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Noise  
Session 2pNSb: Soundscape and its Application

2pNSb3. What will be the influence of e-mobility on soundscape?  
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The increasing electrification of the powertrain after 125 years of continuous development of the internal combustion engine will not only lead to a sound pressure level reduction of vehicle exterior noises but to a complete change of sound quality. With this expected development road traffic noise affected persons hope for quiet cities and a better quality of life. The creation and successful preservation of quiet zones in cities and to avoid harmful effects of noise exposure are special focuses in European noise policy. However, different surveys have shown the increased risk of accidents for pedestrians and cyclists with respect to collisions with quiet vehicles, which caused a lively discussion about acoustical warning systems for the prevention of crashes. But it is obvious, that major conflicts between quietness and safety arise. Consequently, to address this issue, on the one hand sustainable concepts must be developed for the successful avoidance of accidents and on the other hand the general traffic noise must be minimized. The sound of electric vehicles will influence in a significant way our soundscape at places and cities in the future. This is a special challenge for psychoacoustics to provide helpful contribution besides the A-weighted sound pressure level.

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INTRODUCTION

Exterior noise of electric vehicles is currently a hot topic. Since electric motors will continuously replace combustion engines within the next decades, a substantial reduction of road traffic noise in cities is anticipated. Due to the white paper 2011 released by the European Commission regarding the “roadmap to a single European transport area - towards a competitive and resource efficient transport system” [1], the increasing spread of electric vehicles is forced. The European commission proposes to halve the use of ‘conventionally-fuelled’ cars in urban transport by 2030 and to phase them out in cities by 2050. Thus, the increasing spread of electric vehicles to a certain extent can be expected despite current skepticism.

However, it is very well known that the sound pressure level reduction due to the electrification of the drive decreases with increasing driving speed. Thus, the actual acoustical benefit of electric vehicles regarding noise reduction caused by urban road traffic is often overestimated. It seems imperative in order to use the noise reduction potential of electric vehicles as much as possible to know more about their acoustical contributions not only related to single pass-by events but also with respect to full road traffic scenarios. By using measurement data a traffic noise synthesizer for the generation of complete traffic scenarios with different vehicle types and numbers was developed, which provides data about potential future road noise scenarios. The developed synthesis tool allows not only for calculating acoustical indicators of virtual traffic scenarios but also the binaural auralization of resulting traffic noises. The tool was developed in the European research project CityHush [2], which investigated step-change solutions to substantially reduce noise in city environments. The proposal of step-change solutions is necessary to fully utilize the noise reduction potential with respect to Quiet Zones. I.e. holistic noise and vibration abatement approaches addressing issues like tire-road noise, vehicle-type-oriented access concepts, psychoacoustic analyses, infrastructures as well as comprehensive emission considerations and soundscape concepts must be applied.

The investigation of the acoustical contribution of electric vehicles is not only relevant with respect to traffic noise reduction; it is also relevant in the scope of pedestrian safety with special regard to visually-impaired persons and other risk groups. As audible warning signals are recommended to avoid the danger of not hearing quiet vehicles, the “side effects” of such intentions also need to be evaluated. In this respect sustainable concepts and intelligent solutions are needed, not precipitous actions defining the introduction of improper acoustic alerting signals.

COMPARISON OF EXTERIOR NOISE OF ELECTRIC VEHICLES AND COMBUSTION ENGINE EQUIPPED VEHICLES FROM A PSYCHOACOUSTICAL POINT OF VIEW

For the comparison of a vehicle powered by an internal combustion engine with an electrical driven car, two versions of the Fiat 500 were measured on a test track in detail. A Fiat 500 powered by a combustion engine with 1.2 l, 51 kW and manual shift and a Fiat 500 Liion (electric engine) with 30/60 kW and 1 gear were measured. Both passenger cars were equipped with the identical tires (Dunlop Duratech 175/65R14). The stationary measurement was performed with a binaural receiver (artificial head) in 3 m distance to the respective car passing-by.

Figure 1 shows that only for low speed situations a significant sound pressure level difference between the Fiat 500 powered by a combustion engine and a Fiat 500 electric vehicle exists. Already in the speed range of 20 km/h a measurable difference only occurs, when the ICE vehicle is operated in the first gear producing strong combustion engine noise. Moreover, figure 2 illustrates that besides differences in level or loudness, other acoustic parameters related to noise quality should also be considered in order to fully understand the perceptual difference between ICE operated and electric vehicles. In figure 2 the result of a Relative Approach analysis [3] for the driving conditions constant speed of 10 km/h and constant speed of 30 km/h is shown. It can be observed that perceivable acoustical patterns in the time and frequency domain, quantified with the Relative Approach analysis, are more distinctive in the ICE vehicle passing-by scenarios. This means that, although the sound pressure levels are approaching between EV and ICE vehicles with increasing speed, that other signal properties are still different leading to different perceptions. It has to be added that the comparison of noise quality between the different drives is not trivial, since for example the single pass-by events of electric vehicles produces higher sharpness due to the power inverter noise and less low frequency noise. This will also effect the resulting noise annoyance.

This simple comparison shows the limited range of noise and annoyance reduction with respect to the electrification of passenger cars in typical urban driving situations (constant speed of 30 km/h).
In contrast to the moderate acoustical benefit of electric passenger cars, it is possible to achieve great noise and annoyance reduction due to a replacement of motor scooters by electric scooters. This specific noise source and its annoyance potential require particular attention, since in southern European cities powered two-wheelers are widely used and significantly influence the noise climate in urban areas. It is also well-known that scooter noise frequently provokes strong annoyance reactions, even though these noise events are usually only temporary and do not heavily influence the overall noise level.

Different powered two-wheelers were measured for the driving situations: full load acceleration from 30 km/h, 30 km/h constant speed, and starting from a standing position. In all scenarios the sound pressure levels of powered two-wheelers equipped with combustion engines are significantly higher than the SPL values of electric scooter pass-by events (fig. 3). The sound pressure levels are reduced by up to 20 dB almost independent of the respective driving condition. This shows the great noise and annoyance reduction potential by introducing electric scooters and banning motor scooters from cities [4].
HOW WILL ROAD TRAFFIC NOISE CHANGE IN THE FUTURE?

In order to predict road traffic noise of virtual traffic composition mixes beyond simple sound pressure level calculations, it is necessary to apply synthesis and simulation techniques. For that reason a traffic simulation and auralization tool was realized within the international research projects “Quiet City Transport” [5] and “CityHush” [2]. The developed synthesis technology combines measurements with simulation. A commercial traffic simulation software provides detailed information about the vehicle (vehicle type), exact position of all vehicles (x, y, gradient) and their driving conditions (speed) at short time intervals for defined scenarios. The concept of the synthesis technology is to separate between the emission of the sources and the propagation from source to receiver. On the basis of measurements a data base of vehicle exterior noise was created, which stored the noise characteristics of measured signals of different vehicle types. The stored noise characteristics and properties were gained through near-field measurements at relevant sound sources of vehicles that run through different operation modes. The simulation uses this characteristic information to process the vehicle noise emission reproducing signal properties (harmonics and orders respectively, residual noise) in dependence of the actual driving condition of every simulated vehicle within a traffic scenario (fig. 4). For further details see [5, 6].

To exemplarily investigate the effects of the occurrence of alternative drives and their impact on the overall traffic noise on the basis of the traffic noise synthesizer technology, different scenarios were created. The traffic composition (the ratio between combustion powered vehicles and electric vehicles) as well as the speed limit were varied in order to study systematically the influence of certain conditions on the resulting road traffic noise.

In the following the psychoacoustic parameter loudness, which shows a better correlation to the perceived loudness by human beings than simple sound pressure level indicators, is exemplarily considered. The respective proportions of the drives of the different cars were changed ranging from all cars powered by combustion engines to all cars fully electrified. Four mixed traffic compositions were investigated: 100 % vehicles equipped with internal
combustion engines, a ratio of combustion powered passenger cars and electric cars of 50 to 50, a ratio of 20 to 80, and electric vehicles only were studied. It has to be mentioned that the ICE and EV vehicles are modeled as medium sized passenger cars. Of course, the differences in traffic noise would increase, if the traffic would also consist of heavy vehicles with internal combustion engines.

Three receiver positions were considered in detail: close to an intersection controlled by a traffic light, close to a road section far away from any intersection (named continuous flow), a distance to the road of 50 m (named inside park situation).

As expected, the extent of differences in resulting noises varies over the different scenarios. Figure 5 shows the results of the different traffic composition mixes for the traffic light receiver position. It can be seen that due to the combustion engine noise in the phase of a red traffic light loudness differences occur and in the period, where the cars accelerate from the standing position. As expected, the mix with 100 % ICE vehicles produces the highest loudness. However, when the cars reach a certain speed, the differences decrease due to the increasingly dominating tire-road noise, which is independent from powertrain noise.

![Traffic Light (30 km/h) Loudness vs. Time (DIN 45631/A1)](image1)

**FIGURE 5.** Loudness (DIN 45631/A1) vs. time analyses of fully-synthesized binaural noises of four traffic scenarios with different traffic composition mixes with speed limit of 30 km/h and receiver position “close to an intersection with a traffic light” (left ear)

![Continuous Flow (30 km/h) Loudness vs. Time (DIN 45631/A1)](image2)

**FIGURE 6.** Loudness (DIN 45631/A1) vs. time analyses of fully-synthesized binaural noises of four road traffic scenarios with different traffic composition mixes with a speed limit of 30 km/h for the receiver position “close to a road section far away from any intersection (continuous flow)” (left ear)

The loudness of the traffic noise at the position “close to a road section far away from any intersection (continuous flow)”, where a continuous flow of vehicles with a constant speed (approx. 30 km/h) is given, is shown in the next figure. The distance to the street is comparable to the distance of traffic light receiver position. Because
of the dominance of the tire-road noise in this speed range, almost the same loudness is determined for all traffic composition mixes. Only minor loudness differences exist. The 100 % electric vehicles scenario has the lowest loudness value (N5), but this acoustical benefit is almost negligible.

In order to assess the potential differences also from a quiet zone perspective, as a receiver position a larger distance to the road was considered. As expected, the road noise contribution within the park is lower compared to the receiver positions considered in figure 5 and 6. Between the different traffic composition mixes great differences cannot be observed (fig. 7). Only a traffic light situation in great distance, where cars accelerate after idling, results in minor loudness differences (at 12 s). However, in all in all the differences in sound pressure level, loudness, and sharpness are very small within the scenario with a speed limit of 30 km/h. The tire-road noise dominates and the acoustical benefit of the electric engines remains comparatively low.

A very strict measure for effectively creating a quiet zone could be to reduce the speed limit as much as possible. Thus, the noise reduction effect regarding the different traffic composition mixes with the lowest possible speed limit was also investigated. There, the passenger cars have a speed of 7 km/h varying +/-3km/h. It was found that only in case of very low speed limits the noise reduction potential due to the electrification of the powertrain can be fully exploited. If a very low speed limit is given, like 7 km/h, then a complete ban of the ICE vehicles will lead to a high noise reduction. Even a low number of passenger cars equipped with internal combustion engines will lead to a significant increase of road traffic noise. If it is not possible within a quiet zone to establish very low speed limits than the benefit of electric vehicles will be small. The traffic noise synthesizer is valuable to study future traffic noise scenarios beyond sound pressure level calculations.

![Graph of Inside Park (30km/h). Loudness vs. Time (DIN 45631/A1)](image)

**FIGURE 7.** Loudness (DIN 45631/A1) vs. time analyses of fully-synthesized binaural noises of four road traffic scenarios with different traffic composition mixes with a speed limit of 30 km/h for the receiver position “inside the park” (distance to road is 50 m)

**IS THERE A NEED FOR WARNING SIGNALS?**

**Proposed Standard with Respect to Minimum Sound Requirements for Hybrid and Electric Vehicles (USA)**

With the publication of the report from the American NHTSA [7] the discussion about the need for alerting signals for quiet vehicles had started several years ago. In this report it was concluded that hybrid electric vehicles (HEVs) have a higher incidence rate of pedestrian and bicyclist crashes than do internal combustion engine vehicles (ICEs) in certain vehicle maneuvers (making a turn, slowing or stopping, backing up, entering or leaving a parking space, starting in traffic). This has caused a lively discussion about acoustical warning systems for the prevention of crashes to alert blind and visually-impaired persons: Which kind of signals, how loud, when and where must these sounds be emitted?

Although different publications have questioned the NHTSA study accuracy, results and interpretations [8, 9], the general need for acoustical warning signals is still unquestioned. However, it has to be stated that further research is required to reliably determine the crash risk between pedestrian/bicyclists and (H)EVs.
Recently, the U.S. department of transportation proposes new minimum sound requirements for hybrid and electric vehicles [10], which was required by the Pedestrian Safety Enhancement Act of 2010 [11]. “The proposed standard, Federal Motor Vehicle Safety Standard No. 141, would fulfill Congress’ mandate in the Pedestrian Safety Enhancement Act that hybrid and electric vehicles meet minimum sound requirements so that pedestrians are able to detect the presence, direction and location of these vehicles when they are operating at low speeds” [10]. The proposed sound should be detectable under a wide range of background noises when a vehicle is traveling under 18 miles per hour. Each car manufacturer would have a significant range of choices about the sounds, but each vehicle of the same make, model and model year need to emit the same sound or set of sounds. The proposed standard applies to EVs and to those HVs that are capable of propulsion in any forward or reverse gear without the vehicle’s ICE operating [12]. It is estimated that due to the proposal 10 fewer pedestrian and cyclist injuries caused by low speed vehicles will result. Due to [11] the alert sound is not dependent on either driver or pedestrian activation. It is expected that most manufacturers would install speaker systems that emit synthetically-developed sounds to meet the requirements of the proposed standard. It was found that synthetic sounds that resemble those of an ICE (not only containing the fundamental combustion noise) produce similar detection distances as actual ICE vehicles. In some instances, synthetic sounds designed according to psychoacoustic principles can produce double the detection distances relative to the reference vehicle.

It is explained that also the vehicle in “idling” condition (the term stationary is used) has to alert the blind person to the fact that the vehicle is not simply parked and that it may move at any moment.

The proposed timeline is that the final rule will be issued January 4, 2014 and the compliance would commence on September 1, 2015, which would mark the start of a three-year phase-in period.

Table 1: Main facts of proposed §571.141 Standard No.141: Minimum sound requirements for hybrid and electric vehicles [12]

<table>
<thead>
<tr>
<th>One third octave band center frequency, Hz</th>
<th>Min. SPL(A) requirements for sound when stationary but activated (up to 10 km/h)</th>
<th>Min. SPL(A) requirements for sound while backing</th>
<th>Min. SPL(A) requirements for 10 km/h pass-by</th>
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<th>Min. SPL(A) requirements for 30 km/h pass-by</th>
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Pitch shifting of fundamental frequency with speed is needed to signify acceleration and deceleration

The sound emitted must contain at least one tone; at least one tone no higher than 400 Hz

Sound emitted must have broadband content in each one-third octave band from 160 Hz to 5000 Hz

Any two vehicles of same make, model, model year must emit the same sound within 3 dB(A) in each one third octave band

Comments to the Proposed Standard with Respect to Minimum Sound Requirements for Hybrid and Electric Vehicles

It was shown in the preceding chapters that significant acoustical differences between electric vehicles and vehicles equipped with internal combustion engines occur only in the very low speed range. Thus it is reasonable to limit any acoustic emission to the lower speed range. However, the proposed range up to 30 km/h, where minimum third-octave band levels must be reached, could be overdimensioned. A reduction of the relevant speed range without negatively influencing safety aspects, appears possible.

The greatest challenge will be to develop concepts of enhancing pedestrian safety without neglecting ecological aspects and consequences. So far, it remains unclear, whether the goal – introducing sounds without contributing undesirably to surrounding ambient noise levels [12] – will be reached. In worst case for low speed situations the sound pressure level reduction of road traffic noise due to electric vehicles (with synthetic sounds) could be almost negligible. Moreover, the resulting noise annoyance can even be higher because of the attracting character of continuously emitted warning sounds, which due to the superposition of several sounds can lead to an unwanted cacophony level. It is clear that warning signals should not conflict with the long-term endeavors to reduce noise exposure and noise annoyance caused by road traffic noise. Since at least one million healthy life years are lost
every year from traffic related noise in the western part of Europe and approximately 1.8 % of all myocardial infarctions would be attributable to road traffic noise [13], the disadvantages related with warning signals should not be completely disregarded. In particular, with respect to the creation and preservation of quiet zones in cities potentially emerging noise problems related to introduced warning sounds must be discussed and avoided right from the beginning. The costs of noise are not comprehensively considered in the proposed standard with respect to minimum sound requirements for hybrid and electric vehicles.

Moreover, the noise annoyance will increase near intersections, because there vehicles have to decelerate and accelerate usually in the low speed range and additional sound will be emitted. It is known that near intersections annoyance judgments were even opposed to the measured averaged sound pressure levels, since the sound pressure levels are lower compared to the continuous road, but the annoyance is higher. In Germany, according to the German directive for noise control at roads some penalties have to be applied at traffic light controlled intersections and T-junctions in order to account for the fact that they are responsible for the increased annoyance perception due to the changed driving behavior of the vehicles [14]. Due to additional warning sounds the annoyance near intersection will not be effectively reduced.

On the basis of the traffic noise synthesizer technology [6] exemplarily the resulting noise of virtually introduced warning signals was investigated [15]. For it, a scenario was created, where different cars accelerate and decelerate due to the junction and right over left priority. First, the traffic noise produced by electric vehicles only was determined. This traffic noise was compared to the noise, which would result, when the electric vehicles would emit a commercial warning sound. Figure 8 shows that - as expected - the loudness increases slightly (+10%).

![Figure 8](image)

**FIGURE 8.** Loudness (DIN 45631/A1) vs. time analyses of fully-synthesized binaural noises of two scenarios: Left: Intersection with electric vehicles only; right: Intersection with electric vehicles emitting a commercial warning sound

![Figure 9](image)

**FIGURE 9.** Relative Approach analysis (left) [3] and Spec. Prominence Ratio analysis (right) vs. time analyses of fully-synthesized binaural noises of two scenarios: Intersection with electric vehicles only (first and third); Intersection with electric vehicles emitting a commercial warning signal (second and fourth)

Moreover, figure 9 illustrates the annoyance potential of the warning signal scenario. The considered Relative Approach [3] as well as specific prominence ratio analysis [16] can be interpreted in this context as an indicator for noise annoyance. The Relative Approach analysis has been proven in prior investigations to detect specific,
obtrusive, attention-attracting noise features [17]. This analysis simulates the ability of the human hearing to adapt to stationary sounds and to react on the other hand to variations and patterns in the time and frequency structure of a sound. It is clearly observable that by adding warning signals to the vehicle exterior noises of electric vehicles an increase of perceivable noise patterns in the resulting traffic noise is provoked (+20%). The prominence ratio analysis allows the detection of tonal components in the signal. The power output in a band of critical bandwidth is determined around a defined frequency. This is then related to the average power output in both of the neighbouring critical bands. It is very clear for the considered case that perceivable tonal components will occur due to the introduction of warning signals. Thus, any kind of warning sound development must consider the overall community noise impact as well, intending to increase noise annoyance as little as possible due to the introduced alert sounds.

CONCLUSIONS

In the near future the character of road traffic noise will change. Hybrid and electrical vehicles will sooner or later find their way into the future road traffic. With this development the hope raises that road traffic noise and its serious health effects can be significantly reduced. This hope interferes with recent activities to increase the pedestrian safety for blind and visually-impaired person by introducing additional synthetic sounds to electric and hybrid vehicles. It is very important to check both the potential improvement of pedestrian safety and the resulting noise annoyance. In this context, it seems imperative to investigate the effects of multiple superposed synthetic signals and the resulting detectability and recognizability of electric and hybrid cars before all regulations are fixed, instead of focusing only on single pass-by events. Only then the successful identification of the best solution with respect to the general conflict is guaranteed.

REFERENCES