DELIVERABLE 3.5.1

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ACRONYM	**CITYHUSH**	
TITLE	***Definition of a noise & annoyance standard for motorcycles in the urban environment***	
Work Package 3	**Noise and vibration control at source – Acoustically green vehicles**	
3.5.1	**Acoustic definition of quiet motorcycles in their social context and in the scope of Q-Zones**	
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PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restrictec 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

This deliverable has been quality checked and approved by CityHush Coordinator Martin Höjer

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The deliverable describes the work performed within work package WP 3.5 of the CityHush project. Since in southern European cities powered two wheelers are widely spread and significantly influence the noise climate in urban areas, this noise source and its annoyance potential require particular attention. Especially in the context of the preservation and creation of quiet zones in urban areas this influence is of particular importance.

The study mainly considers the acoustical contribution of powered two wheelers to road traffic noise and their impact on noise annoyance with respect to quiet zones (Q-Zones) in cities. To understand the relationship between the noise of powered two wheelers and the noise annoyance, miscellaneous scenarios were measured as well as simulated and were subject to objective and subjective evaluation. It was also examined whether modifications at the dominant noise sources like combustion engine or exhaust can lead to a significant reduction of annoyance.

0.2 DESCRIPTION OF THE WORK PERFORMED SINCE THE BEGINNING OF THE PROJECT

Three main tasks were accomplished within this work package.

First, measurements of different powered two wheelers (electric scooters, scooter powered with combustion engines, motorbikes) on a test track were performed for all relevant driving conditions. The different near-field and far-field measurements were analyzed by different means.

Second, the measurements (near-field and far-field measurements) were post-processed to enable the inclusion of powered two wheelers in the traffic noise synthesizer technology. On this basis, new vehicle models were created in addition to the existing vehicle models. Especially for the simulation of electric driven vehicles the synthesizer technology has been widely extended and optimized. New synthesis methods and a driving condition configuration tool have been added.

Third, the measurements and simulations, which were generated by the traffic noise synthesizer technology, were subject to extensive listening tests in laboratory. The test results were analyzed with respect to the noise annoyance potential of different scooter types also taking into account varying boundary conditions.

0.3 MAIN RESULTS ACHIEVED SO FAR

The noise signals generated by the traffic noise synthesizer were comparably rated by test subjects, which prove the general applicability of the traffic noise synthesizer technology for environmental noise investigations.

The application of the extended traffic noise synthesizer allows for investigating the impact of powered two wheelers on noise annoyance in detail.

Based on the work performed in this work package three major conclusions could be drawn. First, road traffic with a certain share of scooters powered by combustion engines is always perceived as more annoying than road traffic scenarios, where the scooters are powered by electric engines. This trend is even more significant, when the surrounding traffic consists of electric vehicles. Second, the surrounding road traffic consisting mainly of passenger cars (in the context of temporarily occurring scooters) influences noise annoyance only for road traffic scenarios, where only E-Scooters are present. Scooters powered by combustion engines dominate the perception and evaluation to such an extent that the surrounding road traffic is almost insignificant for the overall noise annoyance.

0.4 EXPECTED FINAL RESULTS

This outcome makes clear that a restrictive policy against powered two wheelers equipped with combustion engines will be the preferred solution for Q-Zones. Powered two wheelers provoke strong and lasting annoyance reactions significantly influencing overall noise annoyance even in low noise situations. Finally, it turns out clearly that even considerable modifications at the noise sources of C-Scooters (engine, exhaust) do not lead to a significant reduction of the overall exterior noise and noise annoyance respectively.

0.5 POTENTIAL IMPACT AND USE

The traffic noise synthesizer technology, which allows for creating arbitrary road traffic scenarios also taking into account powered two wheelers, is an effective tool for city planning. It provides meaningful data for acoustical analyses or even subjective evaluation. Thus, proposed actions, intended to reduce noise and annoyance respectively, could be reviewed reliably before their realization.

The knowledge gained in this work package with respect to powered two wheelers allows for drawing crucial conclusions to successfully create quiet zones in urban areas.

0.6 PARTNERS INVOLVED AND THEIR CONTRIBUTION

HEAD acoustics (HAC) performed all work described within deliverable 3.5.1. In the discussions with TTE, TNO and Tyrens new ideas emerged, which were followed in this work package.

0.7 CONCLUSIONS

The acoustical contribution and the resulting annoyance of different scooter types (PTW) were evaluated. The acoustical as well as the perceptual benefit resulting from a complete substitution of scooters powered by combustion engines by electric scooters was investigated in detail.

The evaluation results show that road traffic scenarios with a certain share of scooters powered by combustion engines cause higher loudness perception and considerably higher noise annoyance than scenarios, where only electric scooters are present. This effect is even more significant, when the surrounding traffic consists of electric vehicles. This clearly points out the need to completely deny the access of motor scooters to quiet zones. Only a very restrictive, consequent policy against powered two wheelers equipped with combustion engines in and nearby quiet zones can lead to the intended purpose of the quiet zones.

It was shown that this is still required in case the most dominant sources of powered two wheelers equipped with combustion engines would be significantly reduced. These vehicle types keep their annoyance potential even if their noise contribution would be decreased by several dB.

If road traffic composed of only electrically driven passenger cars is considered, the annoyance effect due to temporarily occurring powered two wheelers equipped with combustion engines is even more distinct undoing the perceptual benefit of electric cars.

All the findings in this work package indicate the basic requirement to inevitably ban powered two wheelers equipped with combustion engines not only from quiet zones but also from roads in urban context. A full electrification of powered two wheelers represents a promising solution with respect to the environmental noise and noise annoyance reduction in general.

1 INTRODUCTION AND OBJECTIVE

The main goal of the CityHush project is to present solutions that reduce the overall traffic noise levels in urban areas significantly. One possible way to achieve this is to limit the access to certain quiet zones (Q-zones) in the city to only quiet vehicles, like hybrid or electric passenger vehicles.

In this context, the consideration of powered two wheelers (PTW) is very important, since this vehicle type frequently causes strong annoyance reactions (see deliverable 3.5.2 "Motorcycle noise evaluated in the developed noise score models for outdoor noise and indoor noise"). In particular, in southern European cities powered two wheelers are widely-used and influence the noise climate in urban areas significantly. This leads to a large number of highly annoyed people.

This report is mainly focused on the impact of powered two wheelers on road traffic noise and the resulting noise annoyance. In this context, the reduction of noise and annoyance resulting from a full electrification of powered two wheelers and its benefits in the scope of quite zones is investigated in detail.

2 TRAFFIC NOISE SYNTHESIZER TECHNOLOGY

The evaluation of noise and annoyance caused by scooters (powered two wheelers) was accomplished by means of measurements and simulations. For the simulation of the vehicle noise the *traffic noise synthesis technology*, initially developed in the European research project *Quiet City Transport* (EU Project "Quiet City Transport" (QCITY), TIP4-CT-2005-516420 (2005-2009)) by HAC, was applied. Within CityHush the synthesis technology has been expanded extensively. The focus in the CityHush project is on simulating electric and hybrid vehicles and studying their influence on road traffic noise and noise annoyance respectively. Moreover, the technology was also extended with respect to powered two wheelers in order to be able to create complex road traffic scenarios with powered two wheelers included. This section gives a brief introduction to the technical details of the traffic noise synthesis technology.

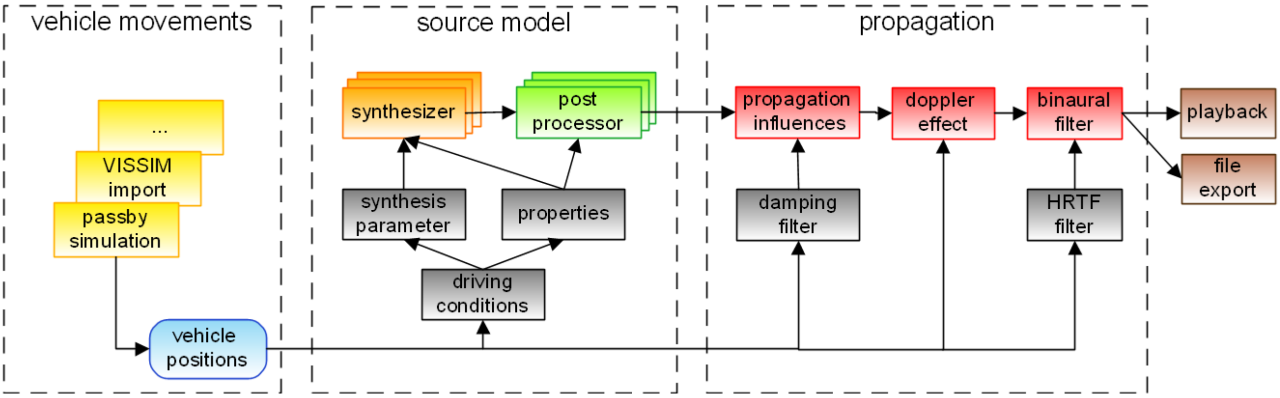


Figure 1 Signal flow of the TNS-technology.

2.1 TRAFFIC FLOW SIMULATION

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

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

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

2.2 SOURCE MODELLING

To achieve a realistic vehicle synthesis an appropriate vehicle model has to be developed and validated. This is done in the TNS software by assembling different sound sources and noise syntheses into a tree structure as shown in Figure 2. The configuration of a vehicle model is done in four steps.

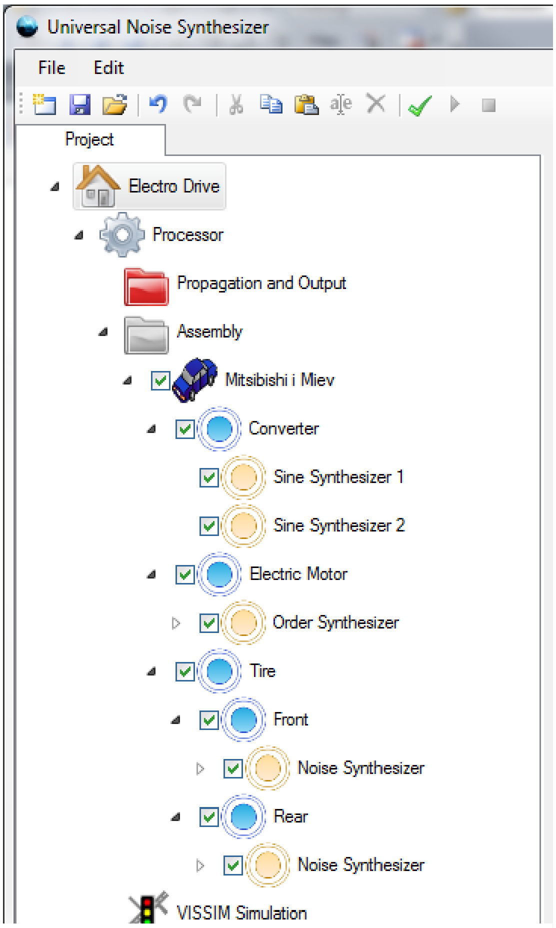


Figure 2: Tree structure of a vehicle model

1. Each vehicle is partitioned into distinct acoustically relevant sources with their respective relative position.
2. The source signals are generated by miscellaneous 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 either in dependence of frequency and direction by the so-called source related transfer functions (SRTF) (or just without SRTF by implicitly implementing an omni-directional directivity) followed by a distance dependent level adaptation and an appropriate time delay.

For validating the constructed models a comparison of the simulated sounds to measurements is possible. The models can be configured to represent certain vehicle classes such as compact class or upper vehicle class. In case very high simulation accuracy is required for a certain vehicle, a detailed model can be applied to it instead of using a generic model for the vehicle class. 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 or heavy vehicles.

2.3 Propagation and output

The simulated source signals can be exported directly to a file or be used for online playback. For realistic traffic simulations also the propagation of the sound has to be calculated. The implemented propagation paths consist of four steps.

1. With different damping filters different propagation effects can be modeled. These filters account for, e.g., air absorption or damping by barriers like walls or forest.
2. The effect of reflections of mirror sources at surfaces can be modeled.
3. The Doppler-Effect has to be regarded, if the vehicles' (noise sources) or the observer's position varies. This is caused by the finite speed of sound and is important for the generation of realistic and authentic auralizations.
4. To be able to perform subjective evaluations of the synthesis results a binaural playback is very important. By using head related transfer functions (HRTF) the spatial information of the vehicles becomes perceivable by the listener.

In general, the TNS provides the option to export the binaural or monaural signals to a file as well as listening to them on the fly. The direct playback option is only possible if the computer hardware can calculate the simulation in real-time, though.

2.4 Analysis of synthesis parameters

The data preparation for creating reliable synthesis parameters is very important for developing a realistic vehicle model. In the following 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 an order generator and a noise synthesizer respectively.

The input parameters for the order generator are order spectra. These order spectra are deduced from near-field measurements of the respective vehicle by means of an order analysis. The output of this analysis is the level and the phase of each order. This information is needed for all acoustically relevant driving conditions of the vehicle like different engine speeds, engine loads or speed differences. One challenge in extracting the order spectra from the measurements is to decide if frequency components are orders or part of the stochastic background noise. The detection 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.

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.

Generally, the quality of the signal analyses for obtaining the synthesis parameters is essential for the quality of the simulation results.

2.5 Conclusions

With the traffic noise synthesizer a tool was developed allowing for a comprehensive investigation of road traffic noise. First, a software prototype was developed for composing sophisticated vehicle models and for auralizing arbitrary road traffic scenarios. Moreover, a work flow was developed to create realistic synthesized sounds based on real vehicle measurements.

This gives the opportunity to generate the noise of single vehicles as well as of complete road traffic scenarios. Especially, it enables the extensive evaluation of electric and hybrid vehicles. Moreover, it provides the opportunity to simulate sounds in order to perceptually evaluate specific effects caused by the virtual implementation of noise mitigation measures or the introduction of traffic regulation measures.

3 SIMULATION OF SCOOTER (PTW) SOUNDS

In chapter 2 the technical details of the synthesis methods and the traffic noise synthesizer software were explained. For the evaluation of scooter noise and its effects on road traffic noise the synthesis tool was applied. Compared to real road traffic measurements the simulation approach gives the following advantages:

- The traffic load and composition can be defined exactly.
- The simulations are independent of environmental influences (weather, background noise, local conditions for measurement set-up, traffic rules, etc.).
- Acoustical modifications of the vehicles can be modeled virtually (e. g. attachment of muffler, etc.).
- The scenarios are reproducible and the noise influencing parameters (e.g. speed limit) can be varied independently from each other.

In the following sections, the application of the synthesis technology referring to scooter sound auralization is explained in detail.

3.1 MEASUREMENTS

For the creation of the synthesis models of the scooters HAC performed different measurements to analyze and extract the synthesis parameters.

For the measurements two data acquisition set-ups were applied. A stationary data acquisition set-up (Figure 3) was used to measure the pass-by noise and a mobile set-up was applied to record the near-field noise of the scooters (Figure 4).

The stationary set-up was configured as follows (see Figure 17):

- Artificial head at a distance of 3 m to the car passing-by
- Artificial head at a distance of 7,5 m respectively
- Monaural microphone at a distance of 7,5 m respectively
- Visor microphone array (acoustic camera)

In the mobile set-up the microphones were placed at the following positions (see Figure 4).

- Front wheel inlet
- Front wheel outlet
- Back wheel inlet
- Back wheel outlet
- Engine
- Exhaust (only for scooter powered by a combustion engine (C-Scooter))

In addition, the engine speed and the velocity of the scooters were measured. A light trigger system was applied to detect the absolute position and time reference between stationary and mobile measurement set-up. This gives the opportunity to synchronize the measured data sets.

Figure 3 Left: Picture of the stationary measurement set-up with artificial head and visor microphone array
Right: Fully equipped C-Scooter during pass-by measurement

Figure 4 E-Scooter (left) and C-Scooter (right) with attached near-field microphones and mobile data acquisition device (multi-channel front-end in the blue box)

For a realistic simulation of the scooter sound all acoustically relevant driving conditions have to be considered. The following list of relevant scenarios was measured:

- Constant speed at 30 km/h
- Full load acceleration from 30 km/h
- Full acceleration from stand
- Accelerated pass-by with low load

- Accelerated pass-by with mid load
- Accelerated pass-by with high load
- Coasting (engine turned off) from 50 – 0 km/h

These scenarios reflect all relevant conditions to extract the synthesis parameters.

3.2 DETECTION OF RELEVANT SOUND SOURCES

The next step to generate the appropriate synthesis models of the considered scooters is the detection of the acoustically relevant sources. It has to be evaluated which sources have a significant contribution to the pass-by noise in the far-field. For that, measurements with a Visor microphone array were realized (D3.1.1 Modified Head Visor microphone array). It gives 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 easily in the pictures shown in Figure 5. The colored spots show the radiation positions, where bright yellow corresponds to high sound pressure levels.

The top left picture shows the engine noise radiation of the E-Scooter 1. The selected frequency band is 800 Hz, which corresponds to the main order frequency of the electric engine during pass-by. The right top figure displays the noise source of the tire-road contact position in the frequency range of 1.5 to 2 kHz.

The lower pictures indicate the main sources of the C-Scooter 1. In the left picture the engine source is highlighted, in the right picture the exhaust can be identified as a dominant source. The examined frequency band for the engine source was 800 Hz and for the exhaust 100 Hz. The tire-road noise of the C-Scooter could not be identified with the acoustic camera. The signal to noise ratio and the local resolution of the array system cannot decompose the tire-road source. Compared to the E-Scooter engine noise the combustion noise of the C-Scooter has a significantly higher sound pressure level what result in masking of the tire-road noise.

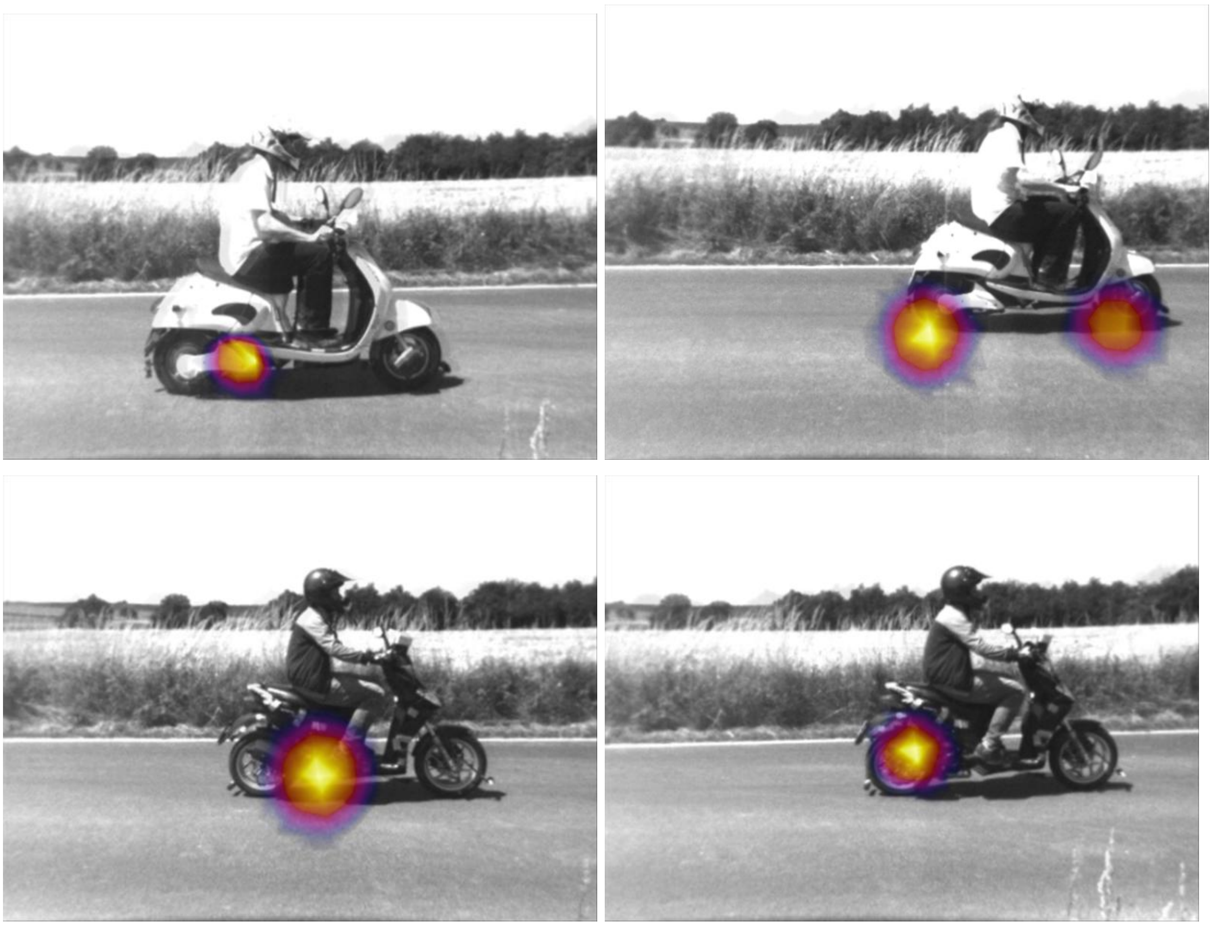


Figure 5 Visualization of sound radiation positions with the Visor microphone array. With the help of different property settings (dynamic range and frequency range) the different sources can be detected. Top: E-Scooter, bottom: C-Scooter

From this examination the following sources for the simulation have been derived.

1. Front and back wheel
2. electric / combustion engine
3. exhaust (only for C-Scooter)

3.3 Source signal synthesis

After the detection of the main sound sources of the scooters the measured near-field recordings of these sources were analyzed and the synthesis parameters were determined.

The evaluation of the source signals showed that the engine and exhaust noise must be synthesized with an order synthesizer and a noise synthesizer to create a realistic sound composition. For the synthesis of the tire/road noise a stochastic noise synthesizer is sufficient.

The following example is presented to explain the processing steps from the measurement to the synthesis. The basis for the analysis was a near-field recording of the C-Scooter 1 at the exhaust outlet. In the upper spectrogram of Figure 6 the dominant engine orders can be seen clearly. For comparison the engine sound of the E-Scooter 1 is shown in the lower spectrogram. Here the orders are much less dominant and the level is lower. As the engine speed changes over time during the recording the order analysis has to be made in dependence of the engine speed.

In Figure 7 the order sound pressure levels corresponding to the engine speed of 3600 RPM are plotted for C-Scooter 1. The outputs of the order analysis are the sound pressure levels of all orders at equidistant points with a fixed order step. In two post-processing steps the orders are validated. The first step clears the errors resulting from imprecise engine speed recordings. The second step filters the orders which are significantly higher than the stochastic background noise. The red lines in Figure 7 show the validated order sound pressure levels after the post-processing. It is very important that only the validated orders were synthesized, otherwise the general sound character of the vehicle would change.

In Figure 8 the spectrogram of the near-field source signal of C-Scooter 1 synthesized with the traffic noise synthesizer is shown. The base frequency of the order synthesizer was set equal to the base frequency of the measured signal. The levels of the orders of measurement and simulation are identical. The simulation signal lacks the stochastic noise components, though, which can be synthesized with an additional noise synthesizer.

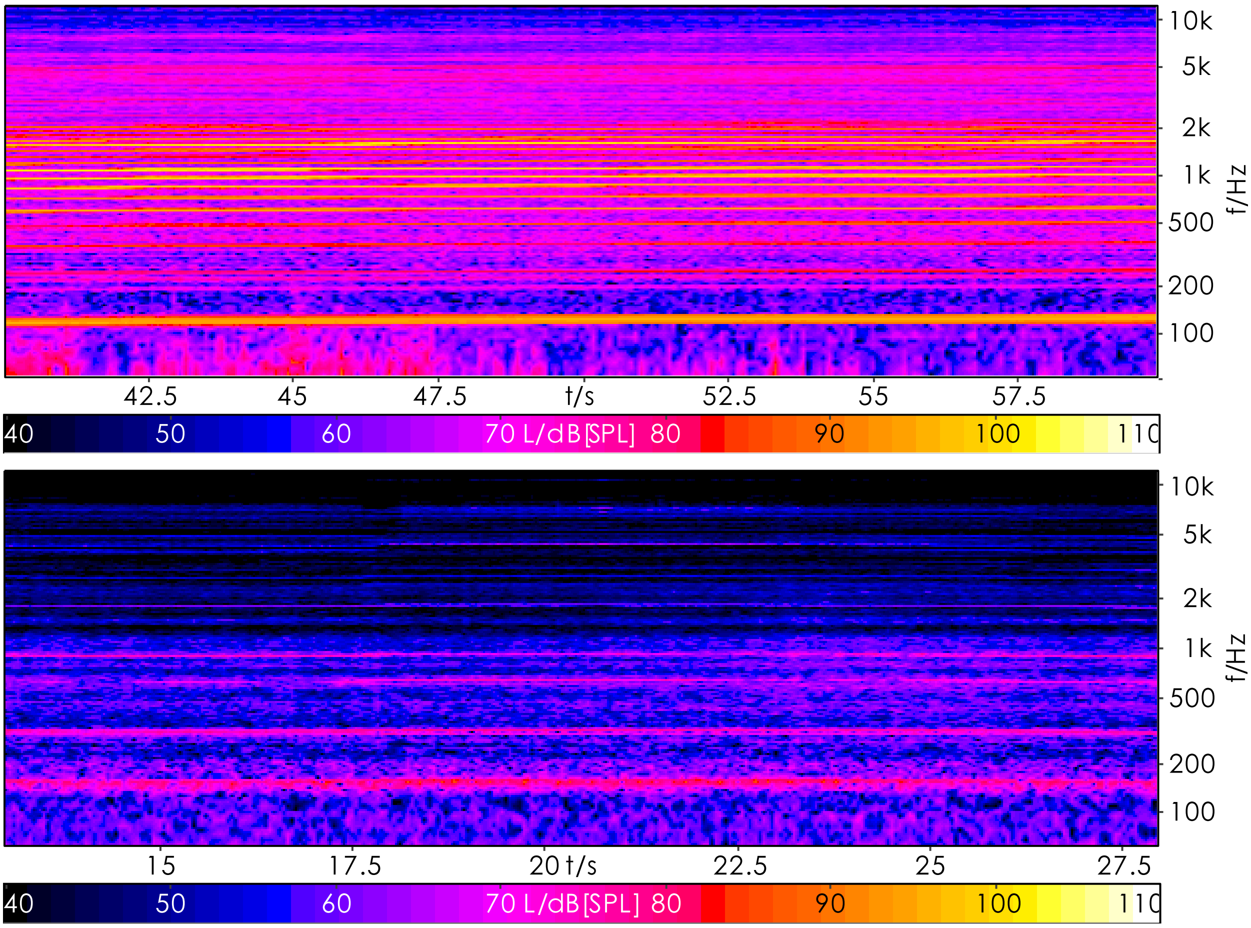


Figure 6 Spectrogram of a near-field recording of the exhaust sound of the C-Scooter 1 (upper) and the electric engine sound of E-Scooter 1 (lower).

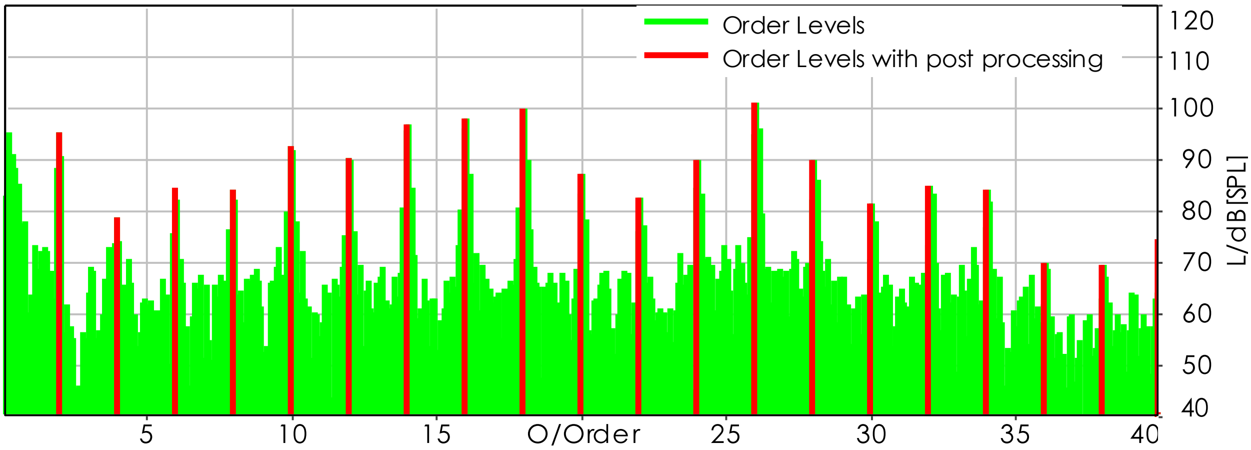


Figure 7 Order spectrum of the near-field recording of C-Scooter 1 at 3600 RPM. The green lines are the orders analyzed with an order step of 0.1. The red lines represent the post-processed order levels.

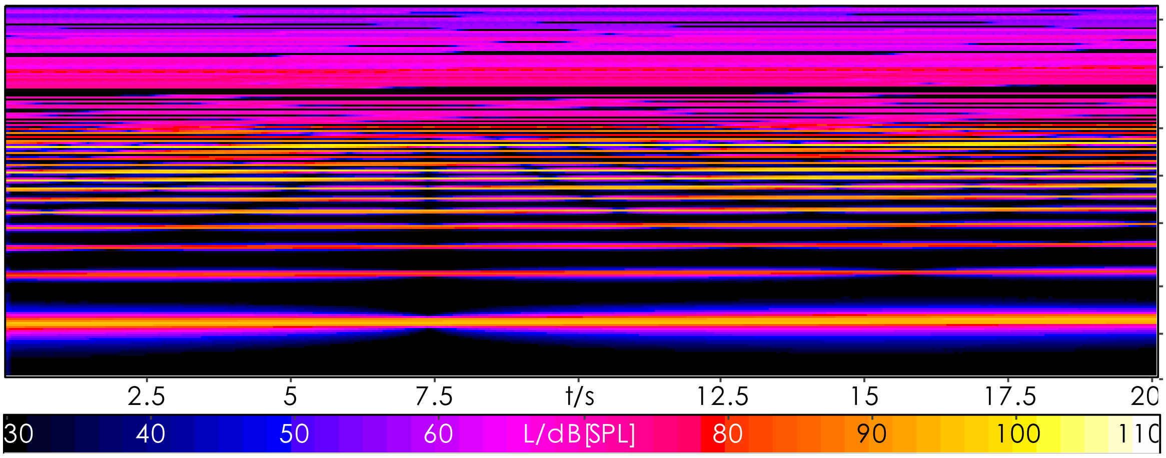


Figure 8 Order synthesis of the near-field source signal of C-Scooter 1. The base frequency of the order synthesis is identical to the base frequency of the measurement.

3.4 Driving condition model

The sound of the engine and exhaust source is dependent on the engine speed as well as the acceleration. The tire/road noise is only dependent on the velocity of the scooter. These relations have to be implemented in the vehicle model.

In Figure 9 the relation between the vehicle speed and the engine speed of the C-Scooter 1 is plotted. First, there is a non-linear relationship in the first part of the acceleration; then the relation is linear for the second part. The modeling of such relations is one example of the creation of a dynamic driving model. The quality of these configurations has direct impact on the auralization quality, because it affects the input parameters of the synthesis, in this case the frequency of the order synthesis.

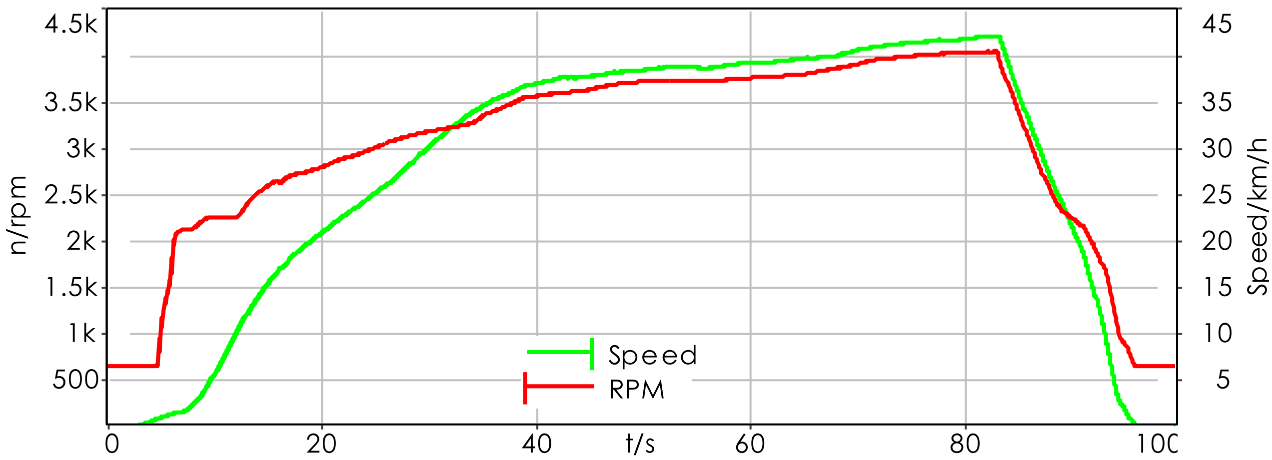
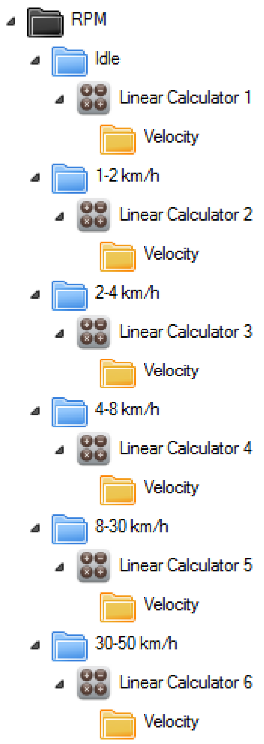


Figure 9 Relation between vehicle speed and engine speed of the C-Scooter 1 during accelerated drive.



In Figure 10 the model of the calculation of the engine speed from the velocity is shown. The orange "Velocity"-items represent the actual velocity of the scooter. The "Linear Calculator"-items calculate the engine speed assuming a linear relation. The blue items provide a case distinction between different velocity ranges. With this approach the relation in Figure 9 can be approximated.

Figure 10 Calculation of the engine speed in the TNS

In contrast to the complex relation between velocity and engine speed of the C-Scooter, for the E-Scooter this relation is almost linear for all driving conditions. Thus, the model for calculating the engine speed can be made very simple. The relation and the calculation model are shown in Figure 11.

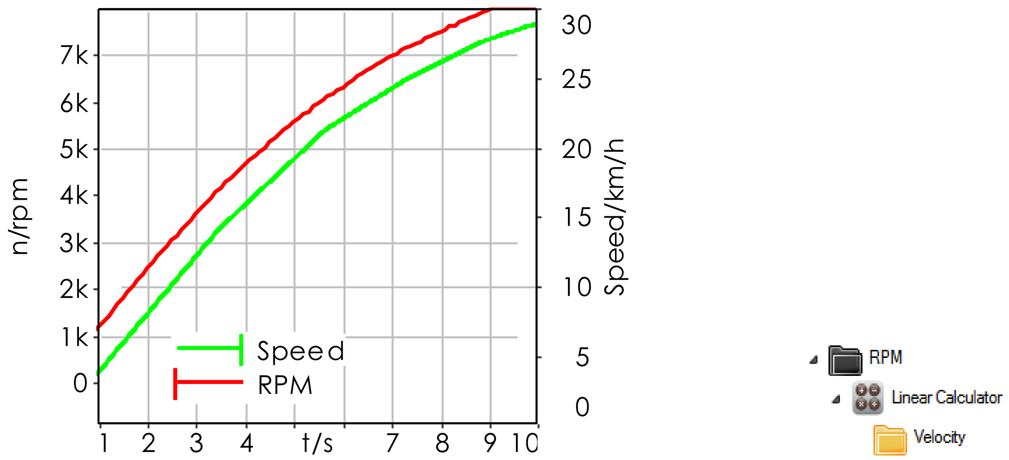


Figure 11 Relation between vehicle speed and engine speed of the E-Scooter 1 during accelerated drive (left). Calculation of the engine speed with a simple linear factor (right).

3.5 CALIBRATION

The last step of the model creation is the calibration of the sources. The radiation of source signals into the far-field is in general dependent on frequency and direction. The most important aspect of this calibration is to ensure that the far-field levels of the composed synthesized sound are valid and fit to the levels of the real vehicle.

To evaluate the directivity of the sound radiation HAC measured the transfer functions from the source to the far-field positions around the vehicle. The positions of the near-field microphones were defined as the source positions. The transfer functions were measured reciprocally (Sottek, Sellerbeck, Klemenz: An Artificial Head which Speaks from its Ears: Investigations on Reciprocal Transfer Path Analysis in Vehicles, Using a Binaural Sound Source, Proceedings of SAE '03, Traverse City, 2003).

Figure 12 shows a measurement set-up to determine the transfer functions. In the foreground the dodecahedron loud speaker system is shown. This device has an omni-directional radiation characteristic, which is important for the verification of the source directivities.

In Figure 13 the source related transfer functions (SRTF) for the exhaust of the C-Scooter 1 are plotted. The transfer functions are referenced to a distance of one meter from the source position. It can be seen that the radiation of the exhaust to the front is about 5 dB lower than to the back direction for lower frequencies. For higher frequencies this difference increases to up to 20 dB.

The source related transfer functions in Figure 14 refer to the front wheel. As the wheel diameter of the E-Scooter and the C-Scooter are nearly identical, the SRTFs of the different scooters are comparable. As the front wheel radiates mainly to the front direction, the opposite characteristic can be seen compared to the radiation of the exhaust.

Figure 12 Measurement set-up to determine the source related transfer functions (SRTF).

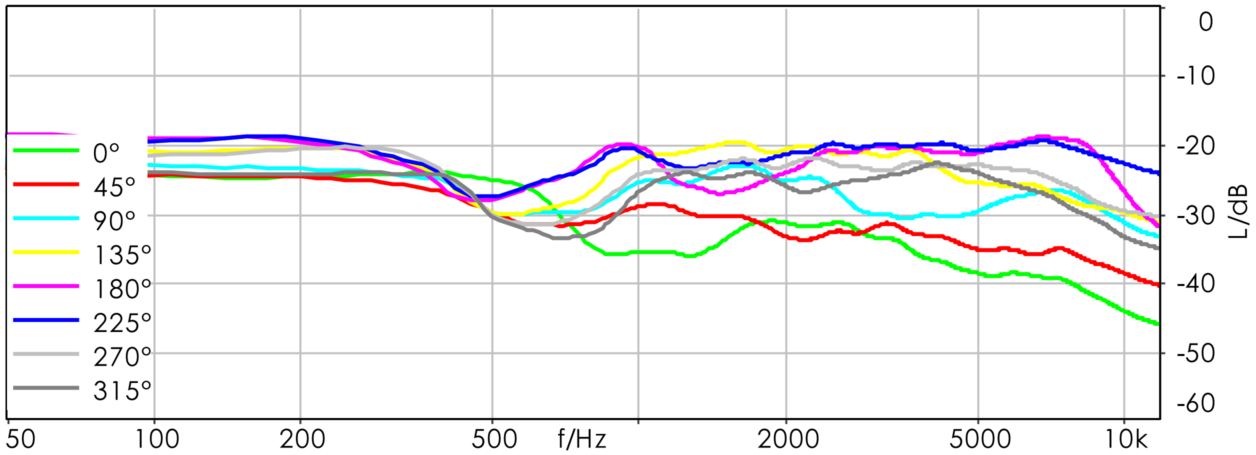


Figure 13 Source related transfer functions (SRTF) of the C-Scooter 1 exhaust radiation in 45° steps azimuth angle. Ascending angles correspond to directions starting to the front of the scooter and turning clockwise.

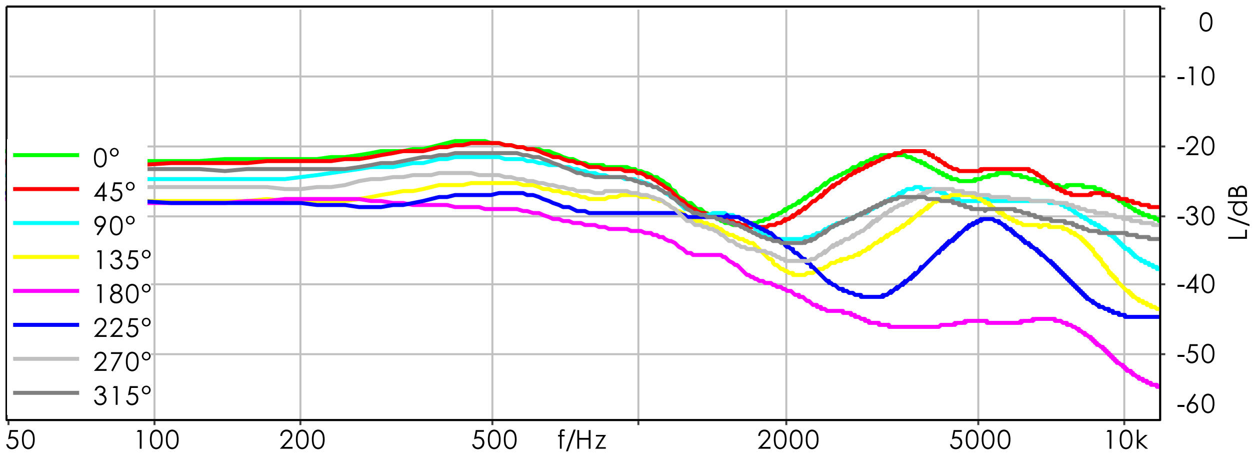
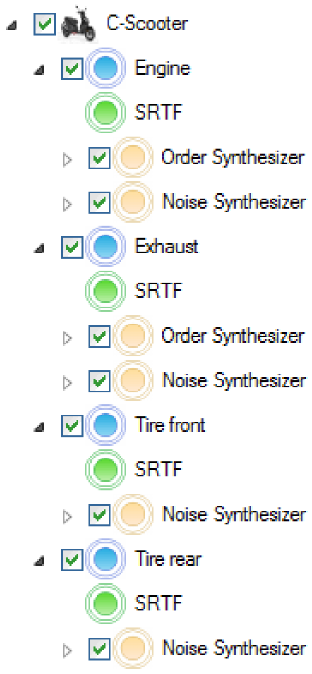


Figure 14 Source related transfer functions (SRTF) of the front wheel radiation in 45° steps azimuth angle. The SRTFs of the wheel sources are similar for the E-Scooter and the C-Scooter.



In Figure 15 the simulation model of the C-Scooter is shown. Each source (blue) consists of synthesizers (orange) and SRTF-filters (green). Each synthesizer has a sub tree structure configuring the usage of the synthesizer parameters.

Figure 15 Simulation model of the C-Scooter

3.6 CONCLUSIONS

The basis of a realistic traffic simulation is the creation of a valid vehicle model using reliable synthesis parameters. This was performed for scooters powered by combustion engines and by electric engines. The procedure was described shortly in this chapter with examples from the C-Scooter and the E-Scooter models.

4 NOISE REDUCTION POTENTIAL OF ELECTRIC POWERED TWO WHEELERS

The first step to evaluate the influence of the electrification of powered two wheelers on the noise annoyance is the comparison of pass-by sounds of different PTW. In this chapter the individual noise characteristics of different PTW are shown and the effect of electric scooters on the subjective perception in comparison to PTW with combustion engine is investigated. Two representative scooter models with electric engine and one with combustion engine have been selected. Additionally a representative motorbike was measured. The investigated vehicles are displayed in Figure 16.

ECO-Flash 2000 (E-Scooter 1)

E-Max 90S (E-Scooter 2)

Aprilia Sportcity One 50 (C-Scooter 1)

Figure 16 Suzuki GS500 (Motorbike)

Type	Alias	Engine	Power	Weight
ECO Flash 2000	E-Scooter 1	electric	2 kW	144 kg
E-Max 90S	E-Scooter 2	electric	2.75 kW	160 kg
Aprilia Sportcity one 50	C-Scooter 1	Combustion (50ccm)	3 kW	105 kg
Suzuki GS500	Motorbike	Combustion (500ccm)	33 kW	189 kg

The pictures and the table above show the considered scooters and the motorbike and their technical specifications. Within the first test series the pass-by noise of the PTW was measured at different positions. The measurements were carried out on a road in a very quiet countryside, so that there are only few disturbing environmental noises and the radiation can be expected as semi-free field condition.

In the following evaluations three pass-by scenarios were considered. In Figure 17 the measurement set-up is shown.

1. **Acc30**: The PTW approaches with a constant speed of 30 km/h from position P1. At P2 the PTW accelerates with full load to position P3.
2. **Const30**: The PTW passes by at a constant speed of 30 km/h.
3. **StartAcc**: The PTW stands at position P2. After a few seconds it accelerates to position P3 with full load.

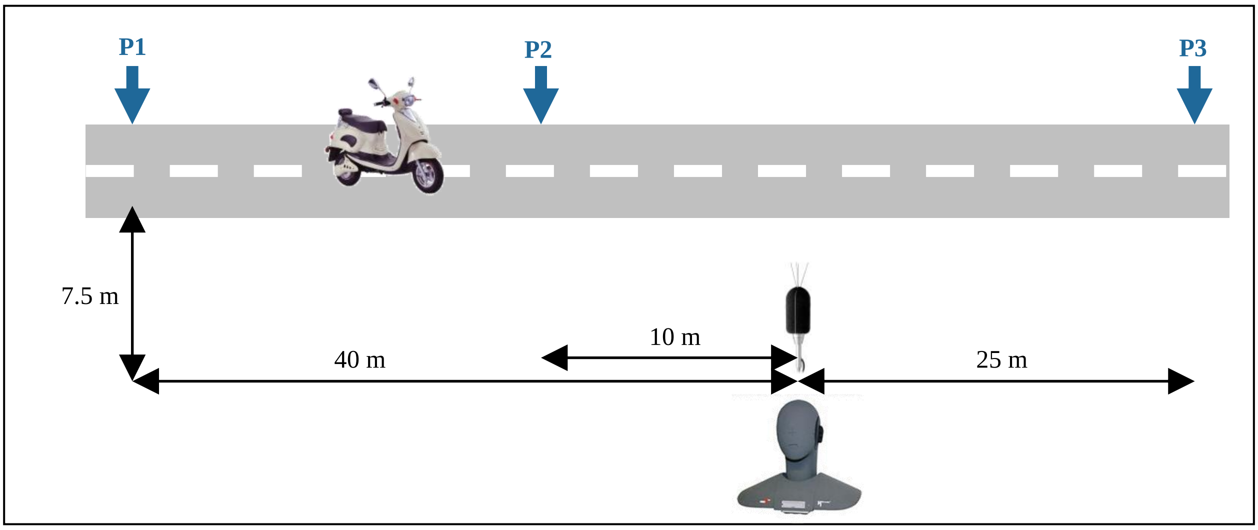


Figure 17 Set-up of PTW pass-by measurements.

The three scenarios have been evaluated by means of objective acoustical analyses.

To introduce the analyzed signals the respective spectrograms are shown in Figure 18 through Figure 21, the spectrograms are displayed. The parameters to calculate the spectrograms were:

- A-weighted sound pressure levels
- FFT-length = 8192
- Overlap 50 % with Hann window

In the frequency band between 100 Hz and 2000 Hz the spectrograms in Figure 18 and Figure 19 show the orders of the electric engines, which are radiated from the transmission system and the electric engine itself.

The orders of the C-Scooter and the motorbike are much more distinct and have significantly higher sound pressure levels, which can be seen in Figure 20 and Figure 21. It is also remarkable that compared to constant drive situations the order levels increase significantly in acceleration conditions. This clear difference between acceleration conditions and constant drive situations is not observable in the E-Scooter pass-by noise measurements. For the E-Scooters there is no significant change of the noise and the prominent orders in dependence of the engine load.

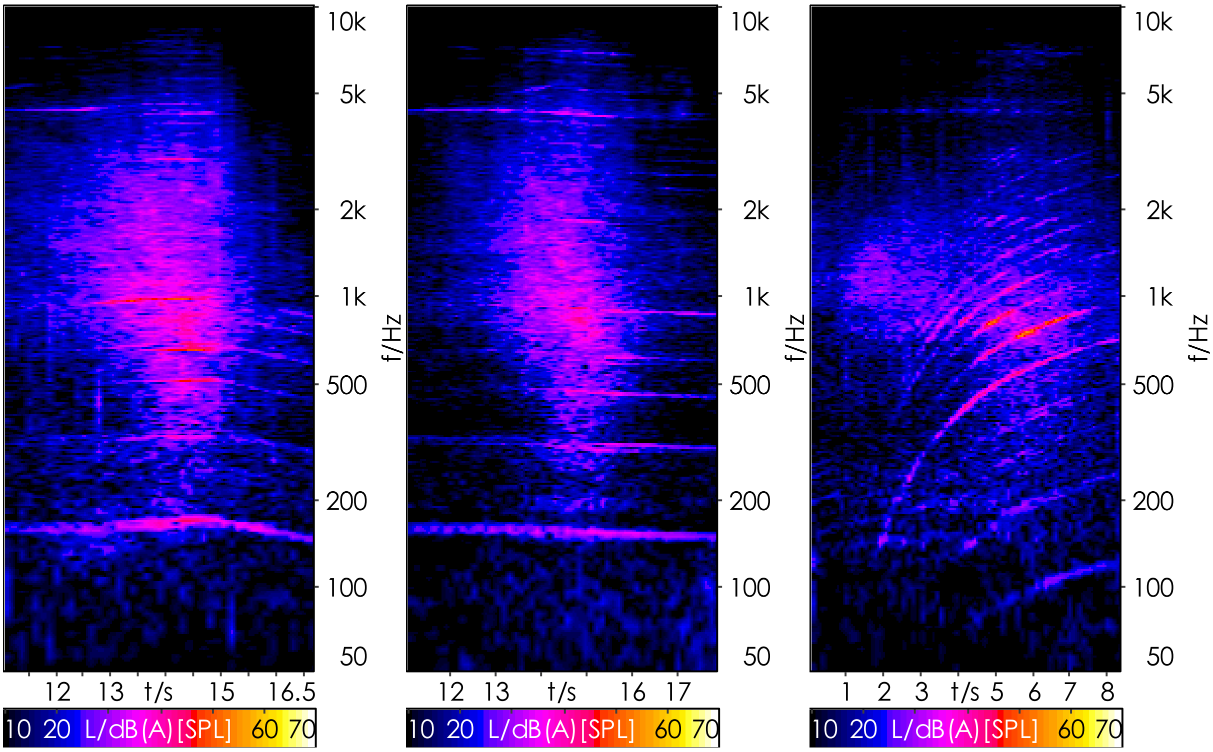


Figure 18 Spectrograms of the three pass-by scenarios of the E-Scooter 1.
From left to right: Acc30, Const30, StartAcc

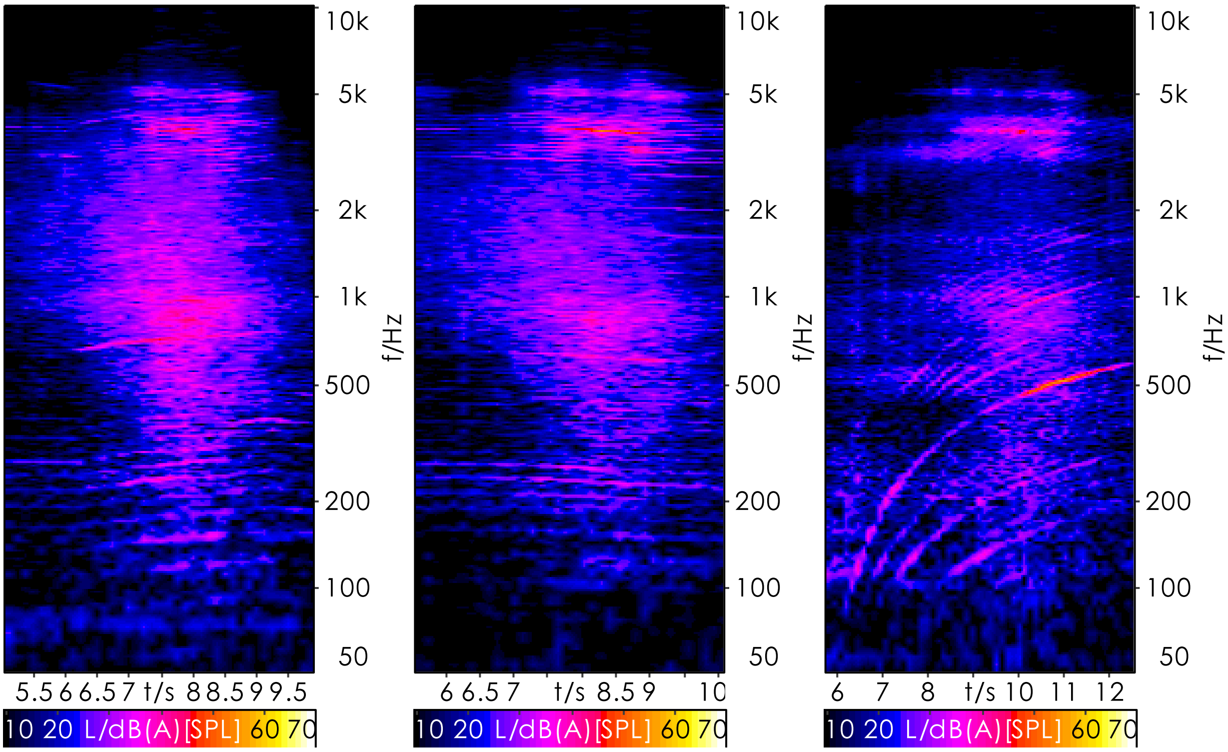


Figure 19 Spectrograms of the three pass-by scenarios of the E-Scooter 2.
From left to right: Acc30, Const30, StartAcc

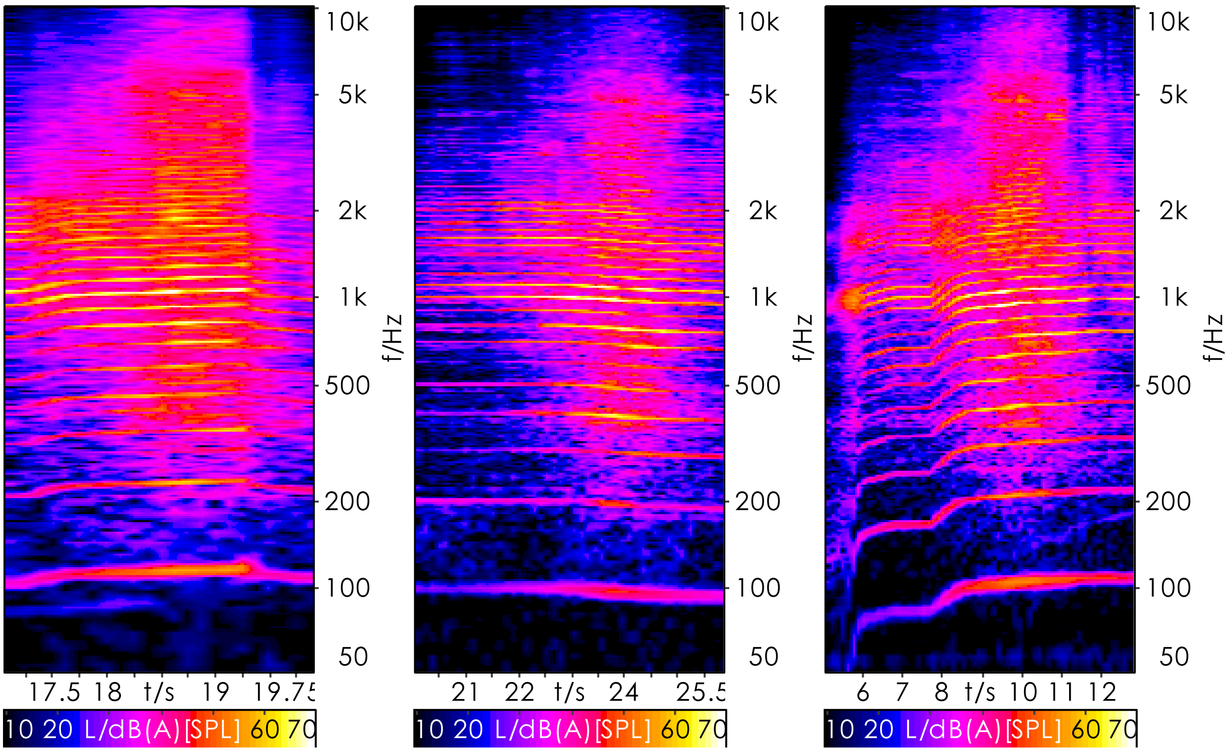


Figure 20 Spectrograms of the three pass-by scenarios of the C-Scooter 1.
From left to right: Acc30, Const30, StartAcc

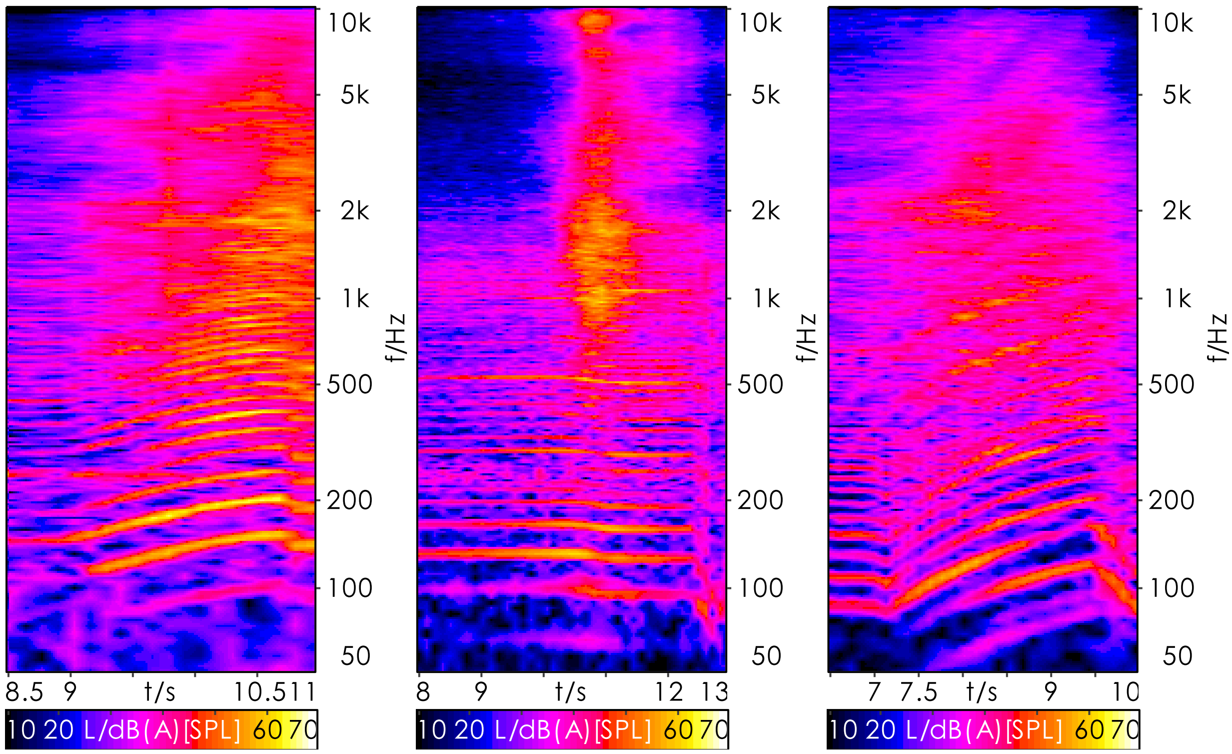


Figure 21 Spectrograms of the three pass-by scenarios of the motorbike.
From left to right: Acc30, Const30, StartAcc

An additional noise source with respect to electric vehicles is the converter. The converter provides the electric voltage for the engine. The frequency of this ac voltage is linked to the engine speed and this frequency determines the frequency offset of the converter orders. The offset is related to the carrier frequency of the converter which is constant. In Figure 22 the orders of the converter of the E-Scooter 1 recorded in the near-field can be seen. The carrier frequency is 15.5 kHz. With increasing engine speed the order frequency offset increases and in the plot a fan like structure can be seen. This is typical for converter sounds.

In Figure 23 a spectrogram plot of the converter noise in the far-field is shown. The noise refers to the E-Scooter 2 and it is clearly observable that the carrier frequency is slightly different (14 kHz). The maximum sound pressure level in 7.5 m distance is about 30 dB(A).

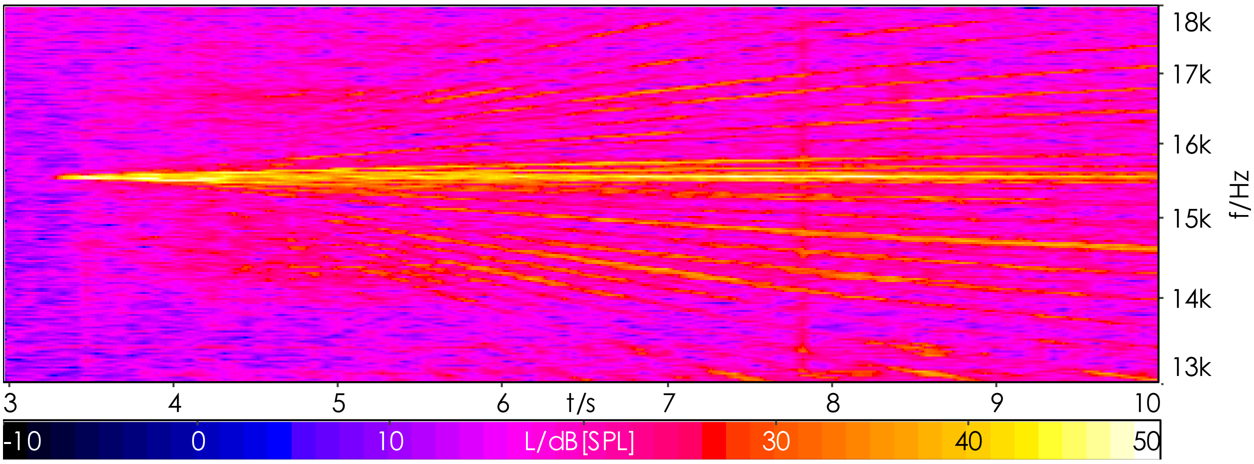


Figure 22 Converter noise in the near-field during accelerated drive of E-Scooter 1.

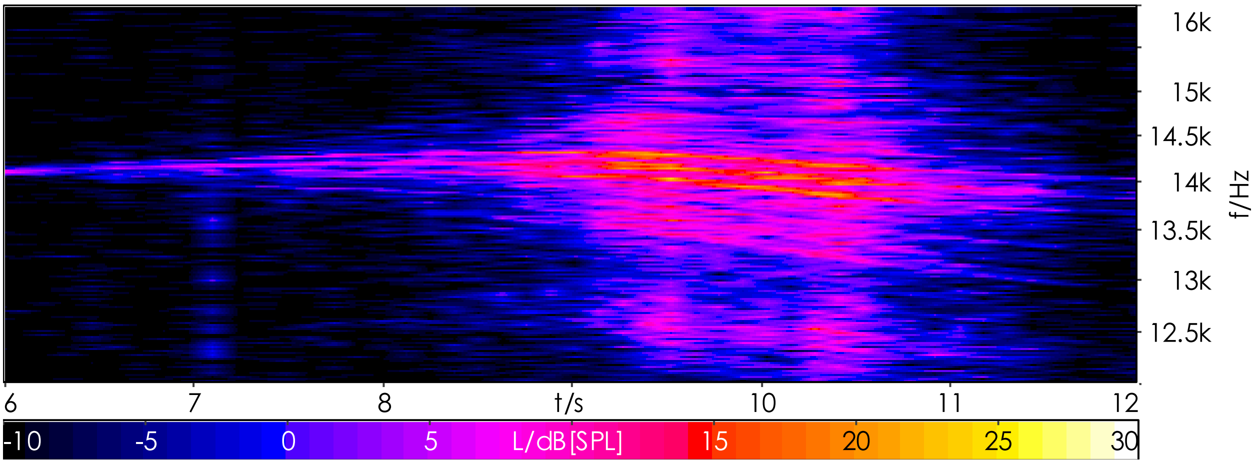


Figure 23 Converter noise in the far-field (7.5m) during accelerated pass-by (StartAcc) of E-Scooter 2.

4.1 EVALUATION OF OBJECTIVE ANALYSIS PARAMETERS

To get a detailed overview of the acoustical properties of the scooter sounds five different analyses have been applied to the measurements. In addition to the standard sound pressure level the signals are described by psycho-acoustic parameters. On the basis of the well-established psycho-acoustic parameters the subjective perception of the sounds can be described in an objective manner. Moreover, it allows for predicting the annoyance impression of the sounds.

The following bar plots show the psycho-acoustic properties of the considered scooters over different driving situations. Additionally, the determined values have been normalized and plotted in a second figure. For the normalization, the analysis values of the C-Scooter are always defined as 100 % and the values of the E-Scooters are given relative to these values. This emphasizes the differences of the scooters on the one hand and gives a good comparison between the different analyses on the other hand. All analysis values are maximum values during pass-by situations.

Sound pressure levels

The A-weighted sound pressure level is frequently used and is the most common parameter for the assessment of environmental noise. In Figure 24 the comparison of the sound pressure levels is shown. The parameters of the sound pressure level calculation have been as follows:

- A-weighted sound pressure levels
- Peak values during recording (L_{Amax})
- Fast averaging (125 ms)

As expected, in all scenarios the noise emission can be reduced significantly if the combustion engine is replaced by an electric engine. The sound pressure level can be reduced by 18 to 20 dB almost independent of the considered driving condition. The motorbike levels are between 5 – 8 dB lower than the C-Scooter levels.

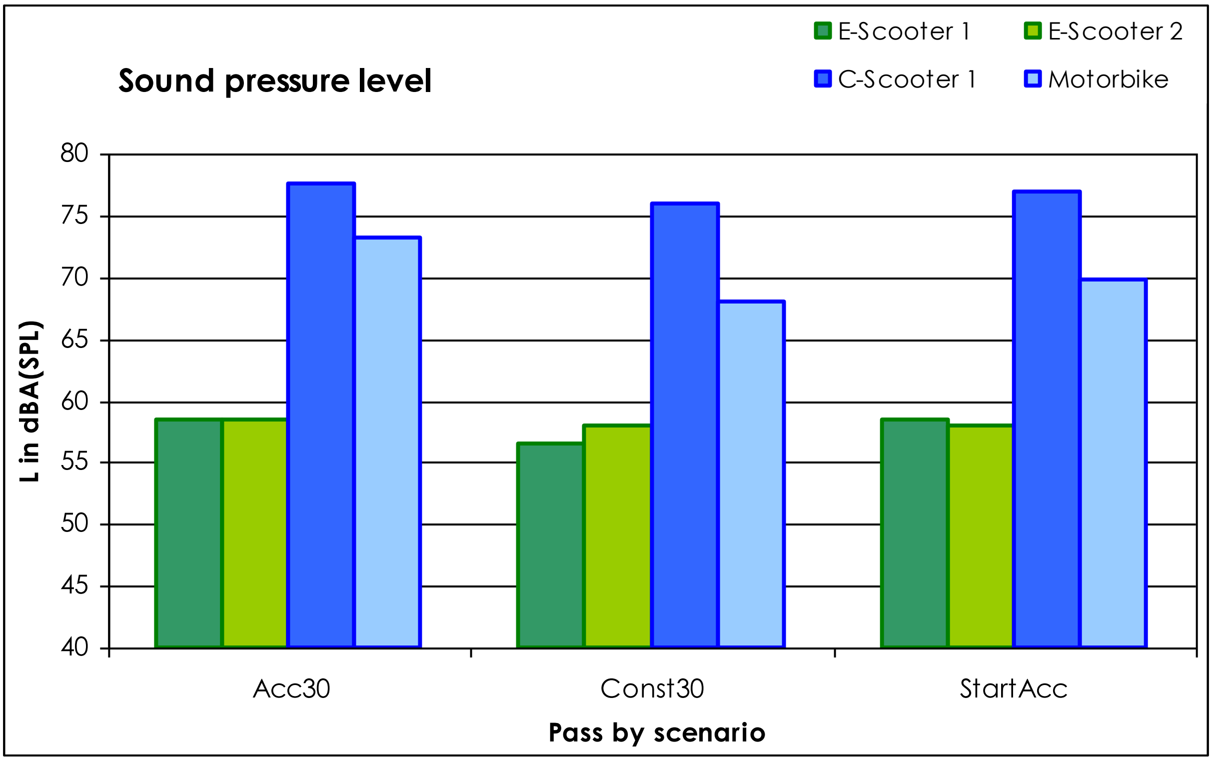


Figure 24 Comparison of the sound pressure levels (L_{Amax}) of the different scooters at three pass-by scenarios.

Loudness

The parameter loudness represents the perceived loudness of a sound and has been introduced as a more hearing-related parameter than the A-weighted sound pressure level and provides meaningful information with respect to the annoyance potential of the environmental noise beyond conclusions only based on the sound pressure level, since spectral and temporal aspects, masking effects, etc. are considered. The calculation method for the time-variant loudness is described in the ISO 532 and the German standard DIN 45631/A1.

There exists a wide range of publications that prove that the loudness is one of the most important parameters regarding noise annoyance (see Fastl H, Zwicker E (2007) Psychoacoustics. Facts and Models. 3. Auflage, Springer Verlag, Berlin, Heidelberg, New York).

As shown in Figure 25 and Figure 26, lower sound pressure levels correspond to lower values in loudness. The loudness of E-Scooters' engine noise is 20 to 30 sone lower than that of the C-Scooters which make a relative difference of 65 – 75 %. This means that the combustion scooter is perceived as four times louder than an electric scooter. This will most probably lead to a reduction of noise annoyance. Compared to the C-Scooter the loudness of the motorbike is only 4 – 7 sone lower, i.e., there is still a significant difference to the E-Scooters. The expected reduction of annoyance will be discussed in the next chapter.

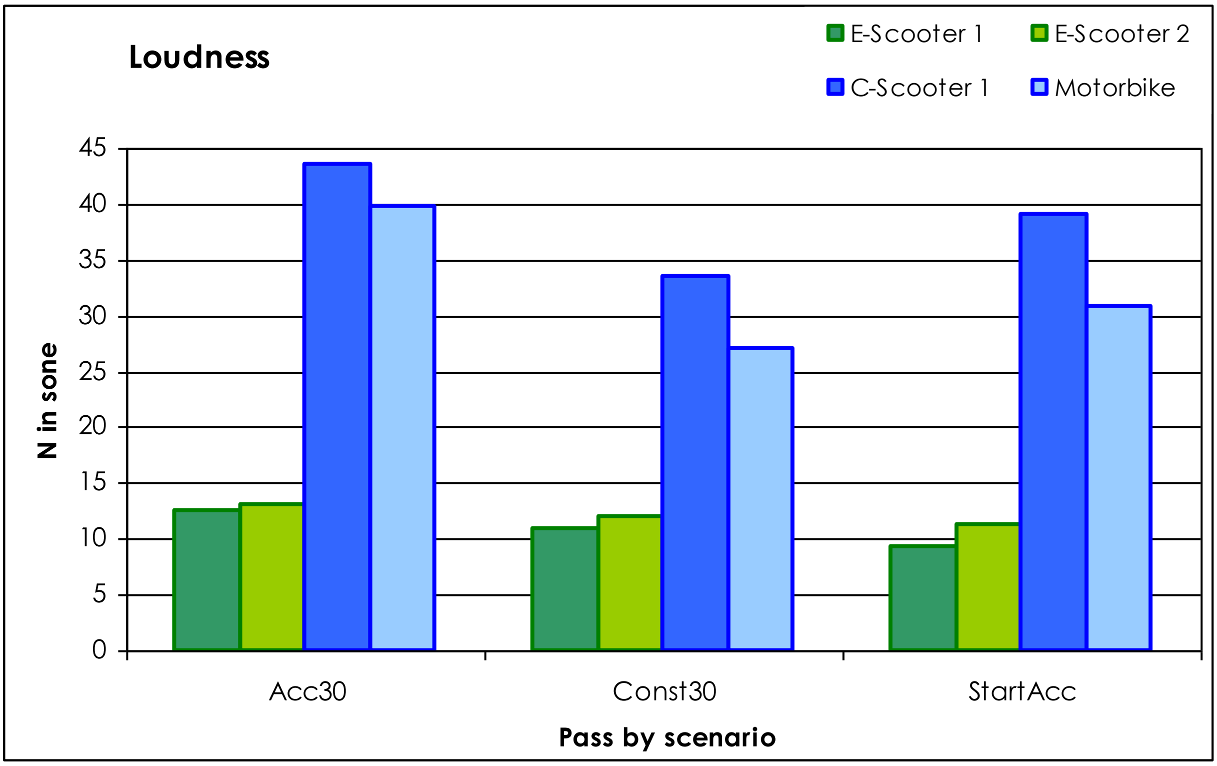


Figure 25 Comparison of the loudness (N_{max}) of the different PTWs at three pass-by scenarios.

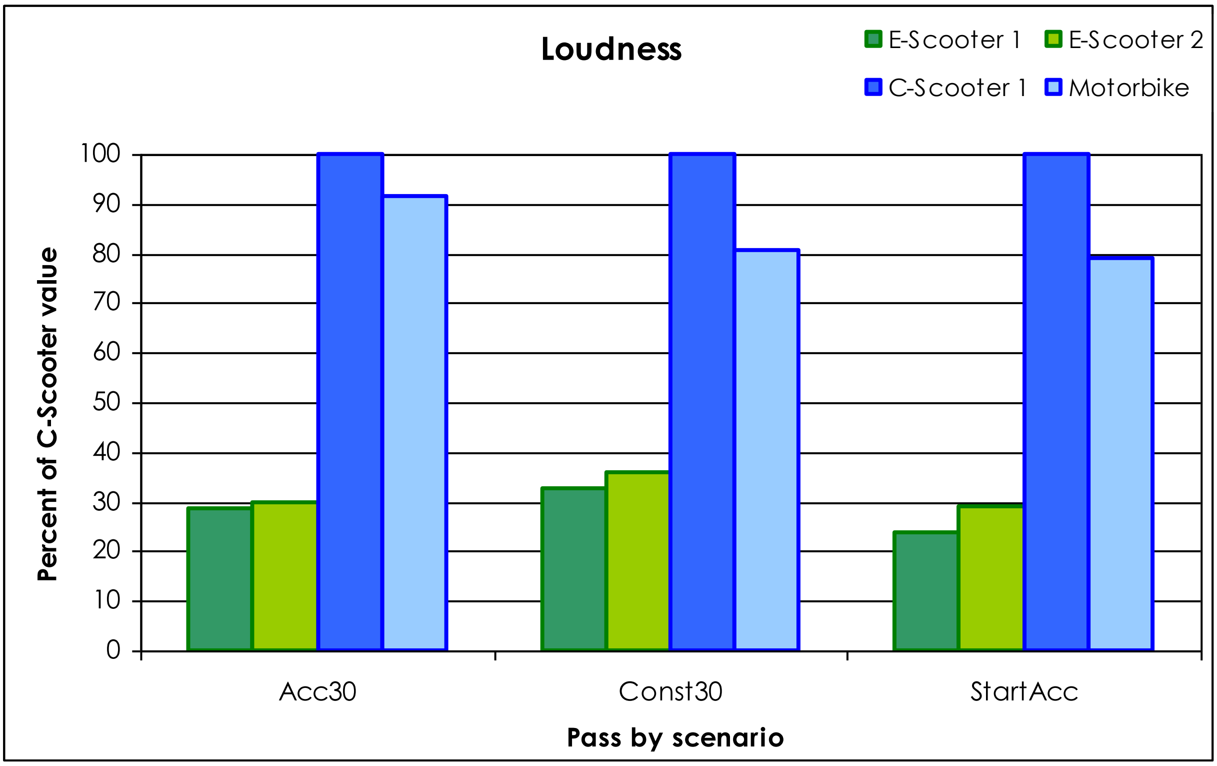


Figure 26 Normalized comparison of the loudness (N_{max}) of the different PTWs at three pass-by scenarios.

Sharpness

The psycho-acoustic parameter sharpness is a measure to determine the impression related to the high frequency content in a signal. Sharpness considers the spectral shape of a noise; it reflects the amount (loudness) of high frequency components of a noise to the total loudness.

The calculation method of the sharpness analysis was performed as described in the German standard DIN 45692 based on the specific loudness calculation using DIN45631/A1 and the frequency weighting proposed by Aures.

In contrast to the other analyses considered above the sharpness varies considerably between the different scenarios (see Figure 27 and Figure 28). While the *Const30* scenario shows differences of about 10 %, the other scenarios have sharpness differences of more than 30 %. This can be explained by the fact that the sharpness analysis is mainly related to the tire noise, which is more dominant in the constant speed scenario than in the others. This tendency is even more obvious in the sharpness values of the motorbike. As the bigger tires of the motorbike produce higher noise levels the dominance of this noise source is increased.

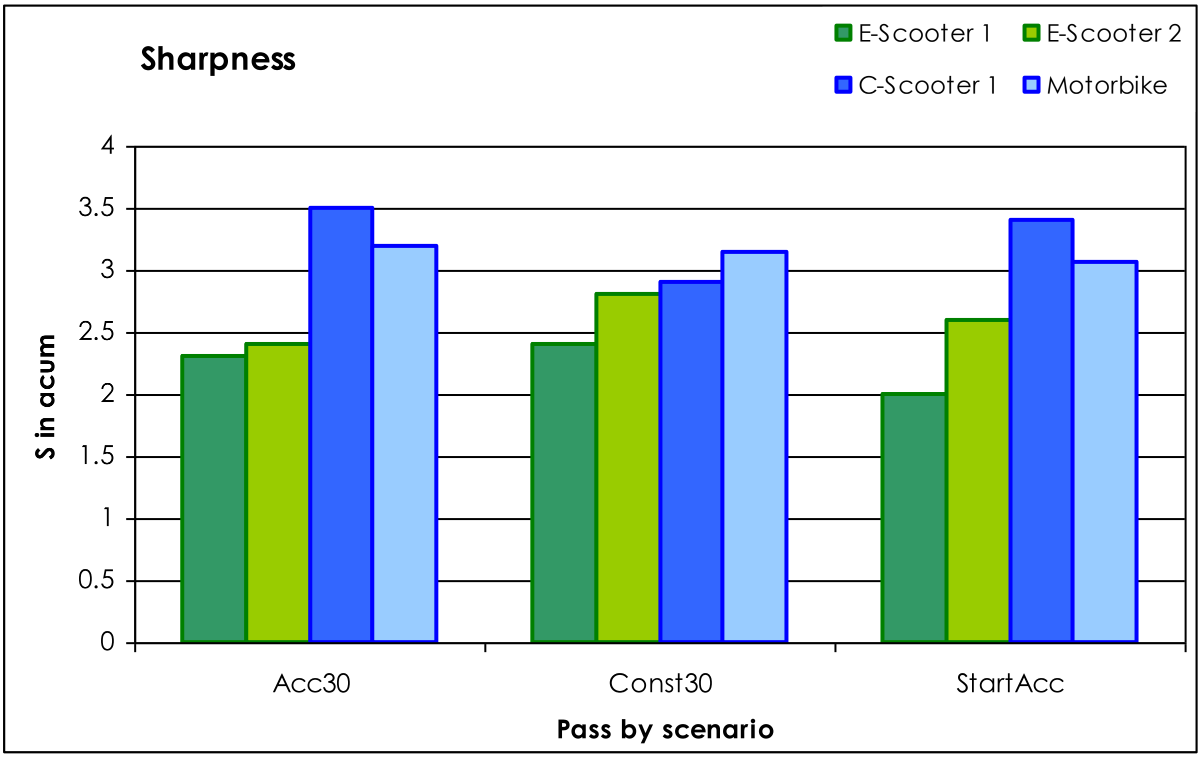


Figure 27 Comparison of the sharpness of the different PTWs at three pass-by scenarios.

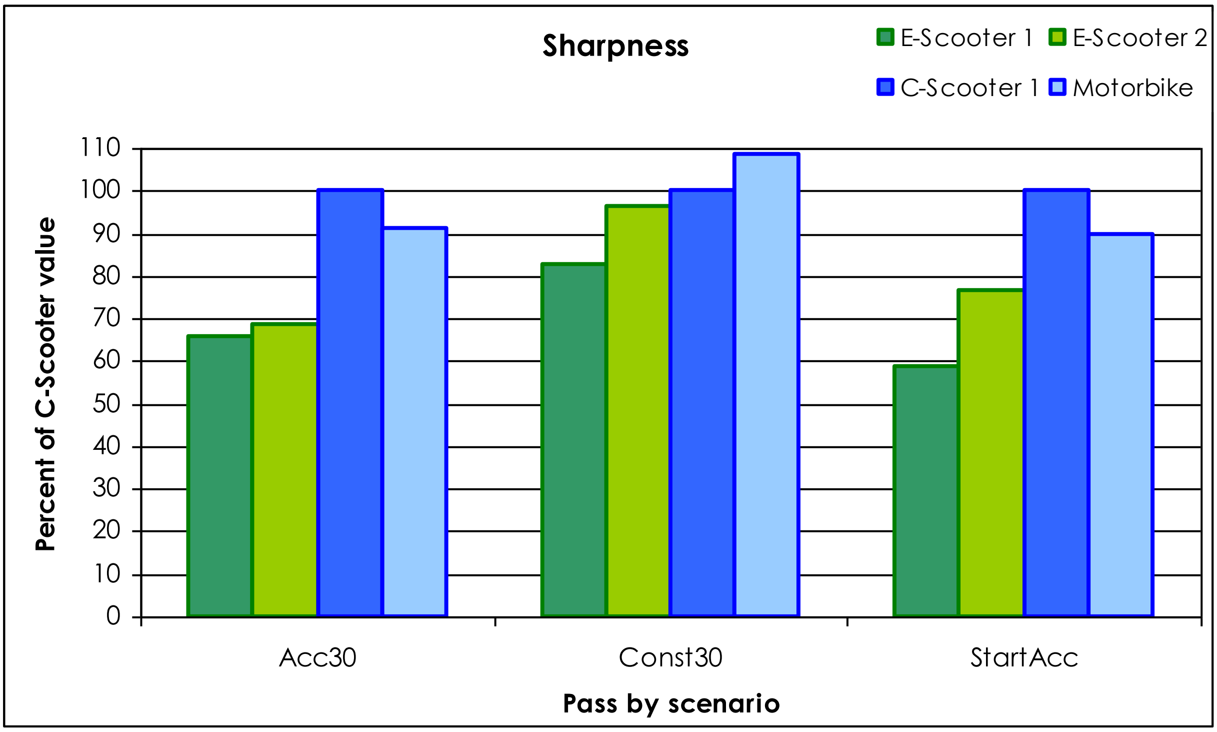


Figure 28 Normalized comparison of the sharpness of the different PTWs at three pass-by scenarios.

Roughness

Up to now, the calculation of roughness has not been standardized. The best correlation between subjective perception and objective calculation gives the hearing model roughness calculation method (see R. Sottek, K. Genuit: Models of signal processing in human hearing, Elsevier, International Journal AEÜ of Electronics and Communications, Int. J. Electron. Commu. (AEÜ) 59, 2005). The hearing model allows for analyses, where time and frequency resolution corresponds to that of human hearing. The hearing model is based on a filter bank consisting of a large number of overlapping band pass filters. Additionally, the model takes the influences of the human hearing physiology and neurologic processing into account. The unit of the roughness is asper. One asper is defined as the roughness of a 1 kHz sine tone with a level of 60 dB, amplitude-modulated at a rate of 70 Hz with a modulation index of 1.

The Figure 29 and Figure 30 display the differences in roughness of the scooter measurements. It is found that the roughness values of the C-Scooter are very high. Only very few natural or technical sounds have a value of about 1 asper. Compared to the values of the E-Scooters the roughness of the C-Scooter is even more evident. The difference in roughness is about 0.7 to 0.9 asper, corresponding to 90 % to 95 %. Unlike the other parameters, for the motorbike the values of the roughness are more similar to the values of the E-Scooters than to the values of the C-Scooter. This is due to the very rough noise of the C-Scooter engine and is probably one reason for the high perceived annoyance of the C-Scooters.

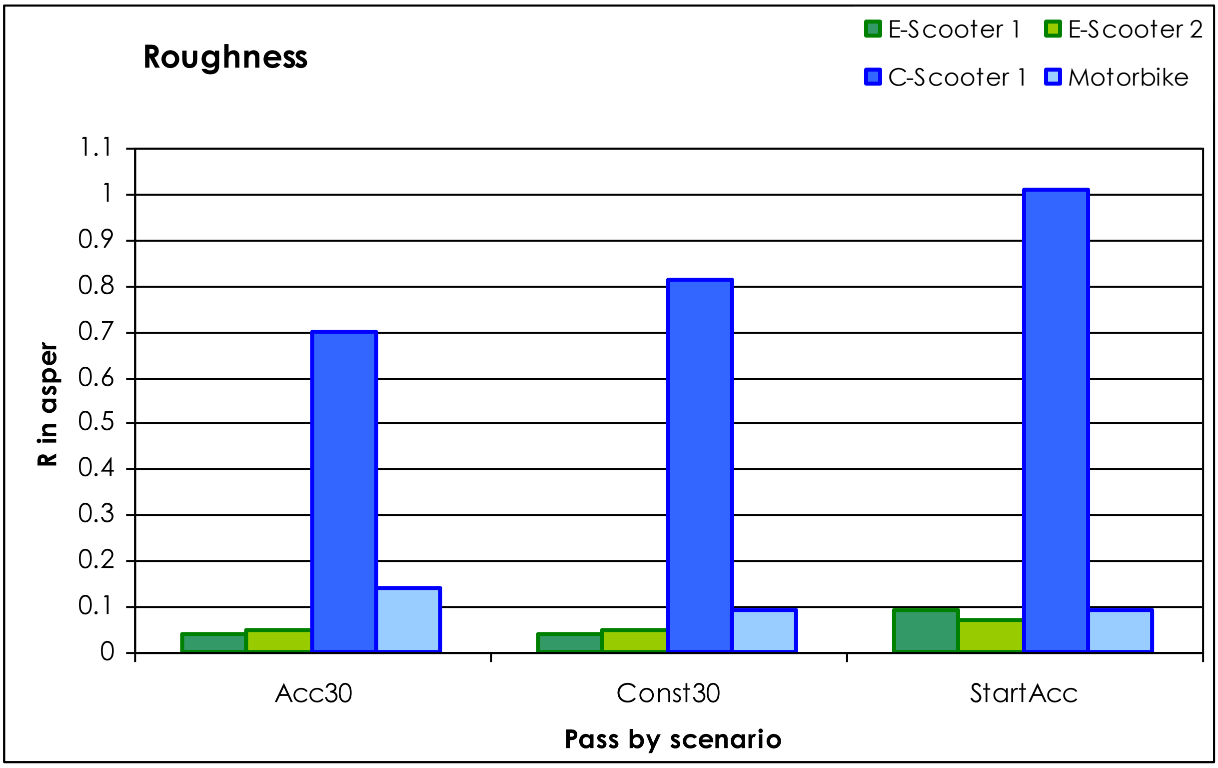


Figure 29 Comparison of the roughness of the different PTWs at three pass-by scenarios.

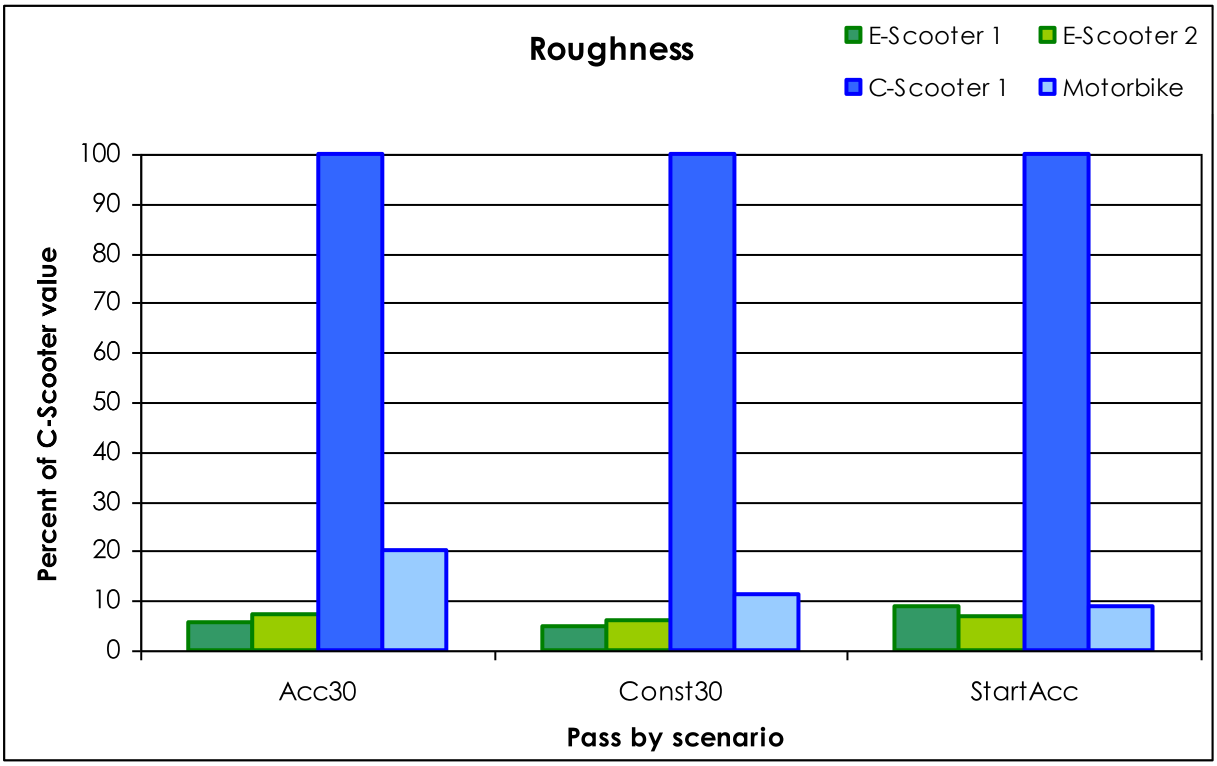


Figure 30 Normalized comparison of the roughness of the different PTWs at three pass-by scenarios.

Relative Approach

The Relative Approach method is an analysis developed to model a major characteristic of human signal processing. Humans have a stronger subjective response to patterns than to slowly-changing levels and loudness. It is assumed that human hearing creates for its automatic recognition process a running reference sound against which it classifies tonal or temporal pattern information moment-by-moment. The difference between instantaneous patterns in both time and frequency domain is evaluated (K. Genuit: Objective evaluation of acoustic quality based on a relative approach. InterNoise 1996, Liverpool, UK; W. Bray, Using the "Relative Approach" for direct measurement of patterns in noise situations, Sound and Vibration, Sept. 2004). Temporal structures and spectral patterns are important factors in deciding whether a sound makes an annoying or disturbing impression (see R. Sottek: Advanced Methods and Tools for Sound Quality Evaluation, SQS 2008, USA). The Relative Approach can be applied to different basis analyses in the time-frequency domain. The parameters of the Relative Approach calculation used for the scooter comparison have been as follows:

- Basis analysis: 6^{th} octave filter bank
- B – weighted sound pressure levels
- FFT-length = 16384
- Overlap 50%
- Regression variation analyses for frequency pattern

The Figure 31 and Figure 32 display the Relative Approach values of the PTWs. The C-Scooter values are between 16 and 20 cPa higher than the values of the E-Scooters. The higher values of the C-Scooter can be explained by the dominant orders and the clear peaks and dips in the spectrum resulting from them. In the normalized figures the difference corresponds to 60 - 70 %. As the spectrum of the motorbike also exhibits multiple dominant orders the Relative Approach values are similar to the C-Scooter values, whereby a slight drop of up to 7 cPa can be seen.

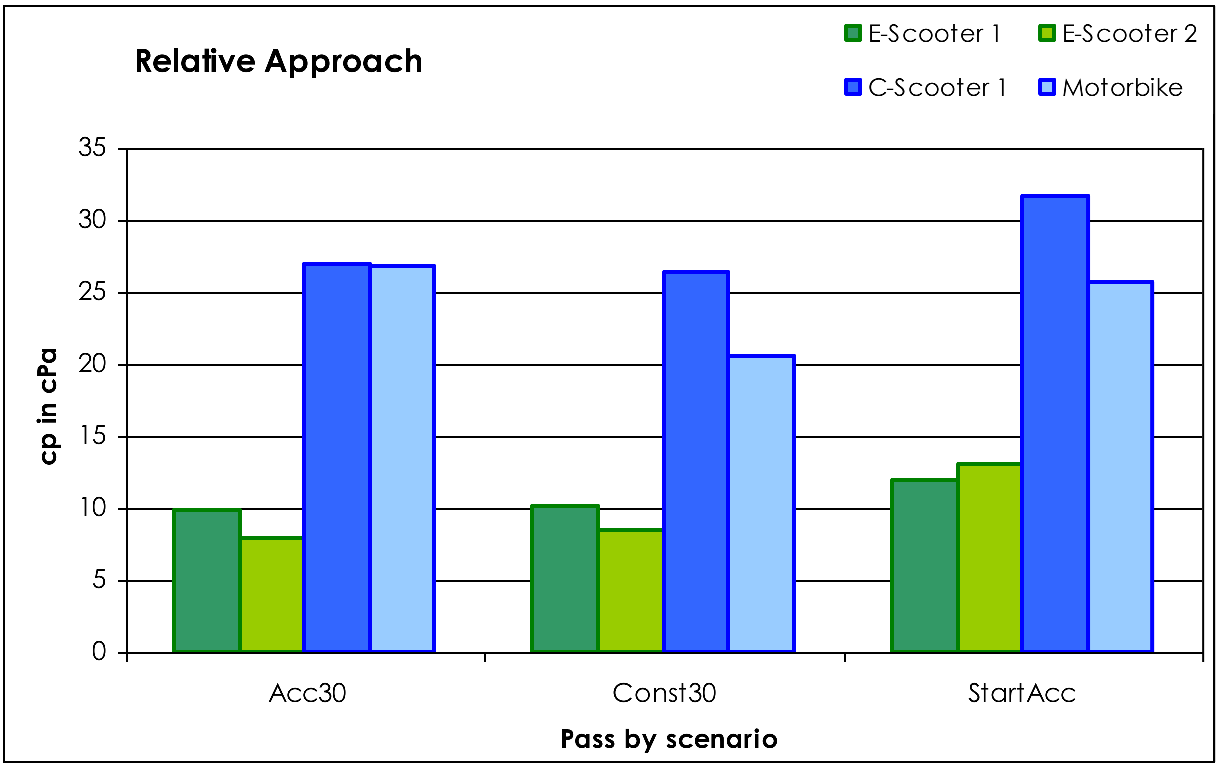


Figure 31 Comparison of the Relative Approach values of the different PTWs at three pass-by scenarios.

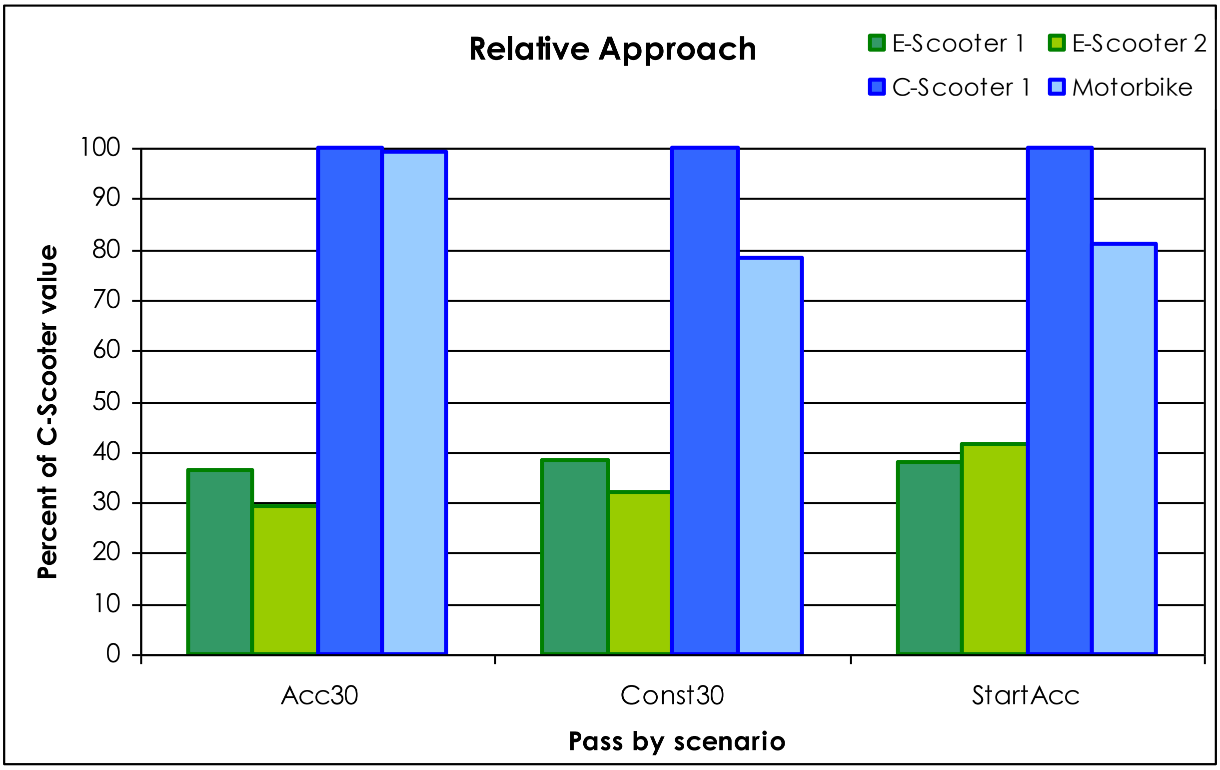


Figure 32 Normalized comparison of the Relative Approach values of the different PTWs at three pass-by scenarios.

Within the European research project QCity a study was carried out develop an evaluation index (EI). This index allows predicting the subjective noise annoyance on the basis of objective psychoacoustic measures (see: EU research project QCity, D2.8 Perception of Vehicle Noise Sources). The calculation of the index is based on the combination and weighting of different objective measures.

The different analyses for the index calculation are:

- Relative Approach (frequency pattern)
- Loudness
- Hearing model Impulsiveness
- Hearing model Roughness
- Sharpness

This evaluation was applied to the different PTW pass-by scenarios. In Figure 33 the values of the evaluation index are shown. The index represents the annoyance on a scale between 1 and 10. A value of 1 corresponds to a very annoying noise and a value of 10 to a sound, which is not annoying at all.

The difference between the E-Scooter and the C-Scooter in the pass-by situations is very big. The clear differences (6 – 8 categories) can be explained by the superposition of the different analysis parameters. The calculation of the evaluation index is nonlinear. For extremely low values the values are coerced to one. For all C-Scooter scenarios this lower bound comes into effect. The values of the motorbike are in between the values of the E-Scooters and the C-Scooter (4 – 6 categories).

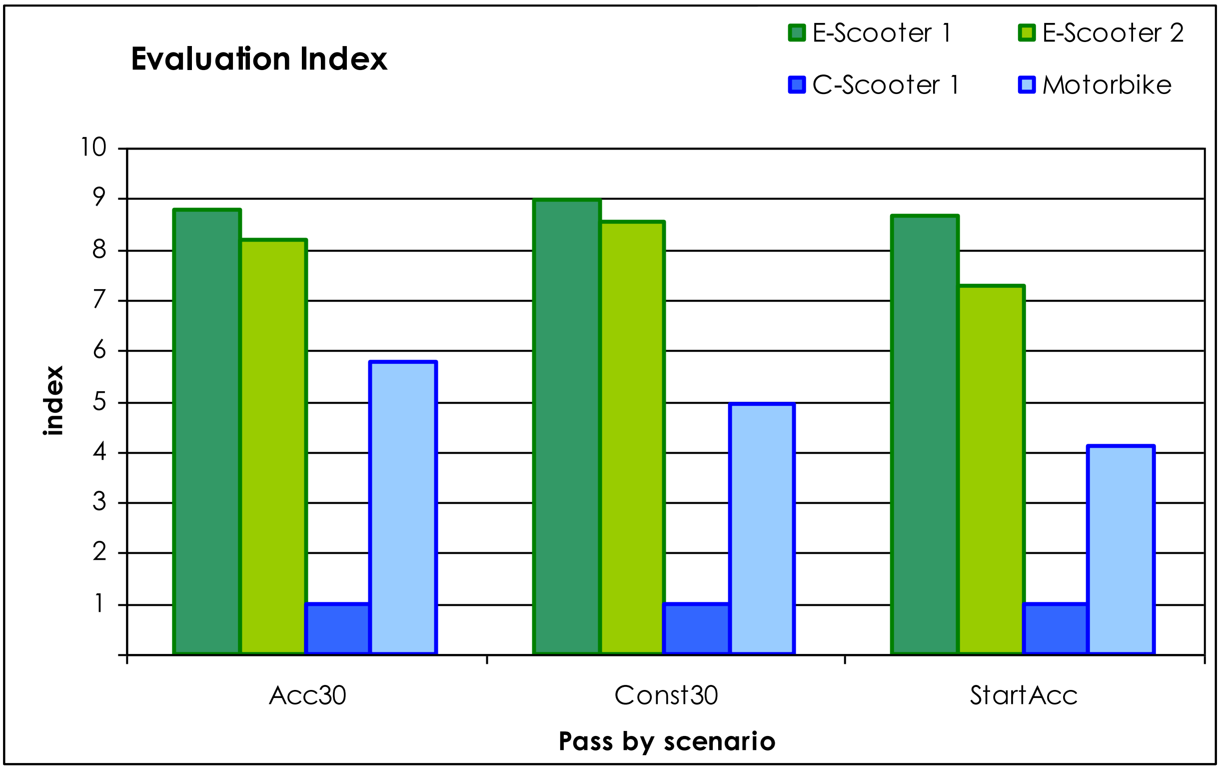


Figure 33 Comparison of the evaluation index of the different scooters at three pass-by scenarios.

The evaluation of the pass-by scenarios clearly indicates the great improvement potential of exchanging combustion engine driven scooters for electric powered scooters. This improvement is indicated by different objective analyses. Moreover, the psychoacoustic analyses do not show significant differences in the improvements between the different scenarios. This leads to the conclusion that within real traffic scenarios, where different driving conditions occur simultaneously, the found improvements related to objective parameters (such as loudness decrease) can also be expected.

4.2 SUBJECTIVE EVALUATION

In the preceding chapter, the PTW sounds have been evaluated by means of objective psychoacoustic analysis parameters. However, the subjective annoyance potential of the single pass-by events of different scooters cannot be reliably determined from these parameters without listening tests for validation. For the evaluation and validation of the predicted annoyance HAC carried out listening tests.

The objective analysis of the powered two wheelers point out that the motorbike noise can be seen as less critical concerning the annoyance rating compared to the C-Scooter noise. The objective parameters like sound pressure level, loudness, roughness and Relative Approach support this statement as described in the last section. Thus, the

C-Scooter can be seen as the worst case of PTW noise. Therefore, the investigations with the help of listening tests have been made on the base of scooter sounds only.

The listening tests were performed in the laboratory shown in Figure 34. The playback system is fully calibrated, so that an exact level reproduction of the measured signals is guaranteed. For an accurate binaural representation of the signals the participants of the listening test wear headphones. The ratings are entered via a touch screen terminal.

Figure 34 Listening room for the execution of listening tests

The selected scenarios are the constant drive (*Const30*), the accelerated drive (*Acc30*) and the accelerated start from a standing position scenario (*StartAcc*). The pass-by noise of different scooters is judged.

In addition, some modified signals were presented:

- The scenario *Const30* of the C-Scooter 1 with a reduced level so that the maximum A-weighted sound pressure level was identical to that of the E-Scooter 1 scenario.
- The scenario Acc30 of the C-Scooter 1 with a reduced level so that the maximum A-weighted sound pressure level was identical to that of the E-Scooter 1 scenario.

The rating of the signals was done with the help of two 11-pt. category scales, one scale for the annoyance ranging from "not annoying at all" to "very annoying" and one scale for loudness ranging from "very loud" to "very quiet". In Figure 35 a screenshot of the terminal display (user interface) is shown. The test persons can give their rating directly by touching the squares on the grey scale.

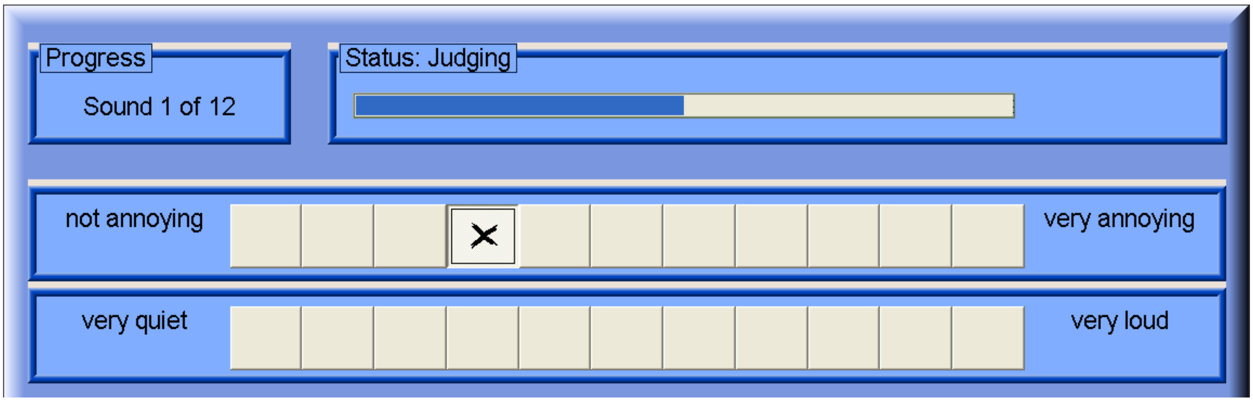


Figure 35 Screenshot of the listening test interface

The test procedure was split into three parts.

1. Greeting of the test persons and introduction to the test. It was mentioned in advance that pass-by sounds of powered two wheelers will be presented including combustion engine driven as well as electric engine driven vehicles. Furthermore, it was mentioned that the test persons should immerse into a situation standing 7.5 m in front of a street and listening to the vehicles passing by.
2. The listening test started with two sounds for training purpose. The sounds represent exemplarily the range of the different sounds. This was done to avoid scaling effects, like the ceiling or floor effect. The sound samples were presented to all listeners at the same time. Then the test persons have to rate the sound on the category scales mentioned above. The persons could only listen once to the sound samples; since they should rate the sounds spontaneously based on the first impression.
3. After the listening test the age and the gender of the test persons were requested. Additionally the listeners should explain their impressions and could give remarks with respect to the test and its procedure.

The number of test persons in this listening test was 47. The age and gender of the persons is shown in the table below.

male	83%
female	17%
21 - 30 year	40%
31 - 40 years	19%
41 - 50 years	38%
51 - 60 years	2%

The statistic evaluation of the listening test is done in two steps. The first is the validation with the help of so called box plots.

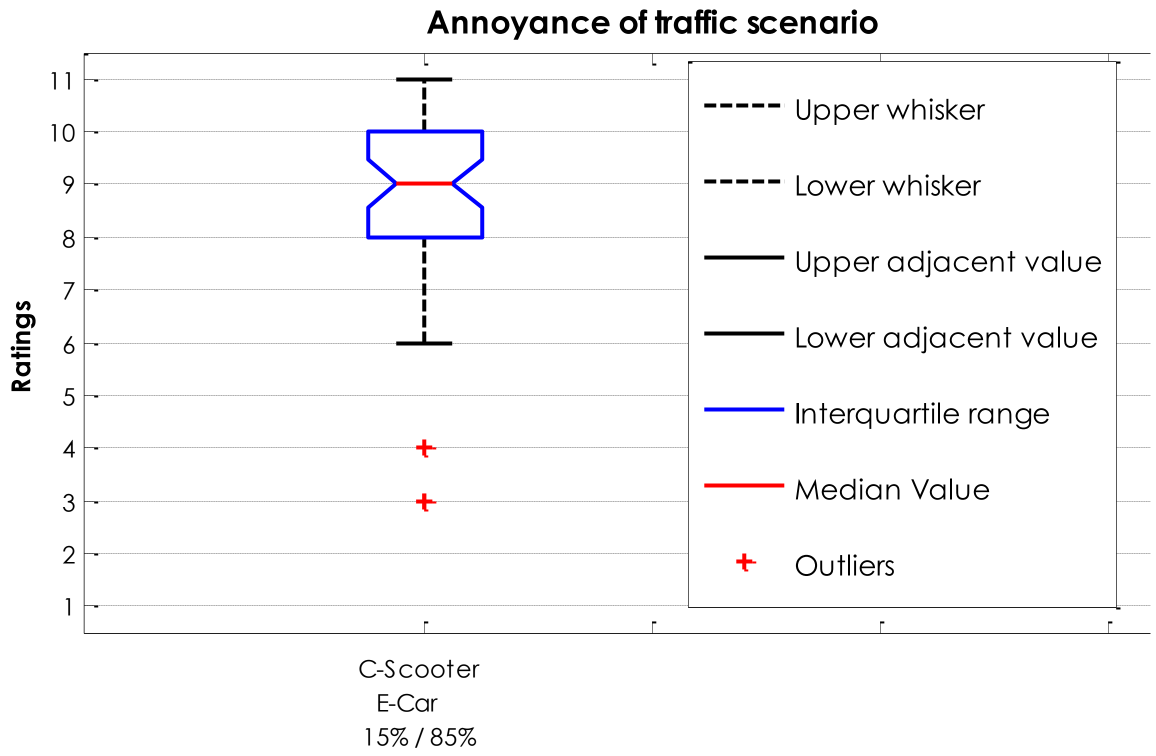


Figure 36 Example and description of the statistic visualization with the help of box-and-whiskerplots.

In order to visualize the statistical data collected from the listening tests, a box-and-whisker plot representation is introduced. Figure 36 exemplarily shows the ratings on annoyance of a certain traffic scenario, which is investigated in chapter 5 (15 % C-Scooter – 85 % E-Car, which means that of the total traffic volume consists of 85 % electric passenger cars and 15 % scooters powered by a combustion engine).

The median value is represented as a red line within the box plot, which is limited by the 25% percentile value at the bottom, and the 75% percentile value at the top (blue lines). The distance between the upper and lower border of the box plot is defined as the interquartile range. Notches around the median value are displayed indicating the

95% confidence interval. This representation is used to visualize the variability of the median between different samples. The narrower the notch, the more robust the median when compared to other distributions. Whiskers above and below the box plots extend to the most extreme data value up to 1.5 times of the interquartile range above or below the box plot. If data values lie beyond these whiskers, additional marks (red plus signs) are displayed indicating outliers.

The box-and-whisker plot representation offers a detailed view on the listening test data and helps indicating the distribution of ratings and the robustness of the results.

In Figure 37 the subjective loudness ratings of the different scooter single pass-by events are plotted as box-and-whisker plots. The first three E-Scooter scenarios are all rated significantly quieter than the C-Scooter scenarios. Neither the confidences intervals nor the quartile ranges of the E-Scooter and the C-Scooter scenarios overlap. This means that the difference in subjective loudness of E-scooters and C-Scooters is statistically significant.

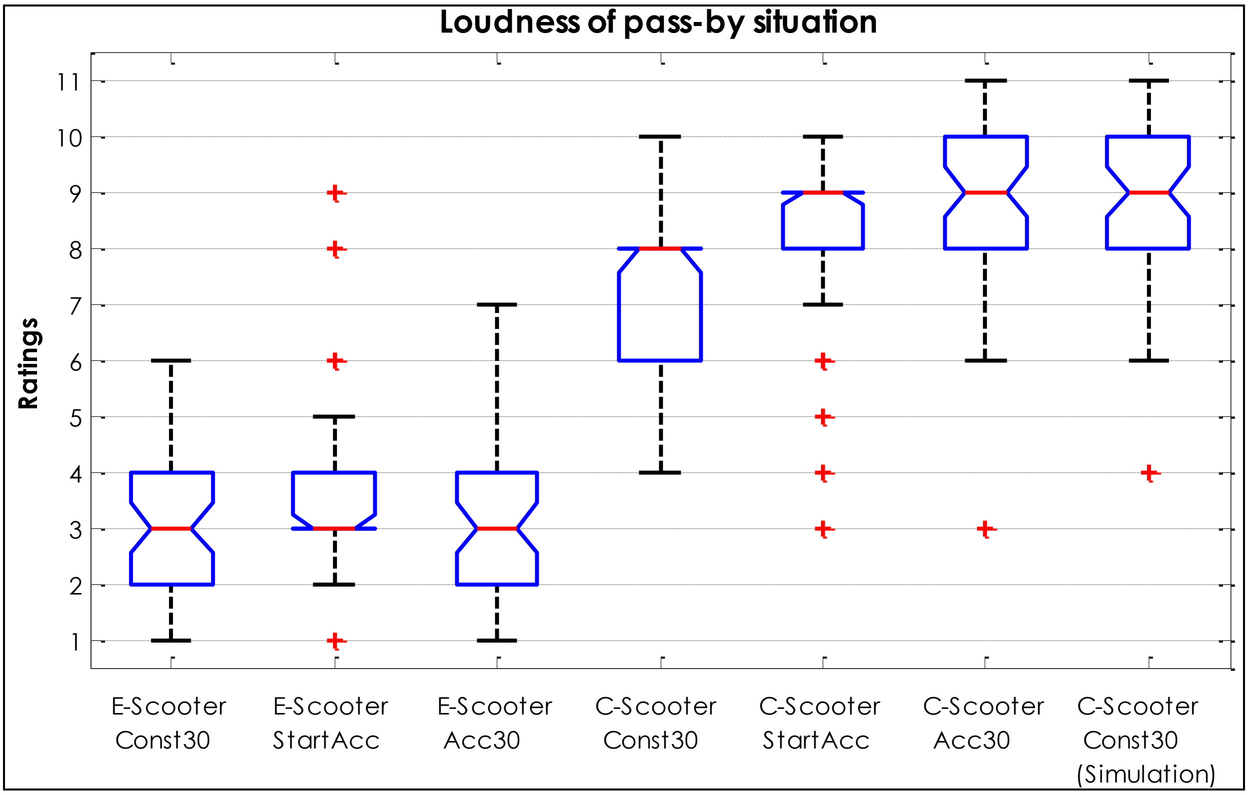


Figure 37 Box-and-whisker plot of the loudness ratings of the different scooter pass-by scenarios.

The annoyance ratings, shown in Figure 38, of E-scooter and C-Scooter single pass-by events indicate the same tendency. This means that the differences in noise annoyance of E-scooters and C-Scooters are statistically significant. The annoyance of Scooters powered by combustion engines is significantly higher compared to E-Scooter pass-by noise. This significant difference in annoyance is present for all driving conditions. The E-Scooter noise is rated as almost not annoying (median: 3). In contrast, the C-Scooter obviously possesses a high annoyance potential.

In addition to the ratings for the pass-by measurements a simulated scenario (Const30) was judged by the test persons. In the ideal case, the ratings of loudness and annoyance should match the ratings of the corresponding measured scenario. It can be seen that both the loudness and the annoyance ratings of the simulated sample are one category higher than of the measured sample. This validates the subjective impression of the simulated sample. The slight difference in the ratings results from the cleaner sound of the simulation compared to the measurement where small additional sound events appear which cannot be synthesized.

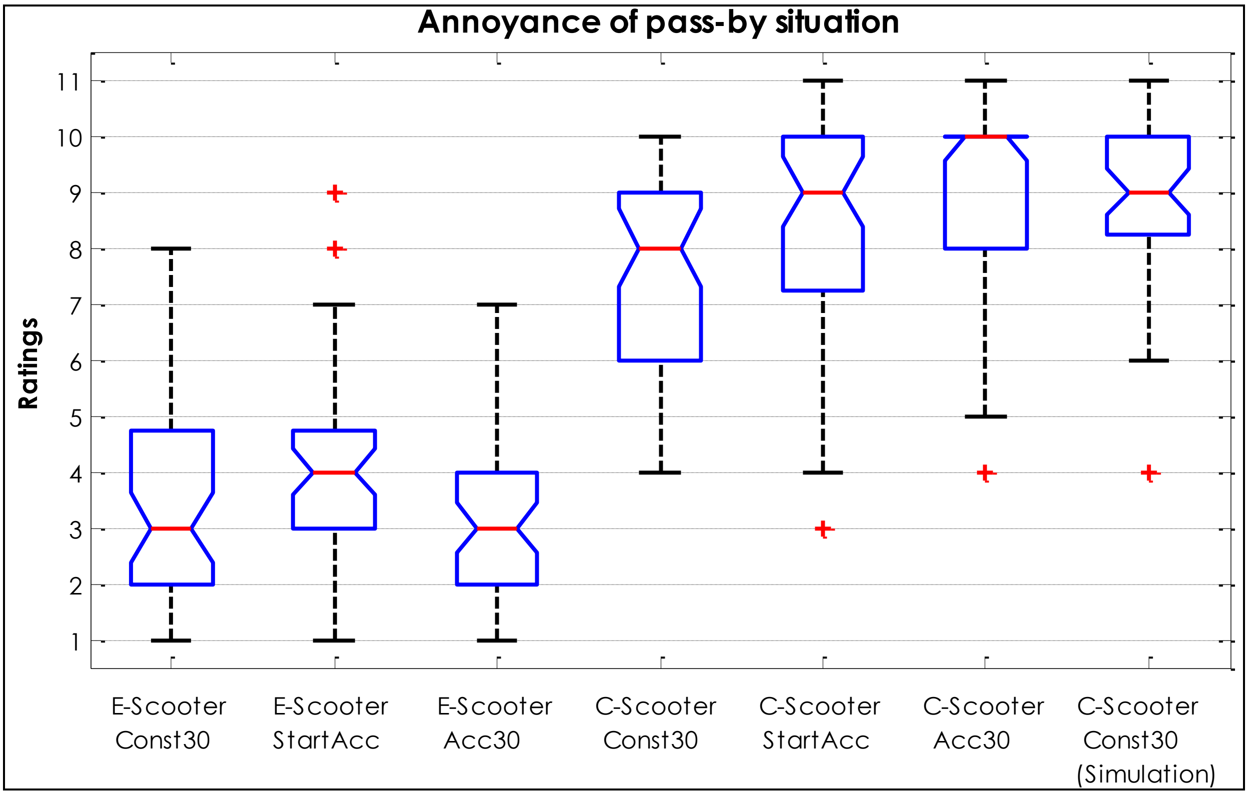


Figure 38 Box-and-whisker plot of the annoyance ratings of the different scooter pass-by scenarios.

In order to enhance the readability of the listening test results only the median and mean values are displayed in the following diagrams. This allows for a better comparison to the acoustical analysis results shown in chapter 4.1.

The loudness judgments, as shown in Figure 39, illustrate a significant increase in loudness for the C-Scooter scenarios in comparison to the E-Scooter scenarios. The loudness ratings of the C-Scooter are between 5 and 6 categories higher than the ratings of the E-Scooter scenarios. There is only a slight difference between the specific driving conditions. This behavior is comparable to the behavior of the sound pressure level and psychoacoustic loudness as presented in chapter 4.1.

A similar tendency can be seen for the annoyance rating. In Figure 40 the C-Scooter pass-by situations were judged between 5 and 7 categories more annoying than the

E-Scooter situations. This is even more than the difference in the perceived loudness on the 11-pt. category scale. This supports the assumption that not only the loudness (or sound pressure level respectively) is relevant for noise annoyance, but also other psychoacoustic properties of the single pass-by noises.

These results already show great potential of noise and annoyance reduction if scooters powered by a combustion engine were completely replaced by electric scooters.

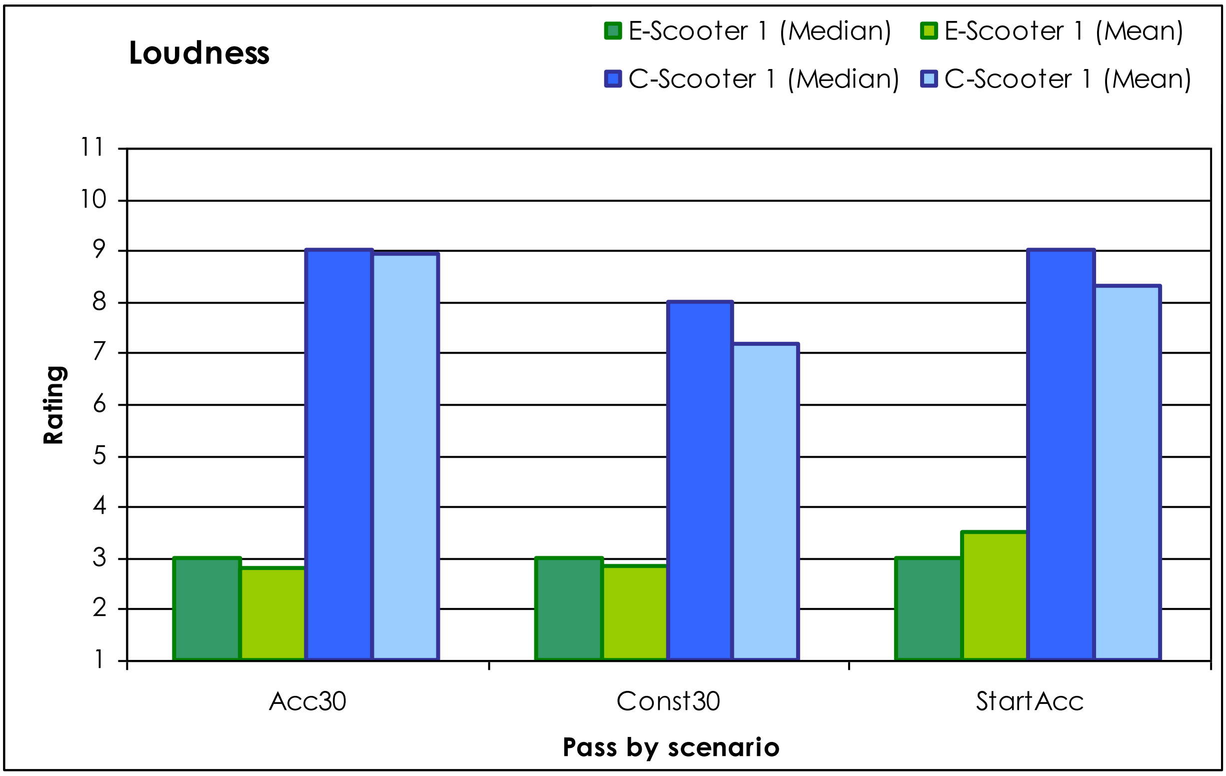


Figure 39 Comparison of the loudness ratings of different pass-by scenarios. The median and mean values for each scenario are plotted.

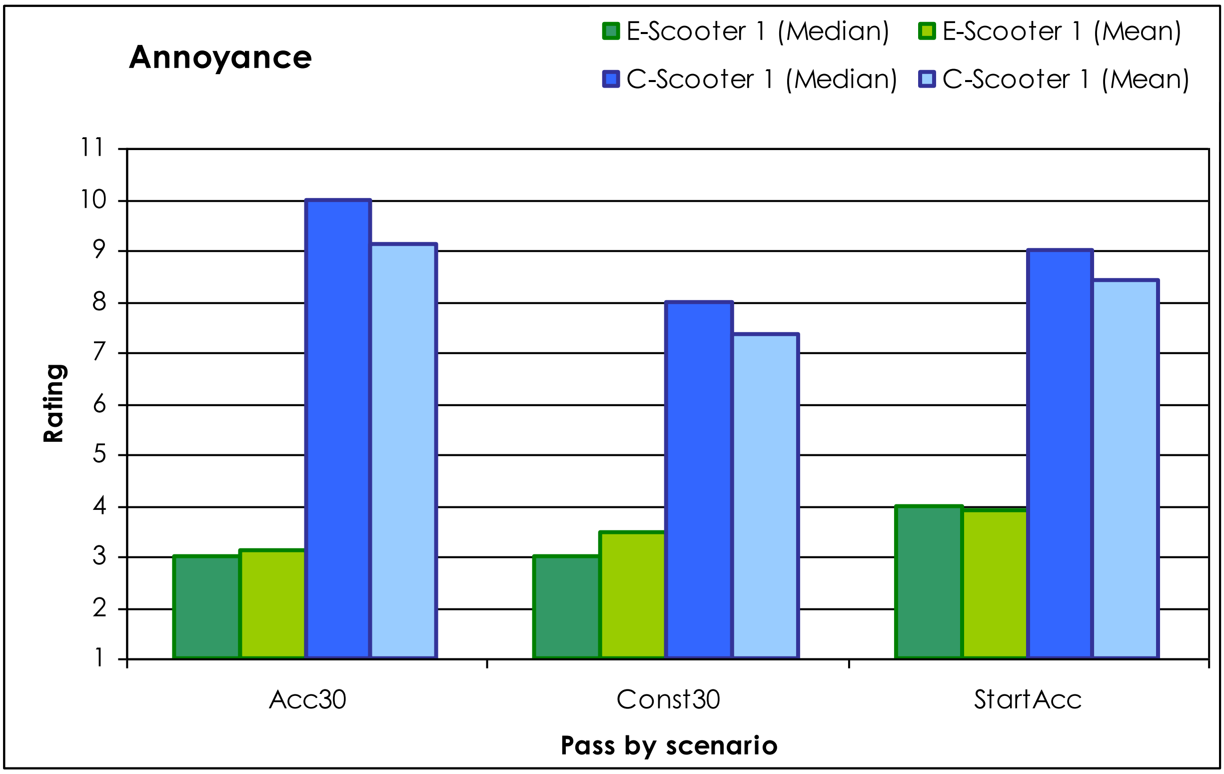


Figure 40 Comparison of the annoyance ratings of different pass-by scenarios. The median and mean values for each scenario are plotted.

4.3 COMPARISON OF SUBJECTIVE AND OBJECTIVE EVALUATION

In sections 4.1 and 4.2 the subjective and objective evaluation of the single pass-by events was discussed. The E-Scooter and C-Scooter situations show significant differences with respect to the acoustical analysis results as well as the perceived annoyance. This means that a good correlation between the chosen objective analysis parameters and the subjective evaluations can be expected. In Figure 41 the correlation coefficient between the annoyance rating and the different analyses is shown. A correlation coefficient (according to Pearson) of 1 corresponds to a perfect linear dependence between dependent and the independent variable. The plotted values which lie between 0.92 and 0.99 suggest that the objective parameters can be used to predict the subjective ratings.

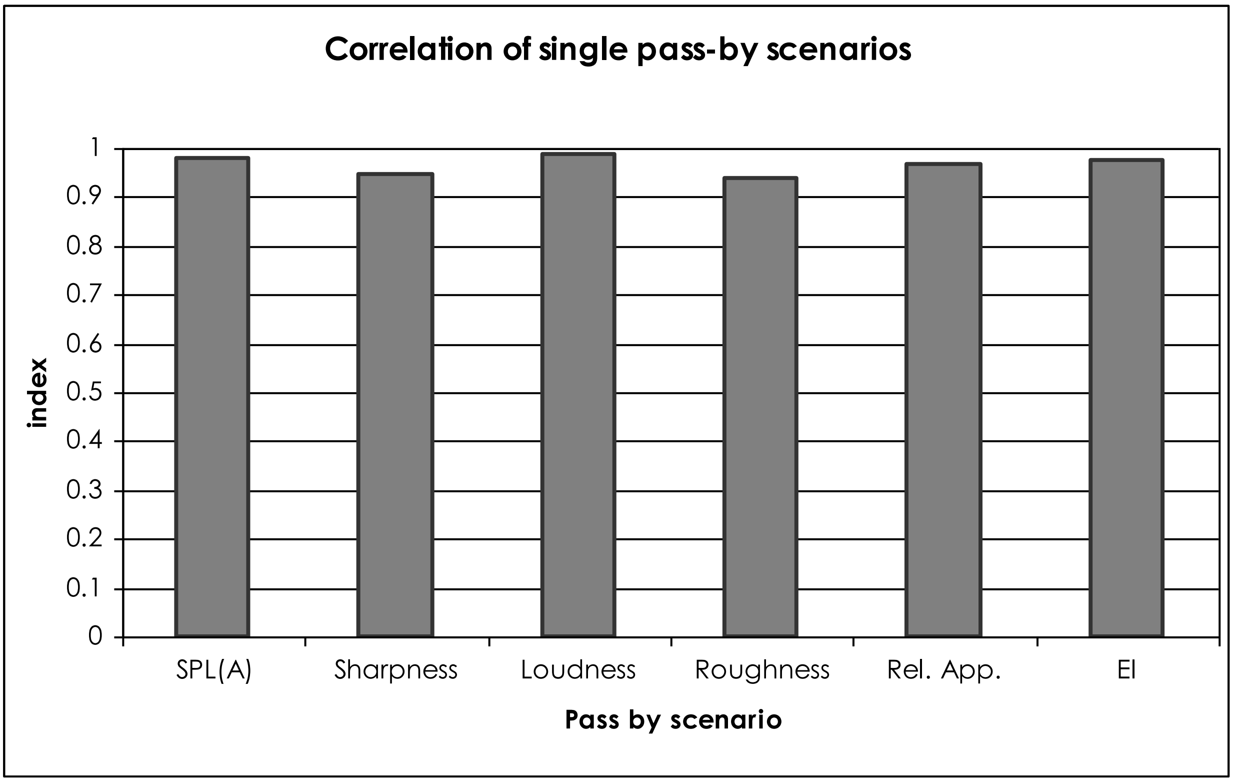


Figure 41 Correlation of the annoyance ratings with different objective acoustical analyses values.

4.3.1 Comparison of level adapted scenarios

In addition to the direct comparison and evaluation of the single pass-by scenarios of measured C-Scooters and E-Scooters, the test persons also judged modified sounds in the listening test.

The pass-by situation *Acc30* and *Const30* of the C-Scooter were reduced in sound pressure level. The files have been adapted so that the A-weighted maximum sound pressure levels of the E-Scooter and the C-Scooter scenario have the same value. These files were also subject to subjective evaluation.

The interesting point of this comparison is that the most significant difference between the E-Scooter and C-Scooter scenarios, the sound pressure level, is equalized. This is almost comparable to the hearing sensation of a C-Scooter with a larger distance to the observer position.

The collected ratings should indicate the annoyance potential of C-Scooters caused by certain psychoacoustic properties beyond the sound pressure level.

In Figure 42 the ratings of the perceived loudness are plotted. The results point out that both adapted C-Scooter scenarios are still perceived as louder, although the sound pressure levels (L_{Amax}) are identical to the E-Scooter scenarios. A possible reason for this observation could be that the test persons recognize the specific source and automatically assign a higher loudness to this source compared to the E-Scooter scenarios.

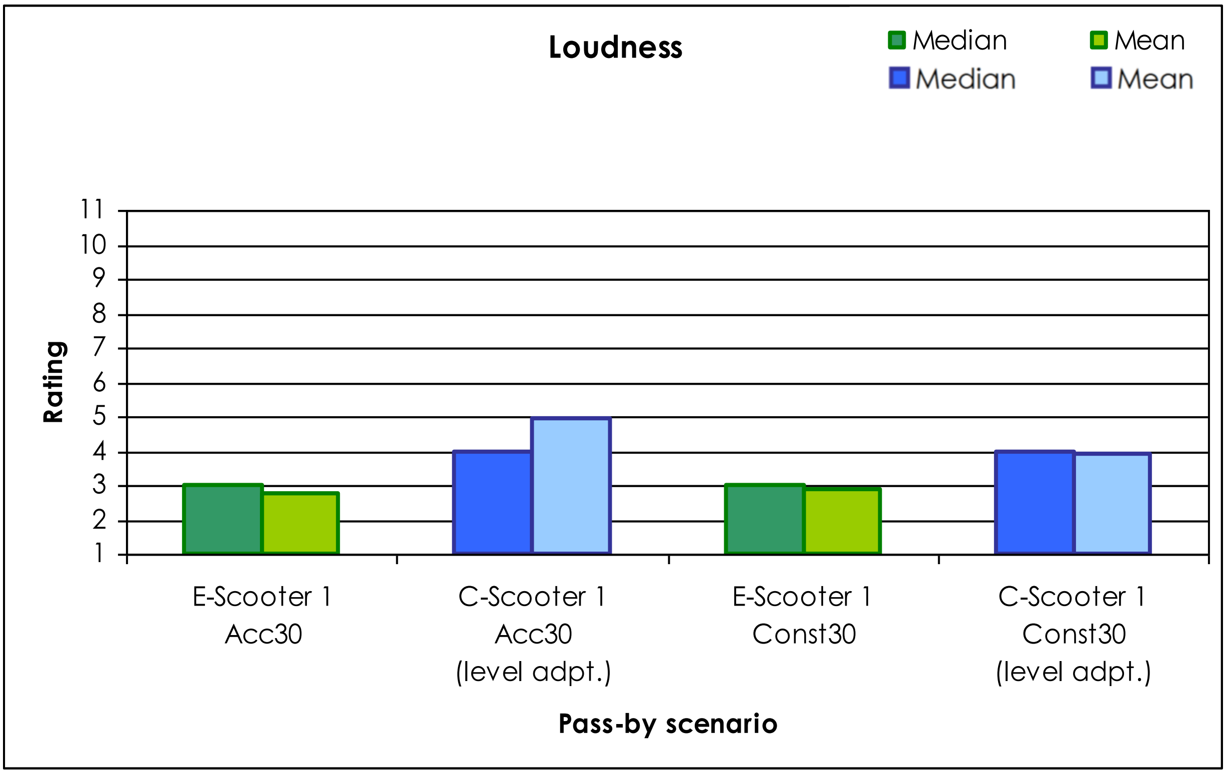


Figure 42 Comparison of perceived loudness between E-Scooter pass-by situation and level adapted (equalized) C-Scooter scenarios.

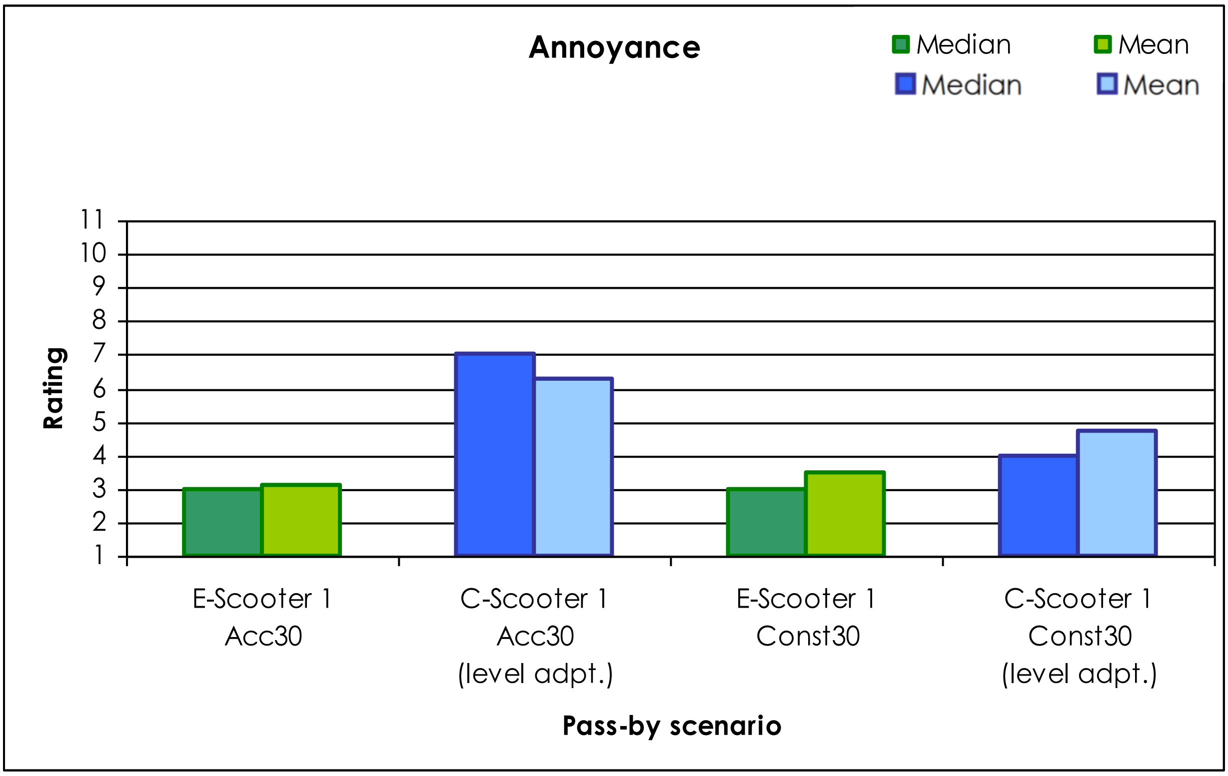


Figure 43 Comparison of perceived annoyance between E-Scooter pass-by situation and level adapted (equalized) C-Scooter scenarios.

In analogy to the loudness ratings of the C-Scooter scenarios, the annoyance ratings of the adapted C-scooter scenarios shown in Figure 43 are considerably higher than the respective E-Scooter scenarios. Besides the source recognition effect mentioned above, the difference of the annoyance ratings can be explained with the distinct order structure of the C-Scooter signals. The prominent and narrowly spaced orders lead to a high roughness sensation and to high Relative Approach values (patterns).

In Figure 44 the correlation between the subjective ratings and different objective analyses is plotted. The Relative Approach and the roughness parameter show high correlation coefficients, what explains very well the higher annoyance for C-Scooters even with the adapted level. Another point, which can be concluded from the plot, is that the perceived loudness correlates very strongly with the annoyance.

In general, the evaluation of the level adapted scenarios leads to the conclusion that the sound pressure decrease of the E-Scooter noise is not the only reason for the decreased annoyance ratings. It is shown that additional psychoacoustic properties and patterns in the C-Scooter noise, like roughness or spectral patterns, additionally influence the annoyance judgments.

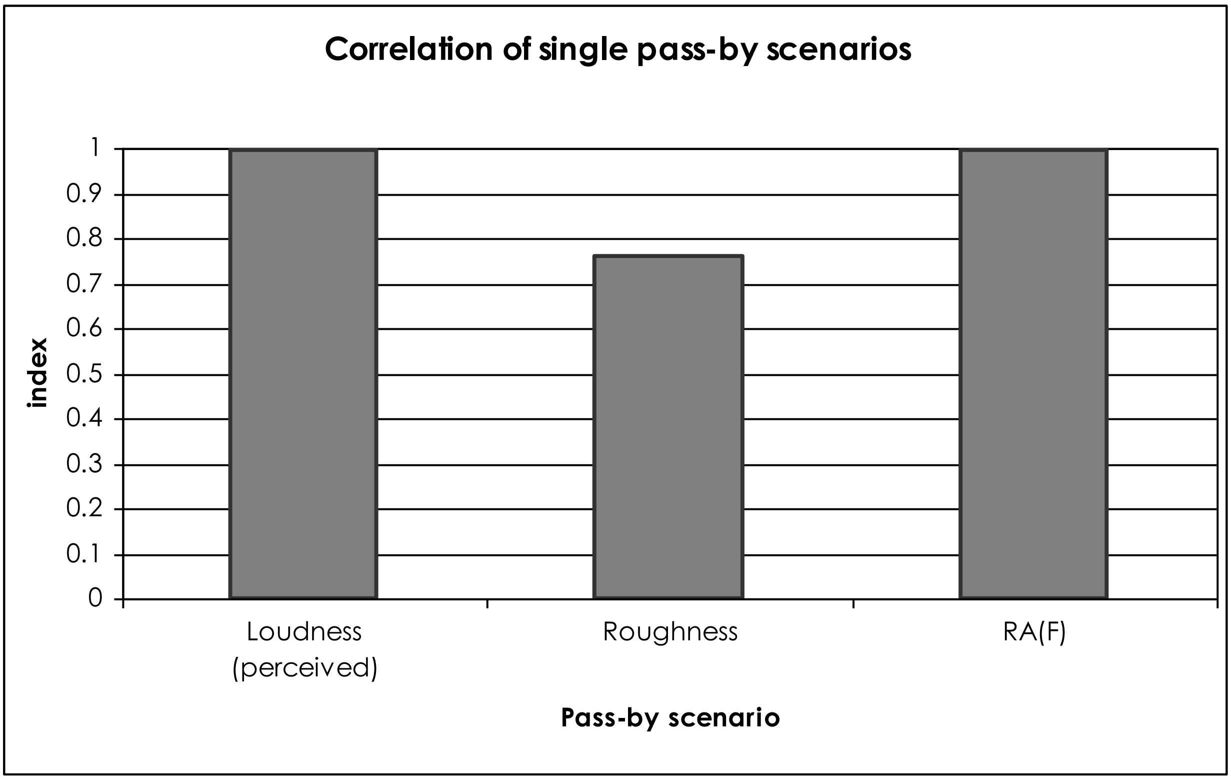


Figure 44 Correlation of the perceived annoyance with different objective analysis values for all single pass-by scenarios.

4.4 EVALUATION OF VIRTUAL MODIFICATIONS

The evaluations above have been made on the basis of measured pass-by noise of the scooters. In this section the traffic synthesis tool is applied to examine the potential of (virtual) sound modifications at the main noise sources of a C-Scooter. The sounds of the C-Scooter have been evaluated with a virtual damping of the engine as well as with a virtual damping of the exhaust noise radiation. To simulate the modification, an appropriate filter has been applied to the radiation of the engine and the exhaust noise radiation respectively. The damping for the lower frequencies (up to 200 Hz) was set to 6.5 dB and for the higher frequencies (above 2 kHz) to 10 dB. The frequency response of the resulting filter is shown in Figure 45.

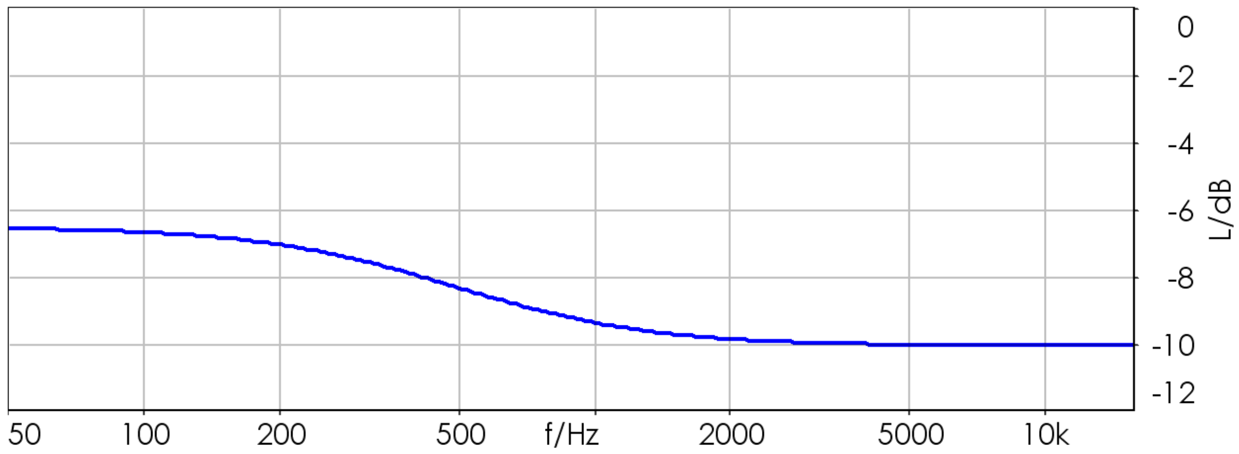


Figure 45 The frequency response of the applied filter realizing the virtual damping at the source is plotted. The values have been chosen to represent realizable damping on the one hand, but also relatively high values to achieve significant changes on the other hand.

The question which is addressed with the modified sounds is, whether it is possible to modify C-Scooters in a way that the resulting noise annoyance can be reduced significantly and an access to Q-Zones could be acceptable.

The evaluation of the modified scooter sounds is done with objective and subjective analyses. As objective parameters the A-weighted sound pressure level and the loudness are considered. Figure 46 and Figure 47 show the values for the sound pressure level and the loudness. Comparing the values of the C-Scooter with the values of the modified engine version there is almost no difference detectable. This means that this modification affects the overall sound only slightly. In contrast to this, the modification of the exhaust radiation results in a significant reduction in sound pressure level (7.5 – 8.5 dB) and loudness (9.5 – 11.5 sone).

In addition to the values of the C-Scooter (blue) the values of the E-Scooter 1 (green) are plotted. Although there is a significant reduction of level and loudness due to the modified exhaust, the loudness and sound pressure level values of the E-Scooter are still lower. Compared to the exhaust damped version of the C-Scooter the sound pressure level and the loudness of the E-Scooter are 10 – 12 dB and 6 – 8 sone lower respectively.

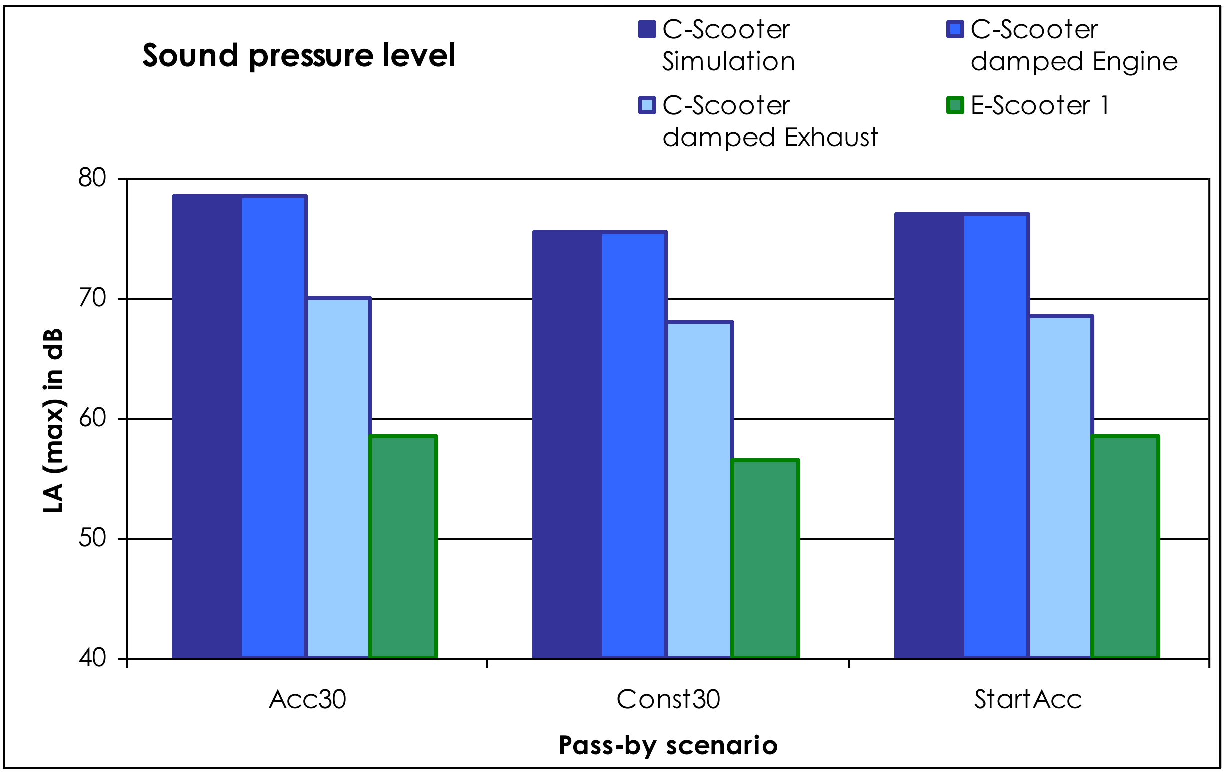


Figure 46 Comparison of sound pressure levels of the damping modifications. All scenarios are simulated with the traffic noise synthesizer.

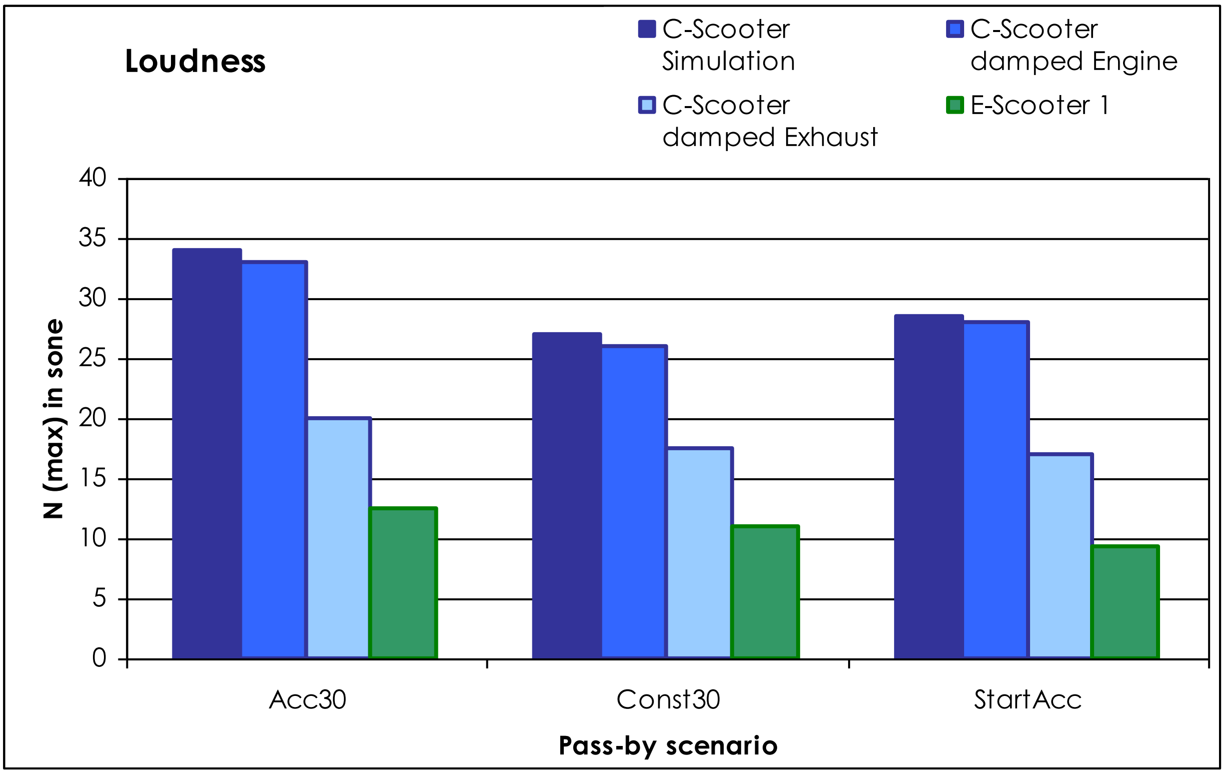


Figure 47 Comparison of loudness of the damping modifications. All scenarios are simulated with the traffic noise synthesizer.

Figure 48 and Figure 49 show the results of the subjective evaluation of loudness and annoyance of the scooter pass-by scenarios with modified engine and exhaust. The figures show the median and the mean ratings of 47 test persons. The transparent green box represents the value of the E-Scooter 1 *Const30* scenario.

In analogy to the objective parameters the effect of the damping of the engine can be neglected. The damping of the exhaust leads to a reduction of perceived loudness of two categories and a decrease in annoyance of one category.

The subjectively perceived improvements are lower than the objective parameters suggest. Comparing the ratings of the modified C-Scooter to the E-Scooter values it is obvious that the damping modifications on the C-Scooter do not lead to significantly higher acceptance (non-annoyance).

From this study, it can be concluded that realistic modifications of a C-Scooter do not lower the perceived annoyance level to a level comparable to E-Scooters.

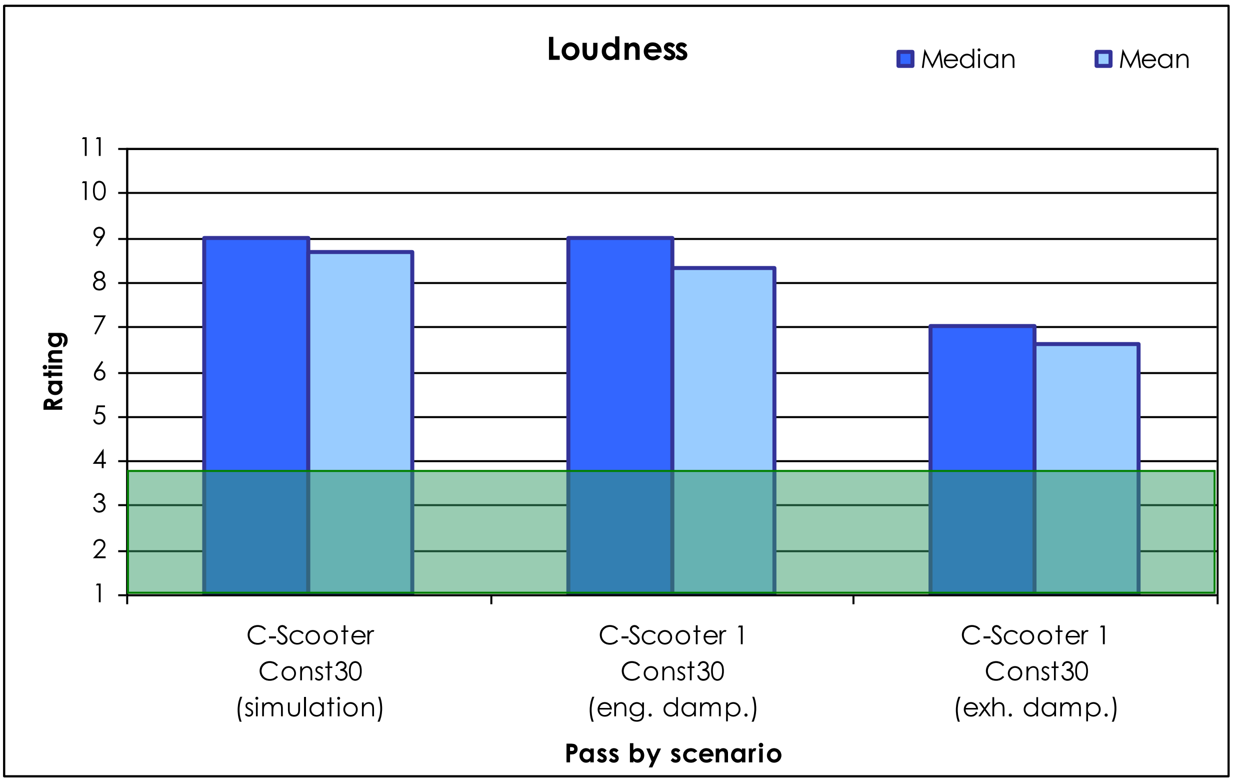


Figure 48 Comparison of perceived loudness ratings for damping modifications at the C-Scooter. The green box shows the rating (median) for the E-Scooter *Const30* scenario.

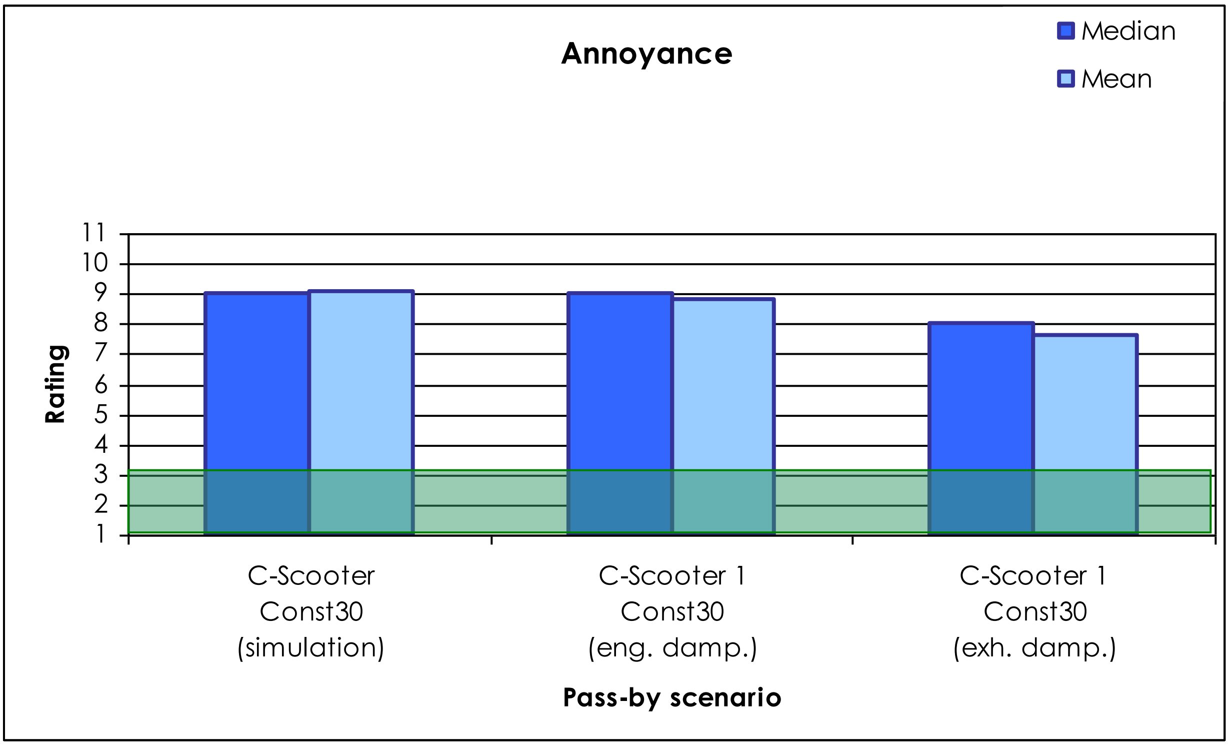


Figure 49 Comparison of annoyance ratings for damping modifications at the C-Scooter. The green box shows the rating (median) for the E-Scooter *Const30* scenario.

4.5 Conclusions

In this chapter, the noise reduction potential and perceived annoyance decrease due to an electrification of scooters was evaluated in detail.

It is shown that a great reduction of the sound pressure level and loudness respectively can be achieved when the scooter drive is changed from combustion engine to electric engine. The electric driven powered two wheelers can help to reduce road traffic noise in cities significantly, especially when considering scooters with small twin-stroke engines. As the tire-road noise has only a minor contribution to the noise emission and the engine is very well covered, the reduction of engine noise is particularly efficient resulting in a considerably lower overall noise. This potential is not directly transferable to passenger cars, where the reduction of engine noise leads to only small improvements of a few decibels.

In order to confirm the objective analyses and to validate the perceptual benefit of E-Scooters, listening tests taking diverse single scooter pass-by situations into account have been carried out. The subjective evaluation covers all relevant driving conditions frequently occurring in urban traffic (pass-by with constant speed, accelerated pass-bys, starting), and provides meaningful data for the comprehensive assessment of scooter noise.

Regarding the rated measurements on existing scooters, loudness and annoyance was low for electrically driven ones, but comparatively high for scooters powered by combustion engines. The differences between both types of scooter drives are considered to be significant. Exchanging scooters equipped with combustion engine for electrically driven scooters leads to an evident improvement of the acceptance, which means considerably lower noise annoyance of single pass-by noise events. The simulated scooter pass-by situations were rated comparably, which proves the applicability of the traffic noise synthesizer technology for environmental noise investigations.

Moreover, the annoyance reduction potential by additionally damping major sources of the scooters equipped with combustion engines was investigated. For that, sounds have been evaluated with virtual damping of the engine and exhaust noise radiation. It was found that even considerable modifications at the sources of C-Scooters (at the engine and exhaust) do not cause a significant reduction of the overall exterior noise and noise annoyance respectively.

5 TRAFFIC SIMULATION EVALUATION

The preceding chapter is focused on the evaluation of single pass-by sounds of powered two wheelers. In the following sections, scooter noise is evaluated in the context of complete traffic scenarios.

Typically, road traffic shows a composition of miscellaneous vehicles and driving conditions rather than a single pass-by situation.

The question of how scooters influence the annoyance impression in the context of complex traffic scenarios is examined in detail. This task is accomplished by means of acoustical analyses and subjective evaluations.

The systematic investigation of traffic noise with the help of measurements is very difficult because of the following reasons.

- The traffic conditions to be investigated (traffic load, traffic composition, etc.) must be found and cannot be fully controlled.
- The behavior of the individual vehicles cannot be controlled (e.g. speed limit).
- The environmental conditions have to be appropriate (e.g. weather)
- The investigation of single parameter changes cannot be examined systematically and in a reproducible way (e.g. change of traffic composition)
- For the evaluation of traffic with high share of electric driven vehicles the actual traffic composition in Germany is not adequate.

These disadvantages can be avoided by using the traffic noise synthesizer to generate auralizations of carefully composed traffic scenarios. As described in chapter 3 simulation models of different scooters were configured. For the generation of more complex traffic compositions car models (passenger cars) are also required. The simulation models of cars powered by internal combustion engines were developed in the European research project QCity. Six different models have been generated and validated for the simulations. These can be used to compose scenarios with passenger cars and scooters with different ratios. To enable the evaluation of scooter traffic in combination with purely electric driven cars also two models of electric cars were configured. The measurement bases for these two models have been the Mitsubishi iMIEV and the Fiat 500 electric.

The evaluation of scooter noise in the context of road traffic compositions was done by creating different scenarios using the traffic noise synthesizer tool. Two different shares of E-Scooters and C-Scooters (5 % and 15 %) with respect to the total traffic flow were simulated. The background traffic flow is simulated as C-Cars (cars with internal combustion engine) and E-Cars (electric driven cars).

In addition to acoustical analyses of the simulation results, the generated sounds of the traffic scenarios were also evaluated in listening tests. There, only a limited duration of the sounds can be presented. A trade-off was determined between reasonable traffic sequence duration to present a realistic traffic situation and a maximum duration accepted by the test persons. The length of the sound samples was set to 100 seconds.

Intending to present the effects of variations of certain vehicle compositions and their type of drive (electric or combustion engine), eight different road traffic scenarios, which consist of a certain distribution of scooters and cars equipped with electric or combustion engines, have been simulated. The traffic scenarios have been defined as follows:

1. 5 % electric scooter and 95 % electric car shares of traffic
   (E-Scooter 5 % - E-Car 95 %)
2. 15 % electric scooter and 85 % electric car shares of traffic
   (E-Scooter 15 % - E-Car 85 %)
3. 5 % electric scooter and 95 % combustion car shares of traffic
   (E-Scooter 5 % - C-Car 95 %)
4. 15 % electric scooter and 85 % combustion car shares of traffic
   (E-Scooter 15 % - C-Car 85 %)
5. 5 % combustion scooter and 95 % electric car shares of traffic
   (C-Scooter 5 % - E-Car 95 %)
6. 15 % combustion scooter and 85 % electric car shares of traffic
   (C-Scooter 15 % - E-Car 85 %)
7. 5 % combustion scooter and 95 % combustion car shares of traffic
   (C-Scooter 5 % - C-Car 95 %)
8. 15 % combustion scooter and 85 % combustion car shares of traffic
   (C-Scooter 15 % - C-Car 85 %)

The actual shares of scooters and cars may differ slightly from the figures given above as only an integral number of vehicles can pass-by at an observer position.

For the composition of the traffic a relatively high scooter ratio was chosen. The reason for that is the wide spread of scooters in southern European countries.

For the simulation of the given traffic scenarios a straight road is assumed. The road represents a traffic-calmed situation with a speed limit of 30 km/h. As traffic load a medium value of 720 vehicles per hour (vph) was chosen, which is a typical road traffic condition in urban areas.

Figure 50 and Figure 51 show the spectrogram and the sound pressure level plot of the simulated audio signal of traffic scenario 7, i.e., *C-Scooter 5 % - C-Car 95 %*. The pass-by events of the C-Scooter can be identified in the spectrogram by focusing on the areas where dominant orders in the frequency range between 500 – 2000 Hz occur. In the sound pressure level plot the peak values around 75 dB(A) correspond to the C-Scooter pass-by events.

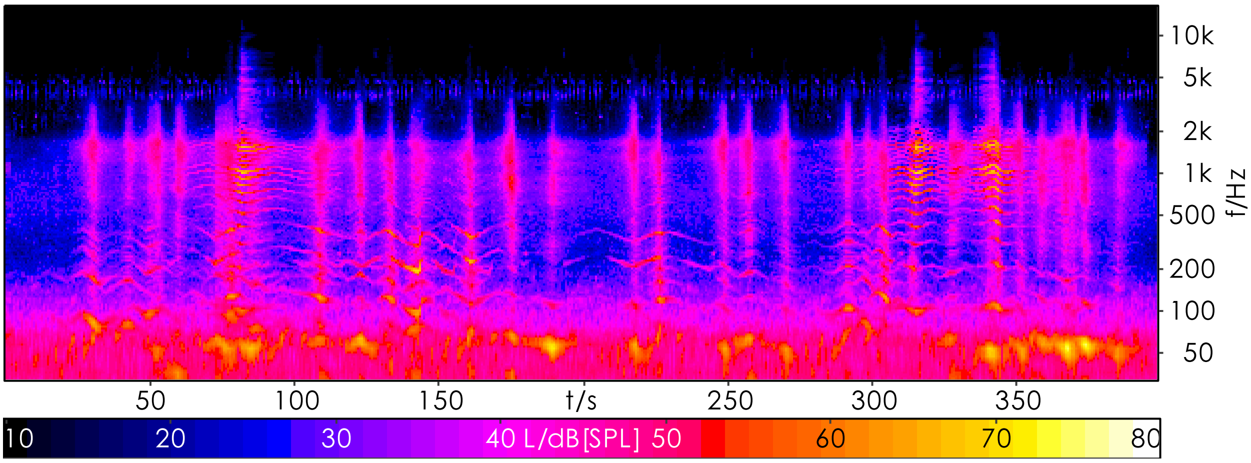


Figure 50 Spectrogram of an auralization with the traffic noise synthesizer: simulation of a straight road with a speed limit of 30 km/h. The traffic load is 720 vehicles per hour (vph) with a share of 5 % scooters and 95 % cars. All vehicles are simulated with combustion engines.

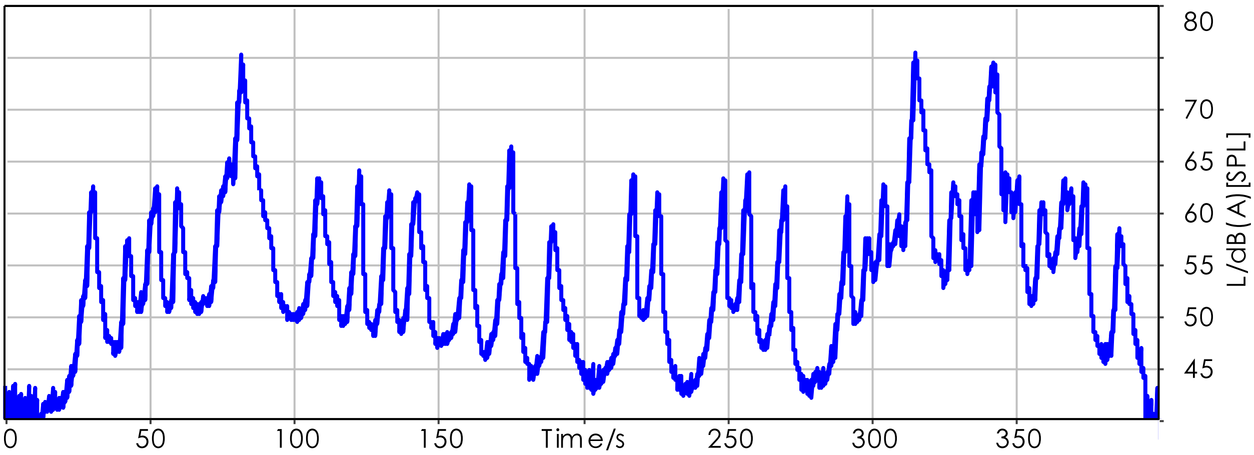


Figure 51 A-weighted sound pressure level versus time plot of the traffic scenario described above.

In Figure 52 and Figure 53 the spectrogram and sound pressure level plot of a pure electric vehicle traffic scenario are displayed respectively. In comparison to the scenario composed with combustion engine driven vehicles the levels are significantly reduced. The pass-by events of the electric cars appear much less pronounced than the ones of C-Cars. For the scooters this effect is also visible but to an even greater extent.

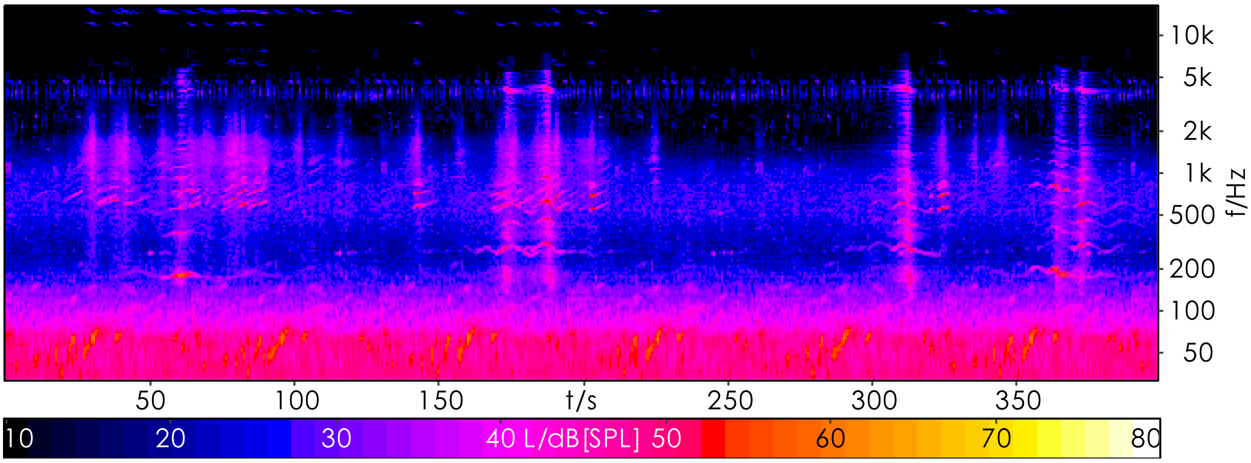


Figure 52 Spectrogram of an auralization with the traffic noise synthesizer: simulation of a straight road with a speed limit of 30 km/h. The traffic load is 720 vehicles per hour (vph) with a share of 5 % scooters and 95 % cars. All vehicles are simulated with electric engines.

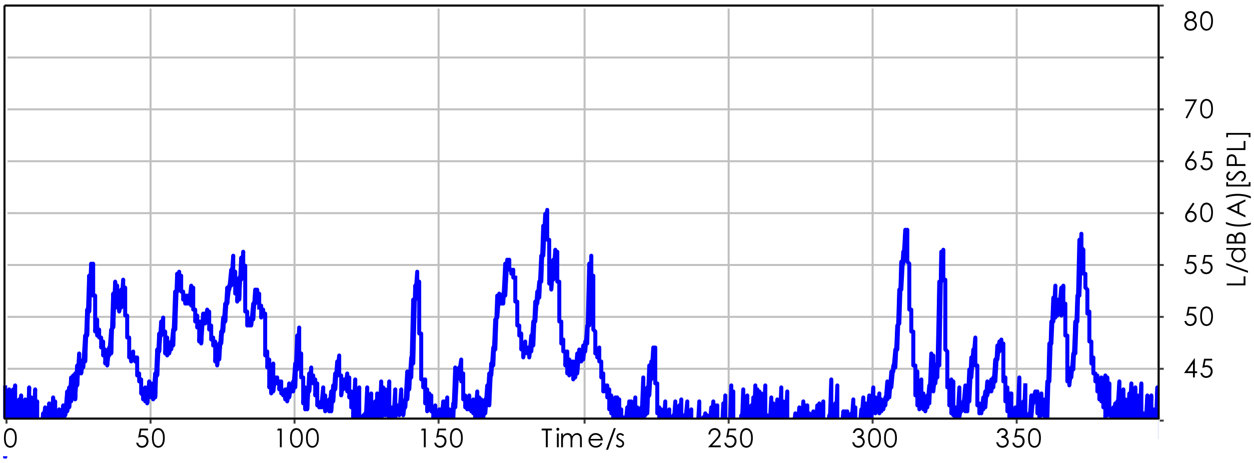


Figure 53 A-weighted sound pressure level versus time plot of the traffic scenario described above.

5.1 Objective evaluation of the road traffic scenarios

To give an introduction to the investigated simulated sound samples the different sound pressure levels of two simulated scenarios are shown in Figure 54 for comparison. While the surrounding traffic of E-Cars is left unchanged the electric scooter are exchanged for scooters with combustion engines. The congruence of the lower peaks corresponding to the pass-by events of the E-Cars can be seen in the chart. The difference between blue and green line exhibits an obvious change during the pass-by moments of the scooters. The much higher level of the C-Scooters does not only have a negative impact on the peak levels but also the levels before and after the peaks. This example emphasizes the big advantage of the simulations compared to measurements where selectively changing specific conditions (like the drive of the scooters) is generally not possible.

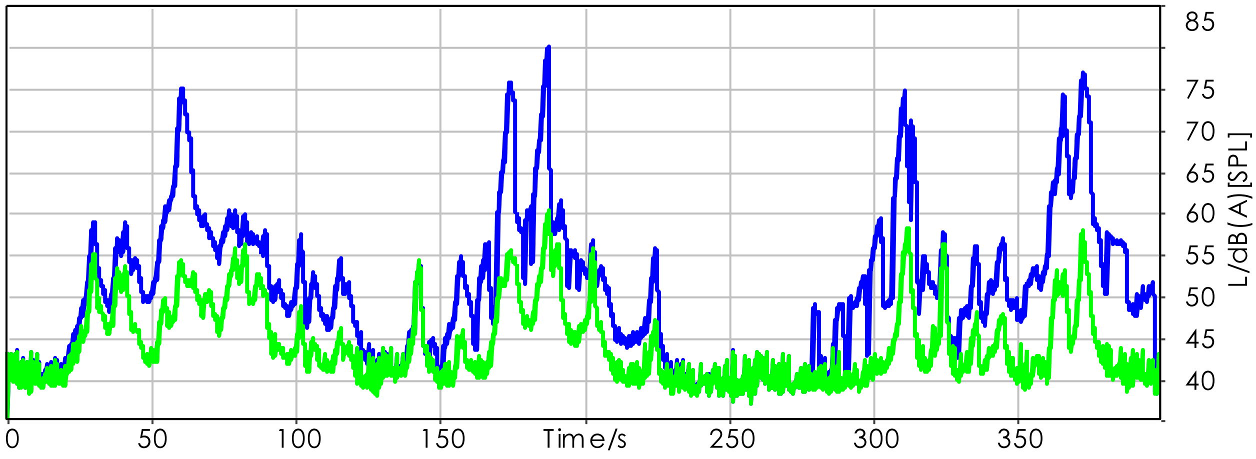


Figure 54 Sound pressure level chart of two simulated traffic scenarios. In both scenarios the surrounding traffic consists of E-Cars while the C-Scooter share (blue line) is exchanged for E-Scooters (green line).

The first step to evaluate the traffic scenarios is the acoustical analysis by means of different objective measures. The chosen analyses are A-weighted sound pressure level, loudness and Relative Approach. From these analyses the following percentile values are derived: 1 %, 5 %, 50 % and 90 %. In the case of the sound pressure level the equivalent continuous sound level (L_{Aeq}) is also calculated.

The following figures show a subset of these analyses as bar plots. Looking at the 5 % percentile values of the sound pressure level and the loudness (Figure 55 and Figure 56) the tendency of increasing values from left to right can be seen, where the left half corresponds to the E-Scooter compositions and the right half to C-Scooter compositions. The L_{Aeq} values follow the 5 % percentile values. The same tendency can be seen in Figure 57 for the Relative Approach values. In contrast, the 90 % percentile values do not show this tendency. Results from the European research project *QCity* brought up a good correlation of the N_5 values (5% percentile loudness) with perceived annoyance. From that it can be stated that the annoyance of the complex road traffic scenarios, where C-Scooters occur, are most probably higher than the same scenarios, where only E-Scooters are present. This conclusion is analogue to the findings derived from the single pass-by evaluation in chapter 4.

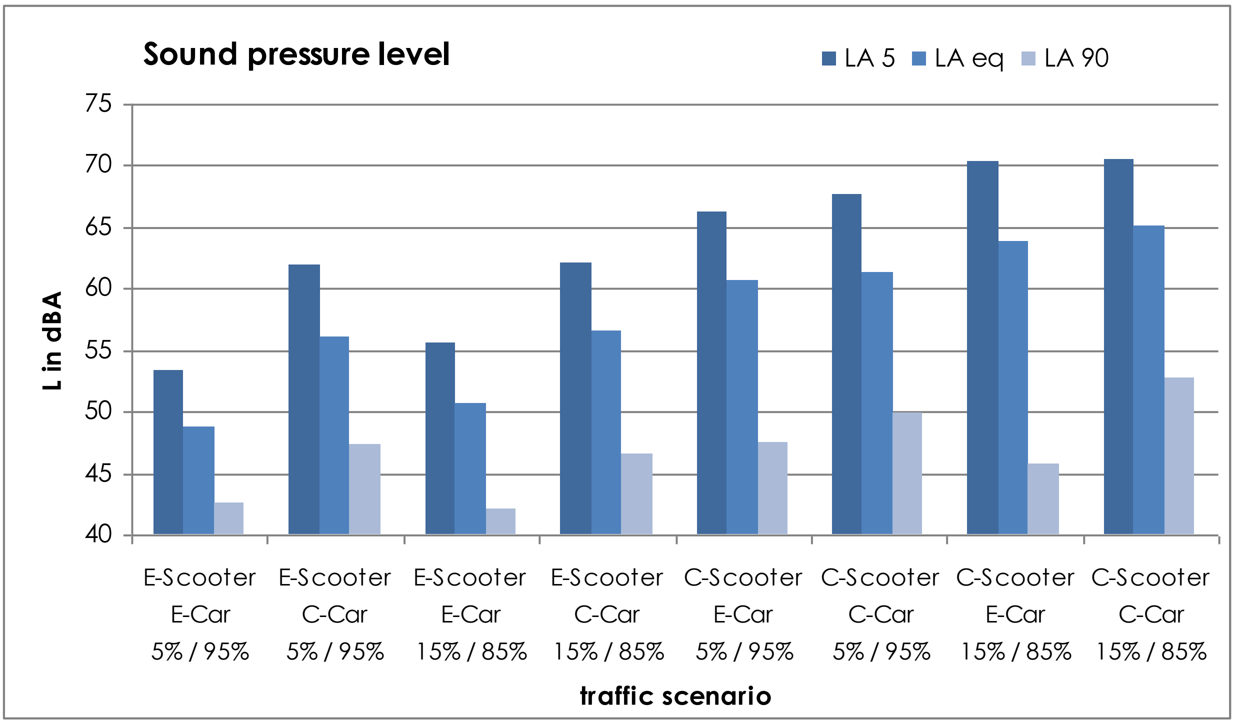


Figure 55 Comparison of the percentile values of the sound pressure level for the different traffic compositions.

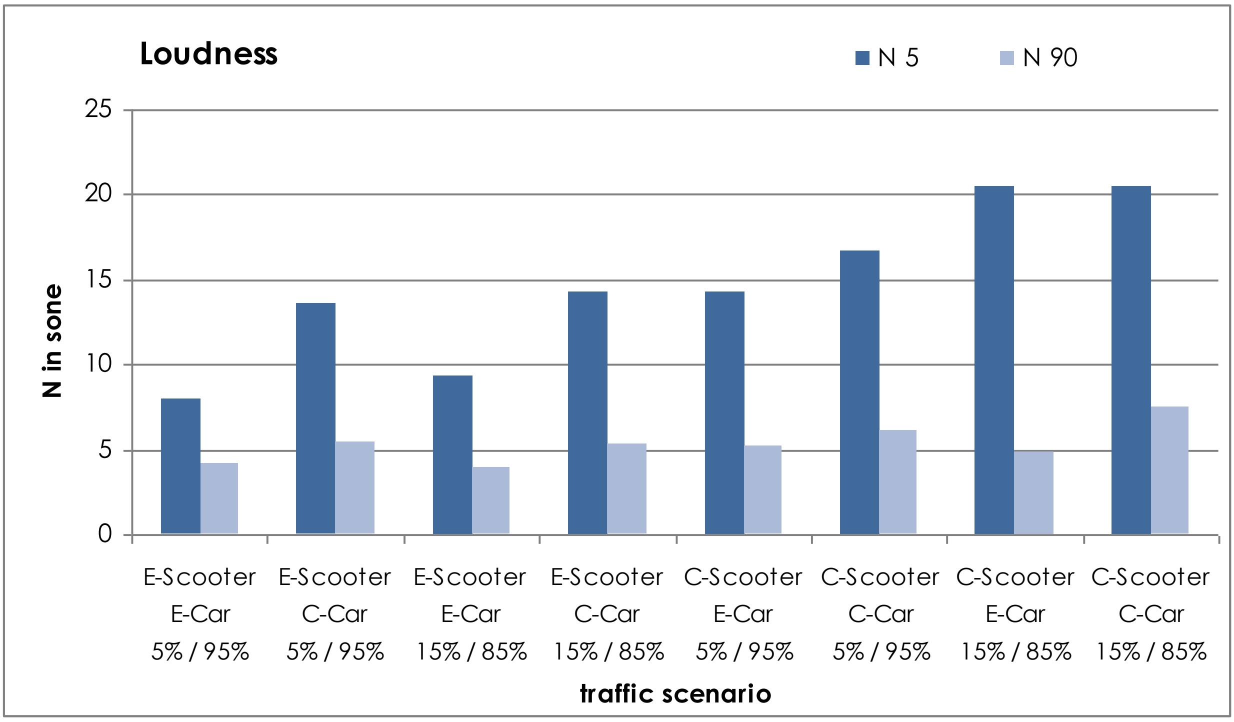


Figure 56 Comparison of the percentile values of the loudness for the different traffic compositions.

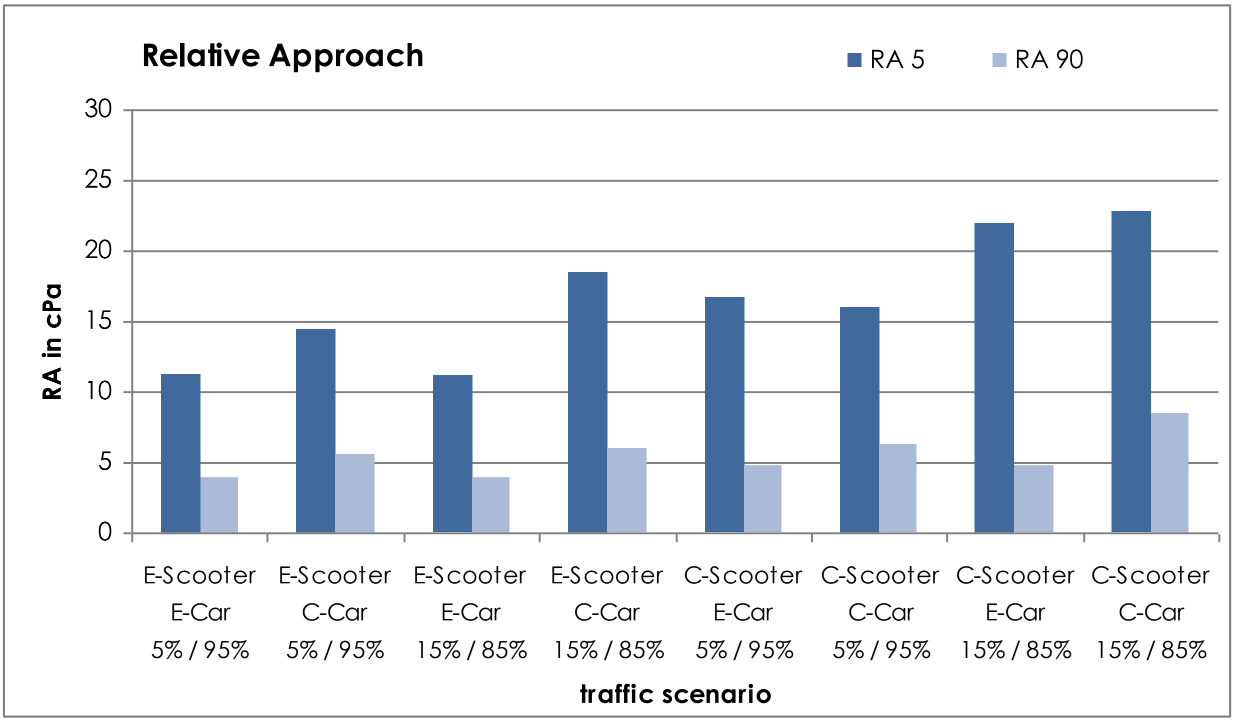


Figure 57 Comparison of the percentile values of the Relative Approach for the different traffic compositions.

The mixed compositions of E- and C-Vehicles require a more detailed examination. In Figure 58 the traffic scenarios are compared in pairs. Each pair corresponds to the same traffic scenario, where only the type of the scooters' drive (electric or combustion) differs. The two pairs on the left side represent the values for the traffic compositions with electric cars as background traffic (95%). In both cases, the change from E-Scooters to C-Scooters shows a clear increase in loudness. The scenarios with the C-Car background traffic on the right side exhibit the same tendency but with only a slight increase.

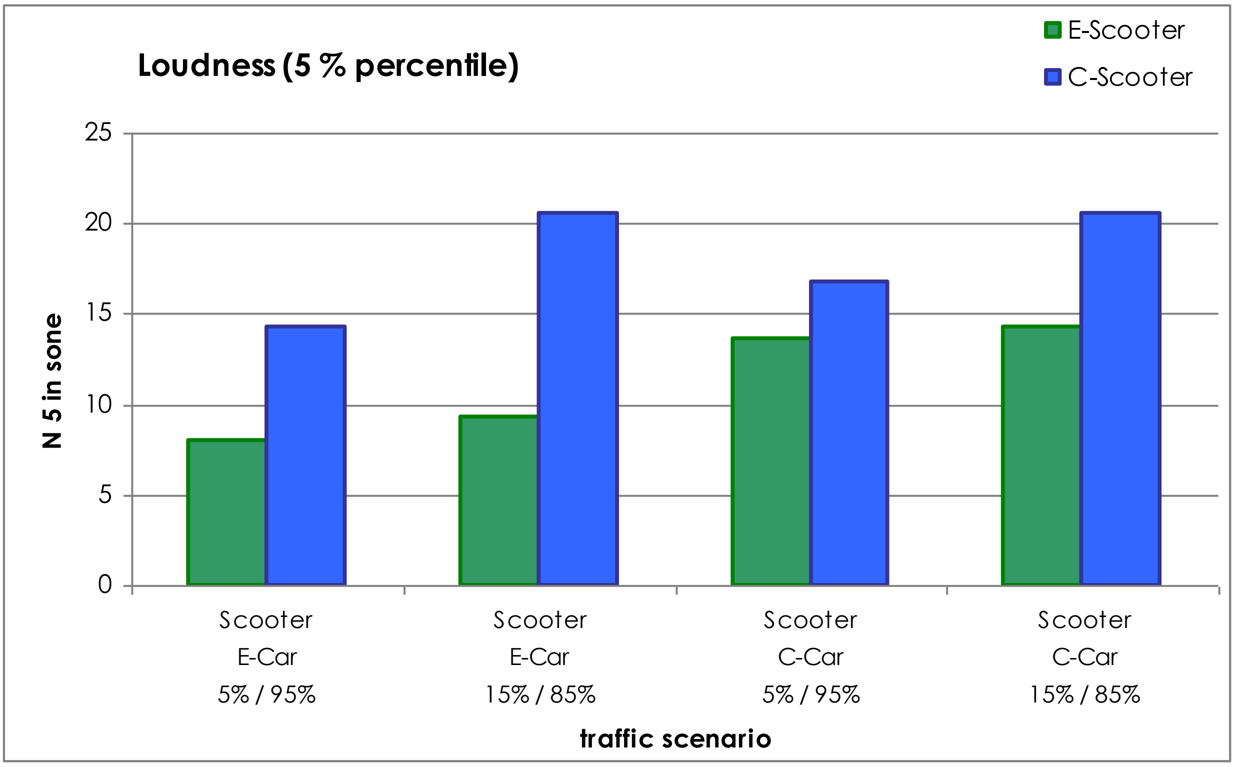


Figure 58 Comparison of N_5-loudness of the traffic scenarios with same car traffic and E- or C-Scooters present.

In section 4.1 the noise analysis with the help of an evaluation index as a combination of different analysis parameters was introduced. The eight simulated traffic scenarios are evaluated with this criterion too.

In Figure 59 the values of the evaluation index for the different traffic scenarios is plotted. High values correspond to a low estimated annoyance and low values to a high annoyance. Analog to the evaluation above the scenarios with C-Scooter shares are classified as being more annoying. Especially for the C-Scooter share of 15 % the index values reach the smallest value of one. It can also be seen that the change of the surrounding traffic from electric to combustion driven cars while keeping the scooter share equal reduces the evaluation indices.

In the following section, the findings of the objective evaluation are compared with results of subjective listening tests.

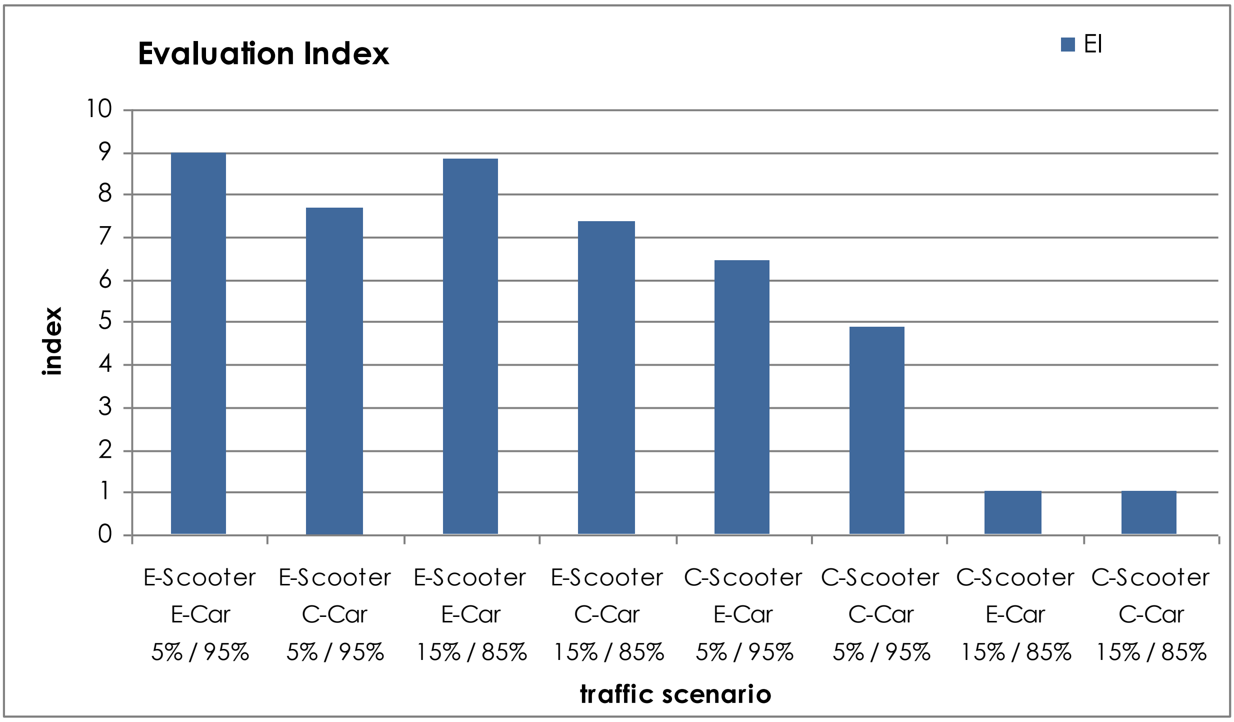


Figure 59 Evaluation indices of the different traffic scenarios.

5.2 SUBJECTIVE EVALUATION OF THE TRAFFIC SCENARIOS

The introduced simulated traffic scenario samples have been judged in a listening test. The listening test participants have been asked to rate the annoyance and the perceived loudness of the traffic scenario, as well as the perceived amount of traffic in the presented scenario. Again, the 11-pt category scale has been used for rating (see Figure 60).

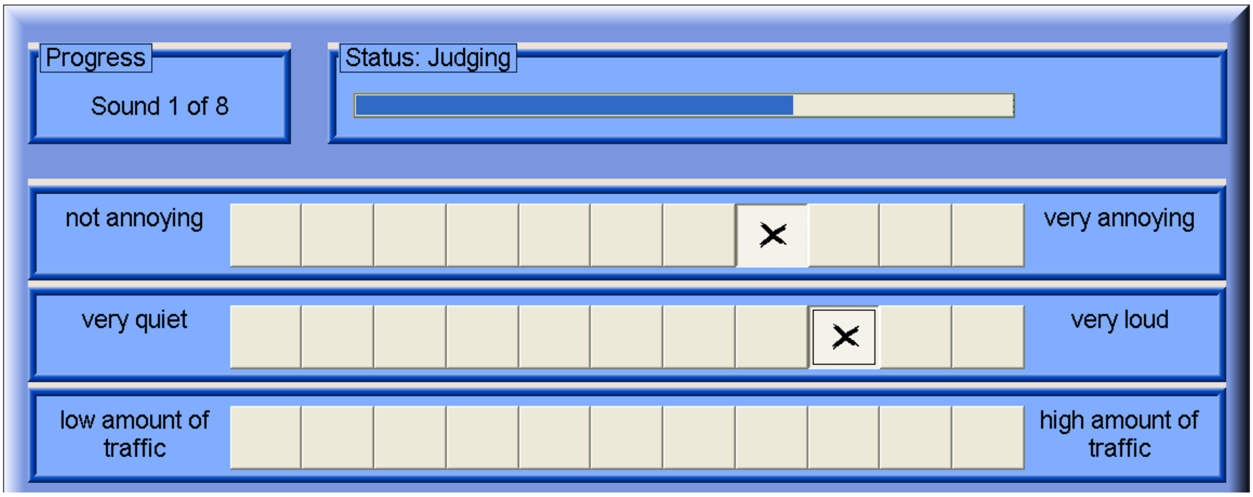


Figure 60 Screenshot of the terminal display during listening test.

The listening tests were performed in the same laboratory as described above (see chapter 4.2). Again, the same fully calibrated playback system, including headphones, is used, assuring an exact reproduction of the test signals.

The test procedure was split into three parts again.

1. Greeting of the test persons and introduction to the test.
2. Start of the listening test. The sound samples were presented to all listeners at the same time. Then the test persons have to rate the sound on the category scales mentioned above. The test subjects could only listen once to the sound samples, since they should rate the sounds spontaneously based on the first impression.
3. After the listening test the age and the gender of the test persons were requested. Additionally the listeners should explain their impressions and could give remarks with respect to the test and its procedure.

The number of test persons in this listening test was 23. The age and gender of the persons is shown in the table below.

male	83%
female	17%
21 - 30 years	52%
31 - 40 years	9%
41 - 50 years	39%

To achieve a better immersion of the test persons a quiet ambient background noise was applied to all sound samples. As background noise binaural recordings of a quiet environment was chosen. In a pre-test two different recordings of background noise were applied to the sound samples to evaluate the influence of the ratings. The first background noise corresponds to a very quiet environment and the second one has slightly higher levels at high frequencies (above 2 kHz) caused by leaves moving in the wind.

It was found that the annoyance ratings of electric vehicles (especially E-Cars) were higher for the first background noise. This can be explained with the high frequency components generated by the electric converters. The test persons complained that the high frequency components increase their annoyance perception significantly.

The second background noise reduced this effect because of the noise components above 2 kHz. For the actual listening test the second background noise was applied, because it represents a more realistic ambient environmental background noise. The background noise has an average A-weighted sound pressure level of 39.7 dBA, which is clearly below an average ambient noise of urban areas. So the focus of the test subjects is on the traffic and not on a distracting background noise.

5.2.1 Analyses of ratings on perceived annoyance and loudness

The following graphs show box-and-whisker plots calculated from the listening test data on the perceived annoyance and loudness of the traffic scenarios. The types of vehicle engines as well as the ratio of scooters and cars are indicated below the particular scenario plot.

Annoyance of traffic scenario

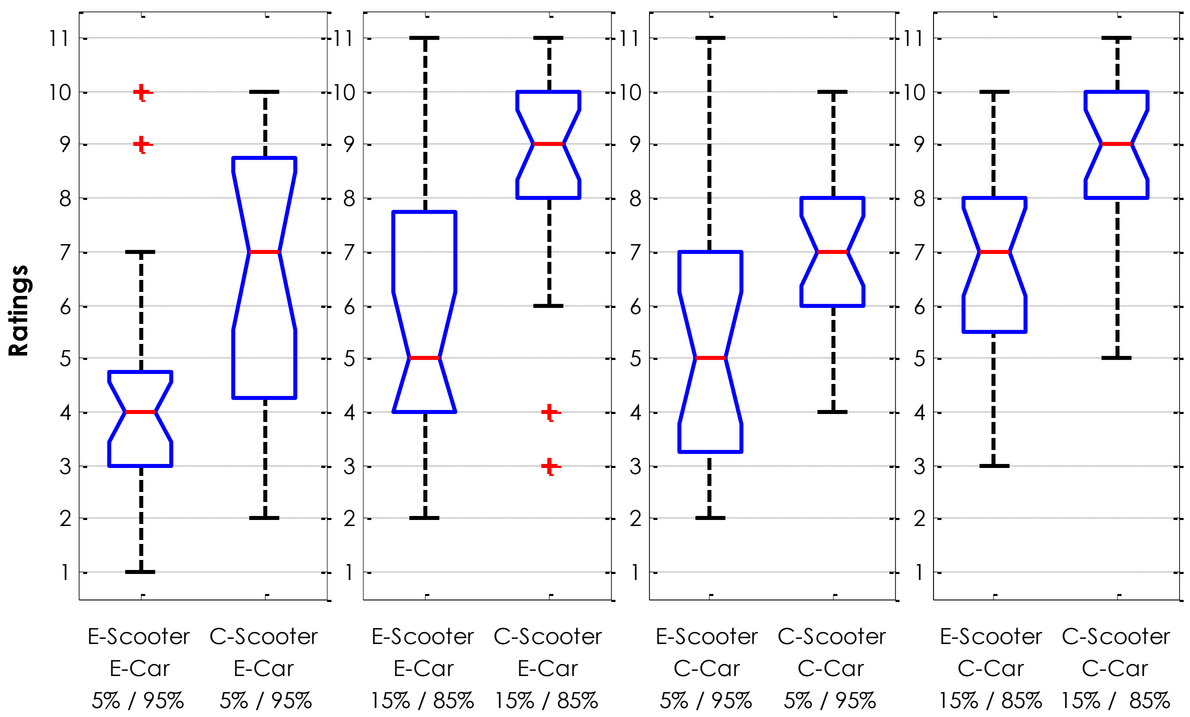


Figure 61 Ratings on the perceived annoyance of the presented traffic scenarios: comparison of scooters.

Figure 61 displays comparisons of the distributions of ratings on perceived annoyance in different traffic scenarios, when the type of scooter drive is switched from electric engine (E-Scooter) to combustion engine (C-Scooter) while the surrounding traffic scenario is kept unchanged.

In the leftmost subplot, a small amount of scooters (5%) is embedded in the surrounding traffic that consists of electric cars only. A significant difference in the annoyance ratings can be observed when switching from electric to combustion engine-equipped scooters. The median of the distributions of these ratings increases by three categories from 4 to 7. This change can be considered to be significant, since confidence intervals (95%) of both distributions do not overlap, even though the ratings in the C-Scooter scenario are spread noticeably wider (wider interquartile range). The carried out t-test described in section 5.2.3 supports this proposition.

The same tendency regarding the annoyance ratings can be observed in the second left subplot. The relative amount of scooters has been increased to 15%. Again, electric scooters have been exchanged for scooters with combustion engines while the surrounding traffic consists of electric cars only. Introducing the combustion engine-equipped scooters leads to a significant increase in perceived annoyance, the median value increases by even four categories from 5 to 9. Listening test participants seem to be more certain about their decision in the C-Scooter scenario when the number of scooters increases, as can be deduced from the interquartile range being narrower than in the same scenario with fewer scooters. Confidence intervals in both distributions do not overlap, which determines the difference between both scenarios to be significant.

Also, for all scenarios with surrounding traffic consisting of cars with conventional combustion engines (second right and rightmost subplots), annoyance ratings increase significantly when electric scooters are exchanged for those with a combustion engine.

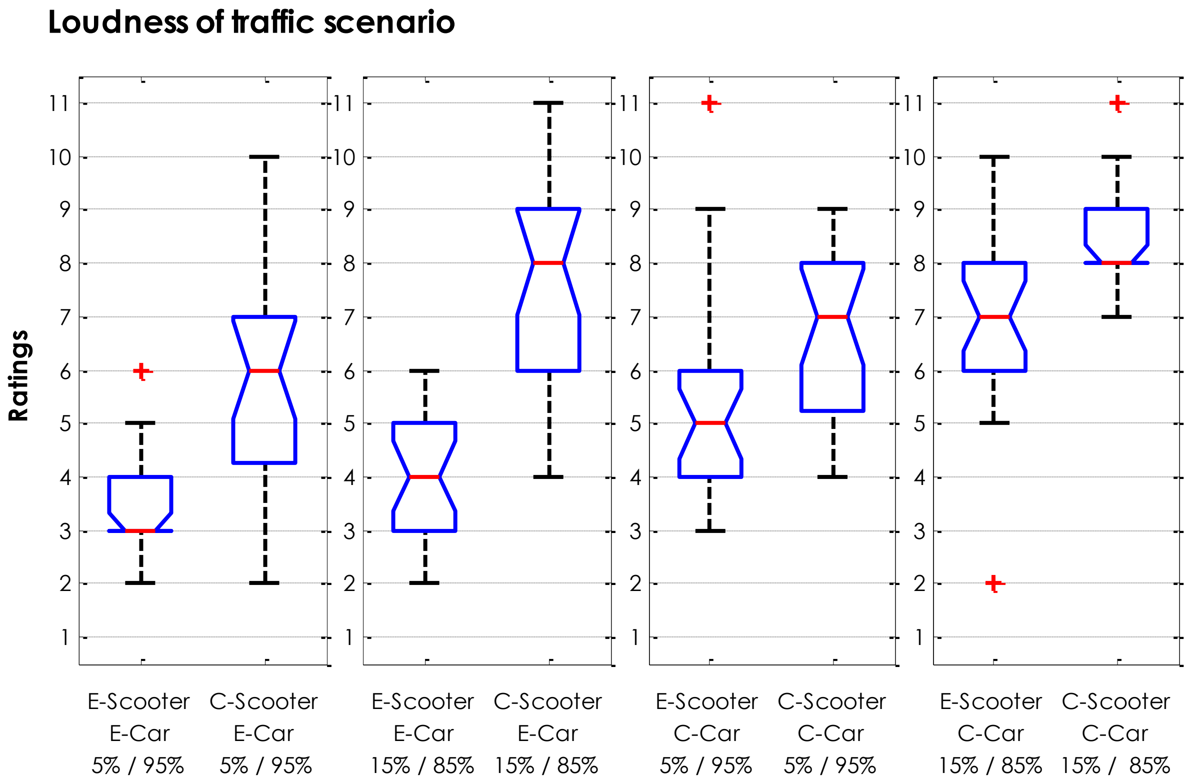


Figure 62 Ratings on the perceived loudness of the presented traffic scenarios, comparison of scooters.

Figure 62 displays the ratings on the perceived loudness of the particular traffic scenarios. Loudness ratings seem to correlate with ratings on annoyance in a way that the perceived loudness increases significantly as soon as electric scooters are exchanged for scooters with combustion engines. This tendency is valid for all surrounding traffic conditions and scooter-car ratios.

Obviously, the difference in perceived loudness is furthermore dependent on the amount of scooters in the particular scenario for both types of drives. The higher the amount of scooters is the higher is the perceived loudness if the surrounding traffic conditions are unchanged. This observation is also valid for the perceived annoyance (see Figure 61).

As expected, the differences between perceived loudness are less prominent if the surrounding traffic consists of cars with combustion engines.

The same graphs can also be sorted in a way that two scenarios with the same amount of scooters equipped with the same type of drive, but different surrounding traffic conditions are compared. This comparison is shown in Figure 63 and Figure 64.

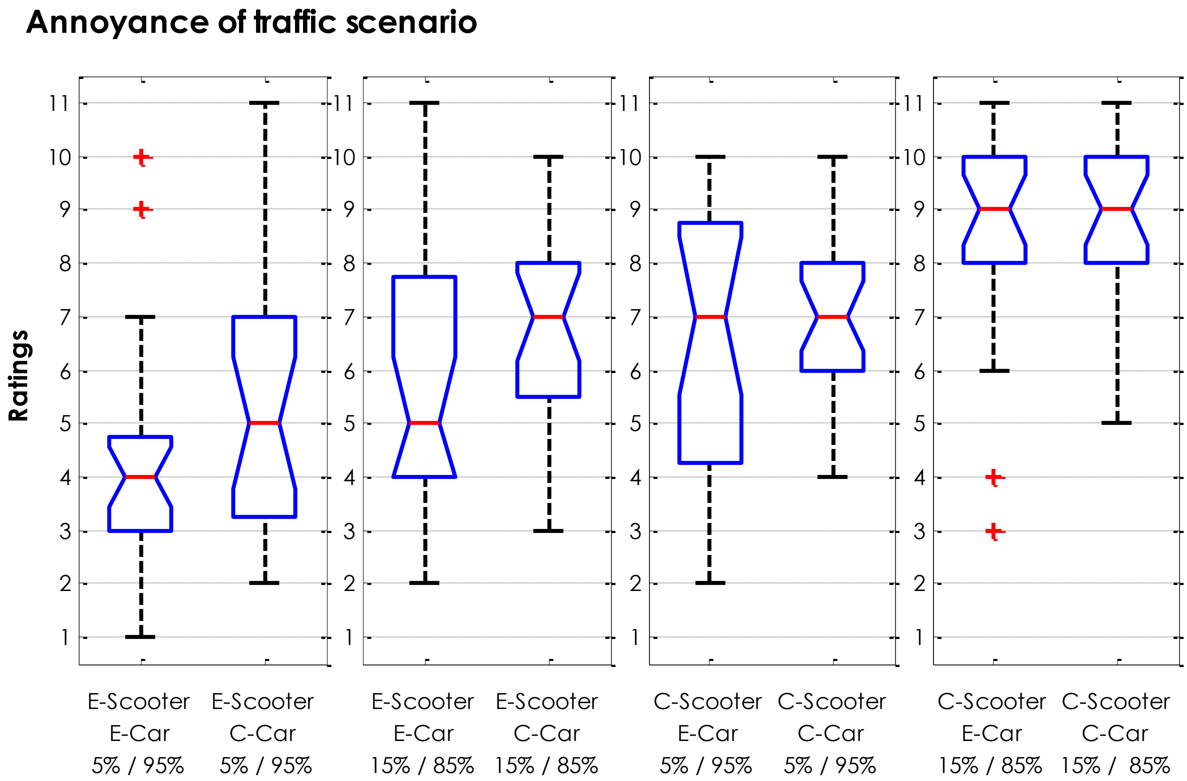


Figure 63 Ratings on the perceived annoyance of the presented traffic scenarios, comparison of surrounding cars.

The first subplot in Figure 63 (leftmost) compares the ratings on annoyance for a low amount of electric scooters (E-Scooter, 5%) when being embedded in surrounding traffic that consists of electric cars on the one hand (E-Car, 95%), and combustion engine cars on the other hand (C-Car, 95%). The median value of annoyance increases by one category when the surrounding traffic is changed to combustion engine cars, but ratings are distributed broader along the rating scale. The interquartile range increases noticeably, but the difference in both rating distributions cannot be considered to be significant since the 95%-confidence intervals do overlap. The t-test results given in Figure 66 support this conclusion.

When increasing the relative amount of electric scooters to 15% of the total traffic (second left subplot), also the perceived annoyance increases for both scenarios. Again, the perceived annoyance increases when changing the surrounding traffic from electric to combustion engine-equipped cars. This time the confidence intervals do not overlap, thus the increase is significant.

Exchanging the electric scooters for combustion engine-equipped ones results in only very slight differences in the annoyance of the traffic scenarios. The median values of both compared scenarios are almost identical; the interquartile ranges differ slightly. It appears as if the surrounding traffic does not have strong influence on the ratings of the listening test participants', most probably due to the high number of C-scooters attracting the full attention.

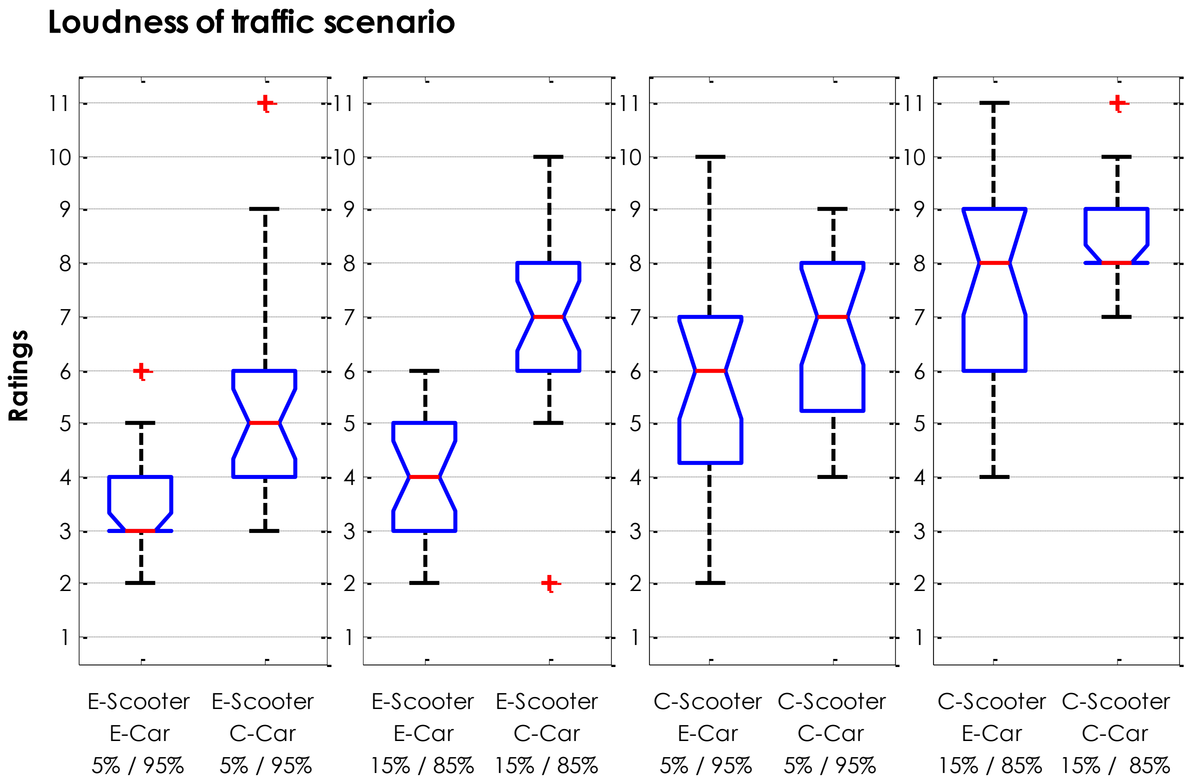


Figure 64 Ratings on the perceived loudness of the presented traffic scenarios, comparison of the surrounding cars.

Regarding the ratings on loudness of the presented traffic scenario (see Figure 64), the differences between surrounding electric and combustion engine traffic are clearly evident, but not as prominent as in the comparisons displayed in Figure 61.

Exchanging the drive of the scooters in the traffic scenarios seems to have a stronger effect on the perceived loudness than exchanging the drives of the surrounding traffic.

5.2.2 Analyses of ratings on the perceived amount of traffic

In addition to the perceived annoyance and loudness of the presented traffic scenarios, the listening test participants have also been asked to rate the perceived amount of traffic in the scenario. As described above, the amount of traffic is constant in all simulations.

Figure 65 presents the distribution of ratings on the perceived amount of traffic, again comparing the scenarios with identical surrounding traffic conditions but different embedded scooters.

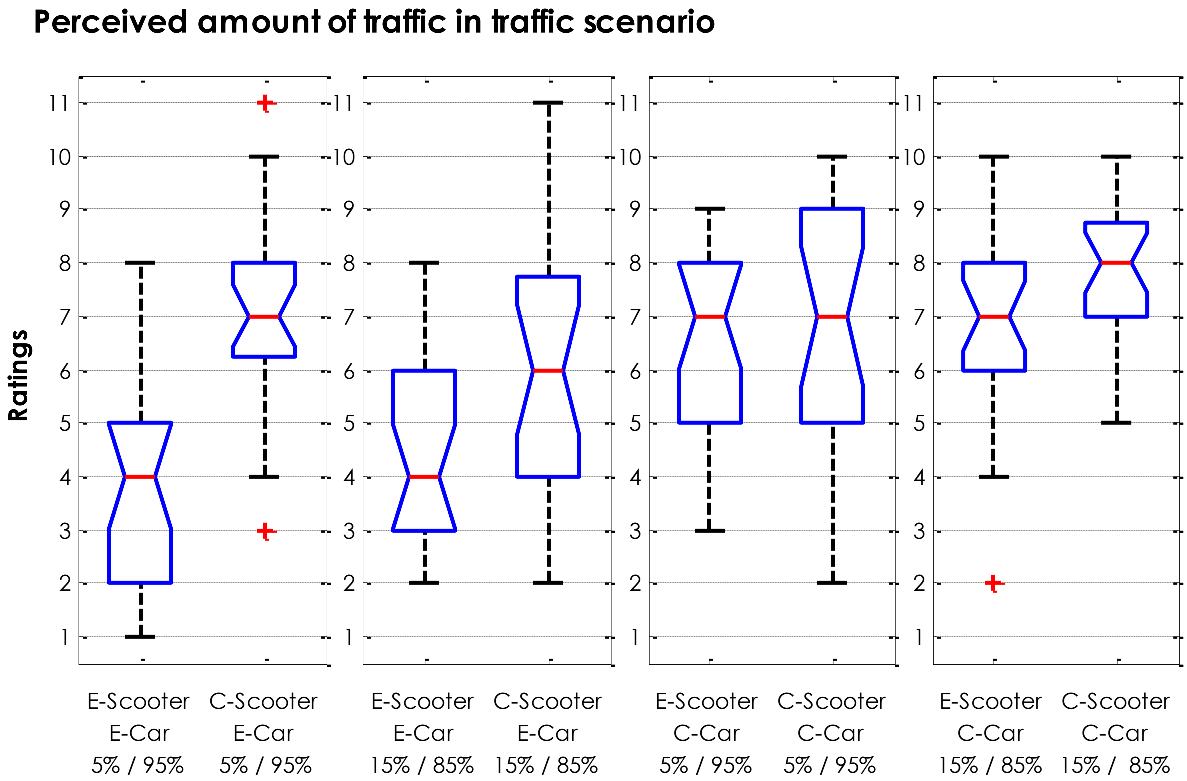


Figure 65 Ratings on the perceived amount of traffic in the presented traffic scenarios, comparison scooters.

When electric scooters are exchanged for scooters with combustion engines, the perceived amount of traffic increases as long as the surrounding traffic is consisting of electric cars only. For a low amount of scooters (leftmost subplot), this increase is considered to be significant since confidence intervals do not overlap.

This effect is reduced when the surrounding traffic is consisting of cars with combustion engines.

This means that fully electric traffic leads not only to a very low perceived loudness and annoyance respectively, but also to a subjectively perceived reduction of the amount of traffic.

5.2.3 Statistical validation

In order to validate the statistical data presented in the previous section, a two-sample, two-tailed t-test has been carried out providing information on the significance of the particular distributions of ratings. As a result of this test, the table of probability values is displayed in Figure 66, describing the probability that the mean values of two corresponding rating distributions are not significantly different when the listening test sample is extended to an infinite group of participants. A smaller p-value therefore indicates a more significant difference between the corresponding distributions.

In this case, the t-test has been carried out on the listening test data for ratings on annoyance.

P-values smaller than 0.05 are marked with (*)-signs and the corresponding differences in the distributions are considered to be significant. P-values smaller than 0.01 are marked with (**)-signs and the corresponding differences are considered to be highly significant.

	E-Scooter E-Car 5% / 95%	E-Scooter C-Car 5% / 95%	E-Scooter E-Car 15% / 85%	E-Scooter C-Car 15% / 85%	C-Scooter E-Car 5% / 95%	C-Scooter C-Car 5% / 95%	C-Scooter E-Car 15% / 85%	C-Scooter C-Car 15% / 85%
E-Scooter E-Car 5% / 95%		0,163	0,064	0,000 (**)	0,005 (**)	0,000 (**)	0,000 (**)	0,000 (**)
E-Scooter C-Car 5% / 95%	0,163		0,574	0,012 (*)	0,117	0,003 (**)	0,000 (**)	0,000 (**)
E-Scooter E-Car 15% / 85%	0,064	0,574		0,070	0,339	0,024 (*)	0,000 (**)	0,000 (**)
E-Scooter C-Car 15% / 85%	0,000 (**)	0,012 (*)	0,070		0,422	0,633	0,021 (*)	0,001 (**)
C-Scooter E-Car 5% / 95%	0,005 (**)	0,117	0,339	0,422		0,213	0,006 (**)	0,000 (**)
C-Scooter C-Car 5% / 95%	0,000 (**)	0,003 (**)	0,024 (*)	0,633	0,213		0,046 (*)	0,003 (**)
C-Scooter E-Car 15% / 85%	0,000 (**)	0,000 (**)	0,000 (**)	0,021 (*)	0,006 (**)	0,046 (*)		0,659
C-Scooter C-Car 15% / 85%	0,000 (**)	0,000 (**)	0,000 (**)	0,001 (**)	0,000 (**)	0,003 (**)	0,659	

Figure 66 Table of resulting p-values for distributions of ratings on annoyance. (*) = significant, (**) = highly significant

5.2.4 Comparison of objective and subjective evaluation

The traffic compositions have been evaluated with the help of objective and subjective analyses. A common approach to merge results of subjective and objective evaluation is the consideration of the correlation. The different objective parameters have been correlated with the perceived annoyance. The correlation coefficients are shown in Figure 67.

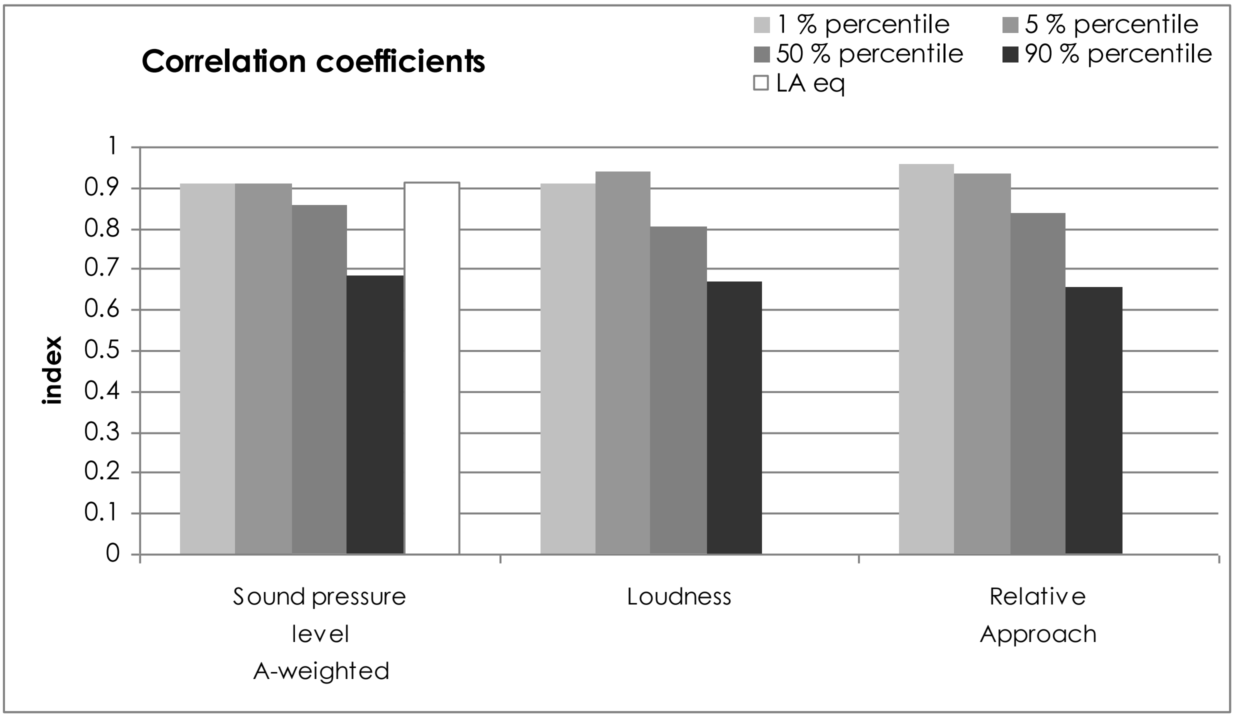


Figure 67 Correlation between the analyses percentile values and the perceived annoyance.

It can be seen that the correlation of the sound pressure level, the loudness and the Relative Approach is very high for the 1 % and 5 % percentiles. This is also true for the L_{Aeq} values. The correlation for L_{A50} and L_{A90} is clearly lower.

The high correlations of the 5 % percentile values with the annoyance prove the experiences derived from preceding research projects (*QCity*). The perceived annoyance is significantly influenced by outstanding, ear-striking and prominent noise events. This is particularly true for the C-Scooter pass-by events.

5.3 EVALUATION OF PURE SCOOTER TRAFFIC

The traffic noise synthesizer offers new possibilities to evaluate traffic noise. Where the systematic examination of traffic on the base of measurements lacks the possibility to change individual simulation parameters without affecting others, the simulation tool can be used. In this section, two different traffic parameters are evaluated separately and their influence on the values of psychoacoustic measures is examined.

The first evaluated parameter is the traffic load. Six different traffic loads from a high traffic road (1440 vph) to a very low traffic road (45 vph). The average speed of the scooters is 30 km/h. All scooters are simulated with combustion engines. The simulated sequences have a length of 400 seconds. In the preceding sections the loudness 1 % and 5 % percentiles showed a very high correlation with the perceived annoyance. For that reason, the loudness values are shown in Figure 68 for comparison of the traffic scenarios. It is remarkable that although the traffic load decreases by the factor of two for each scenario the loudness percentiles are only decreasing slightly for the first three scenarios. The rightmost scenarios exhibit a significant decrease in loudness and only for a very low traffic load of 45 vph the loudness reaches clearly lower values. From this it can be stated that the very dominant and loud events of a C-Scooter pass-by cause high loudness percentile values even when the amount of scooters is reduced significantly.

For the annoyance it can be derived that even a low share of C-Scooters lead to a clear increase of the annoyance.

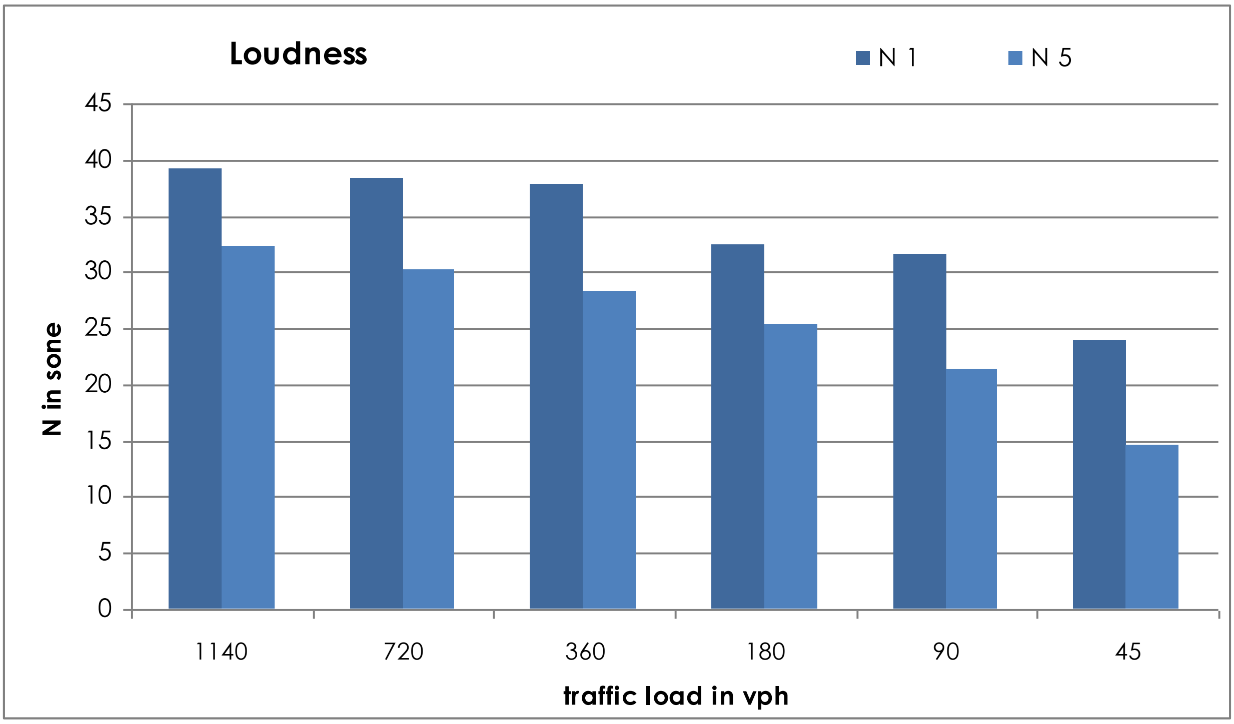


Figure 68 Evaluation of the influence of traffic load on loudness.

Another observation was made on the base of simulated traffic scenarios by varying the composition of scooter shares. The investigated scenario is again a straight road with a speed limit of 30 km/h. The traffic is a composition of E-Scooters and C-Scooters while the mixture is changed (5 different combinations). The share percentages vary from 0 to 100 % in 25 % steps. The different compositions are evaluated for three different traffic loads (360, 620 and 1440 vehicles per hour).

Figure 69 exhibits an interesting effect. While the share of C-Scooters decreases continuously from left to right the loudness percentile values do not decrease till the C-scooter share reaches 25 %. Furthermore the highest decrease in loudness can be seen for the scenario with 100 % E-Scooters.

This finding is consistent with the conclusion made above. The noise annoyance can only be reduced significantly when the C-Scooter share is reduced to a minimum or even to zero.

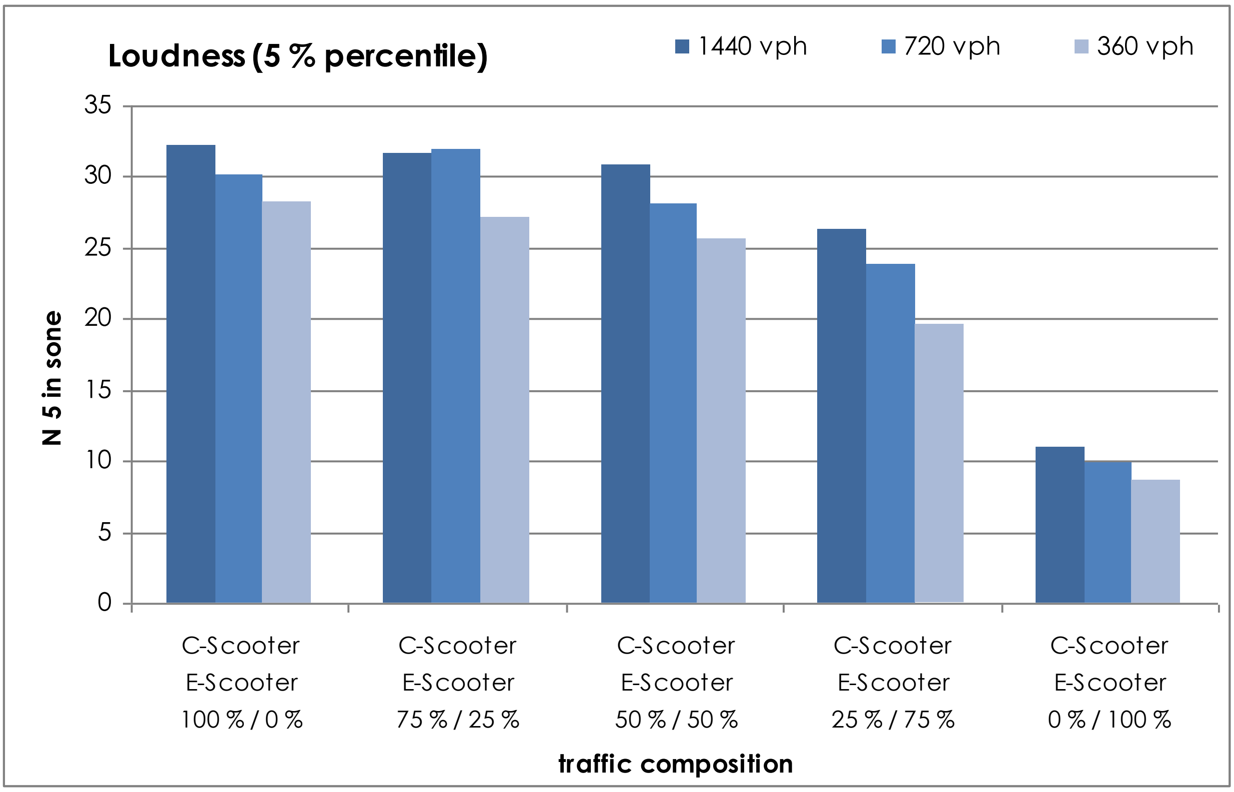


Figure 69 Comparison of different compositions with C- and E-Scooters for different traffic loads. The scenarios are evaluated with N_5 loudness values.

5.4 CONCLUSIONS

The acoustical contribution and the resulting annoyance of different scooter types (PTW) were evaluated in the context of real traffic scenarios.

The effects of an exchange of scooters with combustion engines for electrically driven scooters in different simulated traffic scenarios have been subjectively evaluated in listening tests. As a result, it can be stated that this exchange has a major impact on the perceived noise annoyance, loudness and the perceived amount of. All of these subjective parameters decrease, even for relatively low amounts of scooters within the traffic scenarios, when scooter drives are changed from combustion to electric. As expected, this effect is more prominent when the surrounding traffic consists of only electrically driven cars, since single scooter appearances do attract higher attention under these conditions. In consequence, a higher amount of scooters within the traffic scenario leads to a higher difference between the two types of drives, especially when the surrounding traffic consists of electrical cars only.

The differences in the annoyance ratings of the different traffic scenarios have been found to be significant by means of a two-sample, two-tailed t-test. The listening test results can therefore be considered to be robust and consistent.

In addition, the listening test results were compared with respect to different surrounding traffic conditions (combustion engine-equipped passenger cars vs. electrically driven passenger cars) in the context of the same scooter situation. It was found out that the improvement when introducing electric cars remains low when scooters with combustion engines are still present.

Both the objective and subjective evaluations allow for drawing two major conclusions:

First, road traffic with a certain share of scooters powered by combustion engines is always perceived as more annoying than road traffic scenarios, where only electric scooters are present. This trend is even more pronounced and significant, when the surrounding traffic consists of electric vehicles.

Second, the surrounding traffic (passenger cars) influences the noise annoyance only for road traffic scenarios, where in addition to the passenger cars only electric scooters are present. Scooters powered by combustion engines dominate the perception and evaluation to such an extent that the surrounding road traffic is almost negligible for the overall noise annoyance.