EFFECTS OF LOW NOISE EMISSIONS OF ELECTRICAL VEHICLES FOR PEDESTRIAN ACCIDENT RISKS

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ABSTRACT

Following the political discussion of global warming and the political objective to support green mobility, in particular electric mobility, there is a substantial discussion whether or not electrical vehicles are dangerous for pedestrians based on their low noise level. This paper aims at answering the question regarding the specific injury risk resulting from electrical vehicles.

The study is based on two pillars. On the one hand there is the analysis of published accident data regarding the impact velocity dependent injury risk of pedestrians. On the other hand noise emissions of the same car with electrical propulsion system, gasoline propulsion system and diesel propulsion system in constant speed and acceleration are acquired.

Car noise emissions are caused by the propulsion system but also by the tyres and aerodynamic effects. The study shows that significant differences in noise emissions only exist in high acceleration phases and low speed conditions. Based on the accident data analysis both situations do not appear to be important with respect to severe injuries (low speed) and accident risk (high acceleration). In total it is estimated that the number of killed or seriously injured pedestrians will not change with the largely introduction of electrical vehicles. Accidents that are felt not to be dangerous may occur more often with silent propulsions systems.

INTRODUCTION

Based on the discussion regarding global warming a solution for road transport currently discussed worldwide is the use of electrical vehicles. However, besides the advantage of low CO_2 emissions an important drawback is discussed. That is the potential larger risk for pedestrian accidents resulting from lower noise emissions.

In order to better understand this risk, it is important to compare the noise emissions of vehicles with different propulsion systems and to assess possible differences taking into account the accident situation of pedestrians.

BACKGROUND

Against the background of current discussions on climate change, the widely use of electric vehicles is strongly encouraged by the political side. Thus, for example the German government has set the target that there will be 1 million electric vehicles on Germany's roads by the year 2020. This includes electric vehicles (EV) as well as hybrid electric vehicles (HV). HVs are vehicles that combine a conventional engine with an electric drive. While on the one hand electric vehicles can be sold only in very limited numbers, as their economical operation is still difficult, it is indicated that the use of these vehicles in everyday conditions results in a different problem. Due to the fact that electric motors emit almost no noise, EVs are more difficult to notice, especially for cyclists and pedestrians, compared to vehicles with an internal combustion engine (ICE). What leads on one side to a significant increase in quality of life for people who live in heavily travelled roads may mean on the other side that vehicles are not recognised early enough what might increase the accident risk for these vehicles especially with respect to pedestrian accidents and cyclists accidents. Consequently, this raises the question whether or not there is a need of an artificial noise generator for electric vehicles and hybrid vehicles in certain operating conditions.

REGULATION

To deal with the described issue of the low noise level of electric vehicles the Informal Work Group on Quiet Road Transport Vehicles (QRTV) of GRSP has worked out a recommendation for quiet vehicles in terms of road noise. The focus here is the so called Audible Vehicle Alerting System (AVAS). The system describes a device, which has to be installed on the vehicle to emit sounds to inform other road users on a moving vehicle. Basic intent of this recommendation is to pass it as a Global Technical Regulation (GTR), with the aim to find a common worldwide regulation [ECE/WP.29].

The American National Highway Safety Administration (NHTSA), made also a proposal for regulation for minimum sound levels for hybrid and electric cars. The draft is summarised in the FMVSS 141 and refers to a range of speed up to 18 miles per hour (29 km/h). At speeds above this limit, the driving noise can be regarded as predominant, so that an additional noise source is not necessary. NHTSA estimates that if this proposal were implemented there would be 2.800 fewer pedestrian and cyclists injuries over the life of each model year of hybrid cars, trucks and vans and low speed vehicles, as compared to vehicles without sound [NHTSA, 2013].

ANALYSIS OF PEDESTRIAN ACCIDENTS

The objectives of the analysis of pedestrian accidents were to define relevant test scenarios for the noise emission tests, to rate the noise emission test results with respect to accident data and to compare the performance of combustion engine cars with electrical vehicles. The analysis is mainly based on literature.

Most of the pedestrian accidents are happening inside towns, however, injury severity is considerably higher outside towns, see Figure 1.

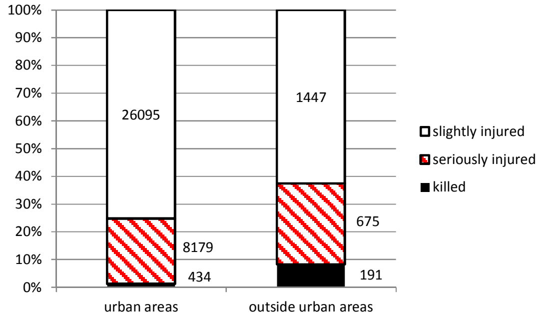

Figure 1. Pedestrian injury severity depends on accident location, German national accident data 2011 [DESTATIS, 2012].

Most of the accidents are happening in situations, where it can be expected that the car driver did not accelerate the car directly before the critical situation occurred; in 59% of the cases the accident occurred in situations outside crossings and in 4% in situations outside crossings but in curves, see Figure 2. In both situations it can be expected that the car is driving with constant speed. In the cases where the car was running straight ahead in crossings, it is unclear whether or not the car was accelerated before the accident situation; both scenarios are possible: starting up after red light or giving priority and running with constant speed. In the 10% of the cases where the car turned before the accident, acceleration of the car can be considered as being likely.

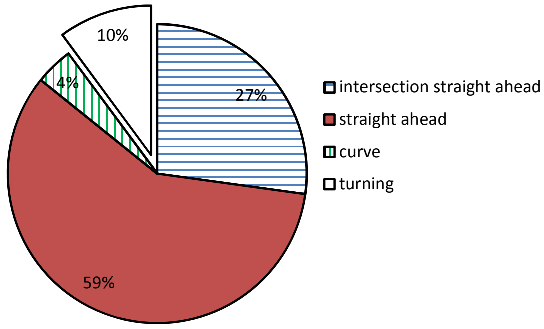

Figure 2. Locations of pedestrian accidents in the road network according to GIDAS 1999 - 2005 [Otte, 2007].

When analysing MAIS 3+ accidents, there are less accidents after the car turns and more in intersections with the car going ahead, Figure 3.

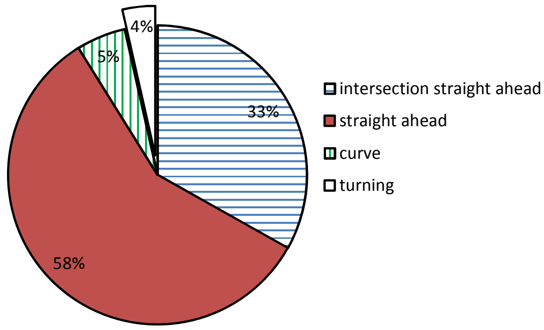

Figure 3. Locations of pedestrian accidents (MAIS 3+) in the road network according to GIDAS 1999 - 2005 [Otte, 2007].

The data is confirmed by UK data (STATS19 from 1997 – 2001) showing 74.4% of the pedestrian accidents happening in areas without pedestrian crossing facilities, and approx. 78% of the vehicles were moving straight ahead while approx. 20% of the vehicles were turning, reversing, starting up, stopping, parking etc. [Parker, 2005].

Based on typical accident situations observed in the accident data base of the German insurance organisations GDV Niewöhner et al. [Niewöhner, 2011] defined scenarios for testing of pedestrian detection systems, see Figure 4.

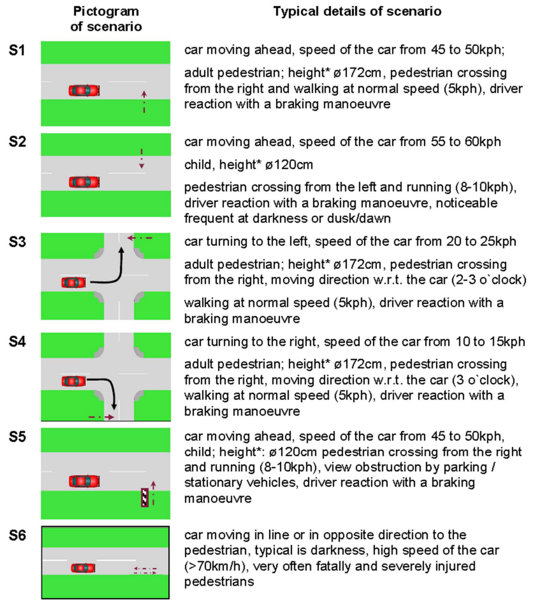

Figure 4. Scenarios for testing of pedestrian detection systems based on GDV accident data [Niewöhner, 2011].

The collision speed in the GIDAS sample ranges from 0 to approx. 70 km/h, see Figure 5. However, when taking into account injury severity severe injuries occur mainly for impact speeds above 20 km/h and fatalities cannot be expected below 50 km/h, see Figure 6.

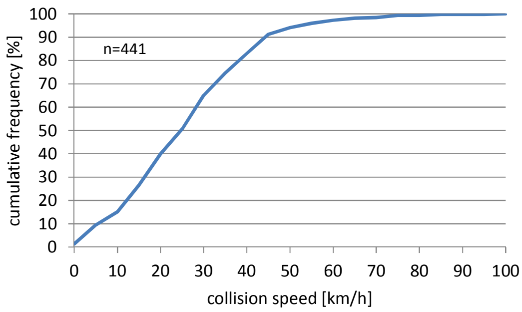

Figure 5. Collision speed, GIDAS data 1999 to 2004 [Oehler, 2005].

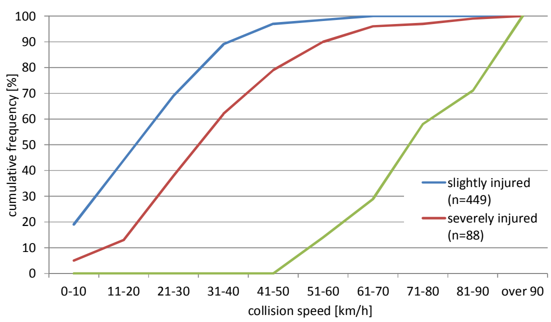

Figure 6. Injury severity depending on collision speed [Kühn, 2006].

Furthermore it needs to be considered that the collision speed is often reduced due to pre-impact braking. Driving speeds up to 20 km/h are occurring in approx. 15% of the accidents, see Figure 7.

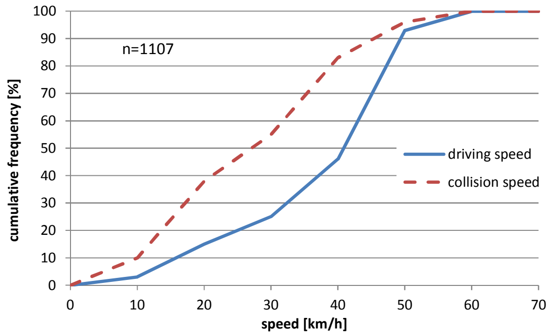

Figure 7. Driving and collision speed in pedestrian impacts [Otte, 2007].

TRL compared the risk of being involved for electrical/hybrid electrical vehicles and vehicles with internal combustion engines and concluded that the risk is equal for both propulsion types based on STATS19 data [Morgan, 2011]. However, it needs to be taken into account that for hybrid electrical vehicles it is unclear whether or not the combustion engine was running at the time of the accident. Depending on the concept of the hybrid vehicle the combustion engine is either used to propel the car directly or is just used to charge the battery. The noise emissions for both concepts are completely different.

A query concerning German national data resulted in a complete number of purely electrical vehicles being involved in any accident of 29 for 2011. Therefore it was concluded that further analysis of these cars would not result in reliable results.

In summary the accident analysis shows that a large number of pedestrian accidents are happening in situations in which the car is going straight, likely with constant speed. However, there are also accidents with cars that were accelerating prior the critical situation. In the majority of accidents the car had an initial speed of more than 15 km/h which is in line with the collision speed in accidents with severely or fatally injured pedestrians.

COMPARISON OF NOISE EMISSIONS OF CARS WITH DIFFERENT PROPULSION SYSTEM

Measurement of Sound Level

To measure the vehicles sound level, there exist different methods. For approval to the European market, vehicles are tested according to the regulation 70/157/EEC. Depending on the vehicle it passes a sound-level meter in a distance of 7.5 meter in a defined operation status. The test are repeated and considered as valid if the difference of the measurements does not exceed 2 dB(A). The sound level of vehicles intended for the carriage of passengers and comprising not more than nine seats including the driver's seat there may not exceed 82 dB(A) [70/157/EEC].

Further noise measurement regulations are described in the SAE standard J/2889/1 [SAE]. The paper specifies an engineering method for measuring the minimum noise emitted by road vehicles. Here the real operating conditions of the vehicle with its background noise are respected.

Comparison of noise emissions of vehicles with different propulsion system

To investigate the real difference of noise between different power train concepts three vehicles with different drive concepts were compared. For this measurement a BMW E-Mini (EV), a diesel-powered BMW Mini and a BMW Mini with petrol engine were used. The tests were conducted in accordance with regulation 70/157/EEC (see above). A comparison of the three vehicles in terms of its technical data is shown in Table 1.

Table 1.
Properties of tested vehicles

Vehicle type, description	**MINI Cooper D Clubman**	**MINI Cooper**	**MINI E**
Engine	4 cylinder/ 16V	4 cylinder/ 16V	electric motor
Cubic capacity	1600 ccm	1600 ccm	(Max. speed 13000 min^{-1}; isolation: Class H, double-insulated)
Nominal power/ rated speed	80 kW at 4000 min^{-1}	88 kW at 6000 min^{-1}	150 kW at 7000-8000 min^{-1}
Max. torque/ number of revolutions	240 Nm at 1750-2000 min^{-1}	160 Nm at 4250 min^{-1}	220 Nm at 0-5000 min^{-1}

<u>**The results of the noise measurement**</u> according to 70/157/EEC have shown that the E-Mini, with a noise level of 73 dB(A), is quieter than the diesel- and the petrol-Mini with 77 dB(A) and 84 dB(A). These values were measured in the second gear with 75% of full power, wherein E-Mini in the corresponding operating condition were used. In all three cases the measured sound levels are above the values that are specified on the registration document. The differences may be due to the fact that the ground was wet at the time of measurement, which increases the rolling noise of tires normally.

Table 2.
Maximum pass-by noise level Mini tests

	Maximum noise level, dB(A)		
Speed [km/h] **Gear**	**Mini diesel**	**Mini petrol**	**Mini electric**
5 (1. Gear)	*	53	*
10 (1. Gear)	57	58	50
20 (2. Gear)	60	58	58
30 (2. Gear)	66	66	63
30 (3. Gear)	*	63	
50 (3. Gear)	71	70	70
50 (4. Gear)	71	*	
70 (3. Gear)	76	75	75
70 (5. Gear)	75	74	

*measurement invalid

The measurement of road noise at different speeds showed a mixed picture. At speeds below 20 km/h, the electric vehicle is clearly quieter; above this speed it is difficult to identify differences between the cars (*Figure 8*).

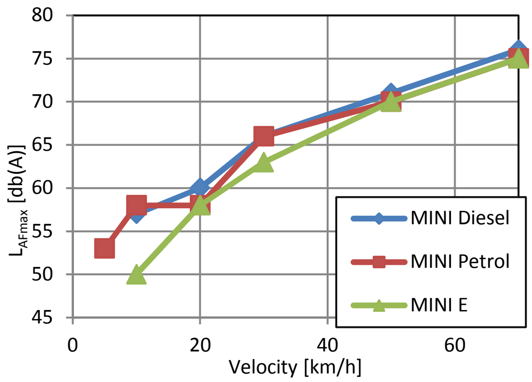

Figure 8. Sound level for different speeds.

It can be assumed that, above a speed of 20 km/h, the driving noise is dominant and noise from the engine, regardless of its type, plays only a minor role.

Thus, according to the objective measurement results of the sound recording significant differences between electric vehicles and conventional vehicles can be observed only at low speeds.

Zeitler et al. [Zeitler, 2010] analysed the distance to a pedestrian when an approaching car (driving speed 10 km/h) was audible recognised under different environmental noise levels. In summary independent of the environmental noise level the electrical car was recognised very late, above 47 dB(A) not until the car approached the position of the pedestrian, see Figure 9. The hybrid car that was used in ICE mode was recognised later than the ICE car and the hybrid vehicle that was used in electrical mode was noisier than the electrical car but less noisy than the ICE car.

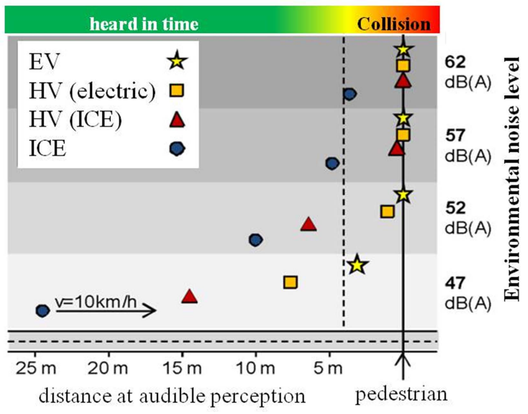

Figure 9. Distance to vehicle when detecting it [Zeitler, 2010].

Tests Conducted by TRL The tests results described below were conducted and published by [Morgan, 2011]. In this investigation two test rows were conducted. On the one hand objective noise measurements, where the noise level of different cars was recorded and on the other hand subjective noise assessments, where probands were asked about their noise perception. It is important to note, that TRL did not distinguish between EV and HE. They were combined to E/HE (electrical and hybrid electrical) vehicles.

For the measurement tests three different test were conducted: A “steady-speed pass-by test”, where a car passes the microphone with a constant speed, a “Pull-away from rest test”, where the car accelerated in front of the measurement device and a “Low-speed parking test”, where vehicles were both driven forwards and reversed out of a conventional parking space at typical speeds.

Table 3.
Maximum pass-by noise levels at microphone position M3 [Morgan, 2011]

	Maximum noise level, dB(A)			
Vehicle	**7-8 km/h**	**20 km/h**	**30 km/h**	**50 km/h**
ICE-01	57	62	69	77
ICE-02 *	65	74	75	81
ICE-03	51	62	68	77
ICE-04	58	66	73	81
E/HE-01	56	64	70	79
E/HE-02	53	63	70	77
E/HE-03	52	63	70	76
E/HE-04	56	66	72	80
*not included in the analysis below				

The results of the pass-by test showed no significant differences between electric vehicles and cars with combustion engine (Table 3).

The E/HE vehicles were from 2 dB(A) quieter to 1 dB(A) louder than the ICE vehicles. On average, the E/HE vehicles were only 1 dB(A) quieter than the ICE vehicles. The quietest ICE vehicle is comparable to the quietest of the E/HE vehicles. For the E/HE vehicles, the spread is less than that for the ICE vehicles. At higher speeds, the range across all vehicles is more consistent because road noise becomes the dominant source. In *Figure 10* the maximum sound level is shown where it can be seen that all vehicles have a similar trend.

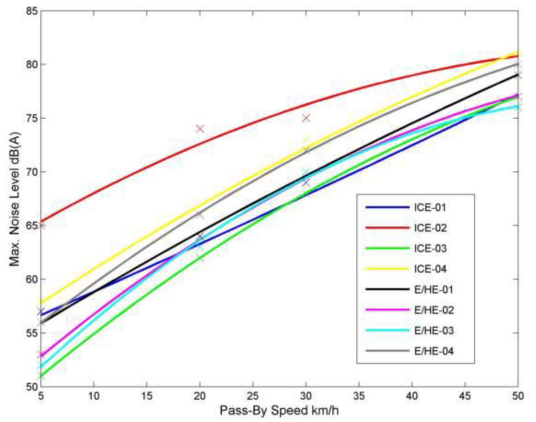

Figure 10. Maximum noise levels for steady-speed pass-by measurements [Morgan, 2011].

The results of the pull-away tests showed, that for low acceleration the electric vehicles were a bit quieter than the ICE vehicles (1 dB(A) in average) and for the higher acceleration the electric vehicles were in average 2 dB(A) quieter.

The parking manoeuvres showed that the absolute noise levels for the majority of the vehicles were not significantly above the background noise levels at the test location.

The objective measurements indicated that for lower speeds where powertrain noise is the dominant source, electric vehicles are in average 1 dB(A) quieter than ICE cars. However, it has to be noted that background noise levels at these speeds are typically only 3dB(A) below the noise level of the vehicles. That means if there is a certain problem with silent cars it possibly should discussed for all cars and not only for electric vehicles.

The subjective tests of [Morgan, 2011] were conducted with 10 vision-impaired participants using a series of audio samples of both vehicle types (electric and ICE), which were moving at different speed and were performing different manoeuvres, which were pass-by at 20 to 50 km/h and a vehicle manoeuvring out of parking spaces. The participant's task was to identify when they became aware of the presence of the vehicle and to find out if they were able to distinguish the vehicle type. The exercise assumed that, for the most part, the vision-impaired participant was a pedestrian standing at the kerbside, as if waiting to cross the road. The background noise was divided into two scenarios: urban area and semi-rural environment.

In the analyses of the results the risk exposure, based on the assumption that there is always some element of risk for road crossing pedestrians, was assessed. Risk exposure was deemed to be 'increased' if the presence of the vehicle was detected at a distance less than typical safe stopping distances or not detected at all. The results showed that the likelihood of increased risk exposure is 1.4 times greater in a semi-rural environment for electric vehicles than for ICE vehicles, irrespective of vehicle speed or manoeuvre, and 1.3 greater in an 'urban' environment. Irrespective of the background environment, the study indicates that the likelihood of increased risk exposure was 1.4 greater for E/HE vehicles than ICE vehicles. The risk exposure for pass-by tests increases with decreasing speed. Under steady-speed conditions, participants were more than twice as likely to correctly identify ICE vehicles as E/HE vehicles in a rural scenario and almost twice as likely to correctly identify the vehicles in an urban scenario. When the vehicles were accelerating from stationary, subjects were far more easily able to identify both vehicle types.

In summary it can be said that the objective tests of the TRL study [Morgan, 2011] confirmed the tests with the Minis. From a speed of 20 km/h or above, there is nearly no difference in terms of noise levels between ICE and electric vehicles. At lower speeds electric vehicles are quieter. The result that noise emissions are equal above 20 km/h is also confirmed by Zeitler et al. [Zeitler, 2010].

By contrast the subjective tests of the TRL study [Morgan, 2011] with vision-impaired people have shown that the risk of insufficient perceptibility of electric vehicles is higher than for ICE. This applies in principle to all performed manoeuvres.

NOISE PERCEPTION

The comparison of the noise emissions of different propulsion systems with the subjective assessment whether or not a car was recognised opens the questions for the deviation between both. In principle the following hypothesises are discussed:

- the A-weighted sound pressure level is not suitable for the evaluation of the detectability of the noise emitter,
- humans are mainly using the engine noise in order to distinguish between moving objects (cars) and stationary objects
  - this vehicle detection strategy is trained following the experience on the road and can be adopted to future changes
  - the strategy is a result of psycho-acoustic capabilities and cannot be adopted

It is likely that a combination of the hypothesis is causing the discrepancy.

There are three main sources for noise emissions in a car. These are the engine noise, the aerodynamic noise and the noise resulting from the wheel-to-road contact. While the first one is different in EV compared to vehicles with internal combustion engine the two latter ones are similar in both propulsion types.

Noise emissions of cars are evaluated using the A-weighted sound pressure level that represents equal noise perception across the frequencies at 40 phon, resulting in heavy filtering in the range of 10 – 100 Hz.

When analysing the frequency band from the TRL study, it is obvious that the vehicles with internal combustion engine show a peak in the loudness in the frequency range between 10 – 100 Hz, see Figure 11. These peaks are resulting from the noise of the internal combustion engine. It can be expected that E/HE-02 is a hybrid electrical vehicle with the internal combustion engine running at the time of measurement.

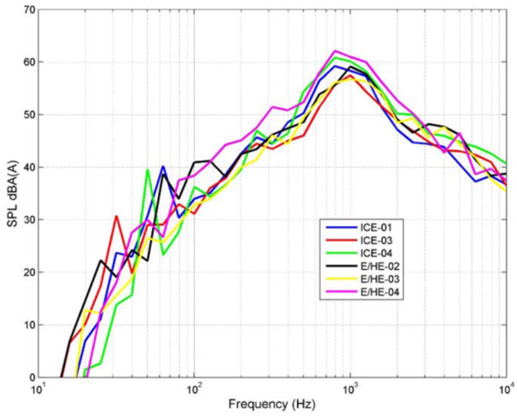

Figure 11. One third octave spectra corresponding to maximum noise level at a pass-speed of 20 km/h [Morgan, 2011].

In contrast to the statement of TRL that the differences in the spectral content do not suggest any difference how a pedestrian would be able to differentiate between vehicle types, the peaks from the combustion engine and exhaust, although weighted in the dB(A) assessment relatively low result in an important difference in the noise perception of a vehicle. Similar results were described by Zeitler et al. [Zeitler, 2010]. It is questionable whether or not the A-weighted sound pressure levels are suitable for assessing the audible vehicle perception by pedestrians.

This analysis suggests that the engine noise is very important for the perception of the noise emitter. However, it remains questionable whether or not pedestrians can train themselves to better perceive vehicles with electric propulsion system. With respect to the aerodynamic noise it can be expected that it is impossible to distinguish between any stationary object that is passed by the wind or a car that moves through the air. Besides this the tire noise seems to be unique and can likely replace the engine noise in the vehicle perception. However, this needs to be further analysed taking into account psycho-acoustic evaluation.

DISCUSSION AND CONCLUSION

The objective noise measurements within this study and the study conducted by TRL show that the noise emission of ICE and EVs is equivalent constant speeds above 20 km/h using the A-weighted sound pressure. Below 20 km/h the ICE noise dominates the vehicle's noise emissions, this is also the case for accelerating vehicles.

Today, the noise of the combustion engine appears to be the main source for the audible detection of vehicles. The absence of the engine noise might lead to wrong assessment of the situation even for EV driving faster than 20 km/h. However, it is expected that the tire noise can replace the engine noise in the perception of cars if the latter one disappears.

The analysis of accident data showed that pedestrian accidents mainly occur in situations where the car driver is going straight ahead and where constant speed of the car can be expected. Accidents with slight or severe injuries are very seldom for vehicle driving speeds below 20 km/h. When transferring these data to the noise emission results, it is obvious that for those situations where EVs are significantly less noisy pedestrian accidents do not occur very often (vehicle is accelerating when approaching the pedestrian) or are not considered to be of high severity.

In total the pedestrian accident risk might increase with the large scale introduction of EVs, but it is not expected that the injury risk for pedestrians is increasing from that measure.

For future developments like the introducing of AVAS for electrical vehicles one needs to consider that there will be more than only one electrical vehicle driven on the road and the artificial noise may accumulate to an unacceptable level [Genuit, 2012]. To get a better understanding of vehicle noise perception further investigation is needed. Especially the need of artificial sound generators should be discussed with respect to accident data.

ACKNOWLEDGEMENTS

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