DELIVERABLE 2.9

CONTRACT N°		TIP4-CT-2005-516420
PROJECT N°		FP6-516420
ACRONYM		QCITY
TITLE		Quiet City Transport
Subproject	2	Perception of Vehicle Noise Sources
Work Package	2.1	Identify/Rank Perception of Noise Sources
		Noise Source Potential for Future Transportation Means

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Date of issue of this report 16.11.2006

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PROJECT START DATE February 1, 2005

DURATION 48 months

Project funded by the European Community under the
SIXTH FRAMEWORK PROGRAMME
PRIORITY 6
Sustainable development, global change & ecosystems

This deliverable has been quality checked and approved by QCITY Coordinator
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TABLE OF CONTENTS

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 months 13 and 18 of the QCITY project. The first objective is the further 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 SVEN approach is implemented. The advantage of this approach is a simplified and more flexible measurement procedure without a dependency on facilities like a chassis dynamometer and semi anechoic chamber. This widens the range of measurable vehicles and lowers costs. The data of the selected vehicles is recorded, synthesized and evaluated. The results are presented.

The second objective is the comparison of the noise source characteristics of the different vehicles and the driving situations. The procedure does not only regard the classical parameters like SPL and spectra but also the result of the listening tests in WP2.2.2. Hereby, the subjective perception and the resulting annoyance ratings are additional bases for the conclusion about the future noise source potentials. So, it can be assumed that derived measures will improve the annoyance of residents and pedestrians.

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 result 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 SENSE. Since the standard SVEN approach is not feasible for larger vehicles like a public transport bus, an extended SVEN approach is developed which allows measurements without facilities like a chassis dynamometer and semi anechoic chamber.

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 comparison of the vehicles and of the driving situations leads to insights about typical noise source problems and techniques that improve these problems. The results

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

of the listening test in WP2.2.2 are integrated in to this comparison to identify characteristics that really improve the living quality in cities by reducing annoyances and not only dB(A)

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 easy application. This SVEN approach was extended, so the measurements can be performed without using facilities like a chassis dynamometer and semi anechoic chamber. This widens the range of measurable vehicles and lowers costs. Additionally, the rolling noise is not tampered by the roller test bench.

0.4 PROBLEMS ENCOUNTERED

About the improvement of the rolling noise the evaluations could not give any decisive conclusions. Here general considerations are stated.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

The data acquisition serves not only for 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) developed the extended SVEN approach and adapted their SENSE software accordingly. The measurements and syntheses of the vehicles using the standard and the extended SVEN approach were performed by HEAD acoustics. Finally, the evaluation of the compiled data was performed by HEAD acoustics.

STIB/MIVB (STIB) supported the tram measurement.

0.6 CONCLUSIONS

The application of the component synthesis procedure has been effective, especially the implementation of the extended SVEN approach. With the new approach it is possible to the measurements in free field. The advantage of the new SVEN approach is a simplified and more flexible application without a dependency on facilities like a chassis dynamometer and semi anechoic chamber. This widens the range of measurable vehicles and lowers costs. Additionally, the quality of the recorded tire noise is increased.

The data for various transportation means has been recorded, successfully synthesized and evaluated. The main conclusions are

1. The main noise and annoyance sources are the heavy diesel engines. Current technology is able to construct quieter diesel engines.
2. Acceleration noise is mainly emitted by the intake and the exhaust. Constructive improvements are possible. More effective would be the extensive introduction of e.g. electric engines.
3. Rolling noise is important for constant pass-by at higher speeds. Acoustical improvements of both interfaces are necessary; whereas the application of quiet road surface is faster and more effective.

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

D2.2: Development of extended SVEN approach and start of measurements

D2.8: Input of data, Output of subjective evaluations

TrafficNoiseSynthesizer (WP2.2.3 & WP5.12): Input of time signals and data for traffic flow scenarios

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) and draw conclusions about the future potential of the noise sources (D2.9). Two different approaches are chosen to collect the data. On the one hand, an 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 quantitative the contribution of a single noise source to the overall noise of a specific vehicle. The former method is subject of WP2.1.1 and its progress is described in D2.10. The latter is the objective of WP2.1.2 and the progress and results are presented in this deliverable.

WP2.2.2 relies on all the gathered time signals to carry out listening test and psychoacoustic analyses. The exterior noise of the various vehicles is compared and the determined contributions of the noise sources are evaluated. The qualitative results of the listening tests are used to define a calculation method using quantitative psychoacoustic parameters and to prepare a bonus-malus-system for vehicles and their noise sources. Hereby, a tool for the calculation of the subjective annoyance of pass-by noise – called evaluation index EI (see D2.8) – is created and implemented in the TrafficNoiseSynthesizer software (WP 2.2.3). This will be further enhanced and improved for traffic flow noise and filtering in WP5.12. Concerning WP2.2.3 the recorded data is a part of the sound library of the TrafficNoiseSynthesizer software and therefore accessible for all the partners within QCITY. It can be subject to filtering. The filters can be calculated in respect to various mitigation conditions defined within ISO 9613 or imported from other measurements or calculations of mitigation measures.

All the topics mentioned above are strongly related to the enhancement of the TrafficNoiseSynthesizer 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. The synthesized traffic flow can then be analyzed concerning its subjective perception using the results of the psychoacoustic analysis.

The following report describes the work done and results gained in WP 2.1.2 during the months 13 – 18 of the QCITY project. The first objective is the application of the quantitative component synthesis developed within the EU project SVEN[2] on selected vehicles of different transportation means. In this process, an extended SVEN approach will be implemented. The advantage of this approach is a simplified and more flexible measurement procedure without a dependency on facilities like a chassis dynamometer and semi anechoic chamber. This widens the range of measurable

[2] using the HEAD acoustics software SENSE

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

The second objective is the comparison of the noise source characteristics of the different vehicles and the driving situations. The procedure does not only regard the classical parameters like SPL and spectra but also the result of the listening tests in WP2.2.2. Hereby, the subjective perception and the resulting annoyance ratings are additional bases for the conclusion about the future noise source potentials. So, it can be assumed that derived measures will improve the annoyance situation for residents and pedestrians.

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 to undertake:

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 and comparison with the synthesis (optional)

2.1 COMPONENT MEASUREMENTS

For the measurement of the input data the vehicle is run on a chassis dynamometer. Further, this standard approach is extended within QCITY by performing input measurements on a test track with specific vehicles. This modification allows measurements independent of chassis dynamometer facilities, which widens the range of measurable vehicles and lowers costs.

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 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). Additionally, the speed of the vehicle is recorded.

Most of the measurements are conducted on the chassis dynamometer at HEAD acoustics in Herzogenrath. 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 4.5 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).

The determination of the SRTF is 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.

As monopole sound source a dodecahedron system of the Institute of Technical Acoustic, Aachen University is used. 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.

2.3.1 Radiation Filter

A radiation filter is used to compensate possible errors due to the modelling of the component monopoles (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 a 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.

If the extended SVEN approach without a chassis dynamometer is used only the power train can be investigated as a separate group of components.

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.

The resulting signals correspond to a measurement with a far field microphone array at a distance of 7.5 m. This data is used to calculate the monaural and binaural time signals.

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.

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.

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.

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, a all-wheel SUV, a truck and a tram. Thereby, different engine types, drive concepts and vehicle classes are considered.

The results of the vehicle evaluation cannot stand for a whole respective vehicle class, since only one specimen is considered. In fact, it is attempted to gather different acoustic characteristics of noise sources and exterior noise. By analyzing these characteristics general statements about the characteristics – and not the vehicle classes – will be made.

4.2 INPUT

The input signals of the near field microphones are recorded either on a chassis dynamometer or on a test track (extended SVEN 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.

Figure 3: Toyota Prius on the chassis dynamometer, 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 or – as an enhancement of the original SVEN method – 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 extended SVEN approach is chosen, 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. 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.

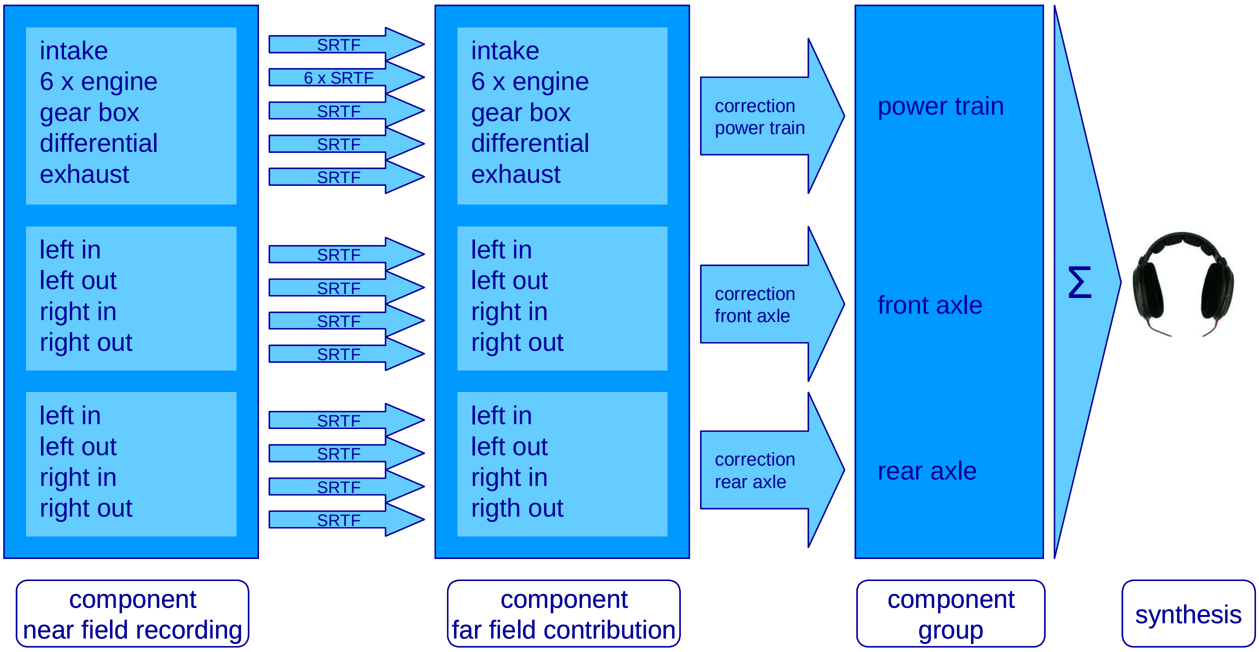

Figure 7: Scheme for the synthesis of a far field signal from component recordings (example of Toyota Prius)

The results of this procedure are signals for the single reference points of a virtual microphone array. Binaural and monaural pass-by noise can be calculated using these signals. A binaural signal is necessary for 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.

In some cases further adjustments are necessary to improve the quality of the synthesis. Since the synthesis model assumes a fixed recording distance between noise source and near field microphone, a level fitting for some components is possibly required. Sometimes it is advisable to adjust the near field recordings of the microphones in the engine compartment.

The engine compartment acts as a pressure chamber especially regarding the low frequencies. This means it exist a homogenous sound field and the recorded signals there are not incoherent anymore. This can lead to an overestimation of the low frequency range of the engine compartment – e.g. main engine orders – during the synthesis. If this is the case, the level of the input signals of the microphones in the engine compartment has to be reduced accordingly.

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.

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 D2.2. The results for the other vehicles are presented as summaries including the main outcomes which are important for the QCITY project.

5.1 LUXURY CAR

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

- 2 x intake,
- 7 x engine,
- gear box
- differential
- 2 x 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.

5.1.1 *acc50*

The main contribution to the pass-by noise is emitted from the tires which are fastened to the driven rear axle (Figure 8). The noise of the power train is characterized by engine orders in the low and mid frequency range and high frequency noise; the noise is mainly emitted through the button of the engine. The front tire noise shows tire orders in the frequency range between 400 Hz and 800 Hz, which are only important at the moment of the pass-by. The dominant contributions of the rear tires are a tire order at about 450 Hz and high levels in the broad frequency range between 700 Hz and 2.5 kHz as well as high frequency noise.

Since this car has an 8 cylinder engine the first relevant engine order is the 4th engine order and can be found at 140 Hz. Generally the engine orders are very unobtrusive and equally pronounced. The main sources for the engine orders are the two intakes and the emissions from the engine bottom. From here also originate the high share of noise in the frequency range above 400 Hz. The only further contribution in the high frequency range comes from the exhausts (above 2 kHz).

The significant contribution of the front tires to the overall pass-by noise consists of two tire orders at about 460 Hz and 700 Hz that reach relevant levels when there are right in front of the observer. They are emitted from the leading as well as the trailing edge of the tires. The dominant source of the front tires is the trailing edge of the left tire.

The driven rear tires are the level dominating component group. They noise emission determines the level of the whole frequency range above 400 Hz from the point of acceleration. The leading and trailing edge of the relevant left tire are balanced in the way that the trailing edge shows the highest level during the approach if the car and the trailing edge during the drive-away. Nevertheless, the important tire orders are emitted mainly by the trailing edge; in fact they are so strong that the trailing edge of the right tire becomes the second important noise source of the rear tires at the end of the test track. This accounts also to the high acceleration of this car.

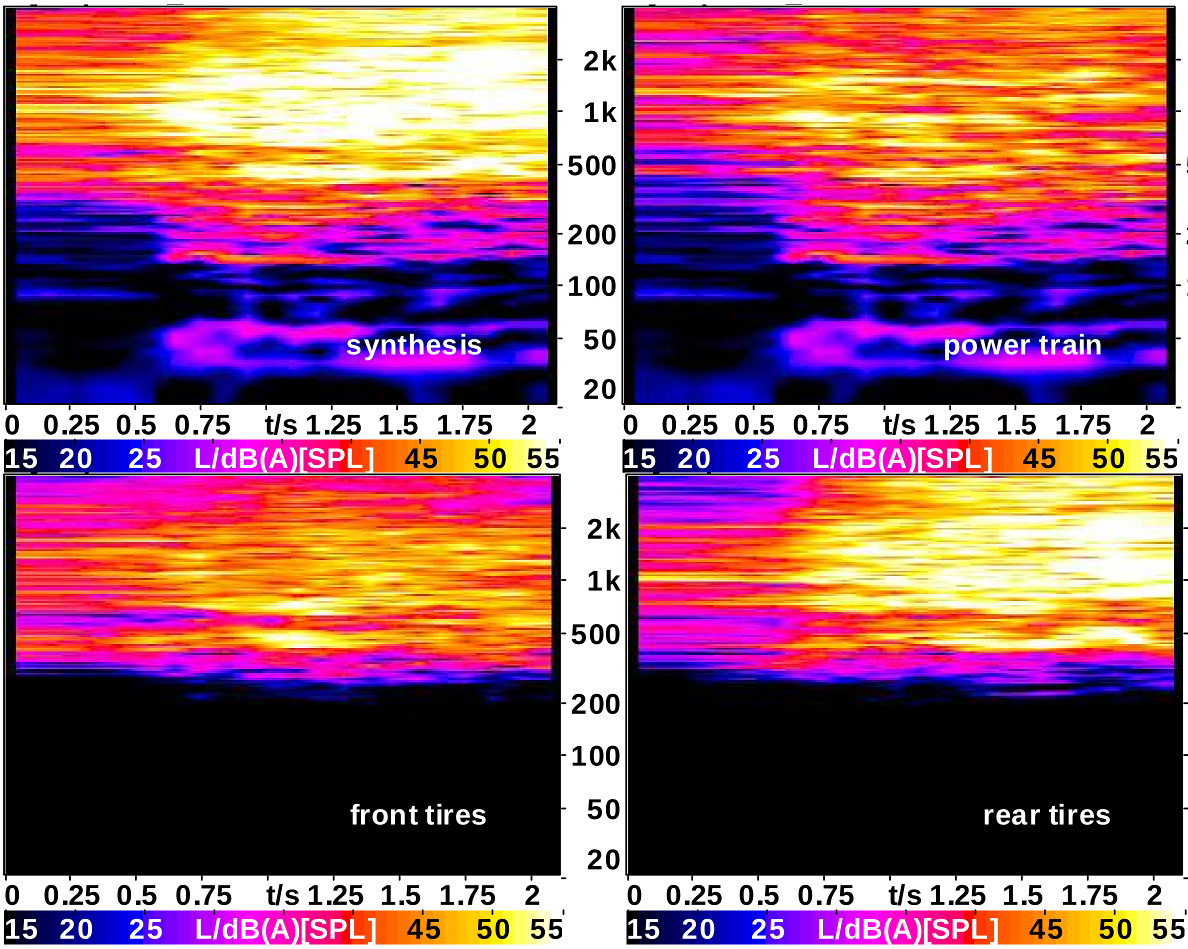

Figure 8: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 9 is depicting the contributions of the component groups to the overall level. During the constant approach the power train and the front tires are balanced. The point of WOT causes the engine to slightly increase its level and when the car actually accelerates and the rear tires approach they become the dominant noise source. At the end of the test track their noise level is almost 10 dB above the other component groups.

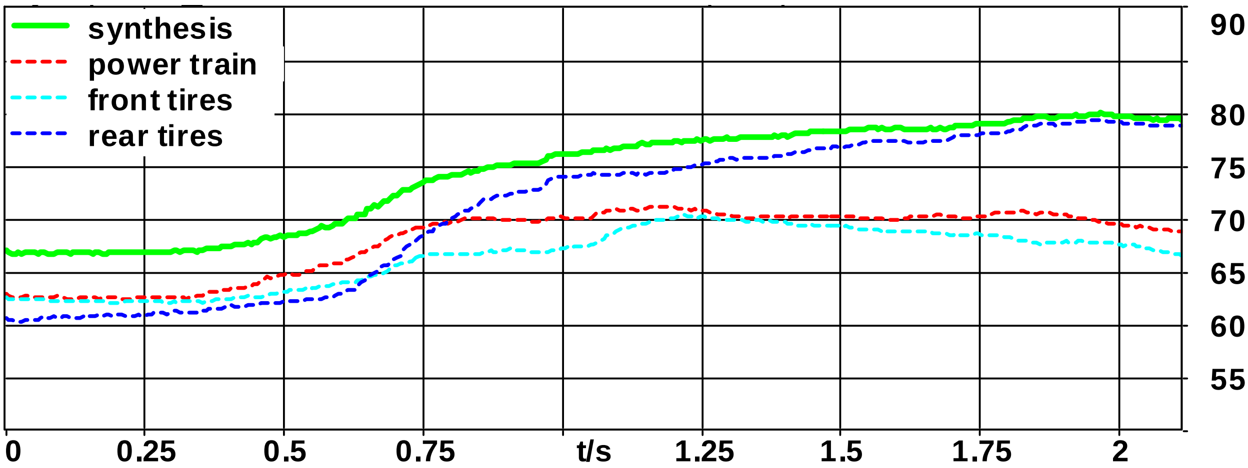

Figure 9: Level vs. distance. Level of the component synthesis and component groups for *acc50*

5.1.2 *const50*

(Figure 10) depicts the FFT vs. time of a real pass-by on test track. The low frequency range lacks distinct characteristics due to the low key power train noise during a constant pass-by. The levels of main frequency range between 400 Hz and 2.5 kHz are determined by the front and rear tires.

Due to the missing acceleration the power train noise has become secondarily. Even the low frequency range which determined by the combustion noise cannot show distinctive characteristics or significant levels. The noise in this frequency range originates again mainly from the intake and the bottom of the engine, which is also emitting mid and high frequency noise; however its level cannot compete with the tire noise in this frequency range.

The noise contribution of the rear tires is now the main source during the approach, which is mainly due to the lower levels of the other component groups. The characteristic tire order at about 450 Hz – not as sharp as at the acceleration – and the broad band noise between 700 Hz and 2.5 kHz during the approach of the car can be accounted mainly to the front tires. The dominant source of the front tires is still the trailing edge of the left tire.

The rear tires show reduced levels compared to the acceleration situation. They become dominant at the second half of the test track. The trailing edges are again the main noise and tire order source but no as dominant as at the acceleration.

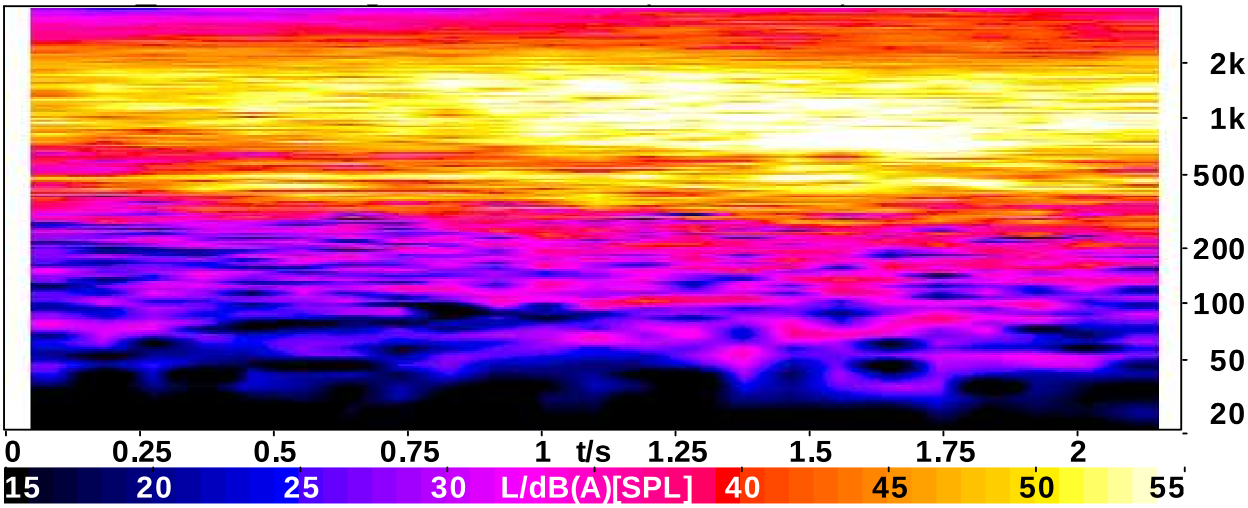

Figure 10: FFT vs. distance. Real pass-by on the test track at constant 50 km/h

Figure 11 is depicting the overall level of a constant pass-by at 50 km/h. The front and rear tires are the main noise source for this pass-by, whereas the approach is dominated by the front tires and the drive-away is dominated by the rear tires. The noise emitted by the power train has only a secondary contribution to the overall noise. In general, the level of the constant pass-by lies well below the level of the accelerated pass-by. Since this difference is mainly caused by the driven rear tires it can be attributed to a high acceleration and a low noise engine.

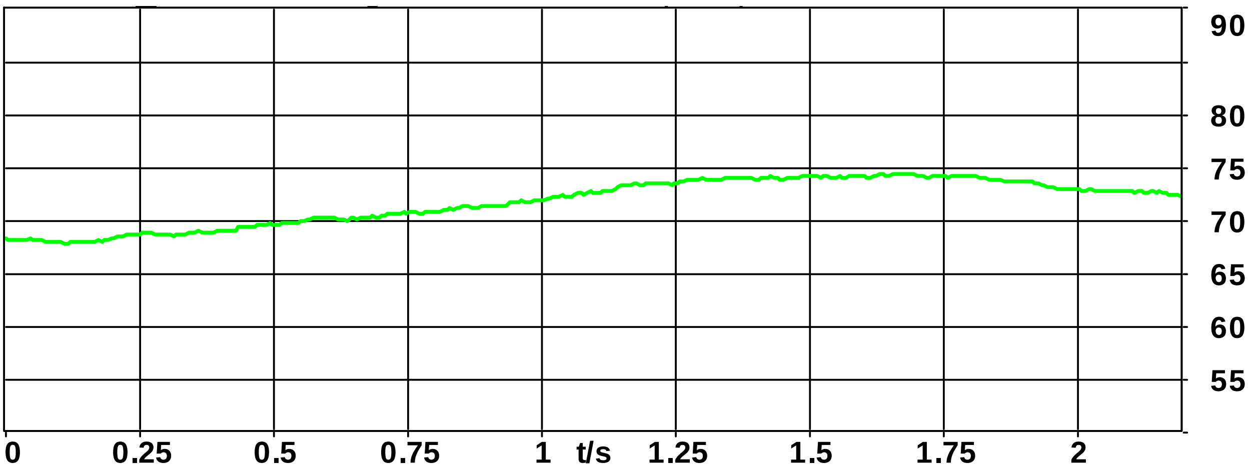

Figure 11: Level vs. distance. Level of the constant pass-by at 50 km/h

5.2 SUV

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

- intake,
- 6 x engine,
- gear box
- converter
- 2 x differential
- 2 x 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.

5.2.1 *acc50*

The contribution of the combustion noise is characterized by engine orders in the low and mid frequency range and relevant shares of high frequency noise. Since this car has got a 4-wheel drive, both axles are driven with approximately the same torque. Therefore the contributions of the front and rear axle are very similar. Beside a narrow band noise at about 470 Hz the main noise emission of the tires occurs in the frequency range between 800 Hz and 2.3 kHz.

The power train noise consists of distinctive engine orders in the frequency range between 100 Hz and 600 Hz and additional noise emission in the frequency range below 600 Hz. The engine orders come mainly from the exhausts, the rear of the engine and the bottom of the car. Also the high frequency noise can be allocated mostly to the emissions through the car's bottom.

Concerning the front tires the trailing edge of the left tire is the dominant noise source. During the constant approach the leading and trailing edges show similar spectra with a main tire order at 1100 Hz. During the acceleration this tire order remains the main order in the spectra of the trailing edges, whereas the leading edges show pronounced orders between 450 Hz and 700 Hz as well as 1.5 kHz and 2.3 kHz.

The rear tires show a very similar behaviour in comparison to the front tires. The trailing edge of the left tire is again dominant and the leading edges change the dominant tire orders when the acceleration starts. One difference that can be found is that already during the constant approach several other tire orders are clearly visible. This can possibly ascribed to a slightly higher torque at the rear axle.

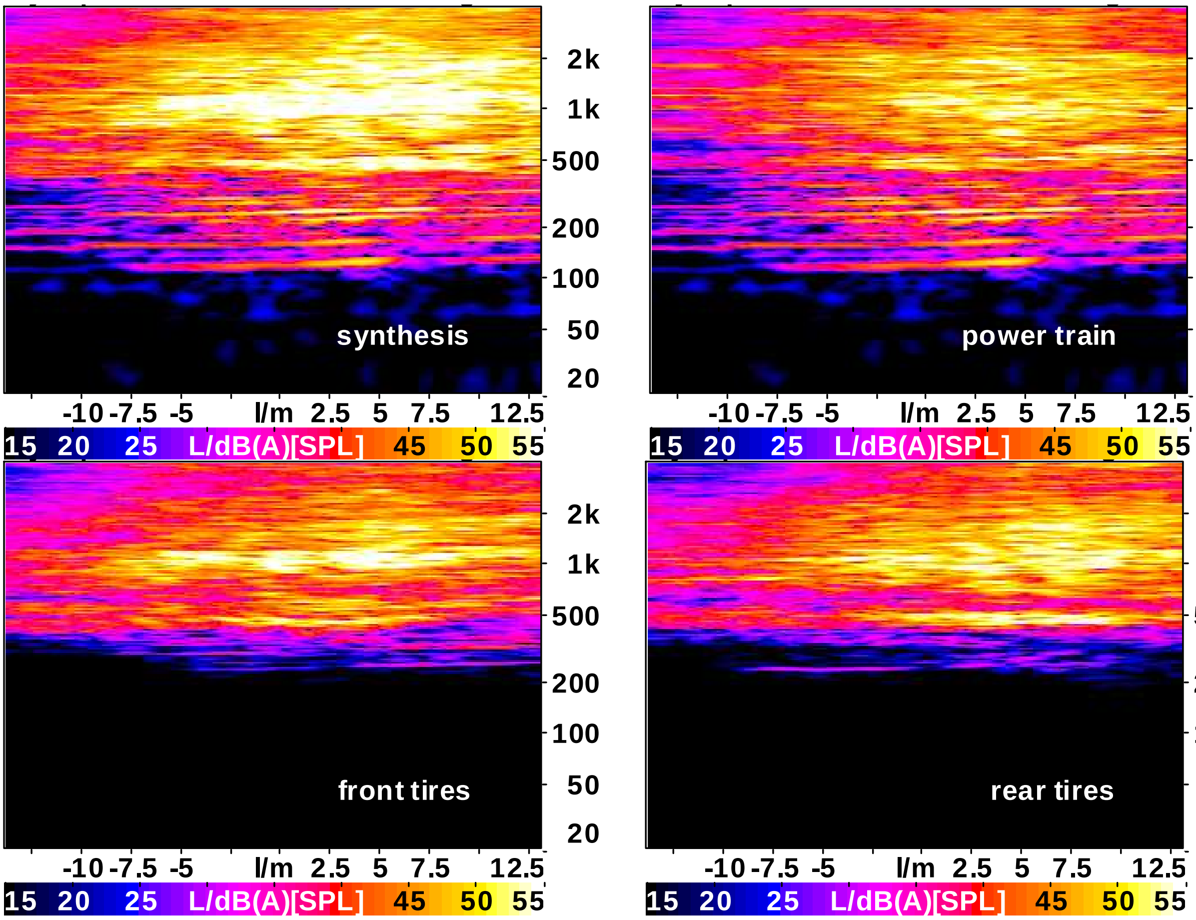

Figure 12: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 13 is depicting the contributions of the component groups to the overall level. In contrast to all the other level vs. distance diagrams shown before, it exists here a very balanced proportion between the three component groups. First of all the 4-wheel drive prevent one axle – the single driven one – to become dominant in level. Since the torque is divided between the two axles, their noise emissions are comparable (it can be assumed that he rear axle gets slightly more since the distance during the approach is bigger). Further the combustion noise level – which often lies between the axle levels – is also comparable to the tire noise levels; which is of course also due to the high levels of the engine orders in the low frequency range. At the end of the test track the level differences between the component groups increase slightly.

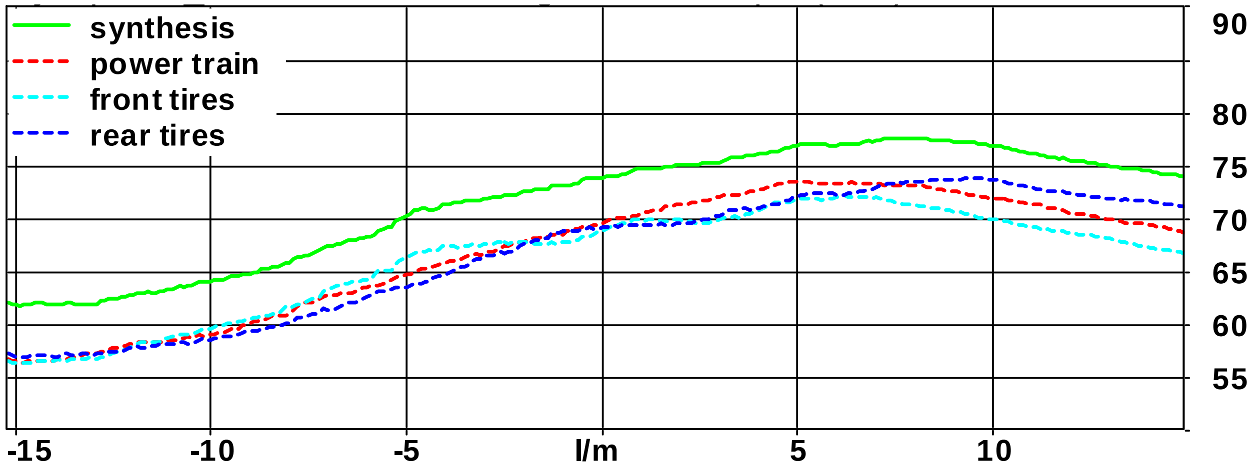

Figure 13: Level vs. distance. Level of the component synthesis and component groups for *acc50*

5.2.2 const50

The main characteristics (Figure 14) of the overall noise derive from the tires in the mid and high frequency range and from the power train in the low frequency range. The engine orders are the main contribution of the power train. They are quite low in level, but dominate the lower frequency range. The tires dominate the mid and high frequency range, whereas the rear tires show slightly more influence on the overall noise than the front tires.

The engine orders are quiet reduced in level compared to the acceleration condition. Their influence on the overall level has decreased. The same applies to the noise emission in the higher frequency range. The engine orders still come mainly from the exhausts, the rear of the engine and the bottom of the car. The bottom of the car radiates the high frequency noise.

The noise of the front tires has become broader than at the acceleration situation. The main frequency shares occur between 700 Hz and 1.8 kHz. Interestingly, this corresponds more to the tire orders found during the acceleration than to the ones during the constant approach. The trailing edge remains the highest in level.

The rear tires show again a very similar behaviour in comparison to the front tires. The trailing edge of the left tire is again dominant. The spectra of the rear tires' components show the same characteristics as the spectra of the front tires except that the orders a bit more pronounced and therefore the overall level of the rear tires exceeds the one of the front tires. Here again it could be concluded that the torque at the rear tires is slightly higher than at the front tires.

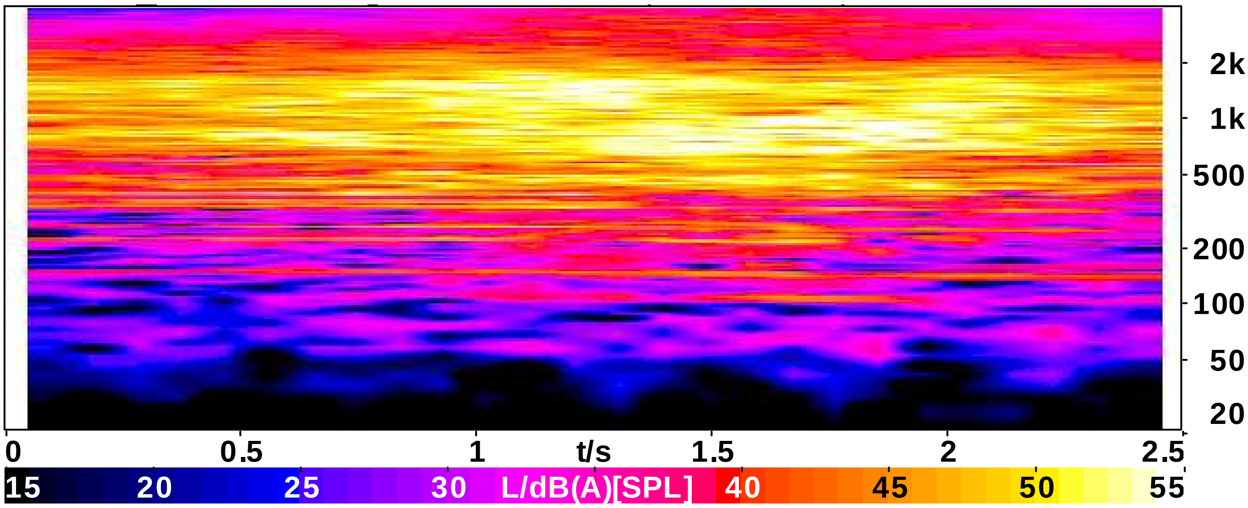

Figure 14: FFT vs. distance. Real pass-by on the test track at constant 50 km/h

Figure 15 is depicting the overall level of a constant pass by at 50 km/h. Since the level of the engine orders is reduced the influence of the power train on the overall noise has significantly decreased. The tire noise is now dominating with the rear tires having a slightly bigger share. It is obvious that at a constant pass-by the torque division has no big acoustical influence.

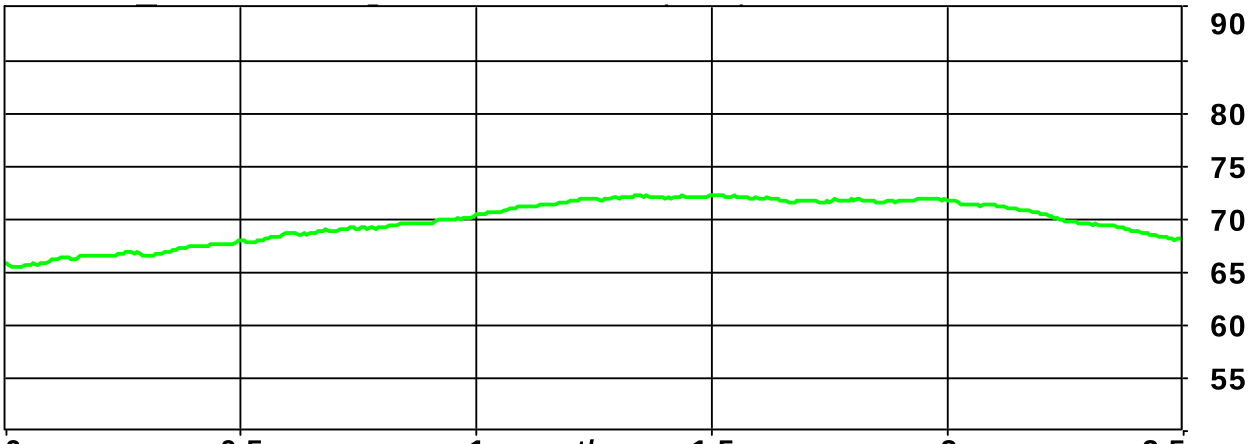

Figure 15: Level vs. distance. Level of the constant pass-by at 50 km/h

5.3 TRUCK

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

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

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

The measurements are carried out on the test track of the IKA, Aachen University. The input measurements for the noise components are performed during a real pass-by and not on 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 SVEN approach proved to be very successful.

5.3.1 *acc50*

The main feature of low frequency range of the pass-by noise is the strong second engine order of the power train and the sixth engine order. Additionally, the power train emits relevant noise in the frequency range between 1 kHz and 2.5 kHz. Nevertheless, the level dominating noise sources are the tires – especially the ones of the driven rear axle. Even during the approach their level and characteristics can compete with the front tires. In the second half of the test rack they become level defining.

The power train noise is on the one hand characterized by the engine orders, above all the strong second engine order causing a humming sound and the sixth engine order. They are mainly emitted by the intake, the top of the engine and somewhat by the exhaust. On the other hand in the frequency range between 1 kHz and 2.5 kHz the typical high whine of a truck gear can be found. Further, it can be seen that it is not possible to really accelerate the truck on the 20 m of the test track.

The noise contribution of the front tires ranges upwardly from 500 Hz. It is rather broad band with one distinctive tire order at 2 kHz which is emitted from all four components of the front tires. Generally, their spectra are very similar except for level differences due to orientation.

The main noise emission of the tires of the driven rear axle lies also 500 Hz. The spectra show several distinctive tire orders covering the frequency range between 500 Hz and 2 kHz and relevant over the whole test track distance. They are emitted also by all four components.

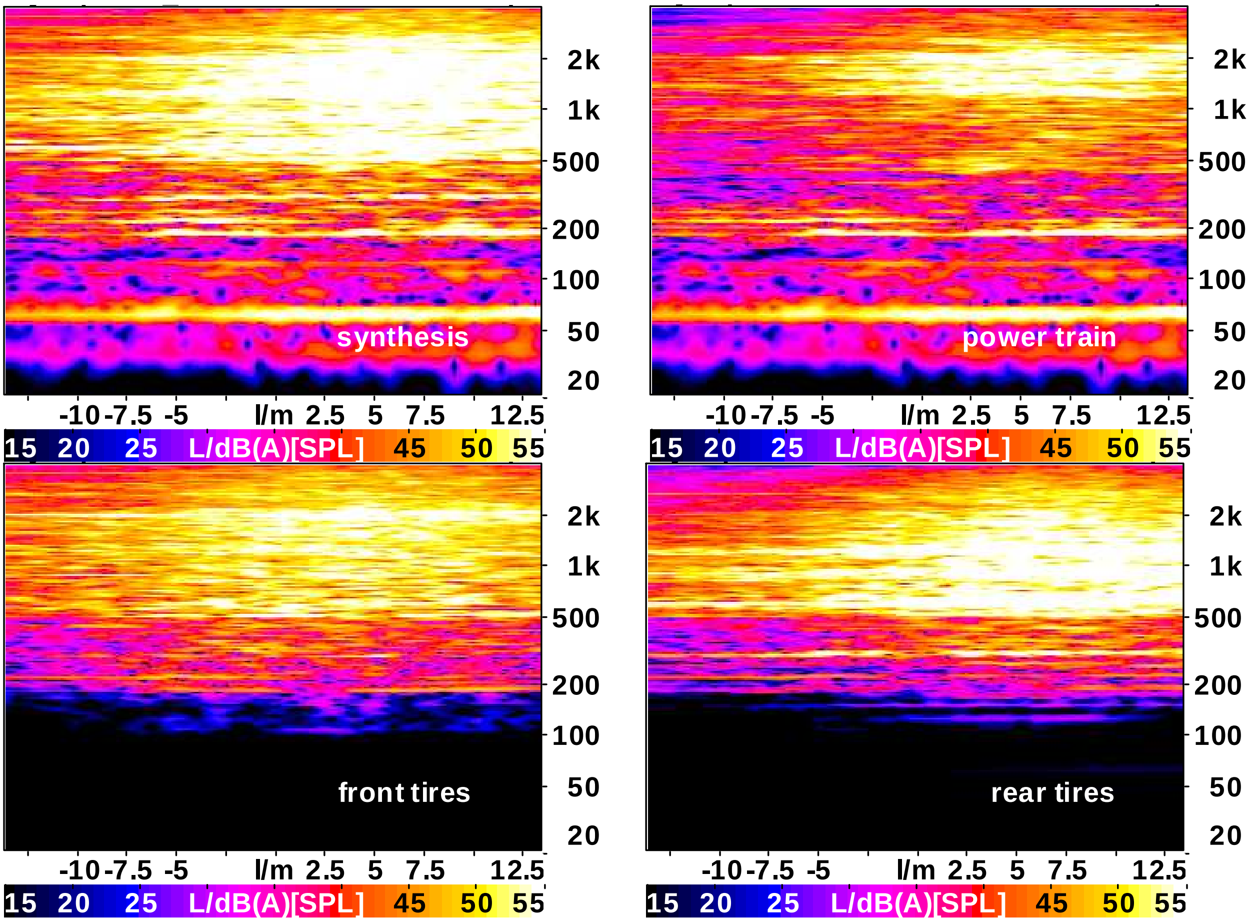

Figure 16: FFT vs. distance. Component synthesis (top left) and contributions of the component groups power train (top right), front tires (bottom left) and rear tires (bottom right)

Figure 17 is depicting the contributions of the component groups to the overall level. Until the truck reaches the middle of the test track the level of the front and rear tires are comparable; considering the orientation this means that the rear tires are actually louder. After the passage of the observer point this becomes obvious. The level of the power train is not significant for the overall level, in spite of its strong second engine order in the low frequency range.

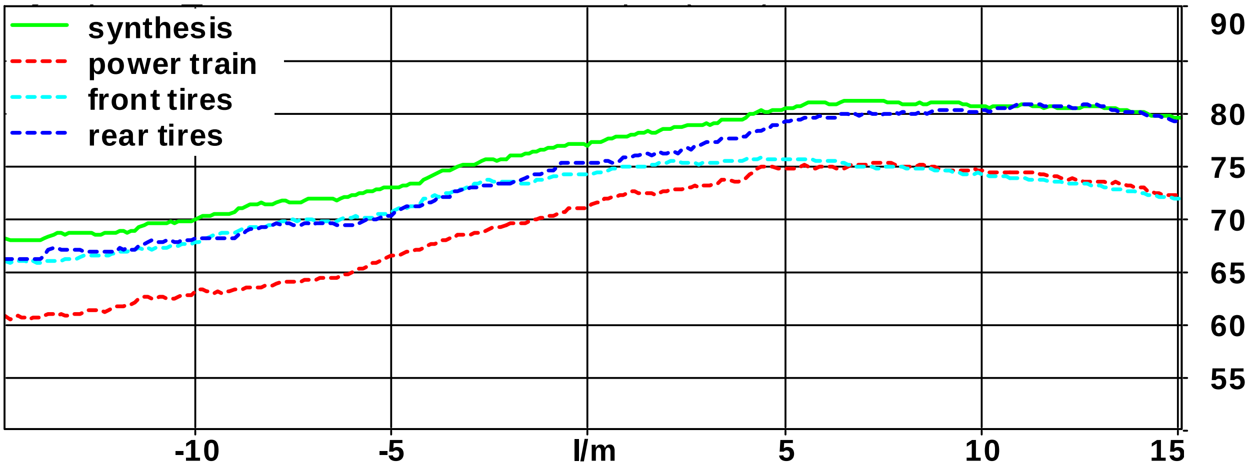

Figure 17: Level vs. distance. Level of the component synthesis and component groups for *acc50*

5.3.2 *const50*

The overall noise consists again of the engine orders in the low frequency range with the dominating second engine order, the fourth and the narrow sixth engine order. The frequency range above 500 Hz is mainly affected by tire orders up to 2 kHz which are mostly emitted by the driven rear tires.

The main feature of the power train noise is again the strong second engine order. The appearance of the fourth engine order at the constant pass-by could have several explanations like changed condition of the engine or the environment or during the SRTF measurements. Nevertheless, the main characteristics remain reproduced. The gear whine is also present but not as pronounced as at the acceleration.

The typical tire order of the front wheels has been shifted slightly to 900 Hz. Otherwise, their noise emission has not changed significantly compared with the acceleration situation.

The rear tires dominate again the mid and high frequency ranges. Several distinctive tire orders in the frequency range between 500 Hz and 2 kHz occur. The noise of the rear tires is already relevant at the beginning of the test track and rising over the test track.

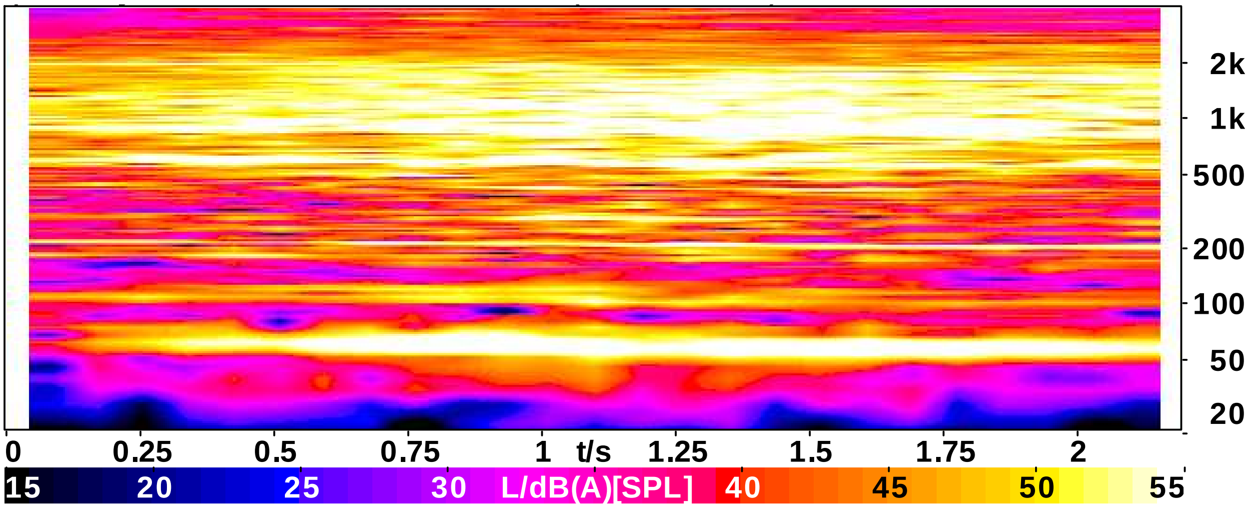

Figure 18: FFT vs. distance: FFT vs. distance. Real pass-by on the test track at constant 50 km/h

Figure 19 is depicting the overall level of a constant pass by at 50 km/h. In general, the levels of all component groups are lower than at the acceleration and therefore the overall level is lower too. The proportion of the component groups has changed in the way that the power train gained more influence on the overall level and the undriven front tires lost influence.

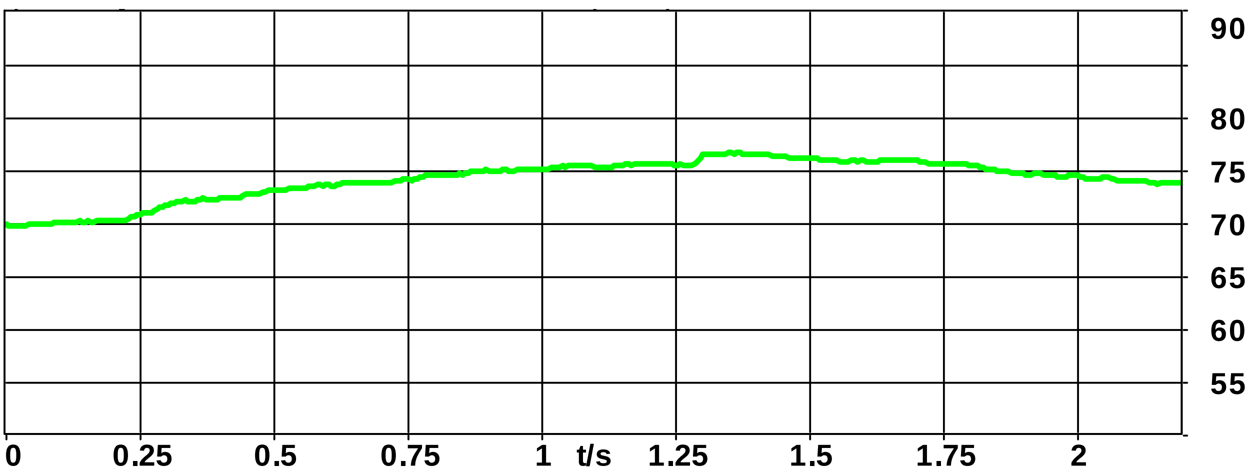

Figure 19: Level vs. distance. Level of the constant pass-by at 50 km/h

5.4 TRAM

So far the SVEN approach was only applied to road vehicles. This tram is the first rail bound vehicle the component synthesis is tested at. Due to its length of 32 m it is not possible to synthesize the whole tram, at least not with the current procedure. It is decided to consider only the front bogies and the roof aggregates.

18 microphones are applied in and at the front bogie and the roof for the input recordings:

- 8 x motor,
- 8 x tires,
- pental,
- differential,
- converter.

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

The measurements are carried out on the test track of STIB in Brussels, Belgium. The input measurements for the noise components are performed during a real pass-by and not on chassis dynamometer. The measurements for the SRTF calculation are performed in the free field. The application of the extended SVEN approach on this vehicle proved to be a big challenge. Unfortunately, not all problems could be solved until the compilation of this report. Therefore, the noise characteristics of the tram are discussed using the input and artificial head measurements.

5.4.1 *acc50*

Figure 20 depicts the FFT vs. time of an artificial head recording of the tram pass-by. Characteristic features of this pass-by are the missing low frequencies, the occurring resonances or orders between 150 Hz and 1.1 kHz, the narrow band noise at 1.3 kHz and high frequency share above 1.6 kHz. It is noticeable that the narrow band noise at 1.3 kHz occurs not only during the actual pass-by but already before and still after it.

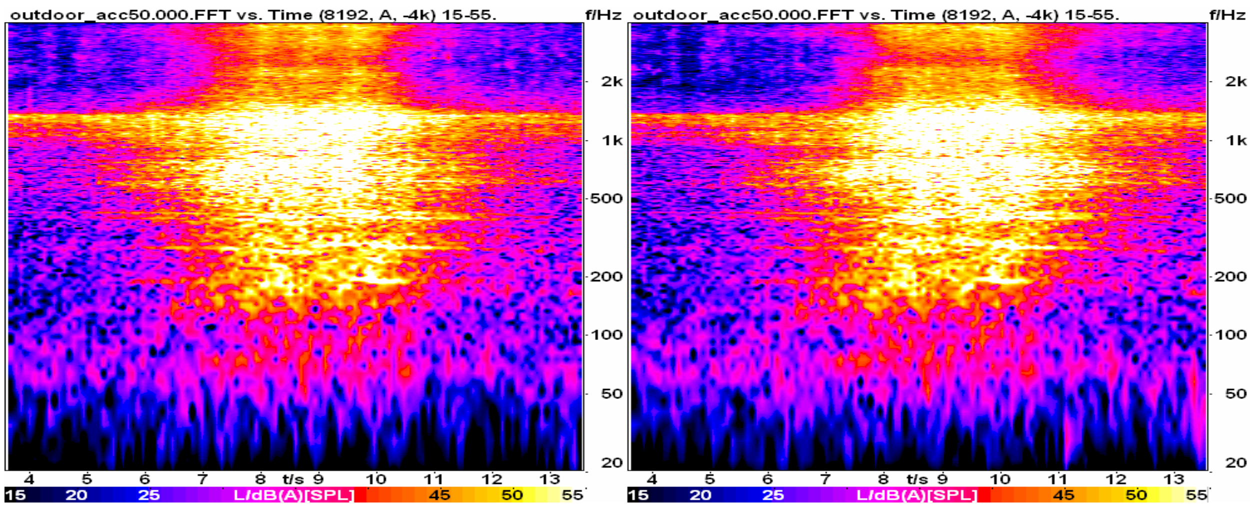

Figure 20: FFT vs. time. Artificial head recording of a tram pass-by, acceleration from 50 km/h

Figure 21 depicts the near field signals of a tire microphone and a motor microphone. They are shown exemplarily for the whole signals of the tires and the motors.

The input signals of the tires show typically the main noise emissions in the frequency range between 400 Hz and 2.5 kHz. The emphasis lies here between 500 Hz and 1 kHz – which is also visible in the far field recording – with a typical resonance at 1 kHz. This resonance is probably also carried by the rails and radiated at 1.3 kHz which explains the occurrence of it already before and still after the pass-by of the tram.

The motor signals show a wider emission span ranging from 180 Hz up to 3 kHz. Also the resonances or orders found in the far field recording occur here. The point of acceleration can thereby be identified. Concerning the high frequency share above 1.6 kHz it can be assumed that it comes also from the motors, but it is also possible hat the pental causes these emissions.

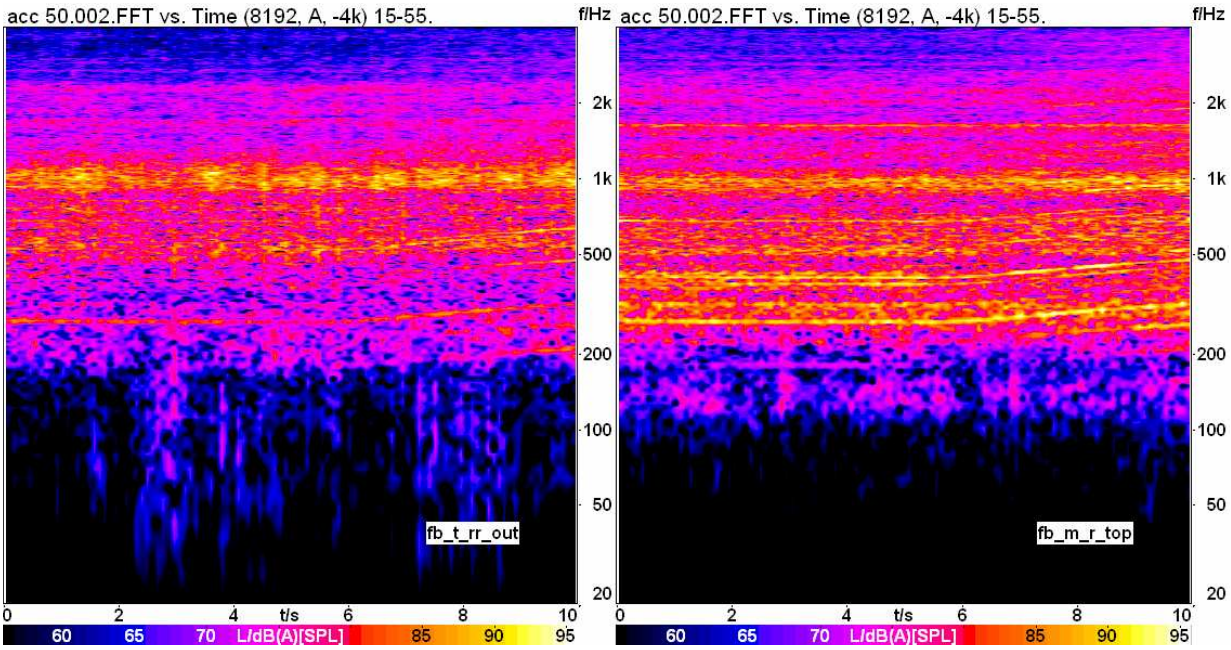

Figure 21: FFT vs. time. Near field signals of the tire's trailing edge (left) and motor (right)

Figure 22 depicts the noise level of the tram pass-by as recorded with the artificial head. Due to its length of 32 m the relatively high level of 80 dB(A) last for at least two seconds which is – in comparison to the vehicles considered so far – a huge time span. The main contributions come from the engine orders and of course the narrow band noise of the tires.

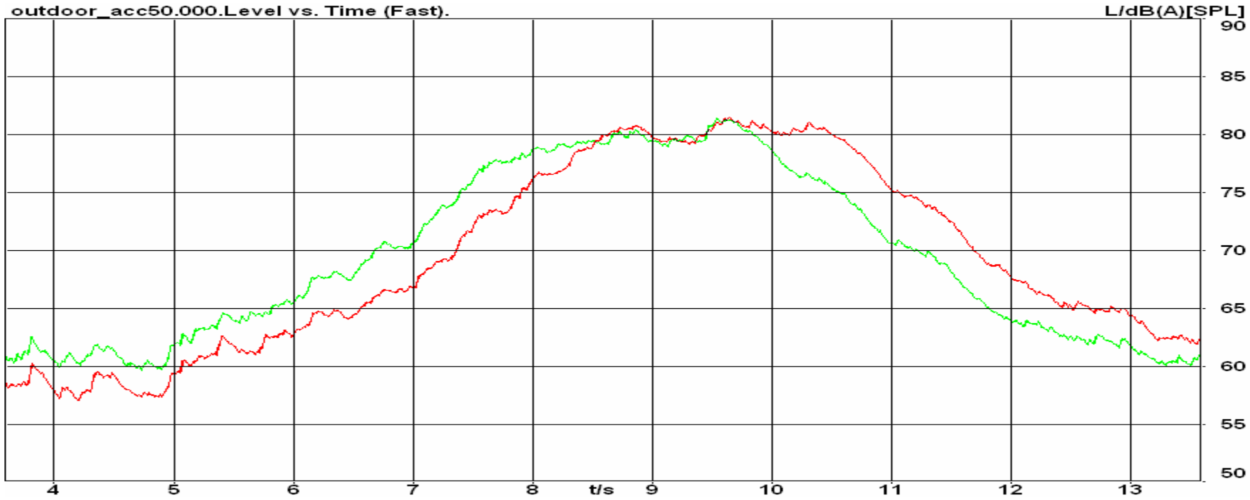

Figure 22: Level vs. time. Artificial head recording of a tram pass-by, acceleration from 50 km/h

5.4.2 *const50*

Figure 23 depicts the FFT vs. time of an artificial head recording of the tram pass-by. It does not differ significantly from the accelerated pass-by accept for missing a certain howl or whine which can certainly attributed to the rising orders. Besides, the same characteristic features can be found: missing low frequencies, orders between 150 Hz and 1.1 kHz, narrow band noise at 1.3 kHz and a high frequency share that occurs not only during the actual pass-by but already before and still after it.

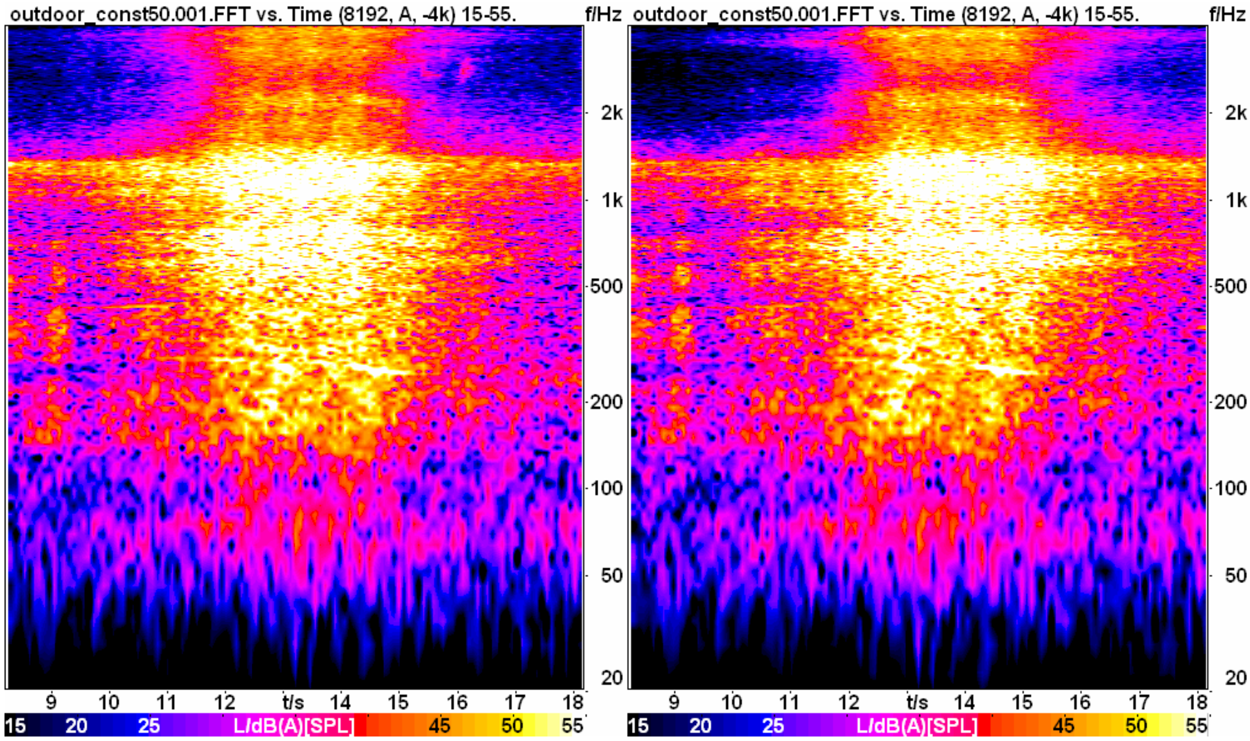

Figure 23: FFT vs. time. Artificial head recording of a tram pass-by, acceleration from 50 km/h

Figure 24 depicts the near field signals of a tire microphone and a motor microphone. They are shown exemplarily for the whole signals of the tires and the motors.

The input signals of the tires and motors resemble the input signals of the accelerated pass-by accept for the constant running motor orders. Considering the spectra of the far field as well as of the near field recordings the two situations constant pass-by with 50 km/h and acceleration from 50 km/h do not differ very much. Maybe this is due to the shortness of the test track and different results are gained if accelerations on longer track section are considered.

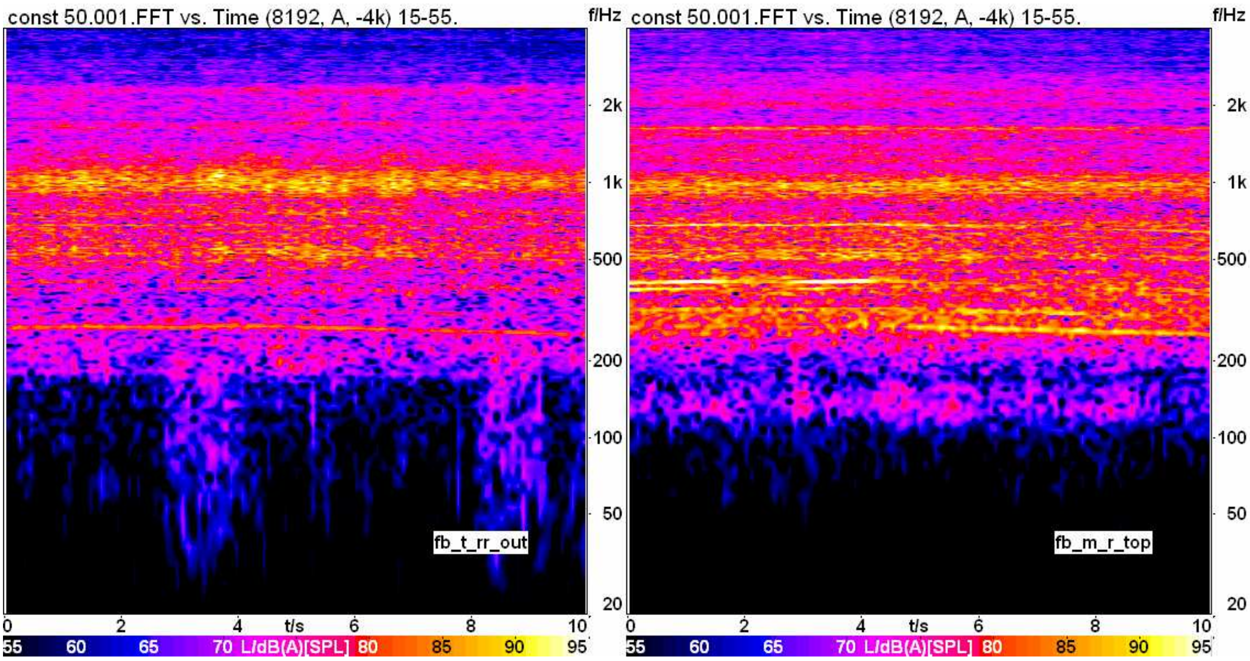

Figure 24: FFT vs. time. Near field signals of the tire's trailing edge (left) and motor (right)

Figure 25 depicts the noise level of the tram pass-by as recorded with the artificial head. Again the relatively long plateau of high level is obvious. The level difference between the two driving situations is only 1 to 1.5 dB. As stated above, recordings on a longer track section can lead to different results.

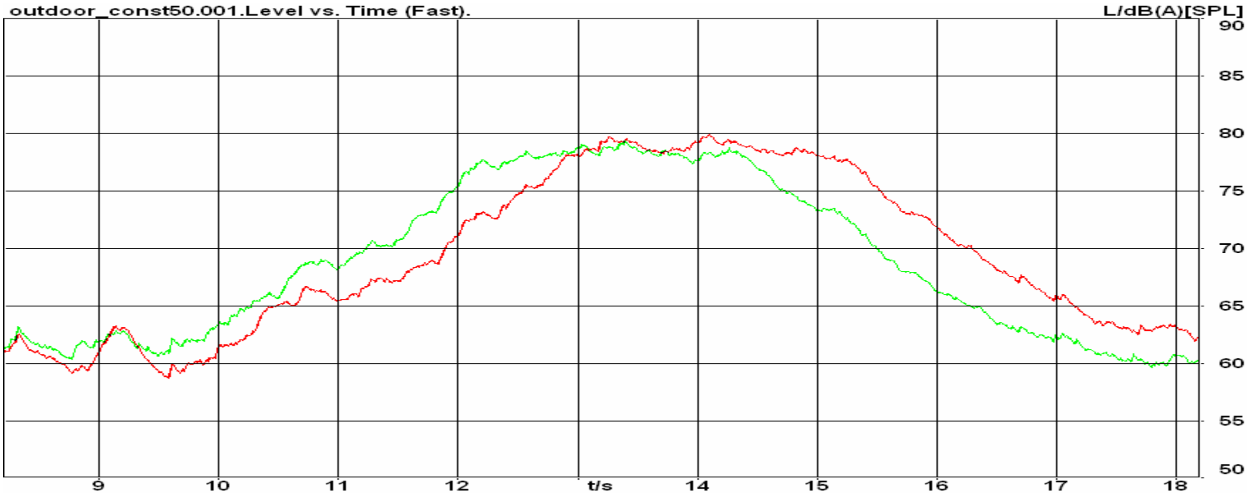

Figure 25: Level vs. time. Artificial head recording of a tram pass-by, acceleration from 50 km/h

6 COMPARISON OF DRIVING SITUATIONS AND VEHICLES

In the following, the evaluations of the different vehicles and their driving conditions are compared and conclusions about potential for acoustical improvement are drawn. Beside the evaluations of the spectra as carried out in D2.2 and D2.9 the results of the subjective evaluations in WP2.2.2 (see D2.8) are considered also. Hereby, it is ensured that the possible future improvements do not only regard the dB(A) value but also the actual subjective perception of pass-by noise.

In general, the heavy diesel engines are the noisiest and annoying noise sources[3] (see Table 1). Here lies the biggest potential for improvement. For one thing, with current technology it is possible to build quieter and less annoying diesel engines that sometimes can even acoustically compete with otto engines. On the other hand, the selection of e.g. public transport busses can directly be influenced by the cities or communities.

Table 1: Annoyance ratings for two sound sets showing the importance engine / diesel noise

idle

vehicle	rating
upper_medium 02	2,31
medium 01	3,31
sub_compact 01	4,31
mini 02	5,15
cabriolet 02	5,69
medium 03 (diesel)	7,77
comm_van 02 (diesel)	8,23
compact 03 (diesel)	8,62

const50

vehicle	rating
van 02	2,75
upper_medium 02	4,17
medium 03 (diesel)	6,00
mini 01	6,08
sub_compact 01	6,42
cabriolet 02	6,67
comm_van 02 (diesel)	7,83
compact 03 (diesel)	8,08

The evaluation in D2.2 and this report proved always the acceleration situation to be louder and potentially more annoying – besides high levels: more tonal components from engine or tire orders – than the constant pass-by. The annoyance ratings of the listening tests in WP2.2.2 confirmed this and additionally showed that especially the acceleration noise of the power train generates higher annoyance (see Table 2 for a comparison of const30 and med_acc30).

[3] Interestingly, the subjective perception of e.g. the truck depends mainly on its diesel engine, although regarding dB(A) and spectra the tires are the main noise source (annoyance ratings: roll50:.6.25; const30: 7.42; const50: 8.17; med_acc30:8.17).

Table 2: Annoyance ratings for the big_mix sound set showing the high influence of acceleration on the subjective perception

big_mix

vehicle	condition	rating
mini 01	roll50	2,29
upper_medium 02	const30	3,00
van 02	const50	3,00
mini 02	roll50	3,14
comm_van 02	roll50	3,21
medium 03	roll50	3,36
sub_compact 01	roll50	3,79
cabriolet 02	roll50	3,79
upper_medium 02	med_acc30	4,07
sub_compact 01	const30	4,14
cabriolet 01	roll50	4,50
mini 01	const50	4,93
upper_medium 02	const50	5,00
mini 01	med_acc30	5,14
medium 02	med_acc30	5,21
medium 03	const30	5,29
cabriolet 02	const30	5,29
sub_compact 01	med_acc30	5,57
comm_van 02	const30	5,64
medium 03	const50	6,14
compact 03	const30	6,14
mini 02	med_acc30	6,14
compact 03	const50	6,21
medium 03	med_acc30	6,29
comm_van 02	const50	6,50
sub_compact 01	const50	6,57
cabriolet 02	const50	6,64
comm_van 02	med_acc30	6,86
cabriolet 02	med_acc30	6,86
compact 03	med_acc30	6,93

One conclusion is that accelerations should be avoided as much as possible. Here traffic control measures can help to improve the traffic noise situation in cities for instance by

- general traffic limitation,
- traffic guidance (roundabouts, progressive signal system)
- support of public transport.

But it is also possible, that driving assistance systems in passenger cars, e.g. navigation system with traffic info, improve the current situation.

Nevertheless, the noise sources causing the acceleration noise should be improved, too. As stated above, the main noise and annoyance source is the power train. The evaluations show that especially the intake and exhaust are responsible for the noise emission, e.g. of strong engine orders during driving conditions containing accelerations. Effective measures would be the application of specific constructional changes at the intake and exhaust or improved damping. Also the usage of smaller engines can be successful.

The most promising approach would be the avoidance of engine systems that show such a high noise level during acceleration. Here the electric engine of the hybrid car has a very good performance at moderate acceleration; unfortunately the combustion engine has to be started when high accelerations are needed. Consequently, the combustion engine should be removed or replaced by an alternative quiet drive. Actually, the tram shows the best performance regarding the avoidance of typical acceleration noise. Here the noise emissions of constant and accelerated pass-by differ only in a little whining sound. Unfortunately, the pass-by level of a constant pass-by of the tram reaches already almost 80 dB(A).

It should be also considered, that the tires of the driven axle emit a considerably louder noise and in general more tonal components during acceleration than at constant pass-by. Especially the tonal components can result in higher annoyance ratings. Although, the tire noise at this situation is currently a secondary factor, it should be regarded as an increasing problem when combustion noise is improved. The SUV with the 4-wheel drive shows a balanced division of the acceleration torque on the two axles and therefore a balanced noise increase between the tires. Maybe this or the general division of several tires also generates lower overall level[4].

Beside the vehicles with heavy diesel engines, the importance of tire noise during constant pass-by at 50 km/h is equal to the engine noise and it will increase with rising speed. For this problem the evaluated vehicles show no distinctive solution. The analysis of the subjective perception of pass-by noise in WP2.2.2 shows that disturbances like a stone in the tread pattern or an unbalanced tire lead to higher annoyance ratings (Table 3). Also specific types of tires like winter tires can have the same effect.

Table 3: Annoyance ratings for the tire comparison sound set showing that specific disturbances cause higher annoyance ratings; driving situation: const50

tire comparison

vehicle	source	rating	remark
upper_medium 02	tire rear	3,83	
upper_medium 02	tire front	4,42	
luxury 01	tire rear	4,67	
luxury 01	tire front	5,00	
mini 01	tire rear	6,17	unbalanced tire
medium 02	tire rear	6,75	stone in the tread

[4] The evaluated SUV did not possess a disengageable 4-wheel drive to test this hypothesis.

The application of acoustical optimised road surfaces is an improvement method that can be carried out relatively fast and affects all vehicles using the newly paved road. In the long term, the development of acoustical improved tread patterns is needed too. The problem arising here is the guarantee of application, which can only be reached by additional control measures or laws.

7 CONCLUSION AND OUTLOOK

The application of the component synthesis procedure has been effective, especially the implementation of the new SVEN approach into SENSE[5] without using a chassis dynamometer.

The necessary input signals of the noise components were previously recorded on a chassis dynamometer. This can be done now during a real pass-by on a standard test track. The data for the calculation of the noise related transfer functions (SRTF) again was recorded in a semi anechoic chamber. With the new approach it is possible to the measurements in free field. The advantage of the new SVEN approach is a simplified and more flexible application without a dependency on facilities like a chassis dynamometer and semi anechoic chamber. This widens the range of measurable vehicles and lowers costs. Additionally, the quality of the recorded tire noise is increased.

The data for various transportation means has been recorded, successfully synthesized and evaluated. The comparison of the different vehicles and driving situations considers the former evaluations based on SPL and spectra as well as the results of the listening test in WP2.2.2[6] to identify characteristics that really improve the living quality in cities by reducing annoyances and not only dB(A). The comparison showed the following

4. The main noise and annoyance sources are the heavy diesel engines of public transport busses, commercial vans and trucks. Current technology is able to construct quieter diesel engines.
5. Acceleration noise is mainly emitted by the intake and the exhaust. Constructive improvements would include changes in inlet and outlet as well as damping measures. More effective would be the extensive introduction of engines without this high noise increase during acceleration, like electric engines of hybrid vehicles or trams.
6. Noise of constant pass-by at higher speeds is characterized by a high share of rolling noise. Here the evaluations gave no distinctive solution. It will be necessary to improve acoustically both interfaces – tire and road surface; whereas the application of quiet road surface is faster and more effective.

The achieved data and conclusions are input to the further work within QCITY. All recorded data is implemented into the sound library of the TrafficNoiseSynthesizer

[5] SENSE – software of HEAD acoustics, developed as an exploitation of the SVEN approach

[6] In WP 2.2.2 the pass-by noise is subject to listening tests and the analysis of annoyance evaluations of the test individuals. D2.8 presents the procedures and results of this analysis. It describes the development of a calculation method that represents the subjective perception of pass-by noise. This will be further enhanced and improved in WP5.12 regarding traffic flow noise and filtering. The listening tests and the so called evaluation index EI is used for a perceptive ranking of noise sources.

software created within WP2.2.3. By this, the time signals will be available to all project partners, who can auralize and filter them.

The compiled data and the gained results from it are strongly related to WP5.12. In SP2 pass-by noise and noise source contribution was evaluated regarding their relative importance and perception. This has resulted into to conclusions about the importance of vehicle noise sources and their contribution at different driving conditions, which again will be combined for the auralization of traffic flow at a specific road section with a specific vehicle fleet composition in WP5.12.