DELIVERABLE 3.1.2

CONTRACT N°	SPC8-GA-2009-233655	
PROJECT N°	FP7-233655	
ACRONYM	CITYHUSH	
TITLE	*Objective and psychoacoustic noise evaluation of pass by of quiet hybrid vehicles and comparison with standard vehicles*	
Work Package 3	Noise and vibration control at source – Acoustically green vehicles	
3.1.2	Objective and psychoacoustic noise evaluation of pass by of quiet hybrid vehicles and comparison with standard vehicles	
Written by	Aulis Telle, HAC	
Due submission date	December 31, 2012	
Actual submission date	December 31, 2012	

Project Co-Ordinator	HEAD acoustics	HAC	DE
Partners	Accon	ACC	DE
	Alfa Products & Technologies	APT	BE
	Goodyear	GOOD	LU
	Head Acoustics	HAC	DE
	Royal Institute of Technology	KTH	SE
	NCC Roads	NCC	SE
	Stockholm Environmental & Health Administration	SEP	SE
	Netherlands Organisation for Applied Scientific Research	TNO	NL
	Trafikkontoret Göteborg	TRAF	SE
	TT&E Consultants	TTE	GR
	University of Cambridge	UCAM	UK
	Promation of Operational Links with Integrated Services	POLIS	BE

Project start date	January 1, 2010
Duration of the project	36 months

Project funded by the European Commission within the Seventh Framework program

Dissemination Level

PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for the members of the consortium (including the Commission Services)	

Nature of Deliverable

R	Report	✓
P	Prototype	
D	Demonstrator	
O	Other	

SEVENTH FRAMEWORK PROGRAMME

TABLE OF CONTENTS

0 Executive Summary ...3
- 0.1 Objective of the Deliverable ...3
- 0.2 Description of the Work Performed since the Beginning of the Project ...3
- 0.3 Main Results Achieved so far ...3
- 0.4 Expected Final Results ...3
- 0.5 Potential Impact and Use ...3
- 0.6 Partners Involved and Their Contribution ...3
- 0.7 Conclusions ...4

1 Introduction and Objective ...5

2 Universal Noise Synthesizer Technology ...7
- 2.1 Traffic Flow Simulation ...8
- 2.2 Source Modeling ...9
  - 2.2.1 Detection of Relevant Sound Sources ...10
  - 2.2.2 Source Signal Synthesis ...10
  - 2.2.3 Driving Condition Model ...12
- 2.3 Propagation and Output ...17
- 2.4 Extraction of Synthesis Parameters ...18
  - 2.4.1 Order Analysis ...18
  - 2.4.2 Noise Analysis ...19
- 2.5 Measurements Needed for Modeling ...20
  - 2.5.1 Driving Conditions ...20
  - 2.5.2 Sound Sources ...20
  - 2.5.3 Source Radiation ...20
  - 2.5.4 Pass-by Measurements ...21
- 2.6 Far-field Synthesis ...23

3 HEAD Visor Technology ...24

4 Measurements ...27
- 4.1 Comparison of Gasoline with Hybrid Vehicle ...28
- 4.2 Comparison of Fiat 500 combustion vs. electric ...30
- 4.3 Evaluation of Low Noise Tires on the Citroën C-Zero ...34
- 4.4 Detection of Relevant Sound Sources ...40
- 4.5 Traffic Flow Measurements for Acoustical Fingerprint Technology ...41
- 4.6 Source Related Transfer Functions ...42

5 Simulations ...45

6 Conclusions ...50

0 EXECUTIVE SUMMARY

0.1 Objective of the Deliverable

The objective of this deliverable was to identify the main noise sources of a vehicle, not only by level, but also by psychoacoustic measures.

0.2 Description of the Work Performed since the Beginning of the Project

Pass-by events were recorded for various vehicles, especially ICE and electric vehicles using different techniques: near-field and far-field measurements using monaural and binaural receivers as well as microphone array measurements.

For the evaluation of the impact of different tires the measurement of the electric car were performed with standard and with low-noise tires.

Simulations of cars with UNS for studying the impact of low noise tires were performed. The dominant noise source for each driving condition was identified for the different vehicles.

0.3 Main Results Achieved so far

Many measurements were performed for the comparison of gasoline with hybrid and fully electric vehicles. The measurements took place on different proving grounds and test tracks. On the Goodyear proving ground, the Citroen C-Zero electric vehicle was tested with two different sets of tires (normal and low noise) on two different road surfaces (rough and smooth). The data was evaluated in many ways using the existing variety of acoustic and psychoacoustic analyses (e.g. loudness and sharpness). The measured data of two measurement campaigns has been processed using the Acoustical Fingerprint approach on the basis of HEAD Visor microphone array data. The applicability of the approach has been proved.

0.4 Expected Final Results

The work is concluded. The final results are the main results described above.

0.5 Potential Impact and Use

The techniques, procedures, and algorithms created within the scope of CityHush will be developed by HEAD acoustics (HAC) into a product for commercial distribution and for use in consulting services and further research projects.

0.6 Partners Involved and Their Contribution

All work described in this report was performed by HEAD acoustics (HAC). Part of the measurements was performed on the premises and with the help of Goodyear in Luxembourg.

0.7 CONCLUSIONS

The measurements show, that on electric cars and hybrid cars in electric mode the tires are the main sound source for a speed of 30 km/h and above. For constant speed and coasting down, this is also true for combustion cars. However, during acceleration the engine sound dominates.

The evaluation of the different tire-road surface combinations gives evidence that the low noise tires are most effective on a smooth surface. The gain on the tested surface is up to 3 dB.

The Acoustical Fingerprint technique, which allows for the synthesis of large and often inhomogeneous data sets acquired during pass-by measurement campaigns, was used successfully for the evaluation of a traffic flow measurement.

1 INTRODUCTION AND OBJECTIVE

Electric motors will continuously replace combustion engines within the next decades, although conventional drives will remain in use for a longer period. The expected increase of quiet vehicles (vehicles with alternative drives) results in new opportunities regarding a substantial reduction of road traffic noise in urban contexts in combination with an optimized composition of future urban soundscapes. However, in order to fully utilize the noise reduction potential, holistic noise and vibration abatement approaches must be applied addressing issues like tire-road noise, vehicle-type-oriented access concepts, psychoacoustic analyses, and infrastructures as well as comprehensive emission considerations and soundscape concepts.

One major issue is the detailed acoustical analysis and psychoacoustic evaluation of hybrid and electric vehicles under various running conditions compared to vehicles with internal combustion engine. Only a detailed understanding of the (psycho-) acoustical differences will allow for benefiting acoustically as much as possible from the expected shift regarding different drive concepts. In particular with respect to the preservation and creation of quiet zones, the knowledge about the resulting exterior noises of different drive concepts and their respective perception is important. Only then the most effective strategies and measures for optimal noise reduction can be implemented.

The measurement of the pass-by noise of a vehicle in the various driving conditions is an important means for describing the noise characteristics of a vehicle comprehensively and for the detailed comparison of different vehicles. In this work package, a large number of such measurements were performed on test tracks for studying the noise of different gasoline, hybrid, and electric vehicles. Moreover, by using the extensive measurement data, the traffic noise synthesizer technology was extended by various acoustical vehicle models. This simulation technology allows for evaluating the impact of distinct model variations on the acoustical features of a vehicle.

Additionally, a large microphone array utilizing the HEAD Visor technology was used for the detection and evaluation of the main sound sources of different vehicles during a pass-by event under various running conditions. In this context, the low noise tires developed by the project partner Goodyear where subject of detailed investigation to predict the noise reduction potential due to optimized tires on different road surfaces.

In Section 2, the Universal Noise Synthesizer technology is described. Especially the concept of modeling the acoustically relevant sources and the sound propagation from the source to the receiver will be described in detail. Also, the required measurements and analyses for setting up proper acoustic vehicle models are discussed in that section. The Universal Noise Synthesizer technology is needed to provide time data about future traffic compositions, which do not exist and cannot be measured today because of the still low occurrence of electric vehicles. These simulations go beyond simple calculations only referring to sound pressure level indicators. Based on generated time data representing certain road traffic scenarios any relevant acoustical parameter can be calculated. The advantage of a noise synthesizer technology providing time data of virtual road traffic scenarios is that the effect of certain measures (like changing the traffic composition, speed limit, road surface, banning powered two wheelers, etc.) can be systematically determined and experienced by listening while all potential confounding variables are kept constant (such as no weather influences, disturbing noises).

Section 3 describes the HEAD Visor technology. Section 4 describes the various measurements that were performed and the respective analysis results. Section 4.6 presents the simulations performed for showing the validity of the simulation results.

2 UNIVERSAL NOISE SYNTHESIZER TECHNOLOGY

The Universal Noise Synthesizer (UNS) technology provides a comprehensive tool box of various synthesis methods for simulating and synthesizing noise sources and the sound propagation from the source to the receiver. The tool items can be assembled to complex synthesis models which represent virtual acoustic models of real vehicles. Its structure is highly modular in order to provide a high flexibility in setting up arbitrary vehicle types.

Compared to real road traffic measurements the simulation approach features the following advantages:

- Settings such as the traffic load and the traffic composition can be specified and controlled precisely for the sake of comparability and reproducibility.
- The simulations are independent of environmental influences (such as weather, background noise, local conditions for measurement set-up, traffic rules, a. s. o.).
- Possible acoustical modifications of the vehicles can be modeled virtually (e.g. attachment of muffler, etc.).
- The scenarios are set up in a reproducible fashion and noise influencing parameters (e.g. speed limit) can be varied precisely and independently from each other.

While the Universal Traffic Noise Synthesizer was initially developed within the scope of the European research project “Quiet City Transport”, within CityHush WP 3.1 this technology has been expanded extensively to allow for synthesizing acoustically green vehicles (e.g., electric and hybrid vehicles) as well as potentially highly annoying vehicles (e.g., powered two wheelers). The large variety of available settings allows for the creation of complex road traffic scenarios. This section provides a brief introduction to the technical details of the UNS technology.

The signal flow of the UNS can be divided into three parts: The simulation of the traffic flow, the generation of source noise signals, and the calculation of propagation aspects (see Figure 1).

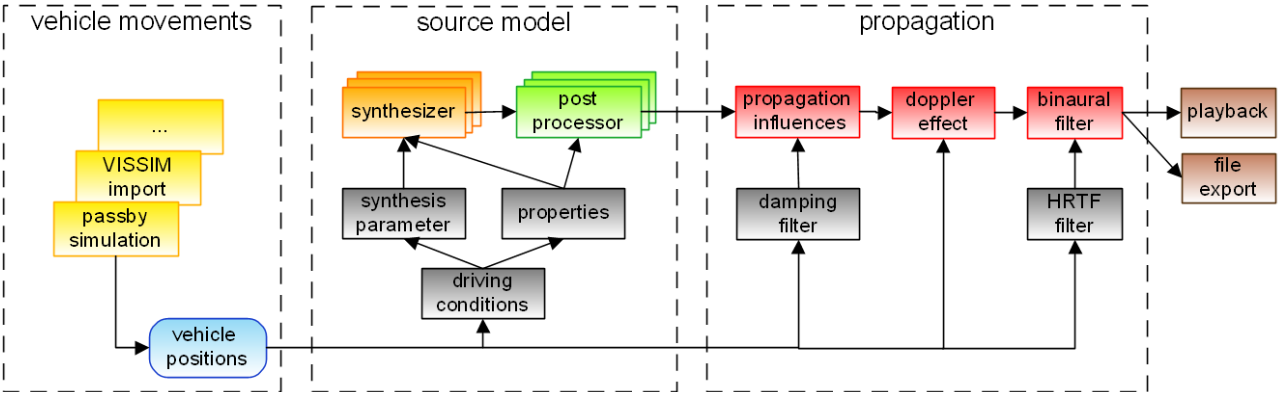

Figure 1: Signal flow of the UNS-technology

2.1 Traffic Flow Simulation

The first information necessary for the synthesis are the vehicle movements considering the trajectory of each vehicle. For very simple scenarios, such as a pass-by of a single vehicle, this information can be calculated within the UNS software itself. However, in case of realistic road traffic scenarios with numerous vehicles, the simulation (micro-simulation) of vehicle movements is a complex and time-consuming task; for instance the interaction between the vehicles must be considered. Thus, the task to simulate a realistic traffic behavior of all vehicles within a scenario is performed with separate software called VISSIM by PTV (www.ptv.de). This software models the geometric information of the traffic scenario while allowing for the adjustment of traffic behavior and the setting of traffic rules.

The resulting simulation data can be exported to a file which is used as input for the acoustical synthesis based on the UNS technology.

2.2 SOURCE MODELING

To obtain a realistic vehicle synthesis, an appropriate vehicle model has to be developed and validated. Within the UNS software, this is done by assembling all the applicable sound sources and synthesis parameters into a tree structure as shown in Figure 2.

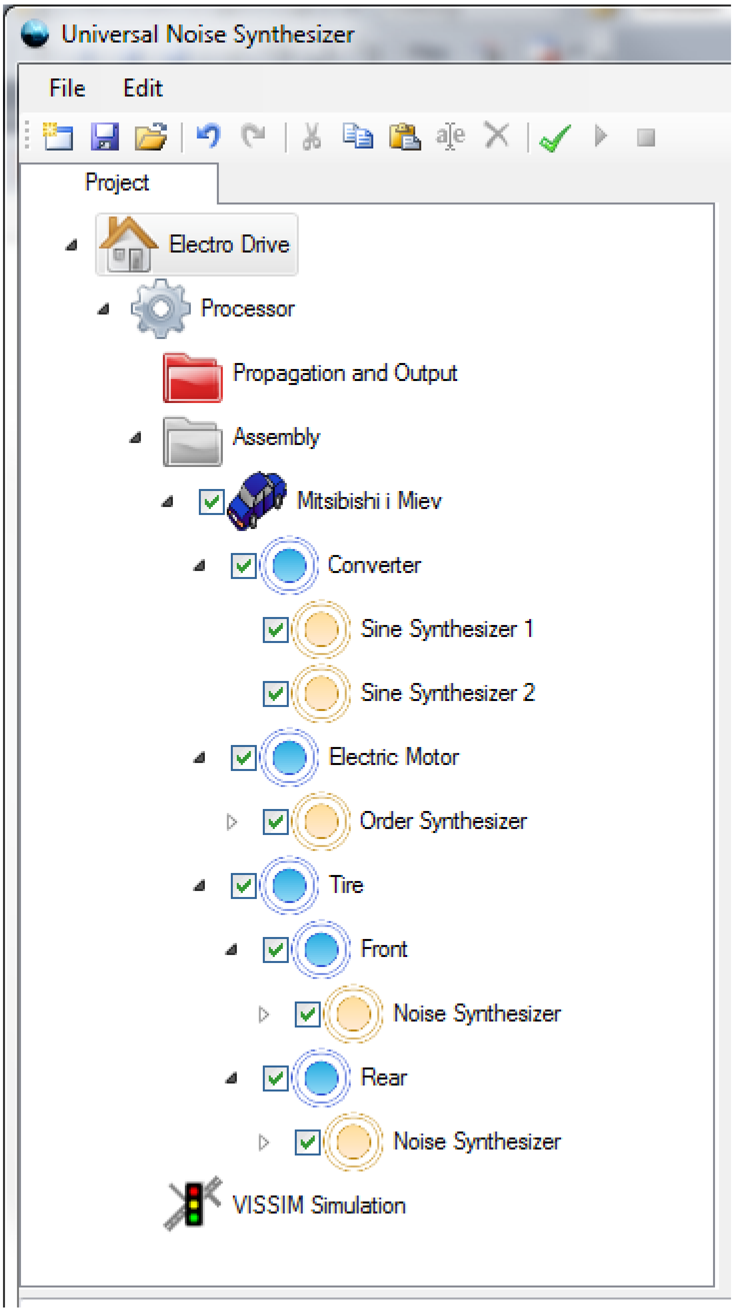

Figure 2: Tree structure of a vehicle model

The configuration of a vehicle model is done in four steps:

1. Each vehicle is described by distinct, acoustically relevant sources with their respective relative position.
2. The source signals are generated by specific synthesizers such as order or noise synthesizers. The synthesizers are carefully designed and parameterized (see chapter 2.4).
3. The generation of the source signals is linked to the dynamic vehicle movement. For example, the source signal is influenced by the velocity of the vehicle which in turn is directly related to the engine speed and the sound produced by the gear. These relations between the movement of the vehicle and the driving condition are configured in the vehicle model.
4. The radiation of the source signals to the far-field is configured in dependence of frequency and direction by the so-called *source related transfer functions* (*SRTF*). Without the implementation of SRTFs an omnidirectional directivity would be assumed. This is followed by a distance dependent level adaptation and an appropriate time delay.

For the validation of the constructed models, it is required to compare the simulated sounds to the corresponding measurements. The level of detail depends on the purpose of the simulation. Thus, if only vehicle classes are of interest, generic models representing a vehicle class such as compact class or upper vehicle class can be constructed. If very high simulation accuracy is required for a specific vehicle, a more detailed model can be applied. Which of the models will actually be used in the simulation can be specified in the traffic flow simulation. The vehicle model is not limited to passenger cars only; it can also be used for the simulation of other vehicle types, such as motor scooters (see "D3.5.1 Acoustic definition of quiet motorcycles in their social context and in the scope of Q-Zones") or heavy vehicles.

2.2.1 Detection of Relevant Sound Sources

In order to set up a compact vehicle model, the acoustically relevant sources have to be detected. For this purpose, the pass-by noise in the far-field is assessed by means of the HEAD Visor microphone array (see "D3.1.1 Modified HEAD Visor microphone array" and Section 3 of this document). The HEAD Visor system provides the opportunity to visualize the main radiation positions of an acoustic scene (see: S. Guidati: Advance processing of microphone array data for engineering applications, Acoustics 08, Paris, France). The most important acoustic sources can be detected in the pictures shown in Section 4.4. At least these identified sound sources have to be modeled to gain a realistic simulation of the pass-by sound.

2.2.2 Source Signal Synthesis

For the generation of the source signals various synthesizers are available. In Figure 3 a simple example of a vehicle source model is shown. The vehicle in this example is composed of two sources. These sound sources can be assigned to individual positions in relation to the vehicle's coordinate system. Each source can be modeled by one or multiple synthesizers which generate the respective source sound signal. The engine source signal is typically generated by an order synthesizer. The properties of the order synthesizer, like the number of orders or the use of the order phase, provide the opportunity to configure the synthesis behavior. The order spectra, which have been generated in the order analysis of measured source signals, are loaded into the model by means of an order configuration item. This item uses an order parameter container which in turn represents a directory where the order spectra are stored. The information which spectrum has to be actually loaded depends on the driving condition of the vehicle. In the displayed case, the driving condition is simply represented by the engine speed (RPM). The order parameter container item needs the value of the engine speed to load the current order spectrum. Additionally, the order information can be interpolated linearly between two order spectra to get smooth signal changes.

The configuration of the tire source is analogous to the engine source. However, instead of an order synthesizer a noise synthesizer is used. The noise synthesis parameters are FFT-spectra. To load the suitable spectra the vehicle velocity is used.

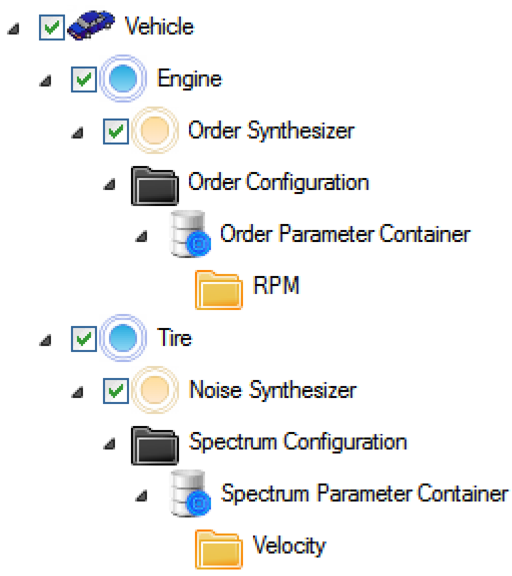

Figure 3: Screenshot of a simple source model of a vehicle implemented within the universal noise synthesizer

In addition to the two base synthesizer types, the universal noise synthesizer provides the following synthesizer types:

- The converter synthesizer, which is specialized on the generation of noise produced from electric converters in electric and hybrid cars.
- The time synthesizer, which is used when the far-field simulation should be based directly on the measured near-field sounds of the sources.
- The resample synthesizer, which can loop a sound sample and tune the pitch based on the driving condition of the vehicle.

- The periodic synthesizer, which can generate periodic signals from analytic curves like sine, gauss, or triangle.

All synthesizers can be combined arbitrarily within the sources of the vehicle model.

2.2.3 Driving Condition Model

It has been mentioned that the synthesis configuration can be made directly dependent on the driving condition of the vehicle.

An important task is the generation of the driving condition values. The simulation of the vehicle movements, which can be done, e.g., by a micro-simulation-software, provides information on position, velocity, and acceleration of the vehicles. From this information all other values describing the driving condition are calculated.

2.2.1.3 Combustion and Electric Vehicles

In Figure 4, an exemplary configuration of a gear shift model is shown. The black RPM-item represents the engine speed, which is the output value of the model. The blue items realize case decisions depending on the velocity of the vehicle. The related branch in the tree is selected in dependence of the velocity value. In each branch, the calculation of the engine speed from the velocity depends on the gear ratio and the idle engine speed of the vehicle.

Figure 4: Example for a driving condition model. The information of the vehicle velocity is used to calculate the engine speed.

Additionally to this example, any relationship between the control values of a vehicle can be modeled. In the following sections, more examples focusing on electric and hybrid vehicles are provided.

The main challenge in modeling the driving conditions of any vehicle is the transmission box. In the special case of pure electric powered vehicles, there is only a single transmission ratio between engine and drive train. As the electric engine is capable of providing an almost constant torque throughout the whole engine speed range, the relationship can be easily modeled by means of a linear calculator item connecting the velocity variable to the engine speed variable.

Another driving condition relevant for the acoustic character of the vehicle is the engine load. The load is related to both the acceleration of the vehicle and the gradient of the road. Figure 5 shows the relation between engine load and acceleration. The values of acceleration are divided into three ranges represented by the blue items. A negative acceleration leads to a load value of -10 %. Between 0 and 0.6 m/s² there is a linear relation with a factor of 60 which leads to a load from 0 to 36 %. Above 0.6 m/s² the linear relation changes to a factor of 80 and an offset of -12 realizing a higher increase of load for higher acceleration values.

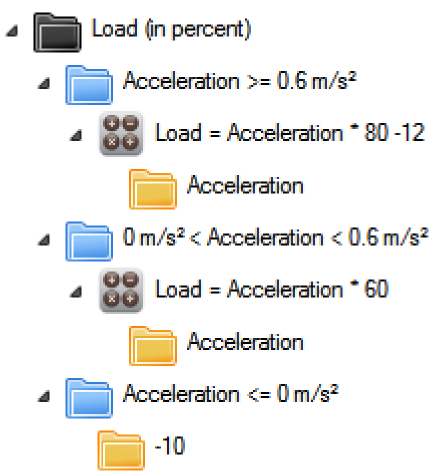

Figure 5: Example for a driving condition model. The engine load is calculated from the acceleration of the vehicle.

The engine source signal changes with the engine load. These changes can be measured by performing recordings of the source signal for different load cases. From these measurements the synthesis parameters are extracted and used in the synthesizers. In Figure 6 the coupling of order spectra with the order synthesizer dependent on the vehicle load is illustrated.

In this example, four load cases are represented by the blue state items. Each (numeric) state is linked to a different parameter set which was generated from a particular measurement. An interpolation item holds a collection of state items and provides an interpolation method to realize a smooth crossover from one load value to another.

The black frequency item at the bottom provides the fundamental frequency for the order synthesis. This value is calculated from the engine speed.

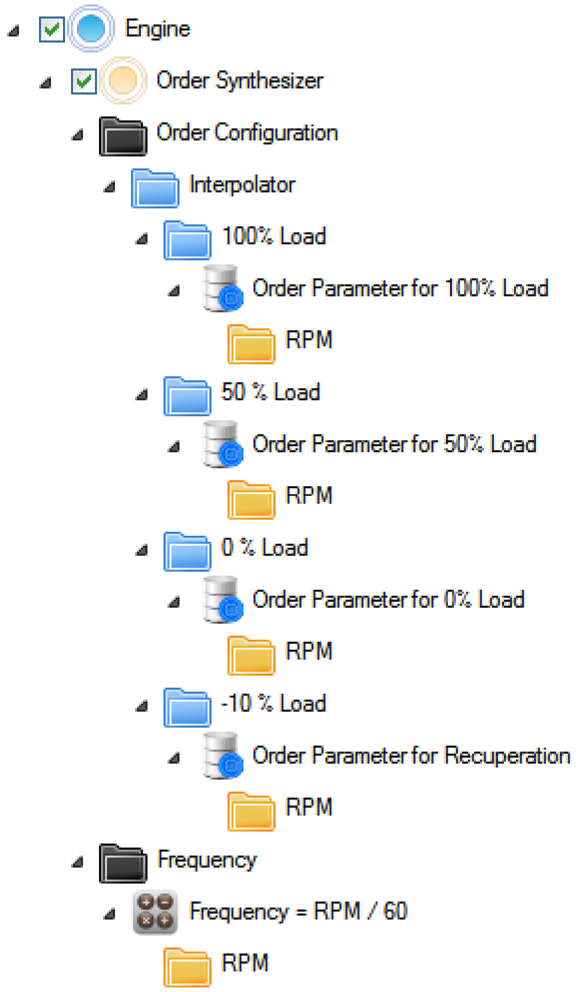

Figure 6: Synthesizer configuration with implemented load cases. The frequency of the order synthesis is calculated from the engine speed.

2.2.2.3 Hybrid Vehicles

A hybrid vehicle is a vehicle featuring a combined actuation with electric and combustion engines. Depending on the technical realization of this combination, there are three different types of hybrid concepts.

The main attribute of the parallel hybrid actuation concept is that both engines, the combustion as well as the electric one, can actuate the vehicle. In Figure 7, the drive train for a parallel hybrid is shown. The battery supplies the electric power to an inverter which in turn generates the AC voltage for the electric motor. Normally, the actuation can be initiated by the combustion engine only; additionally, the electric motor can support the actuation. A purely electric drive is not intended.

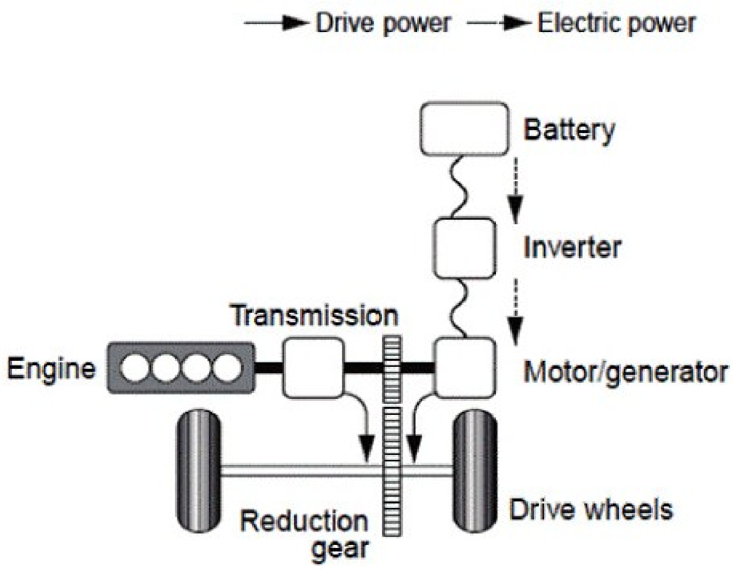

Figure 7: Schematic graphic of a parallel hybrid power train (source: Toyota)

In a serial hybrid vehicle the actuation is normally be performed by the electric motor. The combustion engine is only used to charge the battery. For that reason, this type of hybrid vehicle is also called an electric vehicle with range extender. As shown in Figure 8, the combustion engine has no link to the drive train; instead it is linked to a generator to supply electric power to the battery or directly to the inverter.

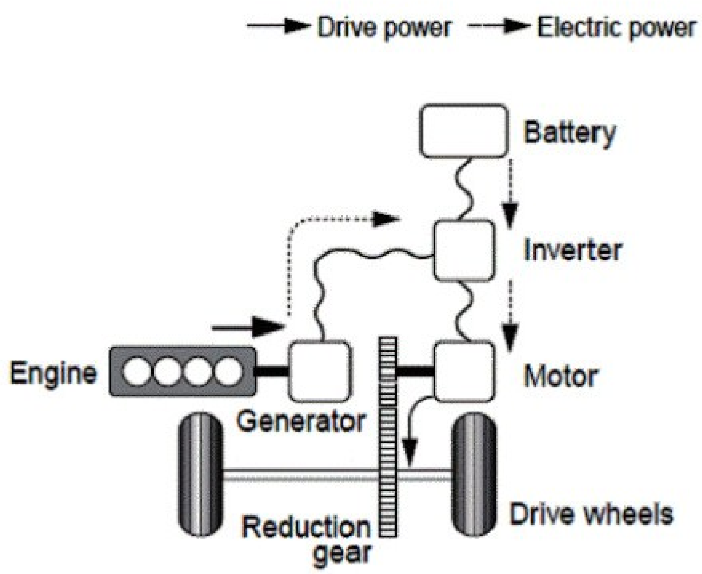

Figure 8: Schematic graphic of a serial hybrid power train (source: Toyota)

The third type of hybrid vehicle is called combined hybrid as it is a combination of parallel and serial hybrid concepts. With this type of hybrid vehicle a variety of implementations is possible. The main reason for the development of combined hybrids is energy efficiency. Different types of combined hybrids are realized by mainly applying different numbers of electric engine units as well as different transmission types interconnecting its electric motors and power train.

Concerning the synthesis of hybrid vehicle noise, the main components contributing to the exterior noise are of high interest. These are mostly the combustion engine, the electric converter, the transmission line, and the electric motor. All these noise components are basically composed of order and noise parts, which the Universal Noise Synthesizer is able to cope with.

The challenge in modeling hybrid vehicles is the high complexity of driving conditions. Especially, in the case of combined hybrid vehicles the number of driving conditions can be rather high.

The first acoustic event to be implemented in a driving condition model is switching on and off the engines. As, for instance, the combustion engine is not working continuously, there must be a mechanism within the model to switch off the combustion engine noise. This can be done easily by adding a conditional factor to the source or the synthesizer.

As shown in Figure 9, the factor of the mute item is set to one if the combustion engine is switched on and to zero if the engine is switched off. The noise generated by the order and noise synthesizers only contributes to the source signal if the factor is set to one.

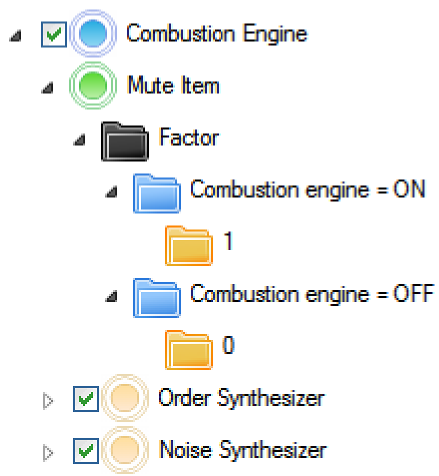

Figure 9: Conditional switching of synthesizer signals to simulate hybrid driving conditions

The more complex configurations to be realized for a hybrid driving condition model are the transmission ratios. The transmission between the different engine units and the drive train can be implemented in a variety of ways. Particularly, in case of a combined hybrid, a planetary gear train can be applied which leads to a continuous variable transmission ratio. In Figure 10, an example of the relation between vehicle speed and engine speed is shown.

The implementation in the vehicle model can be performed analogous to the method illustrated in Figure 4. This method leads to a stepwise linear approximation of the curve.

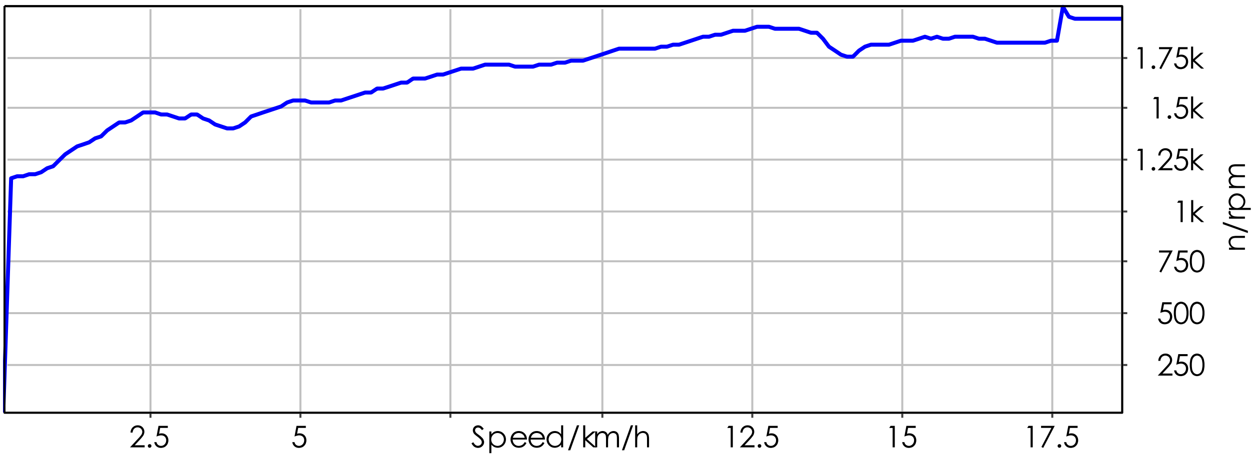

Figure 10: Relation between vehicle speed and engine speed for a Toyota Prius applied with a planetary gear train. In this example the actuation is done only with the combustion engine.

Generally, the challenge in modeling the driving conditions of hybrid vehicles is to detect the acoustically relevant conditions and to establish the level of detail necessary for the realization of these conditions.

2.3 Propagation and Output

For realistic traffic simulations, the sound propagation from the sources to a receiver position has to be calculated. The following propagation paths and effects are taken into account in the UNS:

1. The Doppler-Effect is simulated if there is a relative movement between the vehicles' (noise sources) and the observer's position. The effect is caused by the finite speed of sound and is important for the generation of realistic and authentic auralizations.
2. The effects of reflections on surfaces can be modeled by means of mirror sources.
3. On the receiver side, head related transfer functions (HRTF) can be applied for binaural playback. This way, the spatial information of the vehicles becomes perceivable by the listener and subjective evaluations of the synthesis results can be performed.
4. Miscellaneous propagation effects can be modeled by means of various damping filters. These filters consider, e.g., air absorption or damping by barriers like walls or forest.

In general, the UNS provides the option to export binaural or monaural signals to a file as well as listening to them on the fly. However, the direct playback option is only possible if the computer hardware can calculate the simulation in real-time. For complex scenarios with hundreds of cars to be simulated only the file-export is available.

2.4 EXTRACTION OF SYNTHESIS PARAMETERS

The processing of data in order to obtain reliable synthesis parameters is very important for developing a realistic vehicle model. A short overview is given on how this was done for the vehicle models used in this work package.

The engine noise signal can be divided into two main parts: a harmonic part and a stochastic part. These two signal parts can be synthesized separately by the use of an order generator and a noise synthesizer respectively. Generally, the quality of the simulation results is determined by the quality of the measured signals and the signal analyses for obtaining the synthesis parameters.

2.4.1 Order Analysis

The input parameters for the order generator are order spectra. These order spectra are extracted from near-field measurements of the corresponding vehicle by means of an order analysis. The result of this analysis is the level and the phase of each order. This type of information is required for all of the vehicle's acoustically relevant driving conditions such as different engine speeds and engine loads.

Orders are always based on a common fundamental frequency which is usually linked to the engine speed. To perform the analysis as accurately as possible, the exact value of the fundamental frequency at any given moment is necessary. Otherwise there is a risk of a faulty analysis; particularly the orders at very high frequencies might be missed.

Another challenge in extracting the order spectra from the measurements is to decide whether the frequency components at hand are in fact orders or rather part of the stochastic background noise. The decision is made by comparing the order levels with an estimated background noise level. If the order level has a significant level offset to the background noise level, the order is not masked and has to be synthesized.

For harmonic signals consisting of a large number of orders, the phase relations between the separate orders have a strong influence on the sound character. This can be seen using the example of diesel combustion noise: the diesel knocking sound can only be synthesized correctly if a large number of orders with exact phase and amplitude values are considered. The challenge here is to analyze the correct phase values from the spectra of the measured signals. Especially for higher frequencies the orders are often masked with stochastic noise. This leads to incorrect phase estimations and distorts the reproduced synthesis signals.

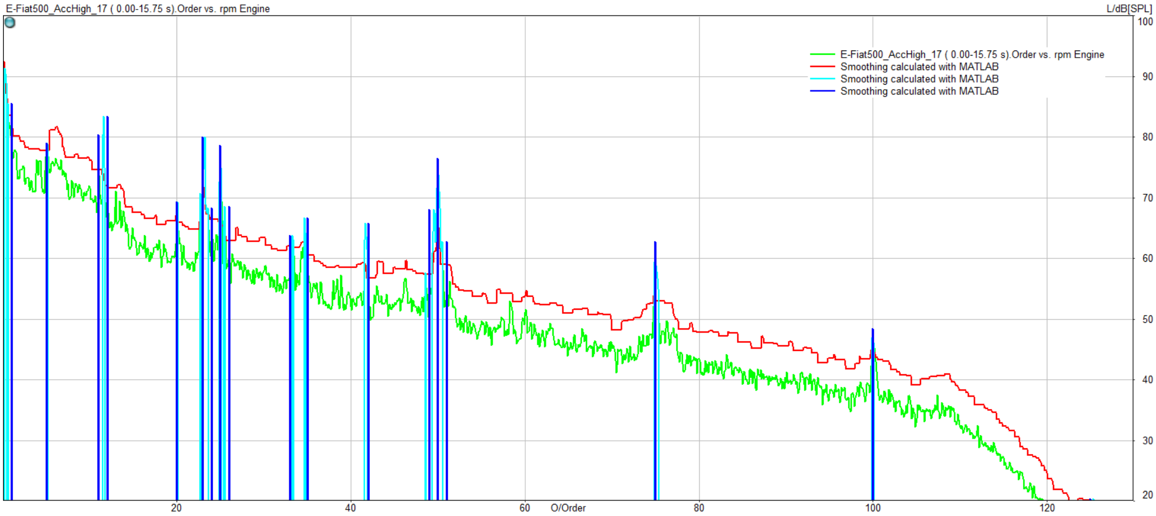

Figure 11: Detection of order components

2.4.2 Noise Analysis

To synthesize the stochastic signal parts, noise spectra are used as input parameter for the noise synthesizer. These spectra were gained by calculating smoothed frequency spectra and removing the tonal signal components. This implies that harmonic parts of the signal are excluded from the spectra. The determination of the stochastic noise part is done utilizing a minimum estimation method. This method is a combination of two smoothing steps of the spectrum and a windowed minimum value calculation. This approach eliminates the peaks in the spectra which represent the harmonic signal parts.

A second step, where the spectra are averaged over a time window, reduces the influence of transient signal parts in the spectra. The final output of this analysis is the noise synthesis parameters in the form of spectra describing the stochastic noise component of the measured signals.

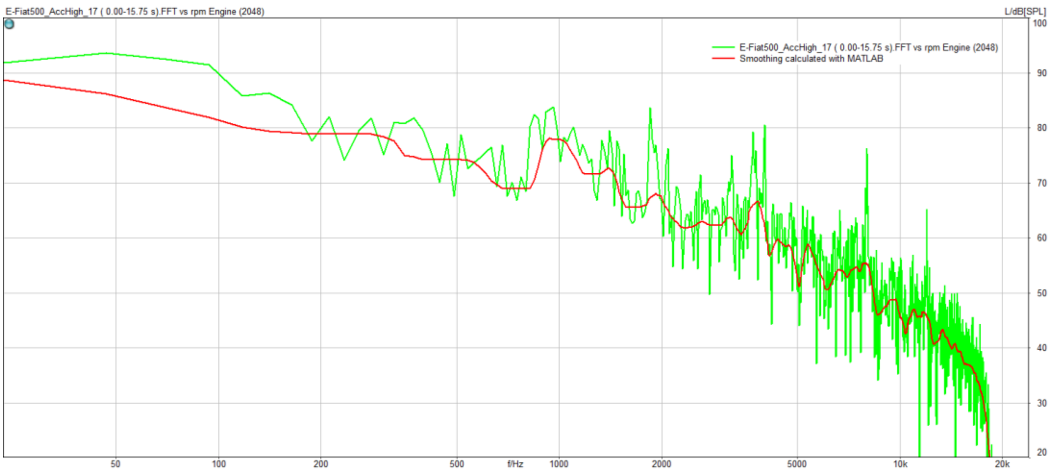

Figure 12: Example for determining the noise spectrum

2.5 MEASUREMENTS NEEDED FOR MODELING

In this section, the workflows of data acquisition and data processing are described. All relevant steps to obtain a valid and realistic simulation model of a vehicle will be covered. The modeling of a vehicle starts with the measurement of the vehicle. To define a measurement procedure different requirements have to be taken into account.

2.5.1 Driving Conditions

All driving conditions which should be simulated within the model have to be measured. Here it has to be checked which changes in driving condition influence the noise of the vehicle. The most common driving condition parameters are engine speed and load for the engine noise and vehicle speed for the tire-road noise. For a better analysis of the data, only one condition should be varied in one measurement. Moreover the change of driving conditions has to be slow as for the analysis the data is assumed to be stationary for short signal parts.

The change of the driving condition parameters has to be measured with separate sensors. The engine speed can often be measured with light trigger systems mounted at the drive shaft. If this is not possible, GPS-based or radar based speed sensors can be used. The sensors have to be connected to a mobile measurement setup in the vehicle for the sensor data to be synchronized with the data of the other sensors.

2.5.2 Sound Sources

The selection of sound sources to be measured is essential for the measurement setup. The question here is which noise sources of the vehicle have a significant (perceivable) contribution to the overall noise emission of the vehicle. It is important to use only as many sources as necessary in order to reduce computation time. A good option to derive the most important sound sources is to apply an acoustic camera such as the HEAD Visor system. This provides a quick and easy method to detect the positions of the noise sources and to assess their contributions to the exterior total noise.

Having acquired the knowledge of the relevant noise sources the positions of the near-field microphones can be determined. These have to be assembled with a mobile measurement setup in the vehicle. The positions of the microphones should be selected under two additional aspects. First, the source signals should be recorded with minimum crosstalk from other sources. Second, the microphones should not be exposed directly to wind because this can cause disturbances in the recorded signals. Wind shields can mitigate these influences. Especially the tire outlet is a position where high wind disturbances can be problematic.

2.5.3 Source Radiation

The measurement of the near-field source signals is the first step to achieve a far-field exterior noise simulation. The simplest way to determine a far-field sound from recorded source signals is to assume an omni-directional point source and calculate the radiation into the far-field. Obviously, this cannot always be assumed for the sources of a vehicle. The source signal can be influenced by the surrounding or covering objects. As an example, this is evident for the engine, which is mounted inside of a compartment. The radiated sound is damped by the cover and the exterior sound differs considerably from the source sound.

Generally, the source signal is modified on its way into the far-field. This modification can be both frequency and direction dependent. In order to determine the radiation characteristic of the sources in every direction, so-called *source related transfer functions* (*SRTFs*) have to be measured.

The required measurements of the SRTFs are conducted by utilizing the reciprocity principle in acoustics: The near-field microphones positioned near the relevant sound sources are excited by an omni-directional loudspeaker system (Dodecahedron, see Figure 13).

Figure 13: Dodecahedron measurement system for the determination of source related transfer functions (SRTF).

The loudspeaker is moved on a circle around the vehicle to measure the frequency dependent transfer functions for the different directions. The angle was varied in steps of 45°. By means of this method, all transfer functions for one direction can be measured for all sources and for the desired frequency range in only a single measurement. Additionally, the reciprocal approach has the advantage of a highly accurate mapping of the sound sources as the microphones can be placed very close to the actual sound sources. Positioning loudspeakers near the sources would lead to inaccuracies due to the directivity of the loudspeakers. Furthermore, as the microphones are located at the same positions as during the pass-by measurements, the SRTFs do not have to be modified.

2.5.4 Pass-by Measurements

The final results of the simulation are exterior pass-by sounds of vehicles. These sounds should match the real pass-by sounds. To validate the simulations, it is very important to also measure the pass-by sounds in the far-field.

The validation measurements should be conducted simultaneously to the near-field data acquisition. Therefore, a stationary measurement setup is placed next to the road. To compare the spatial auralization of the simulation to the measured scenarios an artificial head is set up. Additionally, a microphone records the monaural signal of the pass-by noise.

Figure 14: Artificial head system measuring single pass-by noise events on a test track

The comparison of measurement and simulation can be considered particularly accurate if both the simulated pass-by scenarios as well as the measured scenarios are based on exactly the same vehicle movement. Therefore, the measurements have been conducted in parallel and the mobile recording including the position and velocity signals of the vehicle can be synchronized with the stationary recording. In the course of the diverse measurement campaigns of the CityHush project three different synchronization approaches have been applied.

In the first method applied, a rope is placed across the road at a defined position. When the vehicle drives over the rope a transient noise is emitted. This sound is received by both the tire microphones of the mobile setup and the binaural head of the stationary setup. With respect to the speed of sound the mobile and stationary recordings can be synchronized.

A second method to do synchronization is using a light trigger system. The moving vehicle triggers an impulse generated by a light barrier installed on the test track. This impulse is recorded by both the mobile and the stationary measurement setup. As the position of the light barrier is known the synchronization can be done on the basis of the recorded impulses.

The most advanced opportunity to do synchronization is with the aid of a GPS time stamp. Each measurement setup is connected to a special GPS module. These modules receive a highly accurate time stamp and use it to generate an exact clock signal. The clock signal is recorded with both measurement setups. Thus, the exact absolute time of the recording is known. With this time information the recordings can be synchronized easily.

2.6 FAR-FIELD SYNTHESIS

The final step of setting up a vehicle model in the UNS technology is the calculation of the sound propagation from the near-field to the far-field. As mentioned above, modeling a vehicle as a mere moving point source would not be sufficient in terms of simulation accuracy. Due to the different positions of the identified main sound sources of the vehicle, effects such as sound diffraction and reflection at the vehicle geometry have to be taken into account. This results in a radiation directivity which is not omnidirectional but rather angle-dependent and different for each source. This can be taken into account by applying the source related transfer functions introduced above.

Furthermore, based on the properties of the air used as a medium, the emitted sound is affected on its way from the source to a receiver. The resulting effects in sound propagation to be considered are, e.g., the Doppler Effect, attenuation, and deflection.

The entire process can be divided into three main tasks.

First, the near-field signals utilized for the simulation of the relevant sound sources have to be calibrated. The results of the conducted data analyses, which are necessary for the vehicle model synthesis, highly depend on the analysis parameters used. It has to be made sure, that all analyses are performed with the same parameters like FFT-spectrum size, window block size, window function, etc. As the microphone positions are not the actual source positions the distance between microphone and assumed source position has to be taken into account by appropriately scaling the source signal before the radiation is calculated.

Second, the angle-dependent radiation directivity of the model's sound sources has to be implemented. For that, the previously measured *source related transfer functions* (*SRTFs*) are applied to the UNS models. In order to simulate the Doppler Effect and air attenuation, appropriate technology has been incorporated into the universal noise synthesizer. For the binaural synthesis, *head related transfer functions* (*HRTFs*) can be applied if needed.

Third, the simulation models are validated by comparison to the simultaneously conducted pass-by measurements. The main objective of creating vehicle synthesis models is to be able to predict certain psycho-acoustic parameters as well as noise annoyance for arbitrary scenario setups. Therefore, the simulated pass-by sound of each model was compared with measured pass-by sounds in terms of sound pressure level and several psychoacoustic measures.

3 HEAD VISOR TECHNOLOGY

This chapter gives a brief summary of the work that has been performed in WP 3.1.1. A detailed description can be found in Deliverable 3.1.1.

The task of the work package 3.1.1 was the development of a measurement system for the quantitative analysis of the main noise sources in traffic flows. The starting point is the existing HEAD Visor microphone array system. Using advanced beamforming technology source maps of the observed sound field can be calculated and displayed in real time. Due to the size and channel number the standard Visor is optimized for measurements in the near field of medium size sources. For the task of the observation of traffic flows a larger array with a higher number of microphones had to be developed.

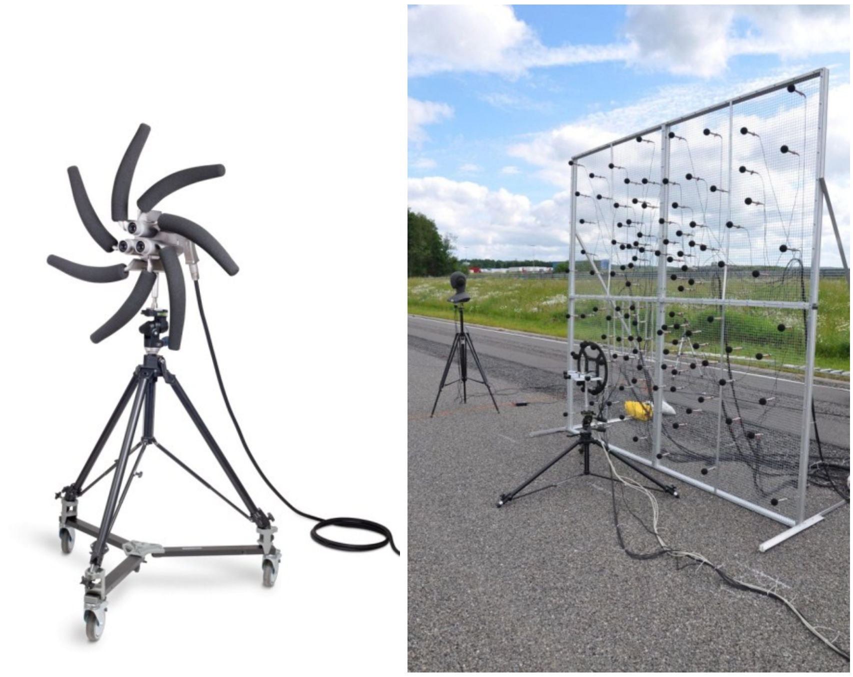

Figure 15: Standard beamforming array optimized for application in industrial application (left), flexible large scale array for measurement of road traffic

The final system consists of modular grids on which up to 192 microphones can be mounted. A wide angle panorama camera module is used for the collection of optical information on the traffic flow. To avoid the optical aberrations of single wide angle lenses the camera module consists of three calibrated cameras with overlapping apertures. The images of all three cameras are merged online to a single wide angle image with a horizontal aperture of 180°. The positions of all microphones in relation to the optical systems are measured and calculated automatically using linear optimization.

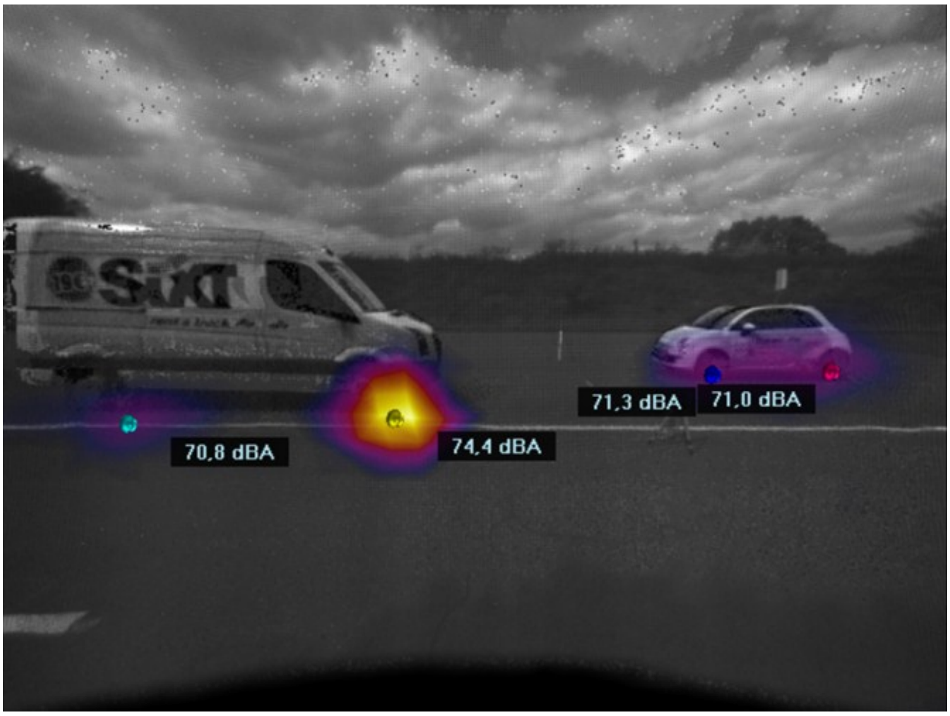

Figure 16: Typical result of the beamforming algorithm applied on microphone array data

The microphone array data is processed using beamforming algorithms. The result is a source map showing the dominant noise sources currently observed by the microphone array. The beamforming technology alone is not able to trace moving sources.

For this purpose advanced image processing algorithms have been applied.

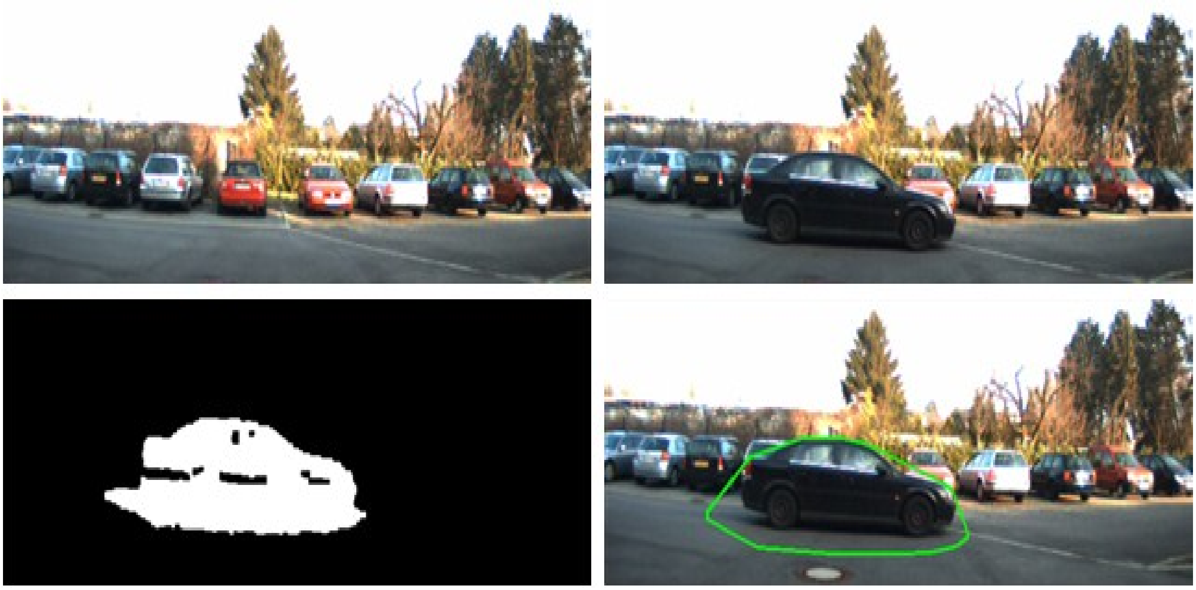

Figure 17: Detection of moving vehicles: background image (upper left image). Moving object (upper right image), foreground detection (lower left image) and contour detection (lower right image)

The video image is divided in background and foreground objects. All foreground objects with a certain size are defined as vehicles and included in a traffic flow simulation. The continuous simulation allows for the tracking of the potential noise sources and is constantly updated with newly analyzed optical information. For each vehicle the current position, speed and acceleration is calculated. Time signals are calculated for the dominant noise sources using the beamforming technology.

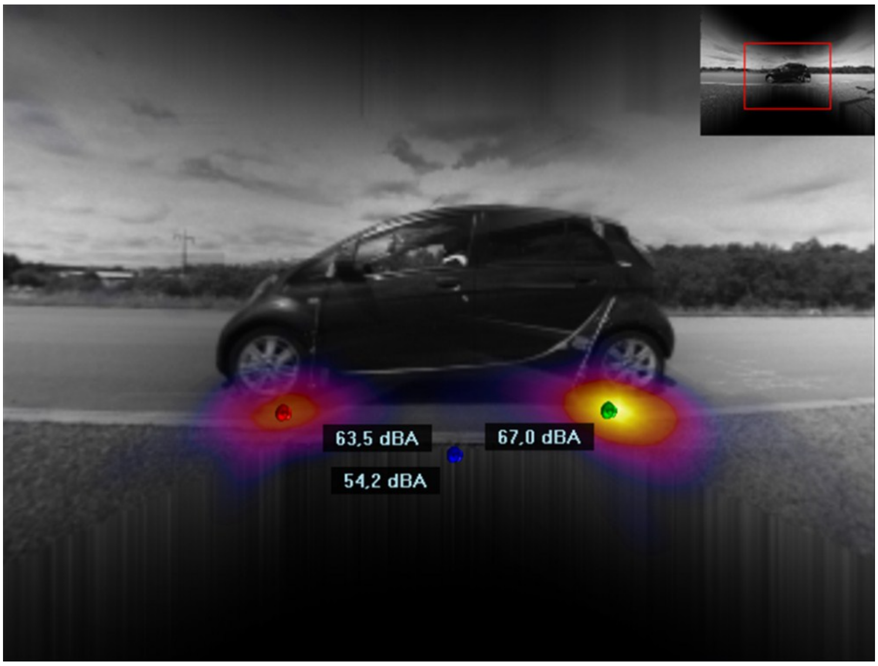

Figure 18: The levels for all three virtual microphones are calculated/exported. Here the levels are referenced to the microphone array position (2.5 m distance)

The combined data, physical descriptors of the vehicle driving condition and source time signals, is collected as an *Acoustical Fingerprint*. This technique allows for the interpolation and evaluation of a large set of heterogeneous data using standard and psychoacoustic analyses.

The *Acoustical Fingerprint* can be used to characterize the emission of single vehicles (comparing e.g. different sets of tires) or road locations. In the latter case the *Acoustical Fingerprint* would be used to characterize the vehicle composition mix, driving behavior and resulting noise emissions.

4 MEASUREMENTS

For the evaluation and comparison of different electric, hybrid, and internal combustion engine drives, different measurement campaigns for evaluating pass-by maneuvers of a variety of vehicles were conducted. As described in section 2, also for the creation of the UNS synthesis models of the vehicles, extensive measurements were performed. In this section, the actually performed measurements with their setup are described.

An important goal of the measurement campaigns has been the validation of the HEAD Visor microphone array technology, tracking algorithms, and evaluation technique (Acoustical Fingerprint). For the use on public roads during long-time measurements further efforts are necessary, e.g., to increase the stability of the vehicle detection under changing weather conditions and to camouflage the microphone array setup to avoid a change in drivers' behavior. This effort is not part of the CityHush project.

The ISO 362 standard intends „to reproduce the level of noise generated by the principal noise sources during normal driving in urban traffic". However, besides the defined driving conditions, the consideration of further typical driving conditions appears to be required to map adequately the acoustic profile of a vehicle. This is of particular importance since listening tests have shown that, e.g., the driving situation "starting from a standing position" causes high annoyance ratings (Figure 19). This perceptually relevant driving situation is not part of the measurement routine of ISO 362 so far.

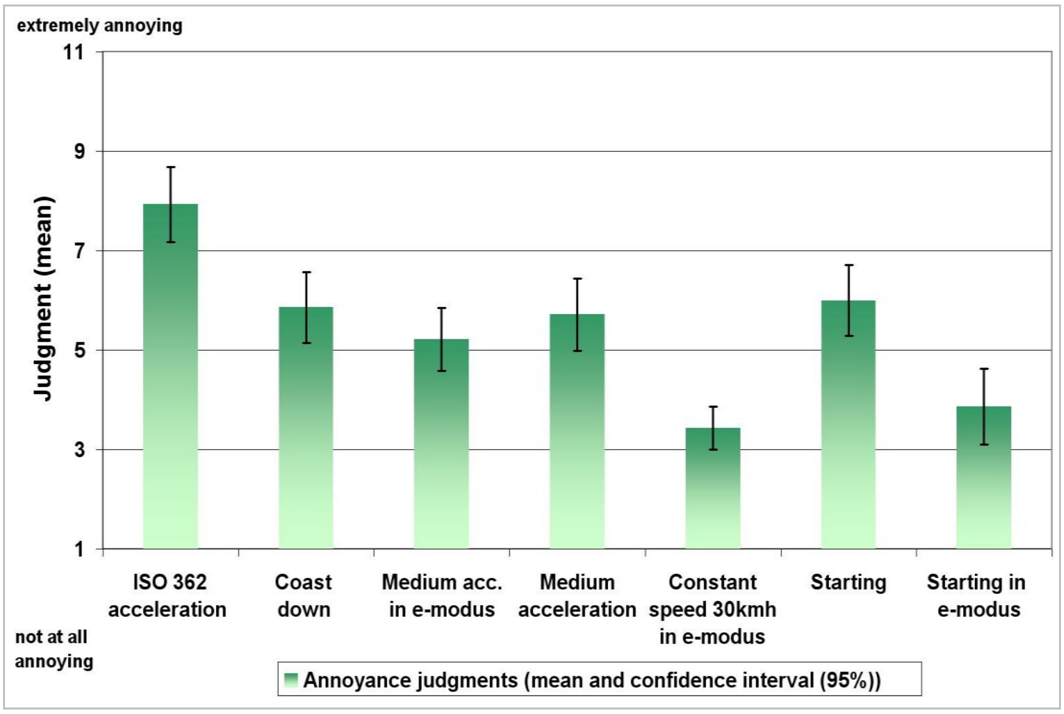

Figure 19: Result of a laboratory listening test: annoyance ratings (means) of different pass-by noises

4.1 COMPARISON OF GASOLINE WITH HYBRID VEHICLE

For the comparison of classical gasoline with hybrid vehicles, an Opel Vectra and a Toyota Prius were measured exemplarily. The measurement setup is shown in Figure 20. Three artificial heads and two microphones were used for capturing the pass-by noise of the vehicles at different distances. Additionally, the pass-by maneuvers were analyzed by means of the HEAD Visor microphone array technology.

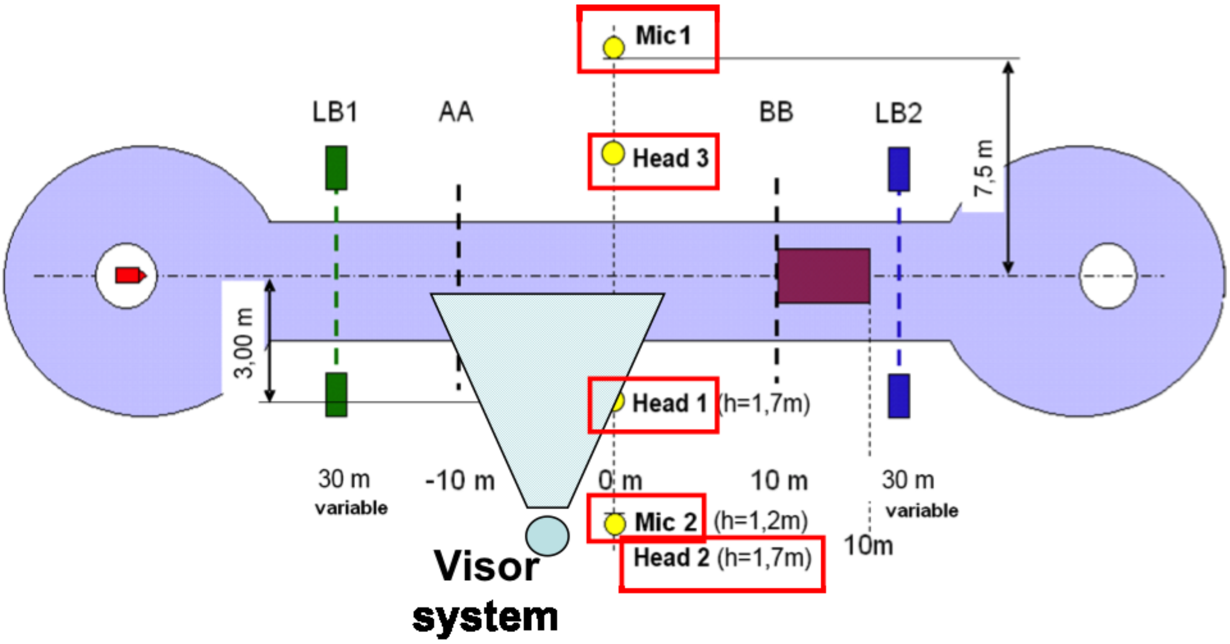

Figure 20: Schematic of measurement setup for measuring an Opel Vectra (combustion engine) and a Toyota Prius (hybrid drive). The part of the test track, where the vehicles were evaluated is marked by AA – BB. The microphones were placed exactly in the middle of this range.

Figure 21: Pass-by measurement of an Opel Vectra (combustion engine, left) and a Toyota Prius (hybrid drive, right) on a test track

The vehicles under scrutiny showed a sound pressure level difference with respect to the starting situation of more than 6 dB (Figure 22) and still more than 3 dB in the constant speed driving situation (30 km/h) (Figure 23). This shows that in electric mode a hybrid vehicle has a significant gain in terms of sound pressure level in the starting situation and in low speed scenarios, where the engine noise is dominant in comparison to the tire-road noise. However, if the hybrid vehicle is in combustion mode, there is no relevant noise benefit. This observation is especially relevant for designing the distinct drive modes of a hybrid vehicle.

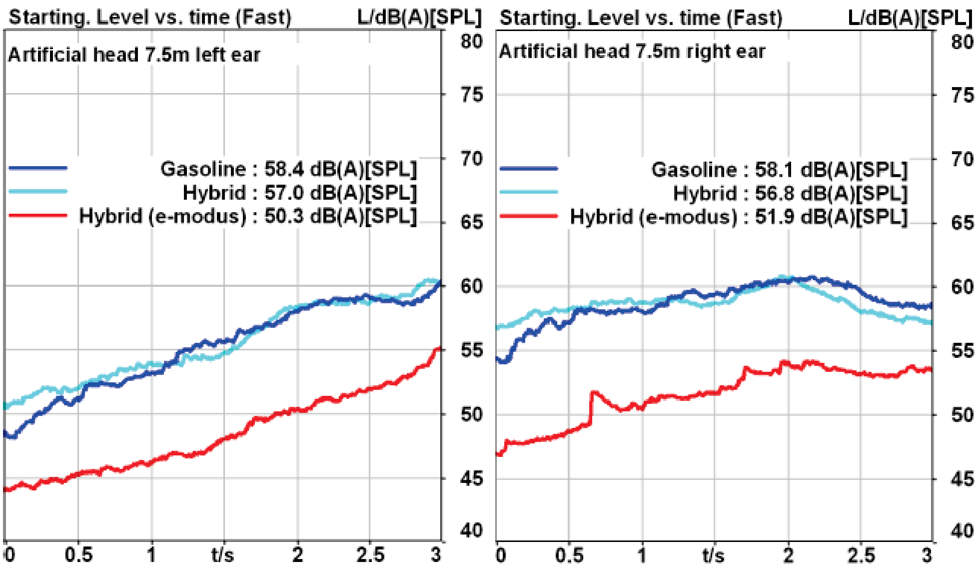

Figure 22: Comparison of exterior noise (artificial head at 7.5 m) of a vehicle powered by a combustion engine with a hybrid vehicle regarding the driving situation "starting" (Level (A-weighted) vs. time analysis)

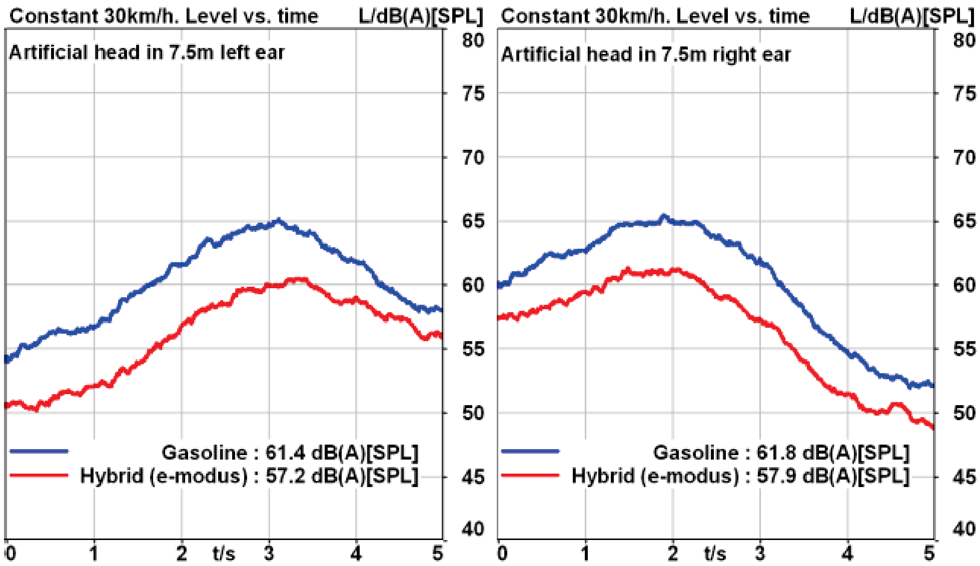

Figure 23: Comparison of exterior noise (artificial head at 7.5 m) of a vehicle powered by a combustion engine with a hybrid vehicle regarding the situation "30 km/h constant speed" (Level (A-weighted) vs. time analysis)

4.2 COMPARISON OF FIAT 500 COMBUSTION VS. ELECTRIC

For the comparison of a car powered by a combustion engine with an electrical driven car, two versions of the Fiat 500 were investigated in detail:

- Fiat 500c (combustion engine) with 1.2l, 51 kW, manual shift
- Fiat 500 Liion (electric engine) with 30/60 kW, 1 gear

Both cars were equipped with the identical tires: Dunlop Duratech 175/65R14. The stationary setup was composed of a binaural receiver (HEAD acoustics artificial head) in 3 m distance to the driving lane, an omnidirectional microphone at 7.5 m and a light barrier for the synchronization of stationary and mobile setup (Figure 24). On the car, microphones were placed at the tire in- and outlets and on the drive-train. Additionally, a GPS receiver was used for recording position and velocity.

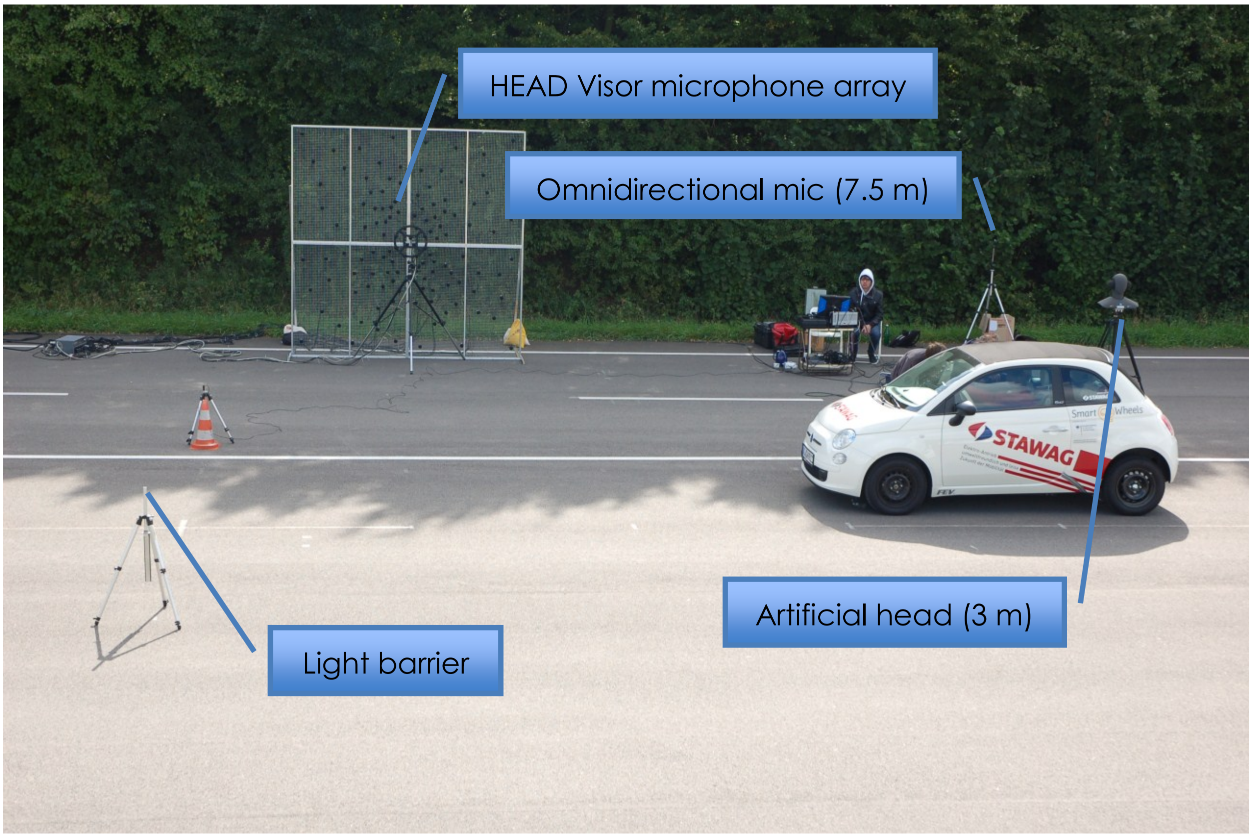

Figure 24: Stationary setup consisting of artificial head, omnidirectional microphone, HEAD Visor microphone array, and light barrier

Figure 25: Mobile setup for measurement of near-field source noise data, e.g., tire-road noise at in- and outlet, for the extraction of synthesis parameters for the UNS technology

The cars were measured in various driving conditions:

- Constant Speed: 10, 20, 30, 40, 50 km/h, combustion engine in 1st (10, 20 km/h), 2nd (20, 30, 40 km/h), 3rd (30, 40, 50 km/h), and 4th (50 km/h) gear
- Full acceleration (ISO) at -10 m (before the receivers), starting speeds: 20, 30, 50 km/h, combustion engine in 2nd (20, 30 km/h) and 3rd (30, 50 km/h) gear

- Coasting down: starting speeds: 10, 20, 30, 40, 50 km/h
- Different accelerations: low, mid, high; combustion engine in 1st, 2nd, and 3rd gear

Most considerable differences are observed for constant speed and full acceleration driving situations. The plots of sound pressure level over time are shown in Figure 26, Figure 27, and Figure 28 for constant speed and in Figure 29 for acceleration. The peak A-weighted sound pressure levels (L_{Amax}) for the two driving conditions are summarized in Table 1 and Table 2. Notably, for constant speed, there is a significant difference of about 10 dB between combustion and electric engine for very low speed (here 10 km/h). However, the difference is negligible at higher speeds. This is due to the tire-road noise being dominant at higher speeds.

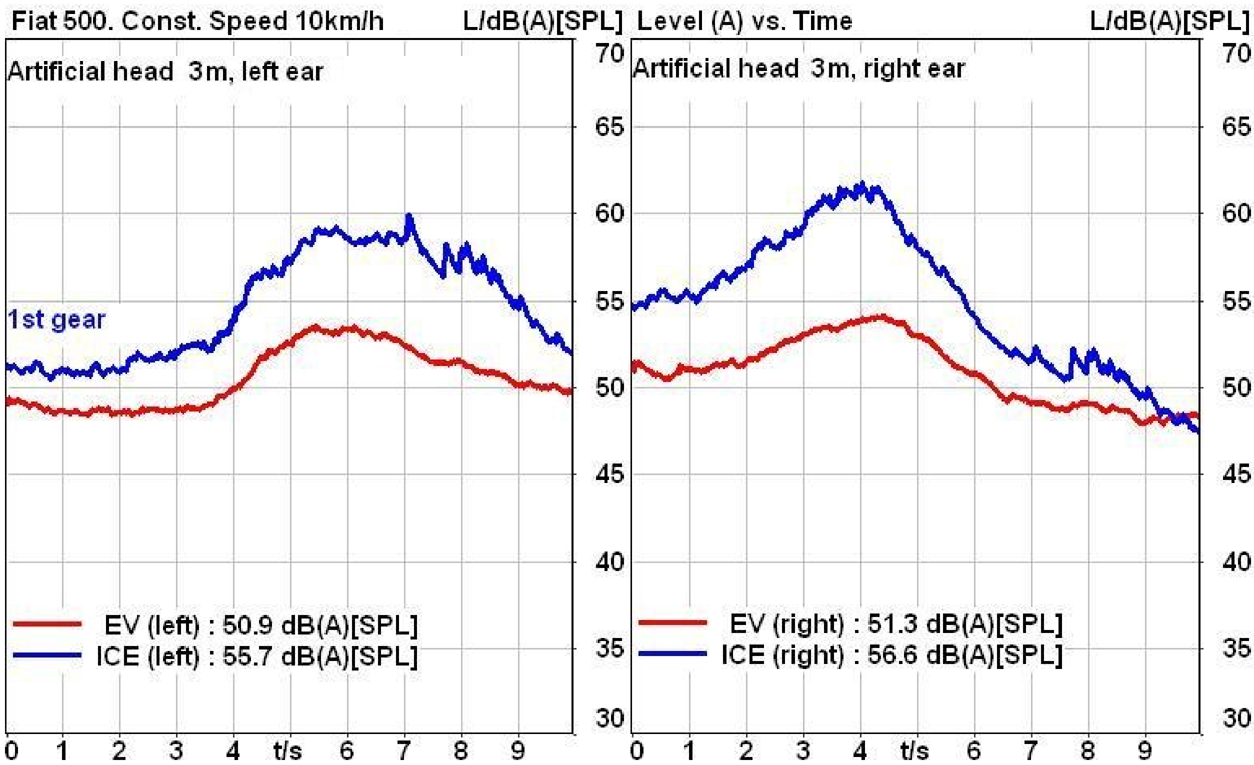

Figure 26: Comparison of electric vs. ICE at constant speed (10 km/h) (Level (A-weighted) vs. time analysis)

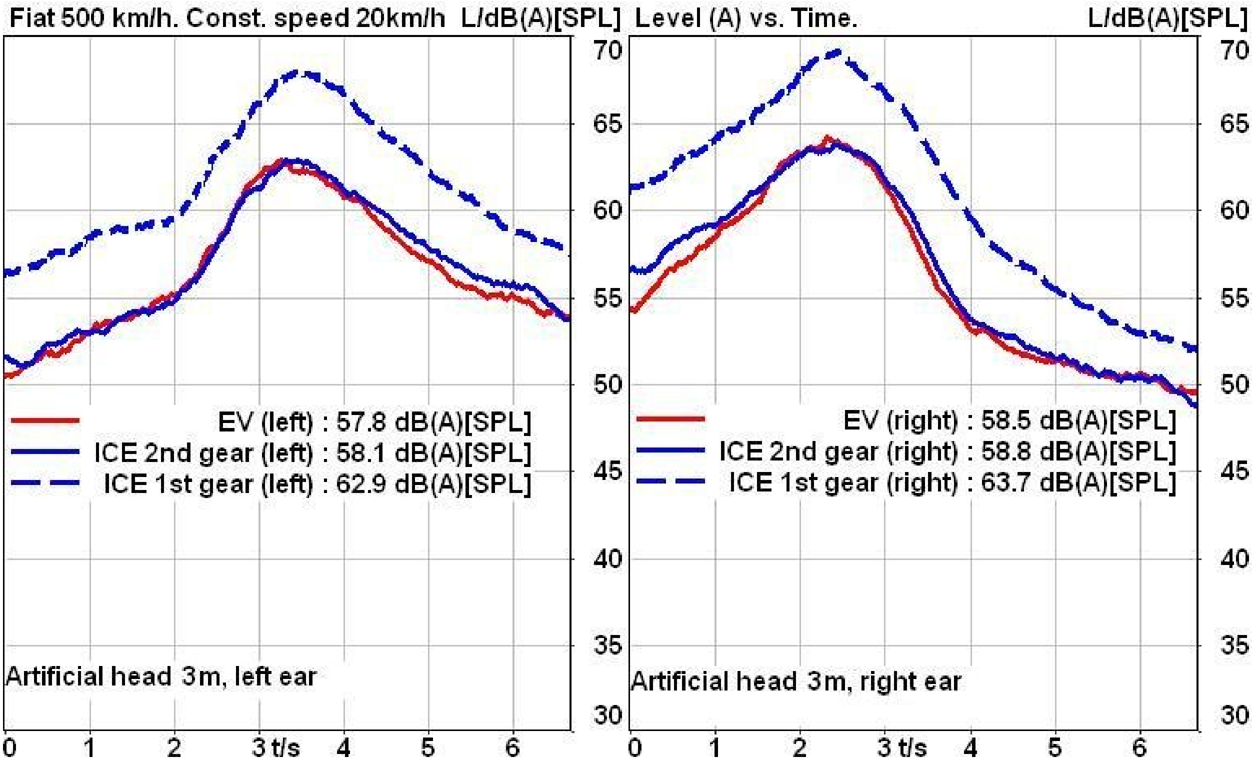

Figure 27: Comparison of electric vs. ICE at constant speed (20 km/h) (Level (A-weighted) vs. time analysis)

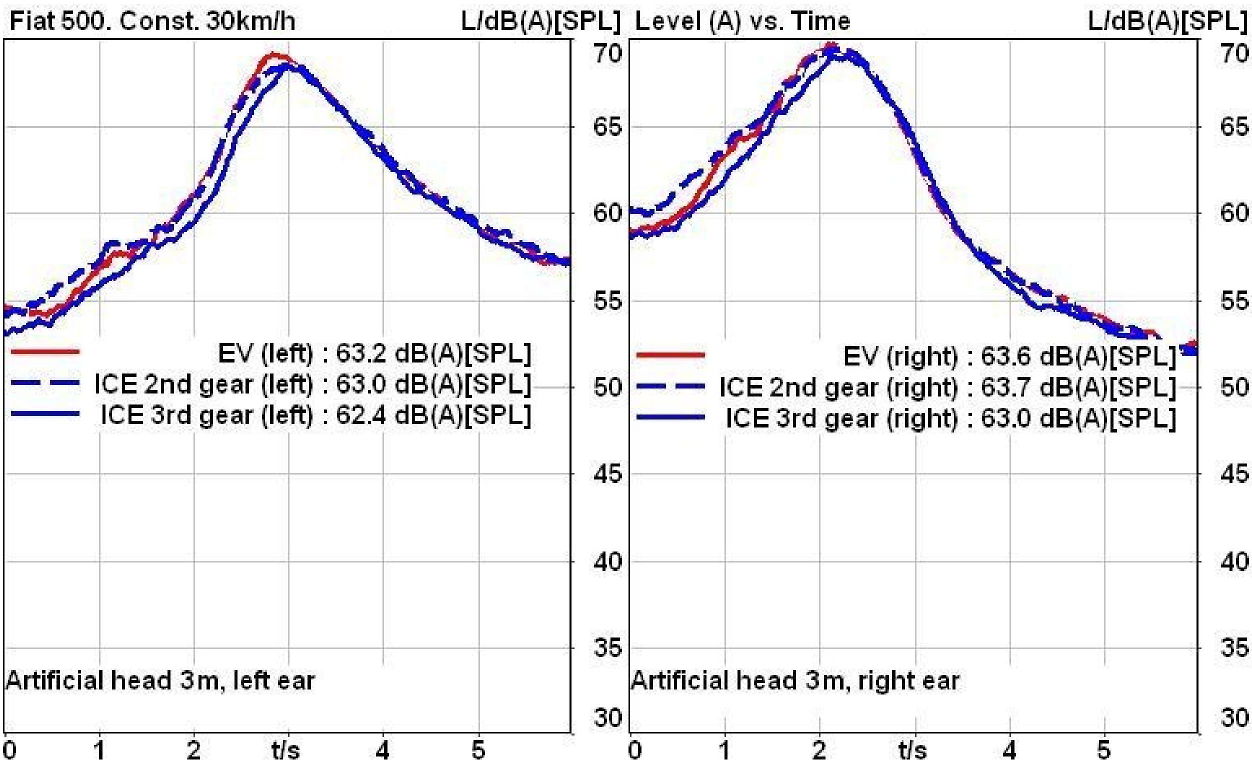

Figure 28: Comparison of electric vs. ICE at constant speed (30 km/h) (Level (A-weighted) vs. time analysis)

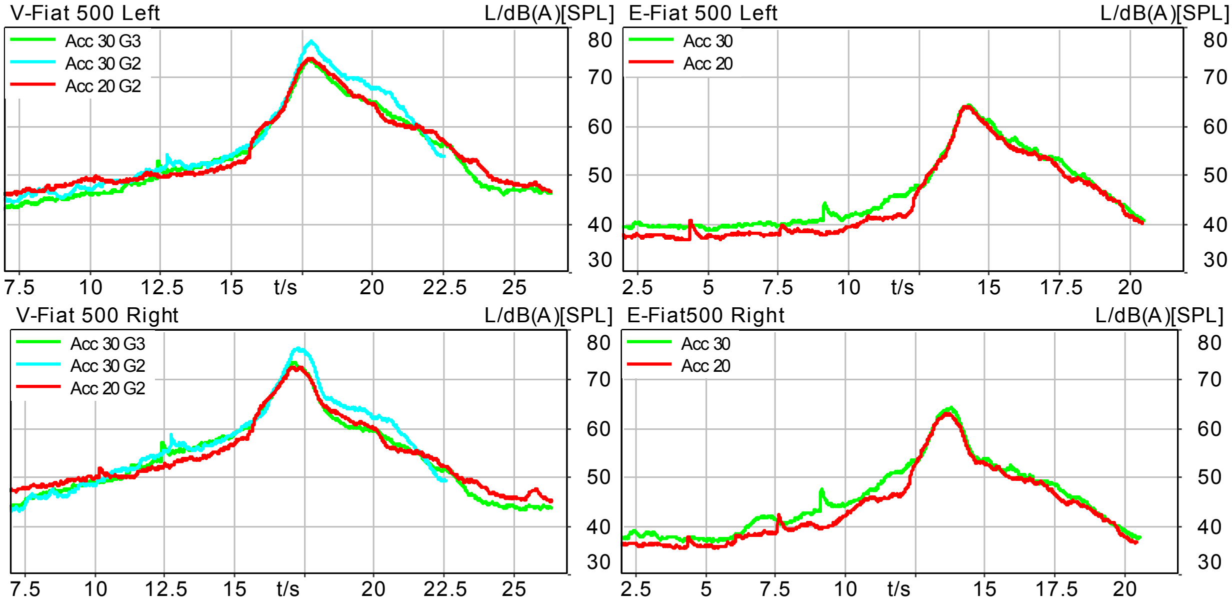

Figure 29: Comparison of electric vs. ICE accelerating from 20 km/h and 30 km/h (Level (A-weighted) vs. time analysis)

	Const 10	Const 20	Const 30
Fiat 500 electric	53 dB(A)	63 dB(A)	70 dB(A)
Fiat 500 combustion	60 dB(A)	63 dB(A)	70 dB(A)

Table 1: Peak sound pressure levels (L_{Amax}) of cars driving at constant speed

	Acc 20	Acc 30
Fiat 500 electric	62 dB(A)	63 dB(A)
Fiat 500 combustion	72 dB(A)	73 dB(A)

Table 2: Peak sound pressure levels (L_{Amax}) of accelerating cars

4.3 Evaluation of Low Noise Tires on the Citroën C-Zero

The Citroën C-Zero was measured with standard and low noise tires on smooth and rough road surfaces on the premises of the project partner Goodyear in Luxemburg.

For the measurements, two data acquisition setups were used: one stationary setup for the acquisition of the far-field pass-by noise and one mobile setup for recording the near-field noise of the vehicles.

The stationary setup, shown in Figure 30, was configured as follows:

- Artificial head at a distance of 3 m from the middle of the driving lane and a height of 1.7 m
- Omnidirectional microphone at a distance of 7.5 m from the middle of the driving lane and a height of 1.2 m
- Omnidirectional microphone at a distance of 4 m and a height of 1.2 m.
- HEAD Visor microphone array (acoustic camera)

Figure 30: Stationary measurement setup for measuring Citroën C-Zero

For the mobile setup, shown in Figure 31, the vehicle was equipped with microphones and acceleration sensors at the following positions:

- Omnidirectional microphone at each wheel's (front left, front right, back left, and back right) inlet and outlet
- Omnidirectional microphone at the converter
- Omnidirectional microphone at the passenger head position
- Acceleration sensor at the gearbox
- Acceleration sensor at the converter
- Acceleration sensor at the electric motor

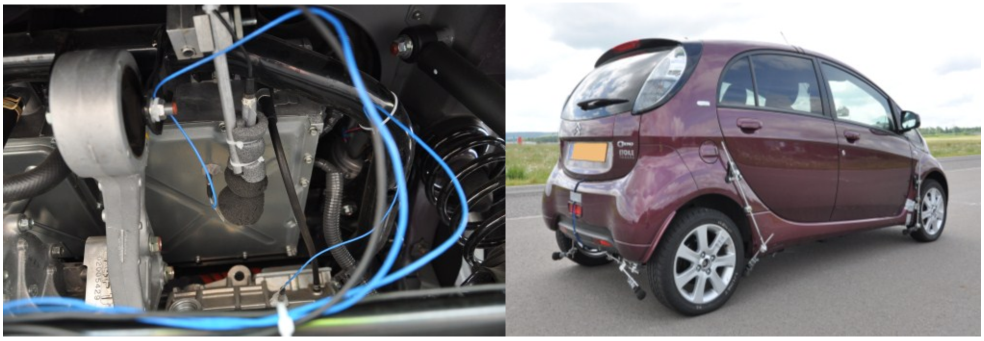

Figure 31: Parts of the mobile measurement setup

The measurements were performed for a set of distinct, acoustically relevant driving conditions (see also Table 3):

- Constant speed at 50 km/h and 80 km/h,
- Coast down from 50 km/h, 30 km/h, and 20 km/h starting at -10 m from measurement position,
- Acceleration from 30 km/h and 50 km/h starting at -10 m from measurement position with full load.

A light barrier, GPS-driven time stamps, and a radar speed gun were used for synchronizing the stationary and mobile measurement data as well as for acquiring the position and speed of the vehicle.

	Smooth Road / standard Tires	**Smooth Road / low noise Tires**	**Rough Road / standard Tires**	**Rough Road / low noise Tires**
Coast down 20 km/h	2	1	1	1
Coast down 30 km/h	2	2	2	1
Coast down 50 km/h	3	2	2	2
Constant 50 km/h	3	2	2	2
Constant 80 km/h	3	2	1	2
Accelerated from 30 km/h	3	2	2	2
Accelerated from 50 km/h	2	1	2	1

Table 3: Number of measurements for various running conditions, two sets of tires, and two road surfaces

The main purpose of this measurement was the evaluation of the low noise tires developed by Goodyear on the electric driven Citroën C-Zero. The mean sound pressure levels (L_{Aeq}) of the tire source signal (measured at the tire inlet) for the distinct tire road combinations and speeds are listed in Table 4 and Table 5. The results show that the low noise tires only have a significant effect on the emitted sound pressure level on the smooth surface and on the driven (here: rear) axle. Then a gain of about 3 dB can be measured.

	Front left tire inlet		Rear left tire inlet	
	Smooth surface	Rough surface	Smooth surface	Rough surface
Standard tire	92 dB(A)	94 dB(A)	96 dB(A)	99 dB(A)
Low noise tire	91 dB(A)	94 dB(A)	93 dB(A)	99 dB(A)

Table 4: Mean sound pressure levels (dB(A)) of tire source signals (measured at tire inlet) at constant speed of 50 km/h

	Front left tire inlet		Rear left tire inlet	
	Smooth surface	Rough surface	Smooth surface	Rough surface
Standard tire	100 dB(A)	103 dB(A)	104 dB(A)	107 dB(A)
Low noise tire	100 dB(A)	103 dB(A)	101 dB(A)	106 dB(A)

Table 5: Mean sound pressure levels (dB(A)) of tire source signals (measured at tire inlet) at constant speed of 80 km/h

Using the *Acoustical Fingerprint* technique described in Section 3, the whole set of measurements can be synthesized to one set of data containing level information as function of:

$$L = L(tire, road, speed, acceleration, frequency, position)$$

This function can now be evaluated and displayed in a various number of ways. The first set of figures, starting with Figure 32, shows the results of Level (dB(A)) vs. speed and frequency analyses. The eight figures show the synthesized and interpolated results for the four different tire/road combinations divided in noise generated by the front and the rear wheels. As expected the noise generation is increasing with the vehicle speed. The sound pressure level generated by the rear wheels is generally higher. The vehicle is rear wheel driven. The rear wheels were developed with a section width of 175 mm due to technical constraints (e.g. weight considerations). In contrast, the section width of the front wheels was only 145 mm. Due to the larger contact patch the wheel with larger width (rear wheel) produces more noise. The found differences between front and rear wheel noises confirm the validity of the measurement results based on the microphone array technology (see figures below).

The noise level of front and rear wheels increases beginning with the low noise tires on smooth surface up to the standard tires on the rough road surface.

Figure 36 displays the same data now as overall noise levels. One can see that for the front wheels the important influence is the surface whereas the tire design is almost negligible. The rear wheels show an almost equal level increase for the four different combinations.

The following figures show the same test cases but now using standard psychoacoustic evaluations. The results of the loudness calculation of the rear wheels are comparable with the level evaluation. The front wheels show almost no difference for all four combinations. The sharpness evaluation differs from the prior results. Here, there is almost no influence of the vehicle speed. The sharpness (v. Bismarck) is almost independent of the sound pressure level. Furthermore, the values are only depending on the road surface and not on the tires. The rougher road surface causes lower values than the smooth surface. The sharpness is an indicator for the amount of high frequency content. Although the rougher road surface generates higher levels the spectral energy is shifted towards the lower frequency. One possible explanation is the increased absorption of the high frequency energy by the open pore texture of the rough road surface. Since the sharpness sensation usually correlates with noise annoyance, the observation indicates that the perceptual benefit of the smooth road surface compared to the rough road surface is less than suggested by the sound pressure level decrease due to the slightly lower noise quality (higher sharpness values).

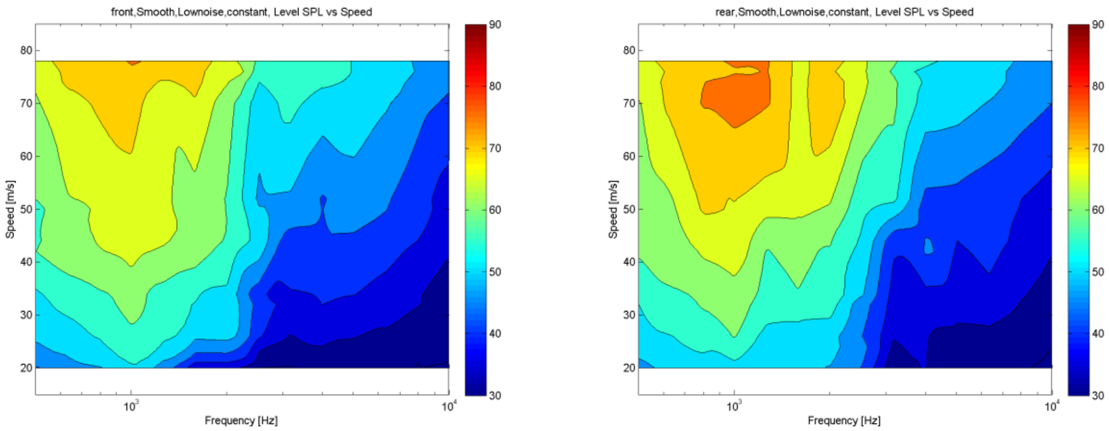

Figure 32: Smooth surface, low noise tires (front left, rear right) (sound pressure level (dB(A)) vs. speed and frequency)

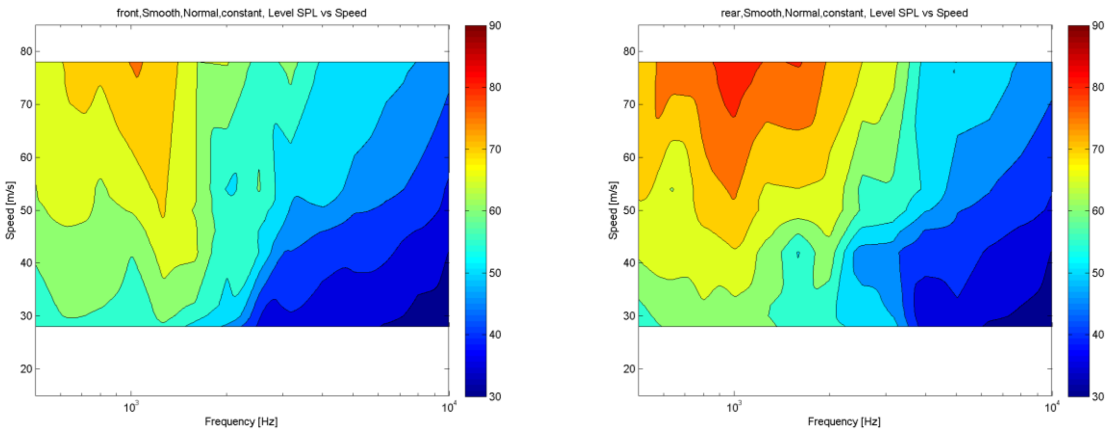

Figure 33: Smooth surface, standard tires (front left, rear right) (sound pressure level (dB(A)) vs. speed and frequency)

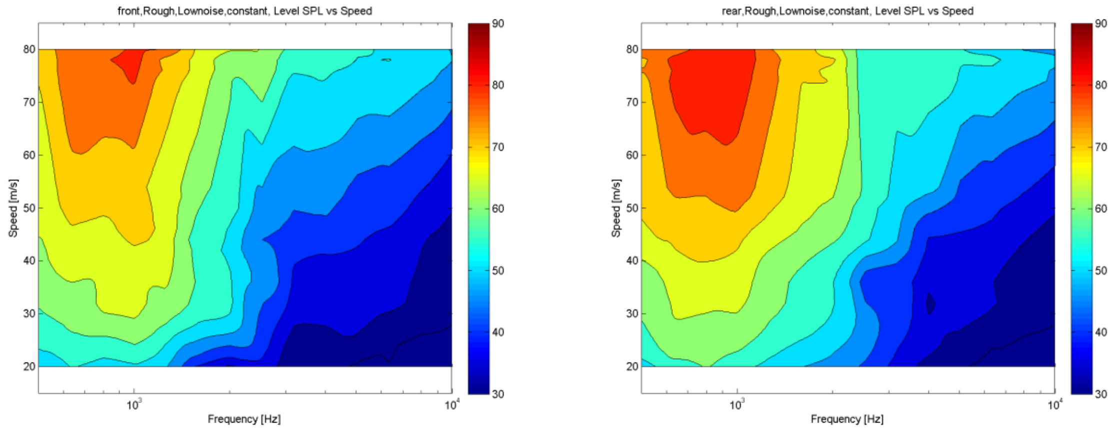

Figure 34: Rough surface, low noise tires (front left, rear right) (sound pressure level (dB(A)) vs. speed and frequency)

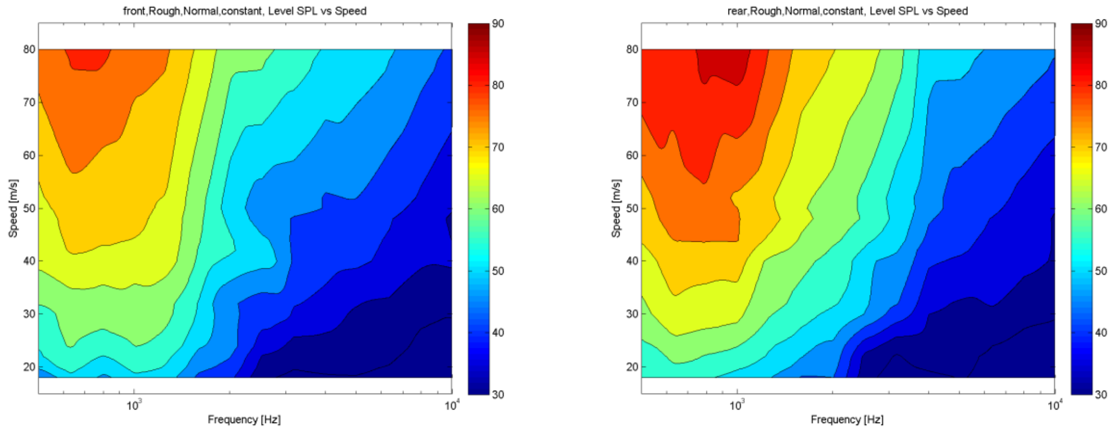

Figure 35: Rough surface, standard tires (front left, rear right) (sound pressure level (dB(A)) vs. speed and frequency)

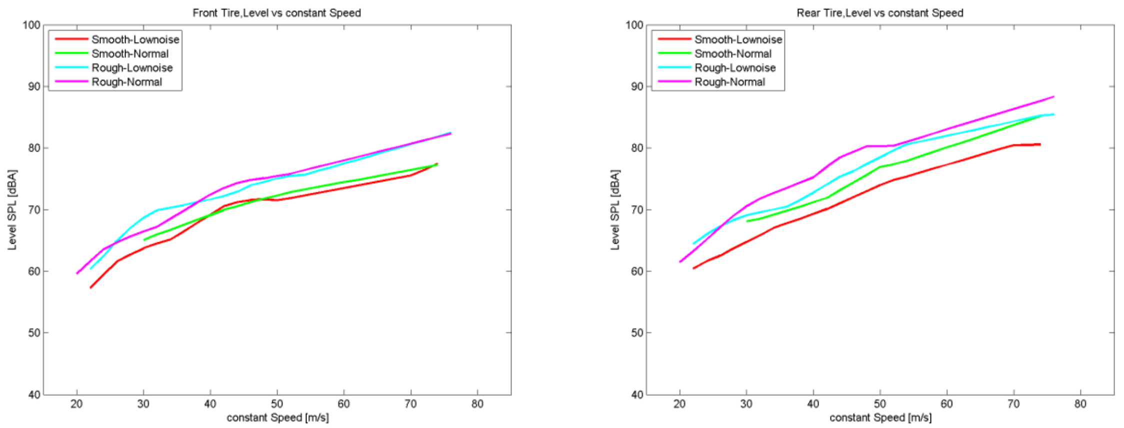

Figure 36: Comparison of tire/road combinations (sound pressure level (dB(A)) vs. speed)

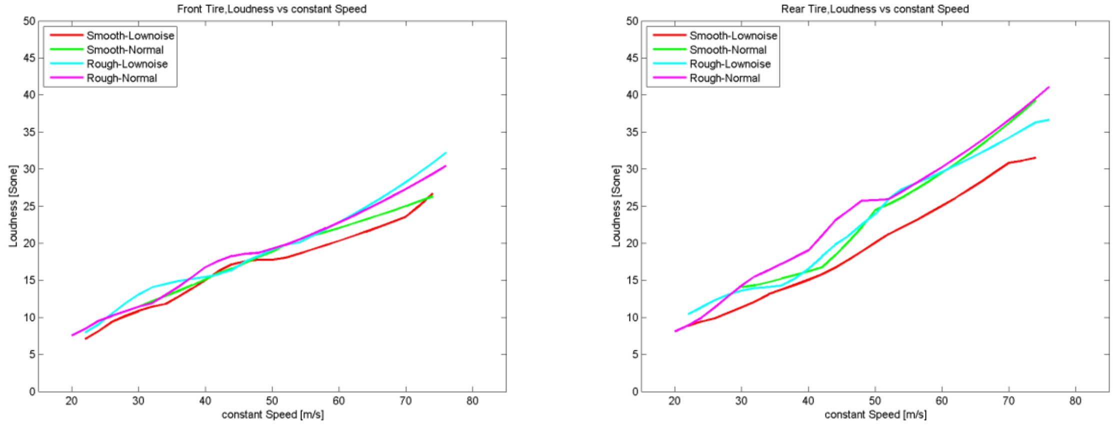

Figure 37: Comparison of tire/road combinations (psychoacoustic loudness vs. speed)

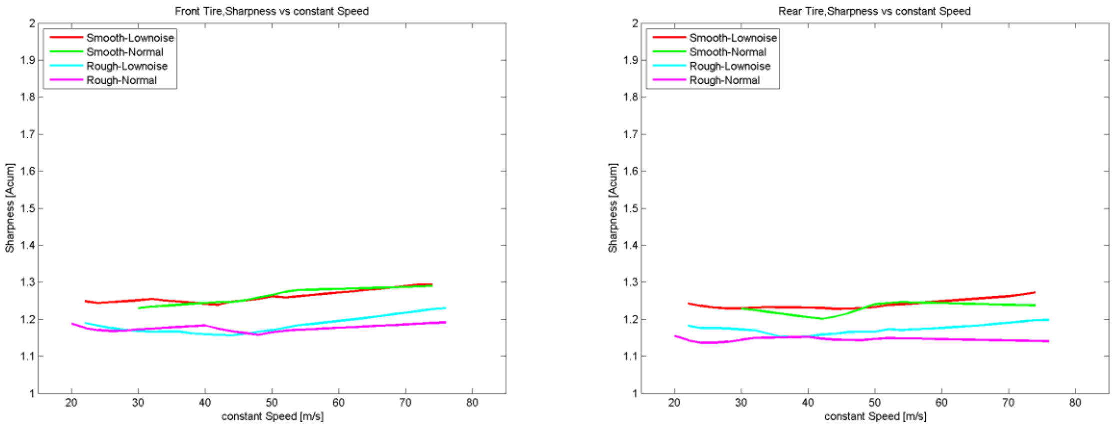

Figure 38: Comparison of tire/road combinations (sharpness (v. Bismarck) vs. speed)

4.4 Detection of Relevant Sound Sources

For the generation of appropriate synthesis models the acoustically relevant sound sources must be detected. The HEAD Visor microphone array technology gives an overview of the sound sources that are dominant for a given observer position (the position of the microphone array). The source ranking depends mainly on the powertrain, the tire/road combination, and the driving conditions (rolling, constant speed, acceleration).

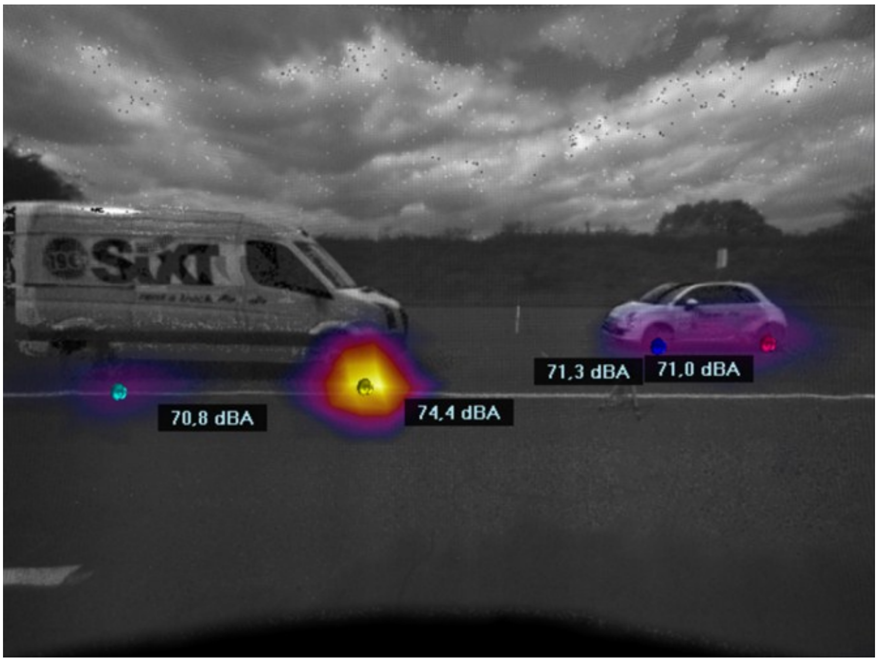

Figure 39: Typical result of the beamforming algorithm applied on microphone array data. The noise emission of the truck on the left is dominated by the engine. The small vehicle on the right emits mainly noise generated by the tire/road interactions.

4.5 Traffic Flow Measurements for Acoustical Fingerprint Technology

Traffic flow measurements on a variety of different vehicles have been analyzed using the *Acoustical Fingerprint* technology (see D 3.1.1 for detailed description). The measurements have been made on a test track (ika, RWTH Aachen). The traffic flow consists of a large number of single pass-by events that are partially overlapping in time. Each single event is analyzed regarding the type (size) of the vehicle and the current speed and acceleration. For the dominant noise sources time signals are calculated. These time signals can then be evaluated using the standard and psychoacoustic analyses. The following figures show examples for such an evaluation. In the considered measurement four different vehicles have been driving in free flow.

- FIAT 500 Electric
- FIAT 500 Combustion
- FIAT Ducato Combustion
- AUDI A5 Combustion

The data points collected during the measurement are not sufficient to create reliable statistical data. However, it can be seen already that the electric vehicle generates the least amount of noise in comparison with the corresponding combustion vehicle. The noise of the truck and the upper class vehicle is dominated by the engine noise. For the truck this is caused by the diesel engine. The upper class vehicle was driven in a sportive manner (high acceleration).

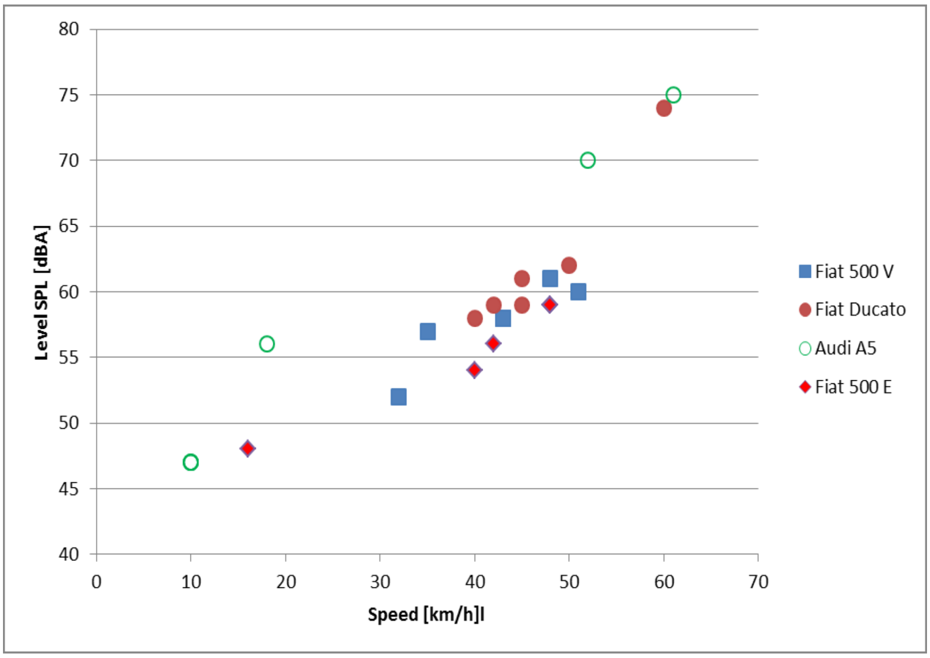

Figure 40: Acoustical Fingerprint analysis (level vs. speed) of a free flow traffic measurement on four different vehicles

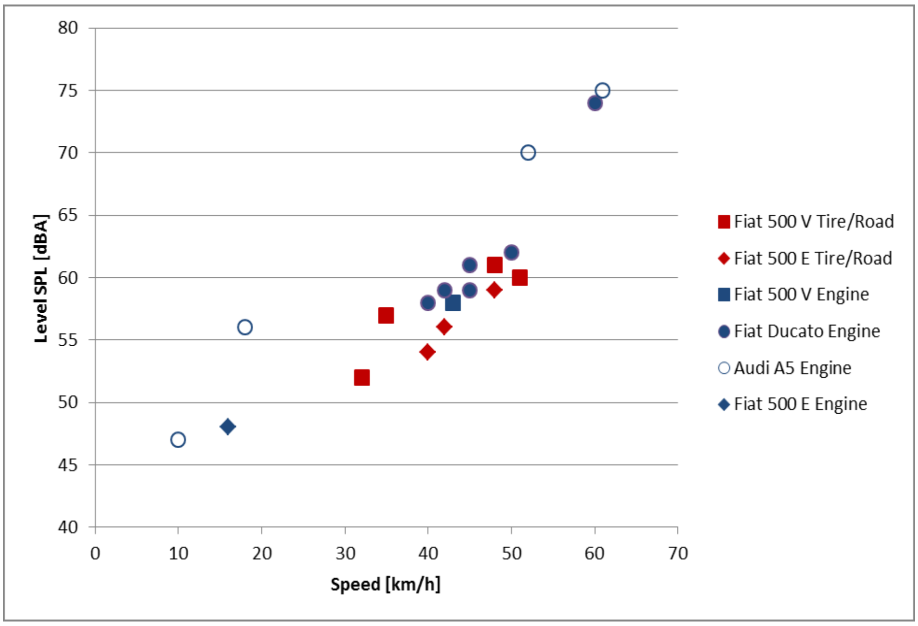

Figure 41: Acoustical Fingerprint analysis (level vs. speed). Same result as shown in the figure above but now clustered by the loudest noise source.

4.6 Source Related Transfer Functions

For the integration of direction dependent sound propagation into the UNS models, *source related transfer functions* were measured. As there is too little space to put appropriate loudspeakers at the source positions, reciprocal measurements were performed with a dodecahedron as sound source (see section 2.5.3).

The car was placed in the middle of a circle with a radius of 4 m. The microphones and acceleration sensors were mounted at exactly the same positions as for the pass-by measurements. The dodecahedron was placed on the circle in steps of 45°. The setup is shown in Figure 42.

Figure 42: Measurement setup for SRTF measurements with dodecahedron

The evaluation of the *source related transfer functions* shows that the noise propagation from the sound source to the receiver is significantly dependent on the direction. Especially the engine shows this dependency. It is significantly more audible in the back and side direction than in the front direction. Figure 43 shows the SRTF of the engine for the directions 0° (front), 45° (front right), 90° (right), and 180° (back). Figure 44 shows the SRTF of the front right inlet for the directions 0° (front), 90° (right), and 180° (back).

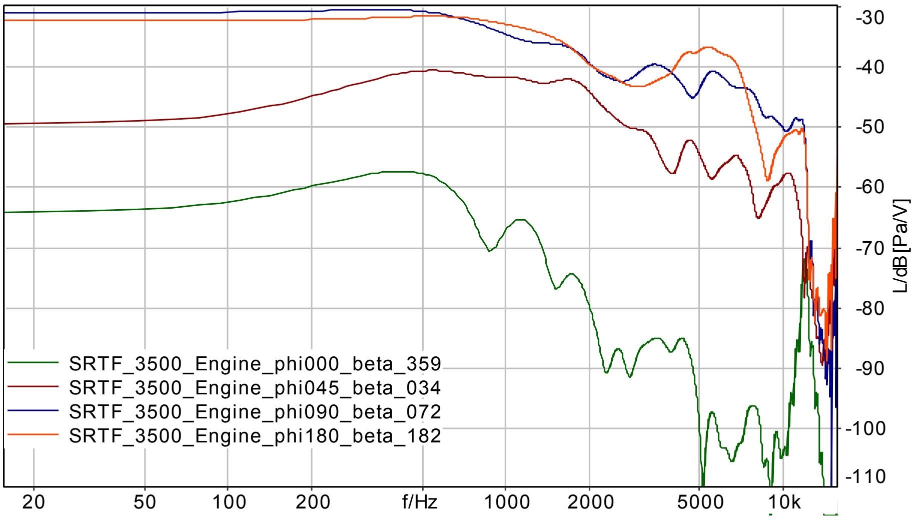

Figure 43: SRTF for engine for directions 0° (front), 45° (front right), 90° (right), and 180° (back)

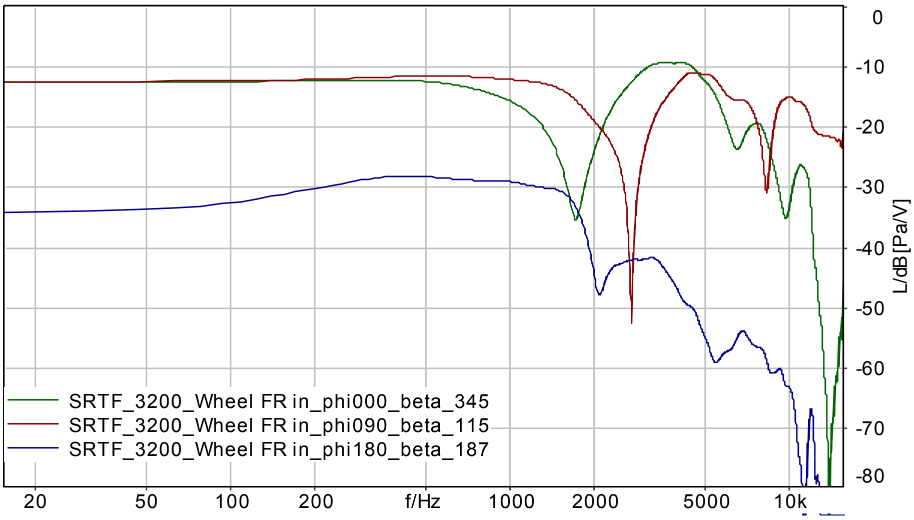

Figure 44: SRTF for tires (front right inlet) for directions 0° (front), 90° (right), and 180° (back)

5 SIMULATIONS

On the basis of the Universal Noise Synthesizer technology, it is possible to experience the resulting noise of virtual road traffic scenarios, to calculate psychoacoustic quantities as well as to study the corresponding human annoyance reactions.

The vehicle models were validated thoroughly for all driving conditions captured in the measurements. In this work package, the evaluation of different tire-road combinations was of major interest. Thus, simulations are presented for distinct tire-road combinations and compared with the corresponding pass-by measurements. Figure 46 through Figure 48 show the spectrograms of measured and simulated pass-bys at a speed of 50 km/h with the simulation on the left and the measurement on the right. In all four combinations the spectrograms match closely. Differences in the spectrograms are mainly due to background noise like singing birds and trucks passing by in the distance during the measurements.

The results show that by means of the UNS technology noise source signals (in this case the microphone signals at tire in- and outlet) can be mapped successfully to far field listening positions. By incorporating head related transfer functions a realistic listening experience can be established.

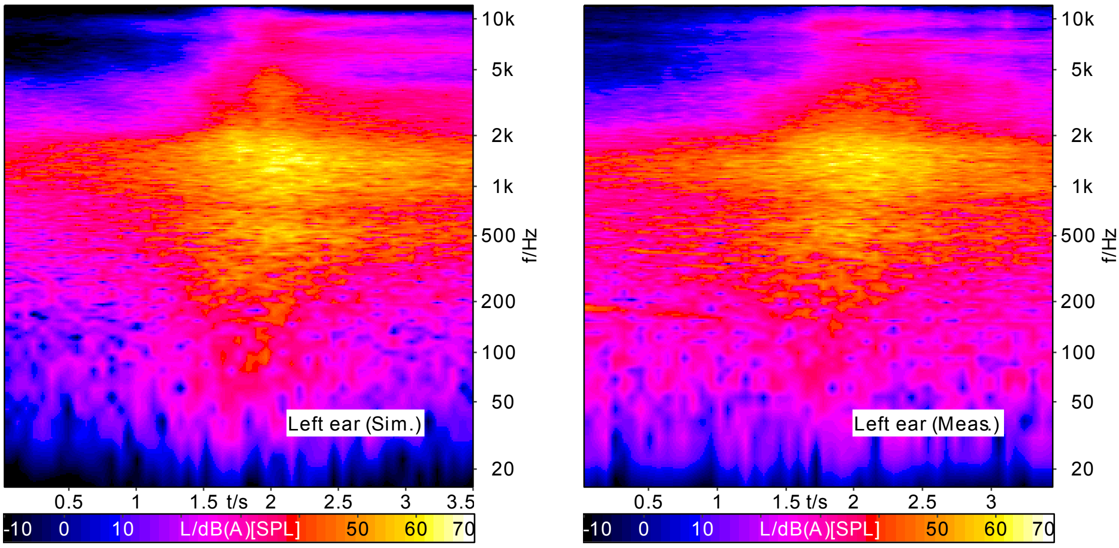

Figure 45: FFT vs. time analyses of pass-by noises of an electric vehicle at 50 km/h (constant), standard tires on smooth road surface; simulation (left) and measurement (right)

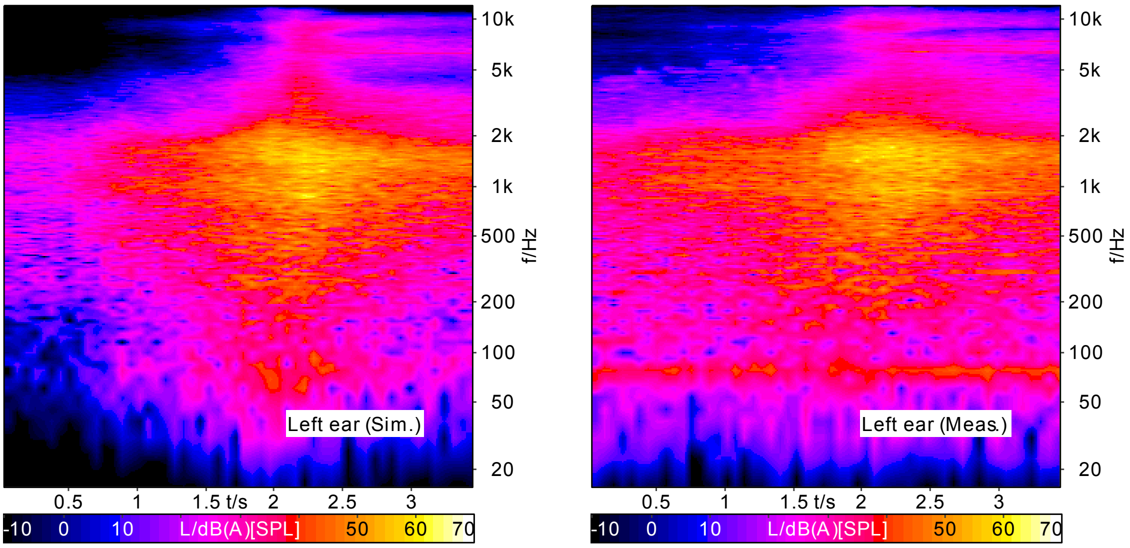

Figure 46: FFT vs. time analyses of pass-by noises of an electric vehicle at 50 km/h (constant), low noise tires on smooth road surface; simulation (left) and measurement (right)

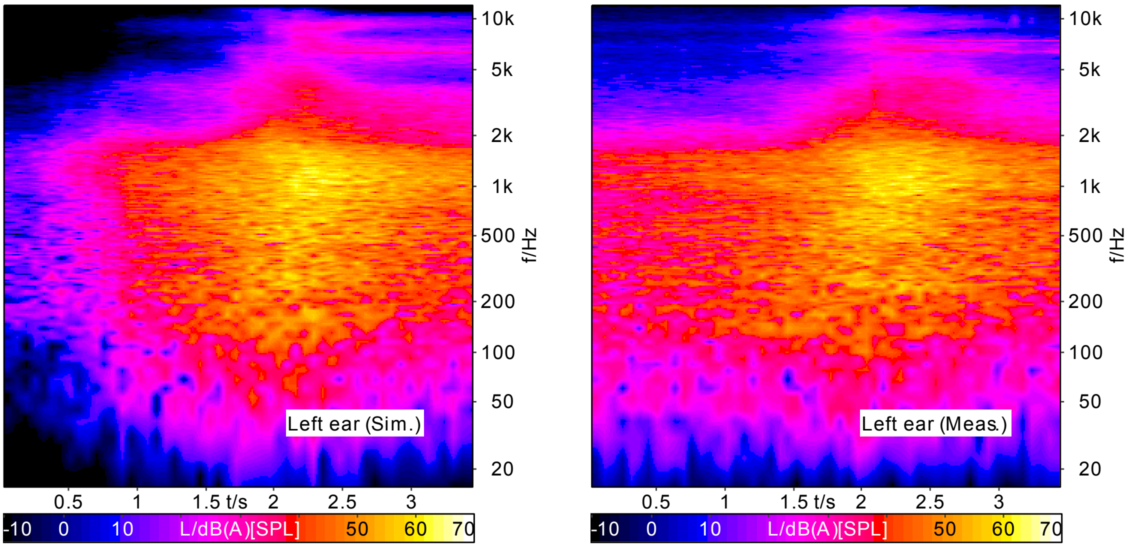

Figure 47: FFT vs. time analyses of pass-by noises of an electric vehicle at 50 km/h (constant), standard tires on rough road surface; simulation (left) and measurement (right)

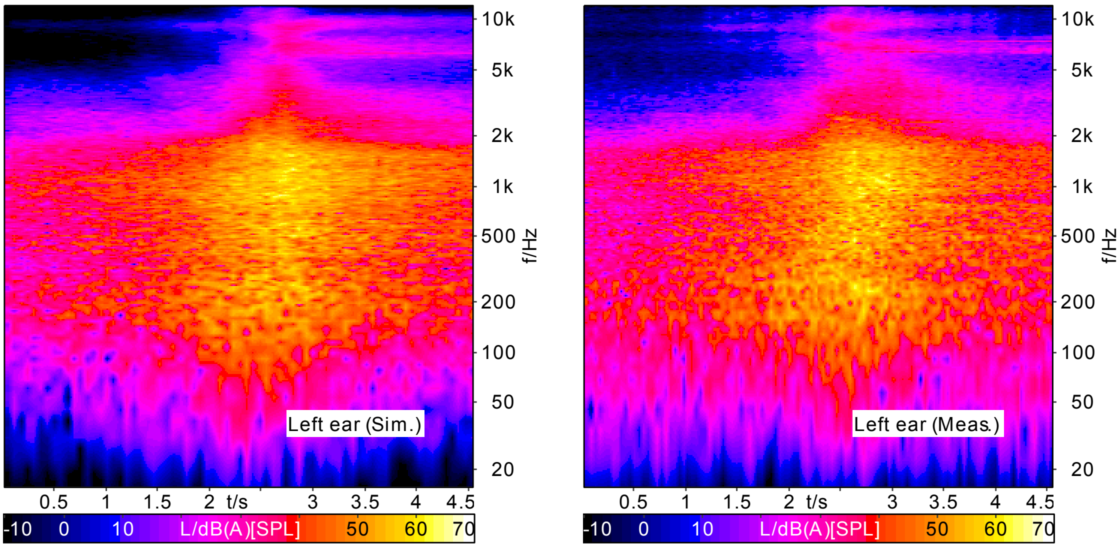

Figure 48: FFT vs. time analyses of pass-by noises of an electric vehicle at 50 km/h (constant), low noise tires on rough road surface; simulation (left) and measurement (right)

To further proof that the simulated signals not only match by level and spectrum but also psychoacoustically, sharpness and loudness over time of the measurements are compared with the simulation results. Figure 49 through Figure 52 show the respective plots.

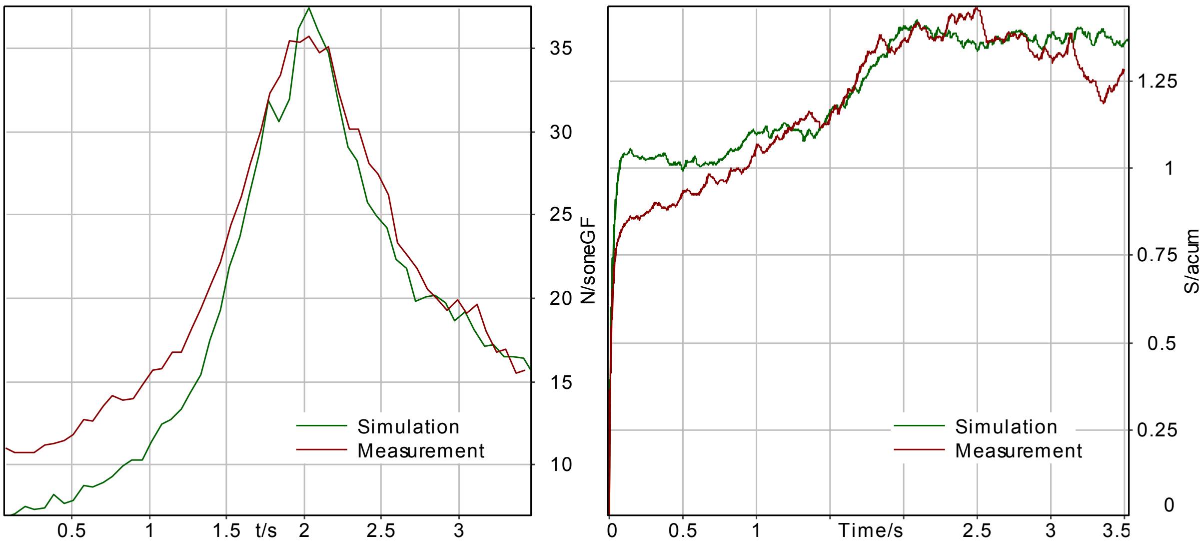

Figure 49: Comparison of simulation and measurement; loudness (left) and sharpness (right) of pass-by noises of an electric vehicle at 50 km/h (constant), standard tires on smooth road surface

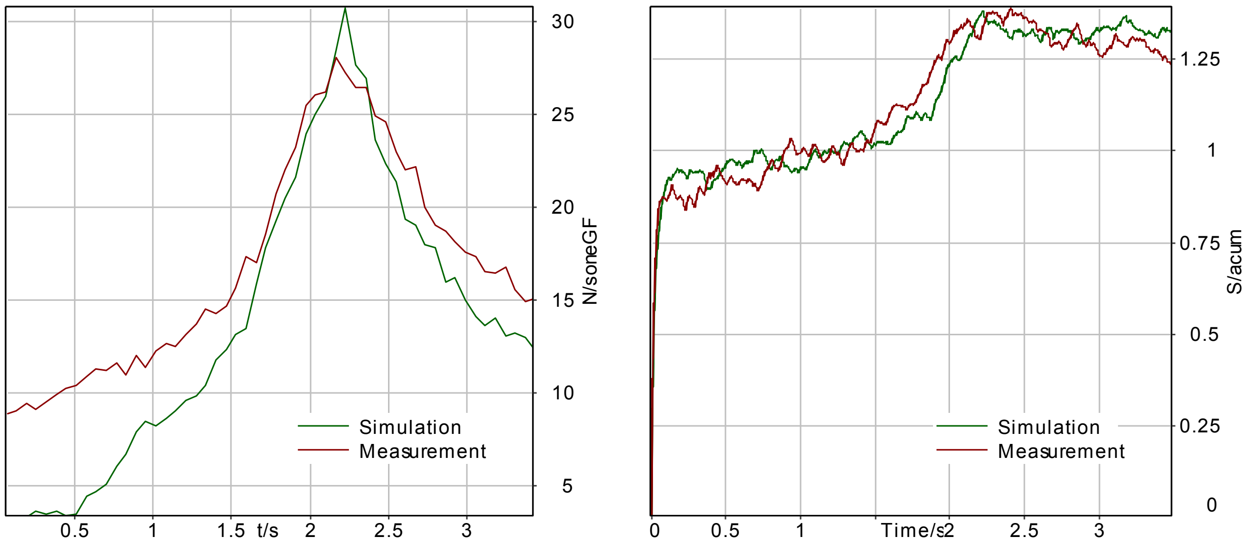

Figure 50: Comparison of simulation and measurement; loudness (left) and sharpness (right) of pass-by noises of an electric vehicle at 50 km/h (constant), low noise tires on smooth road surface

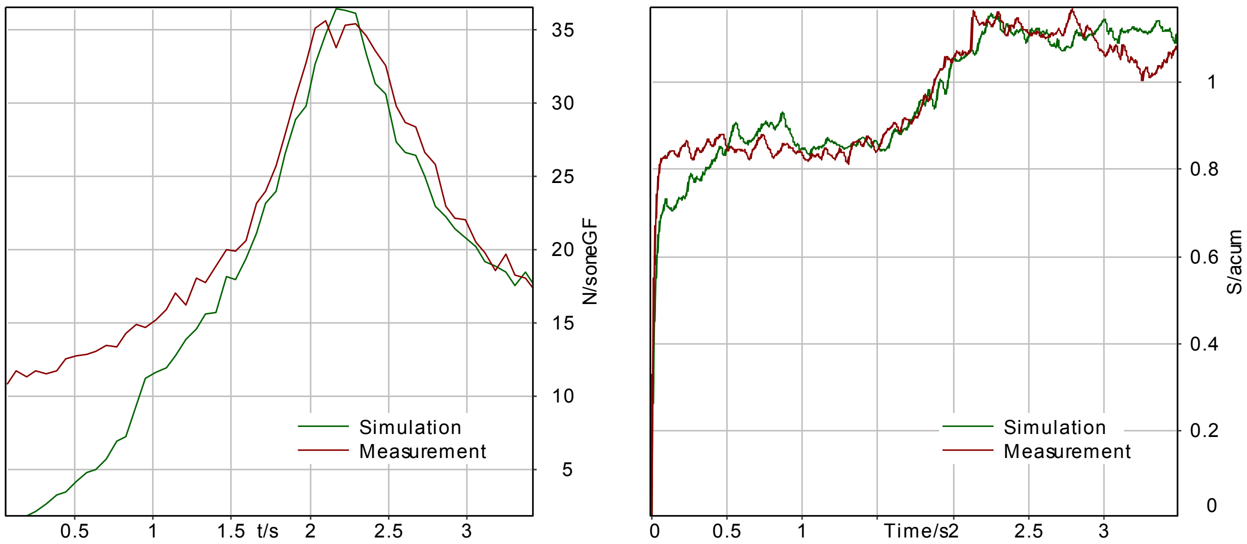

Figure 51: Comparison of simulation and measurement; loudness (left) and sharpness (right) of pass-by noises of an electric vehicle at 50 km/h (constant), standard tires on rough road surface

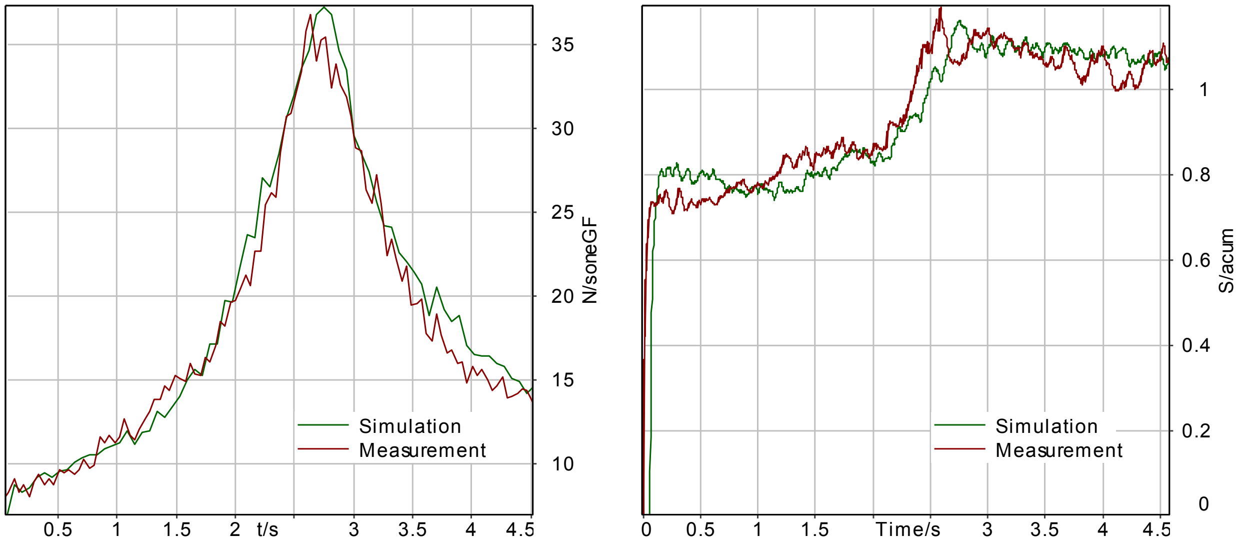

Figure 52: Comparison of simulation and measurement; loudness (left) and sharpness (right) of pass-by noises of an electric vehicle at 50 km/h (constant), low noise tires on rough road surface

The psychoacoustic evaluation of the measurement and simulation signals shows that the Universal Noise Synthesizer technology produces results matching the measurements. Loudness differences especially at the beginning of the signals are due to the background noise present in the measurements. The near field measurements, the HEAD Visor evaluations as well as the simulations show that the low noise tires perform best on the smooth surface. The sharpness of the pass-by noise is not influenced by the low noise tires. In contrast, the road surface has a significant influence on the sharpness. On the rough surface the pass by noise is less sharp than on the smooth surface. However, the difference in sharpness is not enough to compensate for the significantly increased loudness.

6 CONCLUSIONS

The Acoustical Fingerprint techniques allows for the synthesis of the large and often inhomogeneous data sets acquired during pass-by measurement campaigns. The example measurements were performed on the Goodyear proving ground with the Citroen electric vehicle testing two different sets of tires (normal and low noise) on two different road surfaces (rough and smooth). The data can be evaluated in many ways using the existing variety of acoustic and psychoacoustic analyses. As example, three typical analyses have been chosen (level, loudness and sharpness). The results can be synthesized to the following quintessence:

- Level evaluation
    - The tires with the larger section width (in this case on the driven rear axis) are generally louder than the tires with smaller section width. This is due to the larger contact patch touching the road surface.
    - The level of the tire with smaller section width is influenced more by the road surface (smooth, rough) than by the tire design (normal, low noise) with the rough surface being approx. 5 dB(A) louder.
    - For the tire with larger section width the surface and tire design are of equal importance with a maximum level difference between the quietest combination (low noise, smooth) and loudest combination (normal, rough) of up to 8 dB(A).
- Loudness evaluation: The results are similar to the level analysis results but:
    - The influence of the transmitted force on the driven tire noise emission is more prominent.
    - The Influence of the tire/road noise combination on the rolling tire noise emission is smaller.
- Sharpness evaluation: The sharpness does not consider the signal total energy but the amount of high frequency content. Therefore the conclusions are in part the opposite from the conclusions stated above. The sharpness is an important indicator for the annoyance of signals:
    - The sharpness values are almost independent of the vehicle speed (for constant speed).
    - The values are again higher for the accelerated condition but decrease with the absolute speed.
    - The road surface is more important than the tire design with the rough surface creating the lower values. The total noise energy generated on the rough surface is higher than on the smooth surface but it is shifted towards the lower frequencies leading to a reduced sharpness.

The evaluation of the measurements shows that for an electric car the tires are the main sound source for a speed of 30 km/h and above. For constant speed and coasting down, this is also true for combustion cars. However, during acceleration the engine sound dominates the overall noise. Hybrid vehicles have a special role as they switch between combustion and electric drive and thus the sound changes accordingly. This is especially relevant when the car is accelerated. From an acoustical point of view the combustion engine should be switched off during acceleration to keep the overall sound pressure level low.

The measurements as well as the simulations show that low noise tires perform best on a smooth surface. Of all tested combinations, the combination of a low noise tire on a smooth surface produces the least noise and is preferable for the use in quiet zones.

The Universal Noise Synthesizer technology allows for the simulation of complex traffic situation. In this work package the technology was presented. It was shown that the simulation results are valid and correspond very well to the measurements not only by level and spectrum but also psychoacoustically.