payload. E.g. the engine orders emitted by the exhaust do not contribute relevantly to the overall noise.

In general the front tires show in this situation the lowest levels. The before dominating leading edge of the left tire is equaled by the trailing edge of the left tire.

The noise of the rear tires are reduced, too. A shift of the spectral balance point can not be observed as in the *acc50* situations. Nevertheless, the dominance of the 1 kHz component inside the respective spectra is reduced.

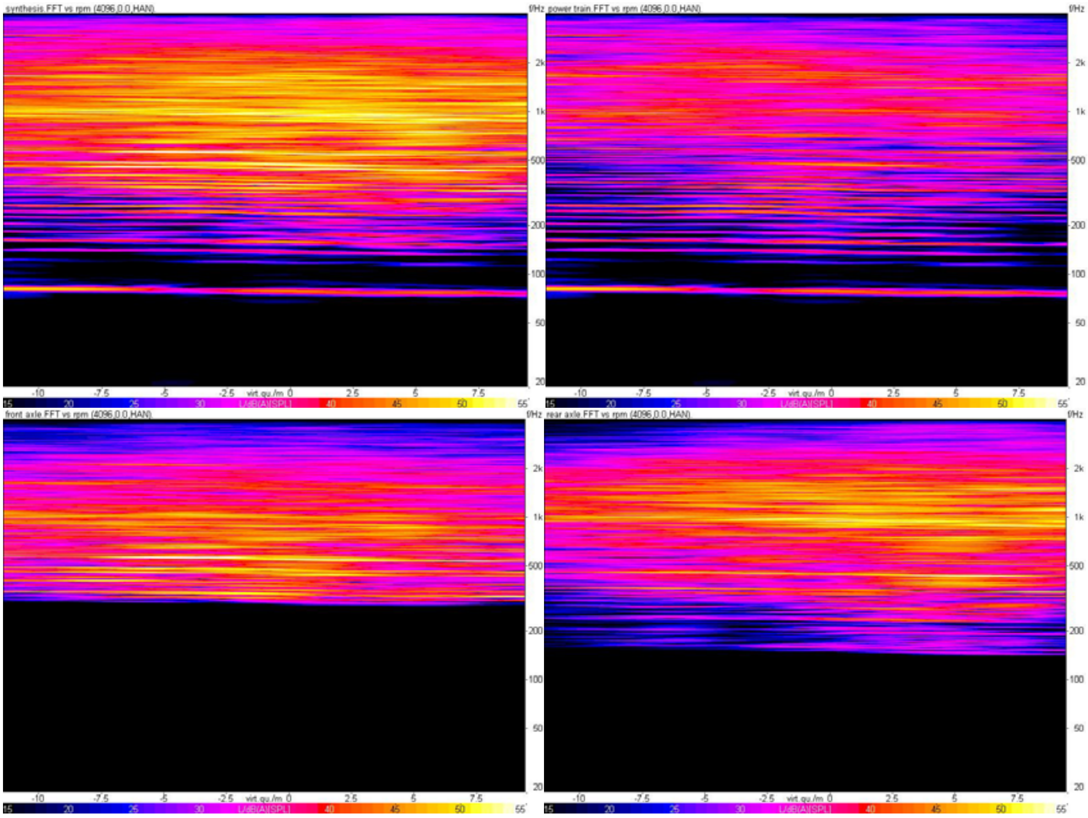

Figure 24: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

The additional payload in the situation *const50* affects the course of the level run in the first half of the test track (Figure 25). The front tires lose their dominance there when the additional payload is not installed. Therefore, the maximum pass-by level is mainly influenced by the rear tires alone in this situation.

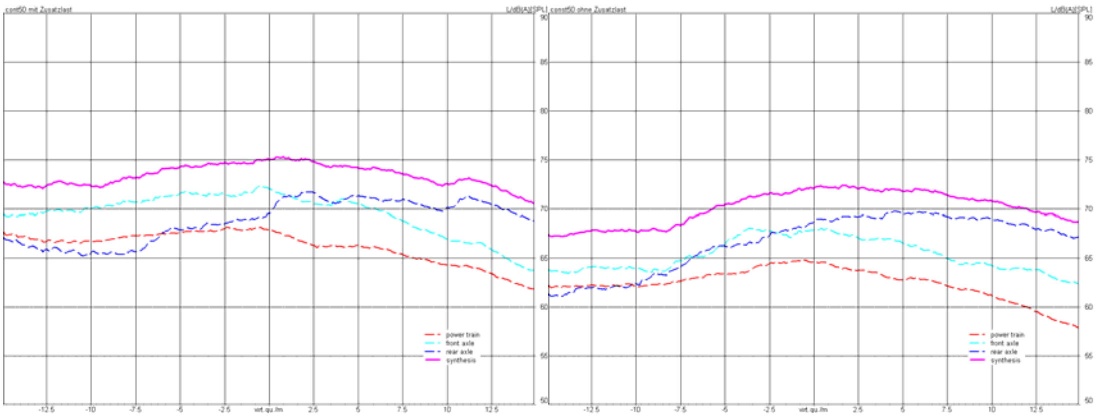

Figure 25: Level vs. distance. Level of the component synthesis and component groups with (left) and without (right) additional payload for *const50*

5.3 PUBLIC TRANSPORT BUS – SMALL

19 microphones are applied in and at the bus for the input recordings:

- intake,
- 6 x engine,
- 2 x gear box
- differential
- exhaust,
- 8 x tires.

The recorded driving situations include *acc38* and *const38*.

The measurements are carried out on the test track of the Goodyear in Luxembourg. The input measurements for the noise components are performed during a real pass-by and not on a chassis dynamometer. The measurements for the SRTF calculation are performed in the free field. A chassis dynamometer or a semi-acoustic chamber is not necessarily needed, which widens the range of vehicle possible to measure and saves costs. The application of the extended synthesis approach proved to be very successful.

5.3.1 acc38

The noise of the accelerated pass-by is dominated by the emissions of the power train (Figure 26). The intake and the exhaust contribute mainly engine orders, whereas high frequency contributions originate from the engine bottom. The front tires show no important contribution to the overall noise. Their level is at least 9 dB(A) below the level of the power train. The influence of tires of the driven rear axle increases towards the end of the test track where the minimum level difference between rear tires and power train reaches values below 6 dB(A).

The main characteristics of the power train noise are the 2nd, 4th and 6th engine order in the low frequency range and the broad band noise in the mid and high frequency range. The mid and high frequency ranges contain also some resonances. The 2nd engine order is mainly emitted by the intake, which is also responsible for the higher levels around 300 Hz, which are already clearly visible during the approach at the beginning of the test track. Additionally, resonances between 1 kHz and 1.2 kHz originate from there. The main contribution to the 4th and 6th engine order derives from the exhaust. The high frequency contribution can be related to the noise radiated at the bottom. A resonance at about 1.6 kHz originates from the gearbox.

The noise emitted by the front tires is quite broad band. The main contributions lie in the frequency range between 1 kHz and 2 kHz. A resonance at about 1.2 kHz generates the highest levels. The highest levels and important resonances are emitted by the trailing edges, respectively.

The rear tires contribution to the far field signal shows a significant dependency on the applied torque. When the acceleration starts the noise level increases and resonances as well as tire orders appear. The highest levels are reached in the frequency range below 800 Hz. Important tonal characteristics appear at 450 Hz and 2.1 kHz. The main contribution to the rear tire noise origins from the leading edge of the left tire (pass-by from the right).

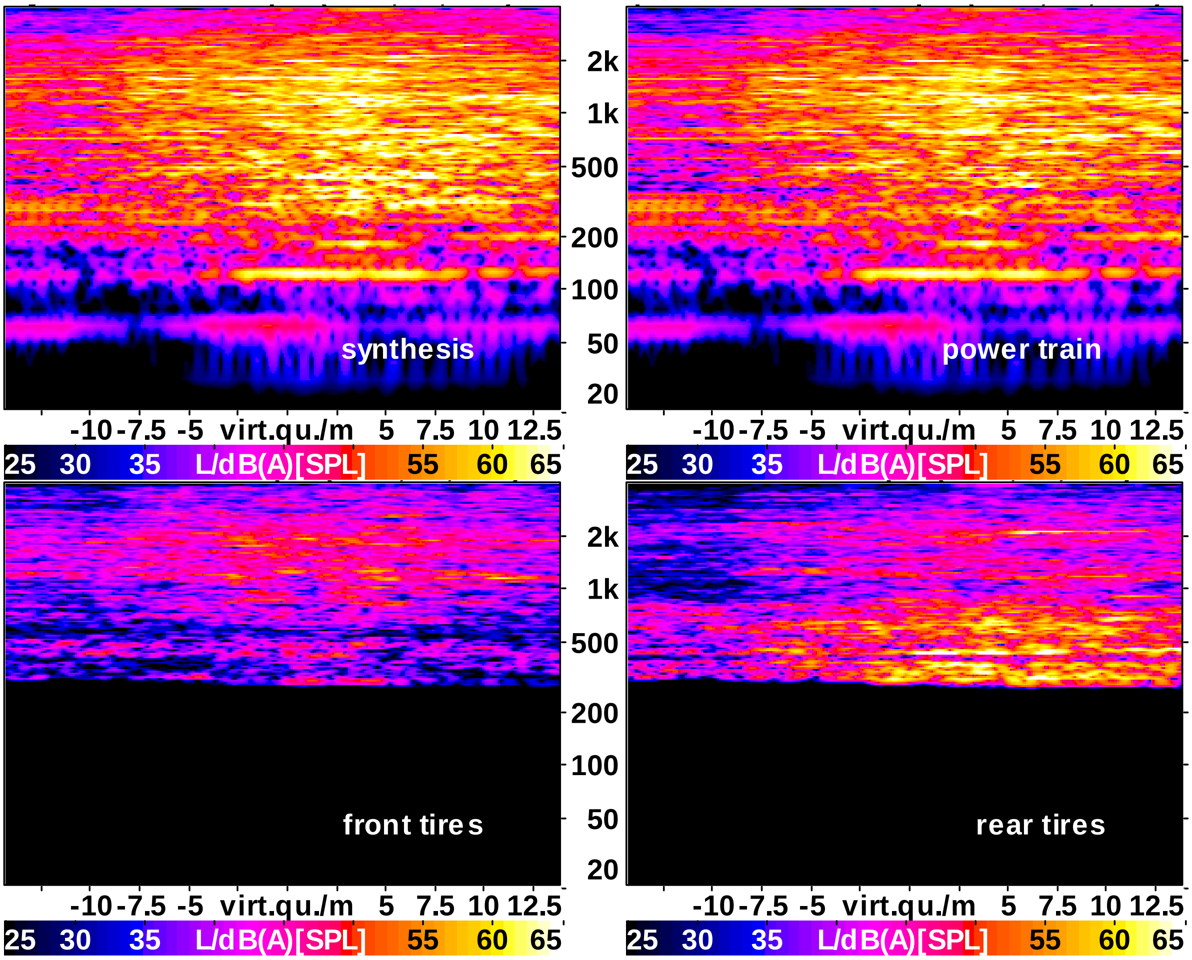

Figure 26: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 27 is depicting the contributions of the component groups to the overall level. The dominance of the power train is clearly visible. The contribution from the rear tires increases with the applied torque and rising proximity, but stays about 7 dB(A) below the overall level. The noise emissions of the front tires are almost irrelevant, since their level is at least 9 dB(A) below the overall level.

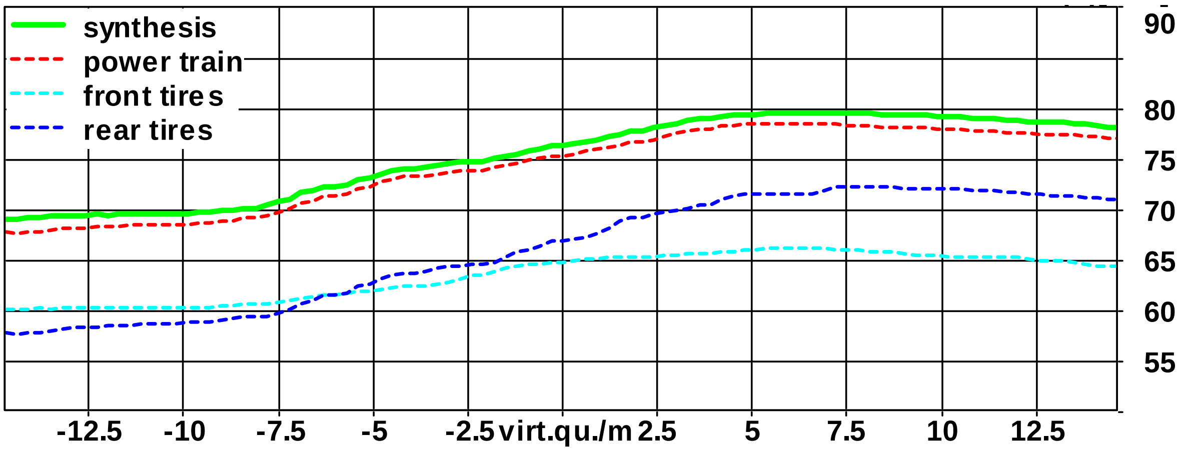

Figure 27: Level vs. distance. Level of the component synthesis and component groups for *acc38*

5.3.2 *const38*

Compared to the situation acc38 lower levels are gained, due to level reductions of the 4th and 6th engine order and in high frequency range (maximum reduction of 4.5 dB(A) at the end of the test track, Figure 28). This is mainly due to less noisy power train components and rear tires. The dominance of the power train is even higher, since the level of the rear tires have more decreased than the one of the power train.

The exhaust contribution has lost its significance, which can be seen at the heavy reduction of the 4th and 6th engine order. The intake is still the main source for the 2nd engine order and the bottom of the engine emits the mid and high frequency contribution recorded in the far field. Since this contribution is reduced in level, the tonal characteristics of the intake (especially between 230 Hz and 330 Hz) gain more influence.

Generally, the level of the emitted noise of the front tires is slightly reduced, but the characteristics described above maintain. The change of the driving situation results mainly in a maximum level loss of 2.8 dB(A).

The noise of the rear tires is reduced drastically by up to 7.7 dB(A). The tire orders and resonances are not as emphasized as in situation *acc38*. This rather balanced spectrum can cause a very different perception, which can be investigated in WP2.2.2. Also the contribution of the leading and trailing edge is more balanced.

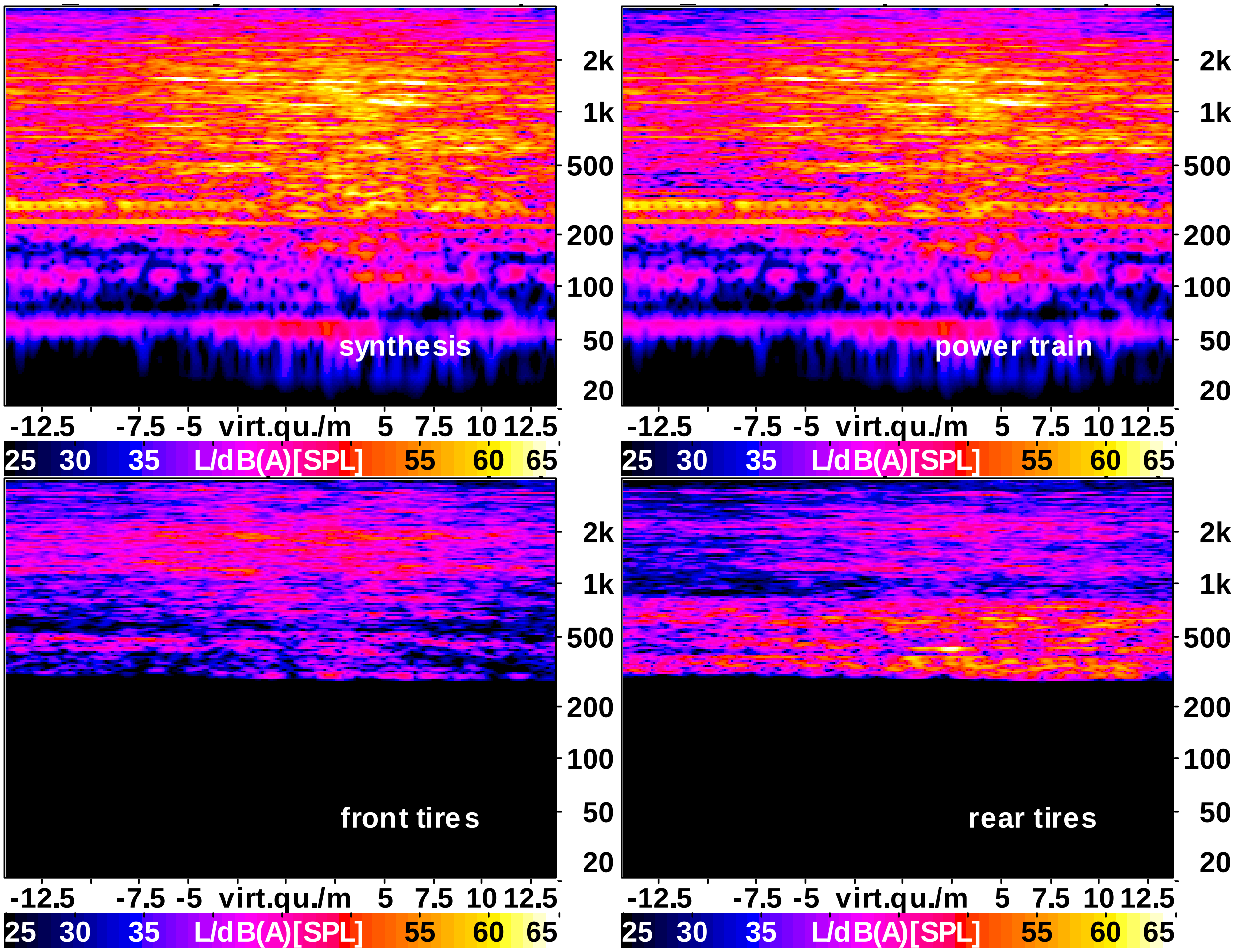

Figure 28: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 29 is depicting the contributions of the component groups to the overall level. Again, the dominance of the noise emitted by the power train is clearly visible. The tires of the two axles contribute quite equally to the overall noise, regarding the fact that the front tires contribute more at the beginning of the track and the rear tires towards the end due to the geometry of the pass-by situation. But still their contribution stays well below a real significance to the overall level.

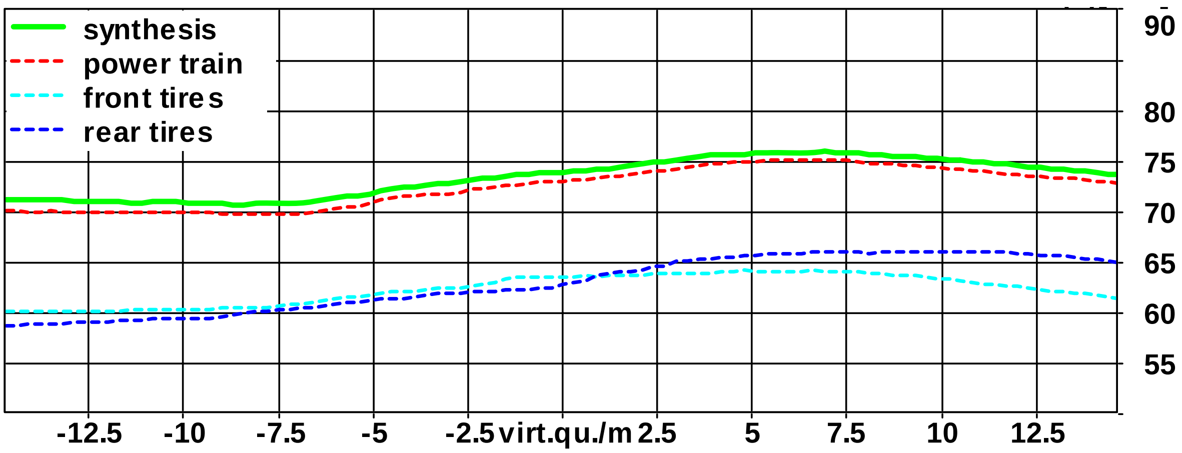

Figure 29: Level vs. distance. Level of the component synthesis and component groups for *const38*

5.4 SUB-COMPACT CLASS CAR

18 microphones are applied in and at the car for the input recordings:

- intake,
- 6 x engine,
- gear box
- differential
- exhaust,
- 8 x tires.

The recorded driving situations include *acc50* and *const50*.

The measurements are carried out on the chassis dynamometer of HEAD acoustics and the test track of the IKA, Aachen University.

5.4.1 *acc50*

The pass-by noise is generated mainly from the power train and the tires at the driven front axle (Figure 30). The noise of power train is characterized by the engine orders and a broad band noise. Main components are the intake and the front of the engine. The dominant contributions of the front tires are two resonances in the mid and high frequency range and high frequency noise.

The main noise characteristics of the power train are the engine orders, especially the 2nd and the 4th, and the broad band noise in the frequency range between 800 Hz and 1.6 kHz. This broad band noise is emitted by the intake. Although, other components have high frequency emissions, the strong contribution of the intake can be regarded as the only significant one. The dominant noise sources for the 2nd and 4th engine order are the intake and the front of the engine. The 6th engine order originates from the front and co-driver side of the engine.

The left tire is dominating the contribution of the front wheels to the overall noise, since it is a pass-by from the right. Generally it is a noise quite broad band with broad resonances at about 500 Hz and 1.2 kHz. This latter resonance is emitted by the leading edge (dominating at the beginning if the pass-by) as well as the trailing edge (dominating towards the end of the pass-by). The leading edge shows more contribution in the frequency range below 1.2 kHz, the trailing edge above.

The noise of the rear tires shows the same two resonances. The dominating component is the leading edge of the left tire, which even at the end of the test track provides the highest levels of the rear tires components. The general lower levels in comparison to the front tires are explained by the driver front axle.

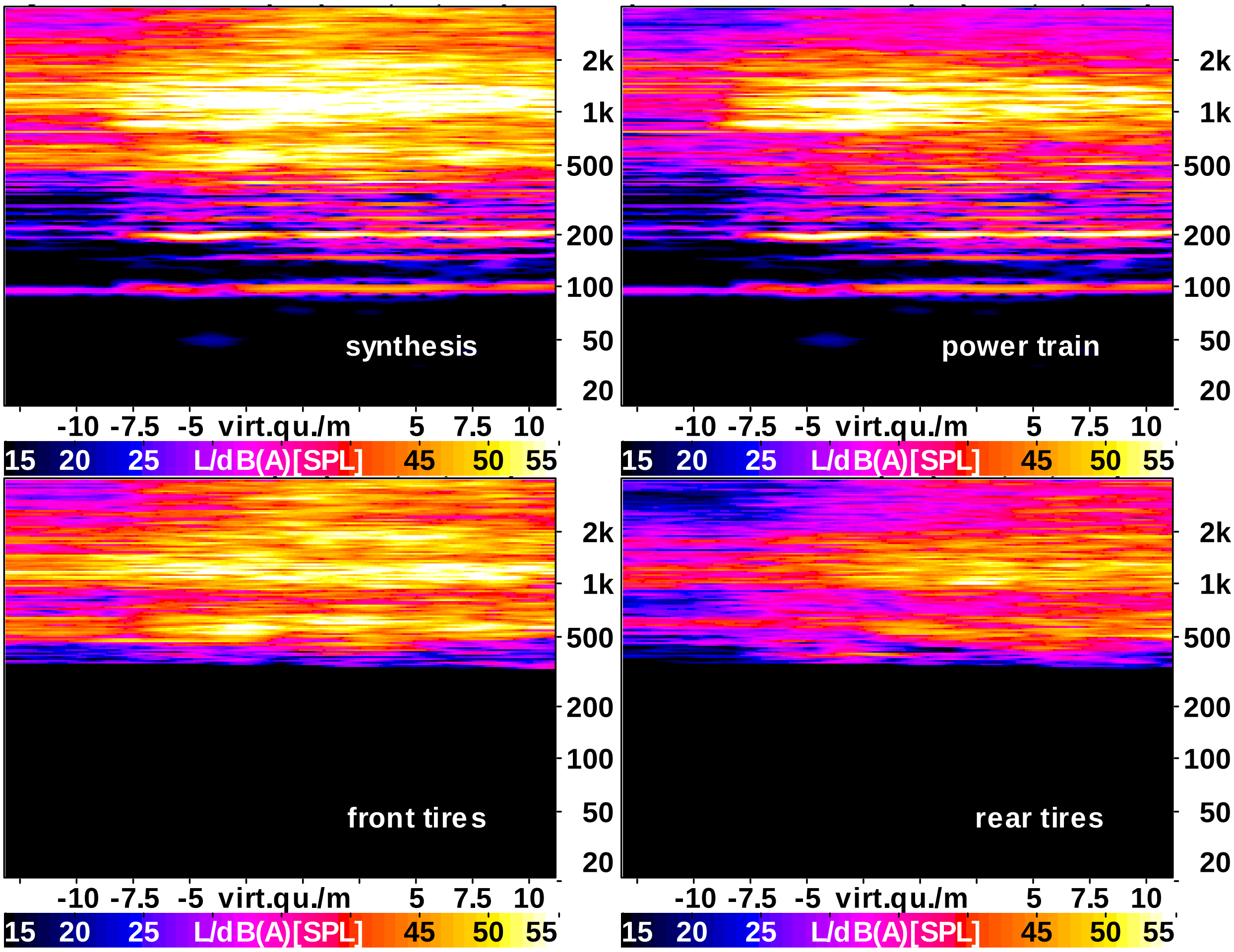

Figure 30: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 29 is depicting the contributions of the component groups to the overall level. Over a large proportion of the test track the power train and the front tires show comparable levels, whereas the level of the rear tires stays well below the level of the other component groups. The acceleration affects mainly the power train, the level of which increases steeply.

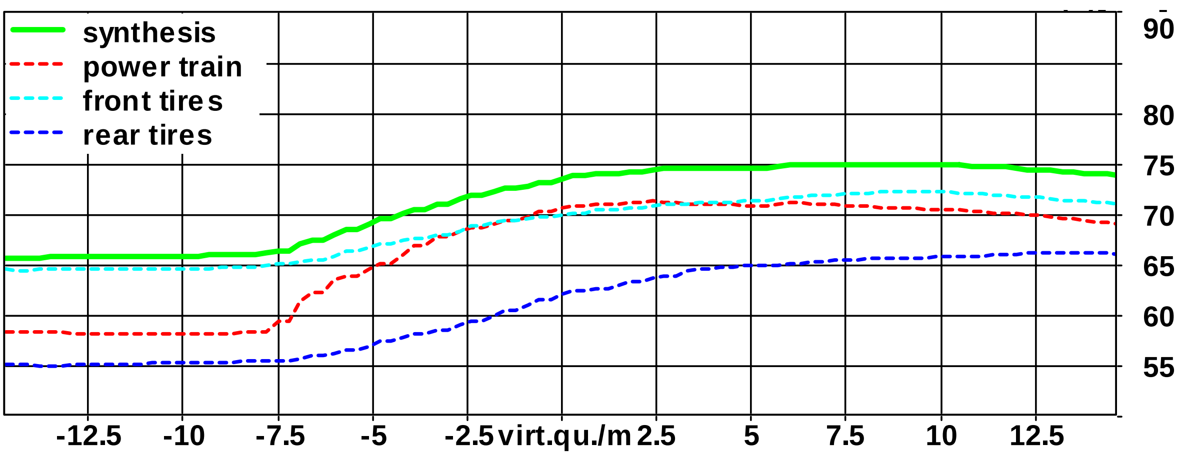

Figure 31: Level vs. distance. Level of the component synthesis and component groups for *acc50*

5.4.2 const50

The main characteristics of the overall noise derive from the front wheels and the power train again. The engine orders are the main contribution of the power train. They are quite low in level, but dominate the lower frequency range. The front tires dominate the mid and high frequency range, yet the rear tires gain more influence towards the end of the test track.

The spectrum of the power train noise is much more balanced as in the *acc50* situation. The engine orders show even levels and the strong broad band noise o the intake is significantly reduced. Now emissions of other components in this frequency range contribute to the overall noise. Significant contributions come especially from the front and the co-driver side of the engine. Also in general, these two components are the dominant noise sources in the other frequency ranges.

The noise emitted by the front tires is lower and not as broad band as before. The resonance at about 1 kHz clearly sticks out. The resonance at 500 Hz is considerably lower. Therefore it can be assumed, that it is directly connected to the applied torque. The emissions in the high frequency range appear mainly when tires are at level with the measuring microphone. This 1 kHz resonance is still emitted by the leading edge as well as the trailing edge. The leading edge shows more contribution in the frequency range below 1.2 kHz, the trailing edge above.

The spectrum of the rear tire noise depicts also the two resonances mentioned above, although they are not so distinctive. The leading edge of the left tire is the dominant noise source up to the end of the test track. So, a slight reduction of the level is the main effect of the different driving for the rear tires.

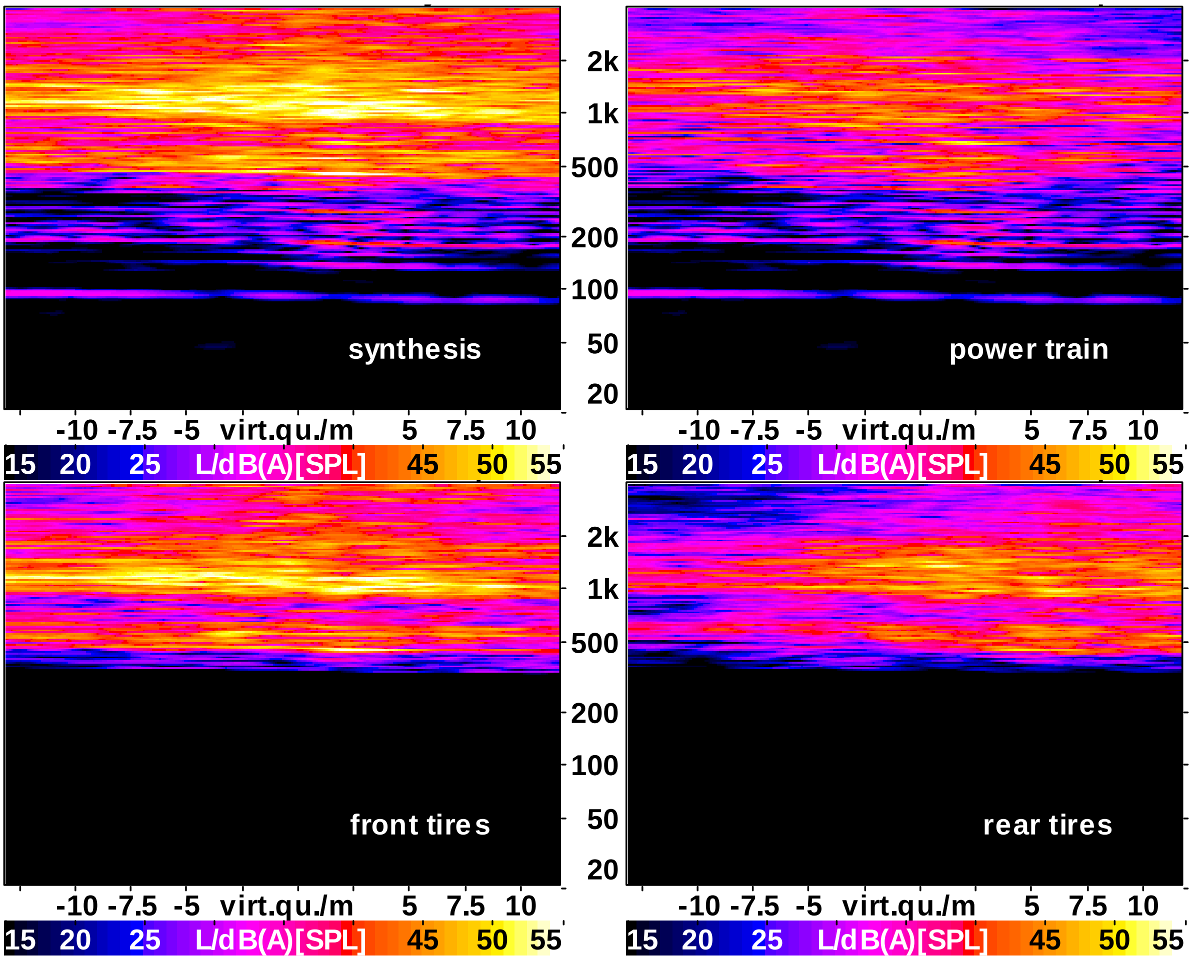

Figure 32: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 33 is depicting the contributions of the component groups to the overall level. The front tires show the highest levels and defines mainly the overall level. In comparison to the *acc50* situation, the missing high engine load prevents a sudden level increase of the power train noise. Therefore the power train influences the overall level only secondarily. Instead, the rear tires become the component group with the second highest level at the end of the test track.

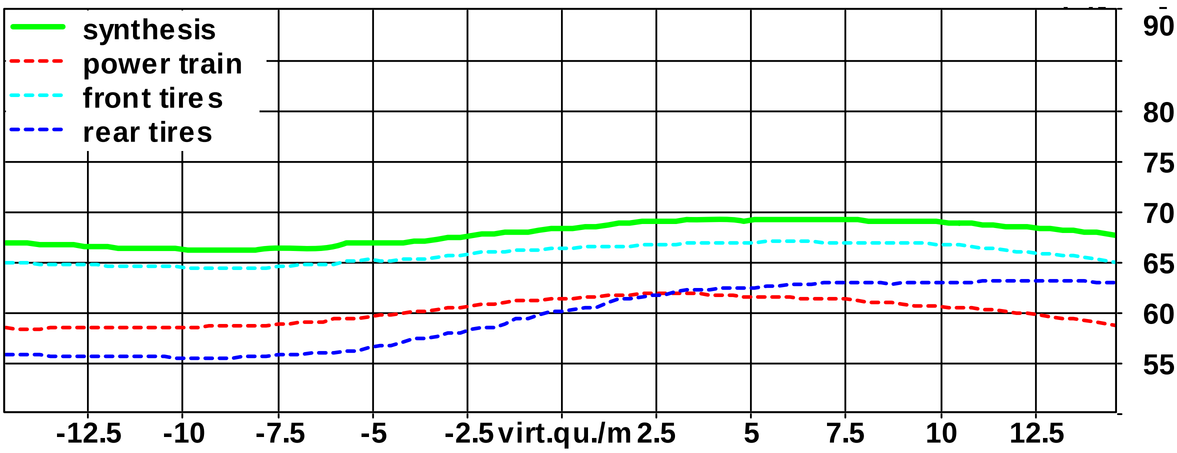

Figure 33: Level vs. distance. Level of the component synthesis and component groups for *const50*

6 CONCLUSION AND OUTLOOK

The application of the component synthesis procedure has been effective, especially the implementation of the extended synthesis approach into SENSE[8] using reciprocal measurements and avoiding a dependency on a semi anechoic chamber.

The data for the calculation of the source related transfer functions (SRTF) was previously recorded directly and in a semi anechoic chamber, which meant a high measuring effort concerning instrumentation and facilities. Further, in the original synthesis approach the input signals were simply filtered with the SRTF and then summed up. The synthesis results were therefore prone to errors from cross talking or wrong radiation models of the components.

With the extended approach the SRTF measurements are performed reciprocally with a monopole sound source, leading to a simplified and faster instrumentation. A special recording and analysis technology has been implemented allowing sample-precise synchronous play-back and recording of pseudo noise signals. The advantages of this are the possibility to perform the measurements without a semi anechoic chamber and more precise SRTF, especially regarding the phase response.

The effect of errors in the radiation models on the synthesis result – which increases for the reciprocal measurements – is compensated by the implementation of radiation filters. These filters consider the radiation characteristics of functional component groups. The determination of these radiation filters requires a chassis dynamometer. Since this is not available for public transport busses, the software had to be adapted to allow synthesis calculation and reviewing using less or averaged radiation filters.

All this widens the range of measurable vehicles and lowers costs.

So far, data for various transportation means has been recorded, successfully synthesized and evaluated. Further measurements and syntheses will follow to complete the data acquisition phase.

The gained insights into the different influences and contributions of the noise components to the overall noise will be evaluated within WP2.1.2 in the next six month. The results of this evaluation will be included in D2.9 M18.

The assessed quantitative contributions of the components will be used for the psychoacoustic evaluation in WP2.2.2. By this, the influence of single components on the perception of vehicle noise can be studied. The qualitative results of listening test will be used to define an algorithm using quantitative psychoacoustic parameters. Hereby, a tool for the calculation of the sound quality of pass-by noise is created, which helps to define “penalty” and “premium” values for vehicle exterior noise. This will be further enhanced and improved for traffic noise in WP5.12.

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[8] SENSE – software of HEAD acoustics, developed as an exploitation of the SVEN project

All recorded data will be implemented into the sound library of the Auralizer software created within WP2.2.3. The time signals will be available to all project partners, who can auralize and filter them with the frequency responses of the screening techniques and mitigation measures developed within SP4.

The compiled data and the gained results from it are strongly related to WP5.12. In SP2 the aim is to evaluate pass-by noise and noise source contribution regarding their relative importance and perception. This will lead to insights into the “acoustic classes” of vehicles and situations, which again will be combined for the auralization and evaluation of traffic flow noise in WP5.12. Further, mitigation measures for specific noise sources can be auralized adequately, e.g. by applying road surface effects on rolling noise.