Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Are vehicles driven in electric mode so quiet that they need acoustic warning signals?

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PACS: 43.50Lj, 43.66.Qp

ABSTRACT

It has been suggested recently that vehicles, driven in electric mode, either hybrid or pure electric vehicles, are so quiet that they constitute a safety hazard for pedestrians and bicyclists in traffic. It is claimed that such vehicles are not acoustically perceived due to the power unit being exchanged from a combustion engine to electric motors; something that essentially cuts away all power unit noise and leaves tyre/road noise, the latter of which is the same as for similar-sized vehicles with combustion engines. There are currently a number of fast and concerted actions by the US and Japanese governments as well as within international bodies such as UN/ECE and ISO, with the expected outcome that "minimum noise" of vehicles shall be measured with a standard method and legal limit values for such "minimum noise" shall be established. The paper present findings regarding possible traffic safety effects of quiet vehicles and concludes that only a US study has identified such effects. A critical review leads to the conclusion that this study may be biased and needs confirmation by further research. After reviewing data from noise measurements in Japan, the authors present own previously unpublished data on noise emission levels for road vehicles which may be considered as "quiet". Special concern is given to noise at speeds below 20 km/h where it is expected that the problem might be the worst and where previous data are missing. It is concluded that already a significant number of our present internal combustion engine vehicles are so quiet at low speeds that normally one cannot hear any difference between an electric and a normal vehicle in an urban area. Tyre/road noise is the dominating noise in most cases where a light vehicle is driven at speeds at or above 15-20 km/h (heavy accelerations are the exceptions), and this is the same whether the vehicle is electric or not. Thus, it is a property of our vehicle fleet which we have had for more than a decade, and few have considered that as a safety problem. Therefore, there is not enough justification for equipping our future quiet vehicles with extra artificial noise or warning sounds. If needed at all, there are better options which are non-acoustical.

INTRODUCTION

It seems that the world's vehicle fleet is rapidly changing. Electric (EV) and hybrid vehicles with electric drive (HEV) are becoming more and more popular and frequent. Also among heavy vehicles for urban use, such as busses and delivery trucks, hybrid vehicles are gaining in popularity. A leading businessman and analyst, Mr Ulrik Grape, President of Ener1 in Europe, recently predicted that in the next 20-30 years "all cars will be electrified somehow" [AD, 2010]. An indication of this trend is that the Japanese Government has announced that its goal is that in 2020 at least 50 % of all cars sold should be electrified [Yoshinaga & Namikawa, 2009].

Driving in electric mode means that the propulsion will be much quieter than for today's quietest cars and trucks, although the electric power units are not silent. This is a breakthrough in urban noise reduction, with a potential to significantly reduce noise emission at intersections, in congested traffic and in other cases where speeds are low. However, due to tyre/road noise being unaffected, the overall effect of a fully electrified vehicle fleet will be approximately 4 dB(A) lower noise at the most favourable location before and after an intersection and 2 dB(A) as an average, according to calculations [Yoshinaga & Namikawa, 2009]. With simultaneous tyre/road noise reductions, which are likely to happen, the overall noise reducing effect will be higher. But how do we make use of the improvement potential, which may mean not only higher quality of life but also less health problems in those environments?

It has been suggested recently that vehicles, driven in electric mode, either hybrid or pure electric vehicles, emit such weak noise that they are a safety hazard for pedestrians and cyclists in traffic. Following such fears, EV:s and HEV:s have sometimes in various documents and press articles been portrayed as "some kind of shark in the water" [NY Times, 2010]. A special informal group "Quiet Road Transport Vehicles (QRTV)" to deal with this "problem" was established within the UN/ECE/WP29/GRB in 2010 [QRTV-1, 2010]. Similar national groups have been established both in USA and in Japan [JASIC, 2009-2]. The interest in this matter is enormous, as illustrated by the fact that at the QRTV's 2nd meeting the number of members in this informal group was 33 and the meeting was attended by more than 50 people.

In this paper, the authors present a review of the problem and the solutions suggested, but also critically look at the relevance of the problem.

THE PROBLEM

Problem statement

So what is the problem getting such an attention?

One of the more common causes of collisions in cities is pedestrians stepping onto the roadway. In the US, more than 11 per cent of all traffic fatalities are with pedestrians and in Japan, this scenario accounts for about 30 per cent of all fatal collisions [Volvo, 2010]. In Europe it is 14 % [DN, 2010].

It is claimed that electric vehicles (EV) or hybrid vehicles driven in electric mode (HEV) are not heard due to the power unit being exchanged from a combustion engine to an electric engine, and that this may cause collisions with pedestrians; especially visually impaired people.

In the terms of reference for the above mentioned QRTV group [QRTV-1, 2010], it is stated:

> The UNECE World Forum WP.29 has determined that road transport vehicles propelled in whole or in part by electric means, present a danger to pedestrians.

There is no information about the source for this statement.

Safety hazard?

It is beyond doubt that visually disabled pedestrians depend to a large extent on acoustical cues in a situation where road traffic is present. Also pedestrians and bicyclists with normal vision use acoustical cues in the traffic, but these are not as crucial for them as for the visually disabled. It goes without saying that eliminating sounds that are used in such situations might pose a safety hazard. Nevertheless and unfortunately, this is frequently a choice of today's younger pedestrians and bicyclists, many of whom listen to music in earphones while standing, walking or cycling in road traffic.

For example, for visually impaired, the following statement was made in May 2010 by the National Federation of the Blind in USA and a few other organizations [NFB, 2010]:

> The National Federation of the Blind (NFB), the American Council of the Blind (ACB), the Alliance of Automobile Manufacturers (AAM), and the Association of International Automobile Manufacturers (AIAM) announced today that they have agreed on proposed legislative language that will protect blind pedestrians and others from the danger posed by silent vehicle technology. The four organizations are urging Congress to adopt and pass the language as part of the Motor Vehicle Safety Act of 2010—which is currently pending in both houses of Congress—as quickly as possible. The proposed language would require the Department of Transportation to promulgate a motor vehicle safety standard requiring automobiles to emit a minimum level of sound to alert the blind and other pedestrians.

When the power unit sound of an ICE vehicle (ICE = Internal Combustion Engine) is replaced with the sound of an electric motor, the latter of which is quieter and probably less distinct, or when the ICE sound is so quiet that it is not easily heard, this might potentially lead to some pedestrians, especially the blind, not observing an oncoming vehicle in due time. However, this "common sense" observation does not necessarily mean that accidents due to this are common.

Reasons are that there is also sound from the tyres, and it is the responsibility of vehicle drivers to observe pedestrians and their behaviour. If they see a blind person (with a stick or a leader dog) they are hopefully extra careful. This is the ideal world, and of course it does not always work like this.

Therefore, one should look at the traffic safety statistics related to especially quiet vehicles. The authors are aware of only two serious studies with scientific approach and relevance, and these are:

- NHTSA report from 2009 "Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles" (from USA) [NHTSA, 2009]
- RIVM report from 2010 "Effect of electric cars on traffic noise and safety" (from the Netherlands) [Verheijen & Jabben, 2010]

The NHTSA report concluded:

> This study found that HEVs have a higher incidence rate of pedestrian and bicyclist crashes than do ICE vehicles in certain vehicle maneuvers.

A chapter later in this report will deal further with the NHTSA report. The RIVM report listed above concluded:

> Up to now, no statistical evidence is found in the Netherlands and in Japan for a higher incidence rate for hybrid cars and pedestrian or bicyclists."

The RIVM authors also critically reviewed the NHTSA report and concluded:

> In the United States, however, a significant relationship has been found. In situations where cars drive slowly (slowing down, stopping, backing up, parking maneuvres) hybrid cars were involved twice as much compared to conventional cars. Though the meaning of that statistical investigation can be argued, it is obvious that attention should be pay to the potential risks.

WHAT IS AT STAKE?

To reduce the anticipated safety hazard it has been suggested, and in Japan even decided, that artificial sound generation shall be required for "quiet vehicles". There are hundreds of more or less serious speculations or ideas of how such sound should be constructed in reports/papers, in mass media and on the Internet, but it is obvious that it should be audible and bring attention to pedestrians in relation to other (masking) sounds. In such a scenario, instead of EV:s and HEV:s giving us a quieter acoustical environment, they will in the best case result in an environment much the same as the present one, and in the worst case result in a cacophony of alerting sounds mixed with conventional vehicle and tyre/road noise.

The RIVM report expresses it in this way in its conclusions:

> If the Economic Commission for Europe (ECE) will adopt such minimum noise levels, the future soundscape at crossings, parking lots, and 30 km/h zones in Europe may be dominated by artifical sounds. This will affect the potential reduction of noise annoyance found in this study and thereby the reduction of adverse health effects that are caused by noise annoyance. In this respect, it is recommended to investigate other safety measures than minimum noise levels or continuous warning sounds.

Thus, one may fear that what is at stake is our future acoustical environment in areas where low-speed road traffic dominates the soundscape.

SOME COMMENTS ON THE NHTSA REPORT

The NHTSA report concluded as follows [NHTSA, 2009]:

> In conclusion, this study found that HEVs have a higher incidence rate of pedestrian and bicyclist crashes than do ICE vehicles in certain vehicle maneuvers. These results should serve as a guide when designing future HEVs' pedestrian and bicyclist crash prevention programs. NHTSA will continue monitoring the incidence of pedestrian and bicyclist crashes involving HEVs. In future, a larger sample size would allow us to perform a more detailed analysis, such as limiting the entire analysis to low-speed crashes, analysing different vehicle maneuvers individually, etc. Data findings on this study will be updated when new State Data System and other data sources become available.

In the study, the incidence rate of crashes between road vehicle and pedestrians and bicyclists were compared for HEV:s versus ICE vehicles, where the rates were counted as percentages of the incidence rate of crashes for the respective vehicle category in total. This way of counting is understandable but has the weakness that the result depends equally much on the number of crashes with pedestrians as it depends on the total number of crashes for that vehicle category. It means that if the number of crashes for HEV:s would be relatively lower than for ICE:s, in relation to the "traffic work" that each category accounts for, the rate of pedestrian crashes would be overestimated in comparison to a case where it is related to the "traffic work" (vehicle-kilometres driven).

The authors think that there are some details in the NHTSA report which are arguable or at least unclear. It should first be noted that the data are from years 2000-2007. The sales of EV:s and HEV:s in USA speeded-up dramatically from 2005 [DoE, 2010]. It means that until the end of the period 2000-2007 it was still a little "exclusive" to own such a vehicle and it is reasonable to assume that the majority of drivers would be people with some extra concern for the environment; usually implying that they would also drive more carefully than most other drivers. It would not be surprising if this would mean that the number of crashes of such vehicles would be lower than for the ICE vehicles if calculated in relation to the traffic work that they actually did.

One may also wonder if it is fair to compare incidence rates between two vehicle categories when one of them (HEV) constitutes only approx 1.5 % of studied vehicles compared to 98.5 % of the other vehicle category (ICE). The 1.5 HEV:s may be exclusive in some way or be driven by exclusive drivers, something which may give a bias to the comparisons rather than showing differences between the vehicle safety aspects. The vast majority of HEV:s in the NHTSA study are of Japanese production and were only a few years old in this study, most of them only 1-2 years old. The authors expect that these new Japanese vehicles would meet higher safety standards, than the probably much older mix of ICE vehicles. If there would be a geographical bias in the data this may also affect the results. So far, California has been the state strongly leading hybrid sales in the U.S.

If HEV:s were driven at very low speeds relatively more frequently than ICE:s, which is unknown but which would not be surprising, this would logically mean that the HEV crashes would have a stronger bias towards the lower speeds, and thus involving cases where the quietness could be of importance more than would be the case for ICE vehicles.

Assume that the overall crash incidence rate in relation to traffic work would be 30 % lower for the new HEV:s than for the mixed old and new ICE:s. Then the (approximately 30 %) poorer incidence rates for pedestrian crashes of HEV:s versus those of ICE:s reported by NHTSA would turn into approximately equal rates.

The NHTSA authors do not discuss these issues.

In conclusion, the authors think that the NHTSA report shows that there was in the US data of 2000-2007 a non-disputable higher incidence rate for crashes between pedestrians/bicyclists and vehicles *in relation to other types of crashes* for HEV:s compared to similar statistics for ICE:s. This is quite clear and consistent for several sub-analyses of the data. However, this does not necessarily mean that the risk for a pedestrian/vehicle crash was higher for an HEV than for an ICE vehicle, since it could well be that the HEV:s exhibited fewer total number of crashes to compensate for it.

Therefore, the authors think that the NHTSA report is not a safe source to say that HEV:s are less safe than ICE:s due to quieter power units. More research on this is needed and then one should attempt to relate the accident rates to traffic work rather than to the accidents of each vehicle category and attempt to remove potential bias due to driving distance, geographical differences and driver behaviour. This is not an easy task, but if the problem is as serious as some people think such analyses are needed, since our future vehicle fleet will be very different to what it is today.

IS THIS A NEW PROBLEM?

It seems to be assumed by most people that the problem of not hearing approaching vehicles is something new which is strongly correlated with the introduction of EV:s and HEV:s in traffic.

The reality is far from that. When this first author started to work with road vehicle and tyre/road noise in the mid-1970's, both Volvo and Scania supplied busses for the Swedish urban market which met the 80 dB(A) noise limits according to ISO 362. They typically emitted 76-77 dB(A), which is comparable to the most modern busses in Europe and Japan today, 35 years later; and far below most of today's busses in USA. The Scania busses had diesel engines mounted at the rear and the Volvo buses had them usually mounted in the middle. The author hundreds of times had the experience that these relatively quiet busses approached sneakingly, sometimes almost inaudibly until some 20-30 meters away, which created surprise reactions. Despite this, there was never any safety problem reported or noted due to this, as far as known to the author or his VTI colleagues who are traffic safety analysts.

From 1996, cars in Europe have had to meet the same noise level limits as today (74 dB(A) according to ISO 362). The spread in results was and is dramatic; some measured only 68 dB(A). The luxury types of these cars are usually designed with quiet engines since this gives an impression of a luxury car (except some of those which also are sold as sporty models). In USA, such luxury cars and limousines (usually having V8 engines) have been common for many decades. It is undisputable that such cars are so quiet that it may be hard to hear other than tyre/road noise from them when they approach a listener, and at idling they are very quiet.

When a car approaches a stop light or an intersection when it is necessary to slow down to very low speeds; i.e. at most low-speed (< 20 km/h) driving conditions, it is common that the driver uses the clutch to release the transmission and run the engine in idling condition. In idling condition, the power unit is hardly heard unless one stands nearby a stationary car. This means that already many years before HEV:s were introduced, it was common that cars approaching an intersection with stop lights (showing red) were running with idling engines; i.e. at essentially equally quiet conditions as today's EV:s and HEV:s in electric mode. This is verified in a later section of this paper.

For example, in a VW Golf ecomatic, which was released about 20 years ago, the engine was cut-off every time you took your foot off the accelerator pedal; thus tyre/road noise was the only sound emission source. Furthermore, there are people in Europe who do this in "normal cars", which means, they switch-off the engine when they are coasting (the authors think that this may apply only to modern cars equipped with automatic “engine cut-off” systems). Many driving schools in Germany teach their students to drive in this way in order to save fuel. In none of these cases, some extra sound source has ever been suggested [Kirrman, 2009].

Based on the above qualitative discussion (later in this paper verified by measured data), the authors conclude that quiet vehicles approaching a place where pedestrians may want to cross a street or road have been common-place in the past 20-30 years; at least as common as today's EV and HEV vehicles. Under certain conditions, these vehicles are more difficult to hear and to identify than "normally noisy" vehicles, but we have lived with this potential problem for several years without identifying it as a traffic safety problem causing accidents at a noticeable rate.

THE URBAN ACOUSTIC ENVIRONMENT

What kind of sound levels do we have in urban areas today? Close to streets and roads, where pedestrians or bicyclists would dwell it would be rare to find places with LAeq < 55 dB, except in residential streets with relatively little traffic. As an example, in [Yamauchi et al, 2010], the quietest background noise was at 60 dB(A) in an environment described as "narrow road in shopping area". The three other conditions used as typical cases had levels of 66, 68 and 73 dB(A). In the background noise situations used in [JASIC, 2009-1], levels of 45 or 53 dB were used as low and medium backgrounds, but the areas typical of these were low traffic areas where vehicles typically pass one by one.

According to the traffic noise prediction model Nord 2000, the AADT of a road in a residential area with 30-40 km/h traffic will have to go below 500 to give an L_{Aeq} level of around 50 dB at 10 m from the centre of the road. A traffic volume of 500 vehicles per average 24h day, means approximately one vehicle pass-by per 2 minutes.

In cases where vehicles pass one by one, it is likely that they would run at a speed of at least 30 km/h and, as shown later, there would be no difference in sound between a typical HEV and a typical ICE vehicle. Exceptions would be if the vehicles would be forced to stop for some reason, but in such a case they should have been observed acoustically already while they were still running at 20-30 km/h. Such situations would not be potentially very dangerous as there would normally be only one vehicle present and probably only one or a few pedestrians, who would be easy to observe by the driver.

The authors therefore argue that, with few exceptions, cases where background noise levels are below 55 dB at the street-side would normally mean that most vehicles pass one by one and at speeds well above 20 km/h, and if ever below 20 km/h, the overall traffic situation should be non-critical. However, it is recognized that blind people may find these few situations at speeds below 20 km/h worrying, but one should then keep in mind that the drivers should normally observe the blind in such a low-conflict situation. Of course, there will always be cases, albeit rare, when all possible exceptions (blind pedestrian stepping out in the street, speed of approaching car below 20 km/h for several seconds and driver stressed by something unusual) occur simultaneously and an accident may be close or actually happen. But the authors believe that such occasions would be so rare that they would give very little impact on accident statistics in relation to all other vehicle-pedestrian collisions.

It must be pointed out that the A-weighted noise level of a passing vehicle or the A-weighted equivalent level of background noise are inadequate descriptors related to sound perception. Sound perception is a very complicated matter, as was apparent at the presentations made at the 2nd meeting of the QRTV (see above) or at any major conference on acoustics. However, if it would be meaningful to add artificial sound to EV:s or HEV:s, this sound must be easy to notice by pedestrians and bicyclists. No matter what metrics are used to describe this, the result of an effective system must be an increase in the perception of noise.

NOISE LEVELS OF QUIET VEHICLES COMPARED TO "CONVENTIONAL" VEHICLES – JAPANESE DATA

A general problem with data relevant to this topic is that the interesting speed range is 0-30 km/h and at such low speeds a lot of data is not available. In fact, it is extremely difficult to drive a car at speeds of 5, 10 or 15 km/h in a reproducible manner. Furthermore, few measurements on EV:s or HEV:s have been presented. The following shows some recent noise measurement results of relevance.

Measured sound power levels of a small electric vehicle (915 kg) and a much larger hybrid vehicle (1535 kg) were presented in [Yoshinaga & Namikawa, 2009]. Figure 1 shows the results, where the values for the conventional average car are taken from the Japanese traffic noise prediction model.

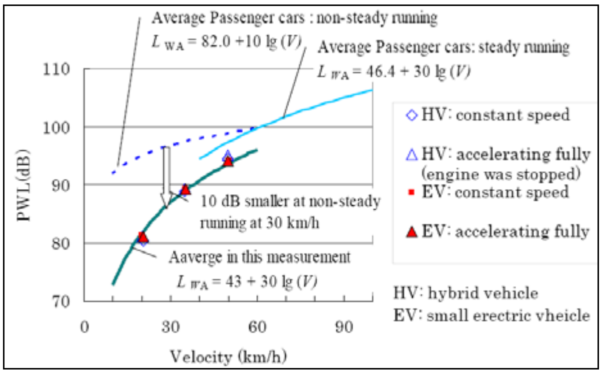

Figure 1. Sound power levels from an EV and an HV (HEV) vehicle in Japan, compared to conventional average cars in Japanese traffic under constant speed and under acceleration/deceleration. From [Yoshinaga & Namikawa, 2009].

The EV and HV cars are 3-10 dB quieter, depending on speed and driving condition. Note that the 3 dB difference for constant speed might be due to quieter tyres on the electrified vehicles than on the average cars.

Results from another Japanese measurement series are shown in Figure 2 [JASIC, 2009-1]. A hybrid car (no details given) driven in electric mode was measured for the speed range 0-35 km/h and compared with two ICE cars (named GE1 and GE2 where G means gasoline). "Ground noise" means background noise at the site. Note that differences in tyres (not specified) may account for the differences in the higher half of the diagram.

The results show that there is a significant difference in noise emission levels only at speeds below 20 km/h (JASIC's conclusion); in fact only at speeds below 15 km/h (these authors' conclusion).

The JASIC report also includes a description of an experiment in a laboratory of perception of sound by 20 subjects for the same vehicles as presented in Figure 2, in an approaching operation, using recorded vehicle noises and three background noises.

It appears that at 20 km/h there is no significant perception difference, at 15 km/h there is a small difference for the quietest background, and at 10 and 6.5 km/h there is a difference in the favour of the ICE vehicles at the two lower background noises. It is argued in the report that stopping distance at a speed of 10 km/h in an emergency would be 3 m under average conditions and 6 m under maximum unfavourable conditions. The latter might be too long to stop the HEV in a case where a pedestrian steps out in the street not hearing the car.

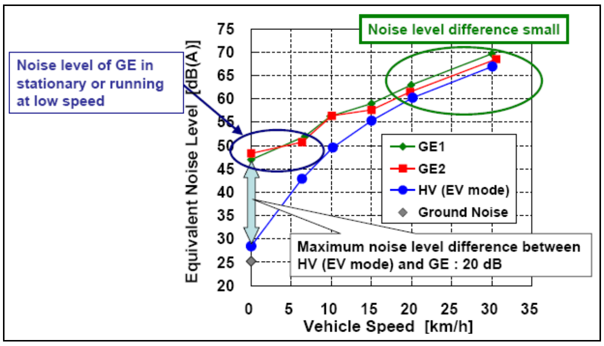

Figure 2. Equivalent A-weighted noise levels from an HEV car, compared to two ICE cars in Japan at low speeds. From [JASIC, 2009-1].

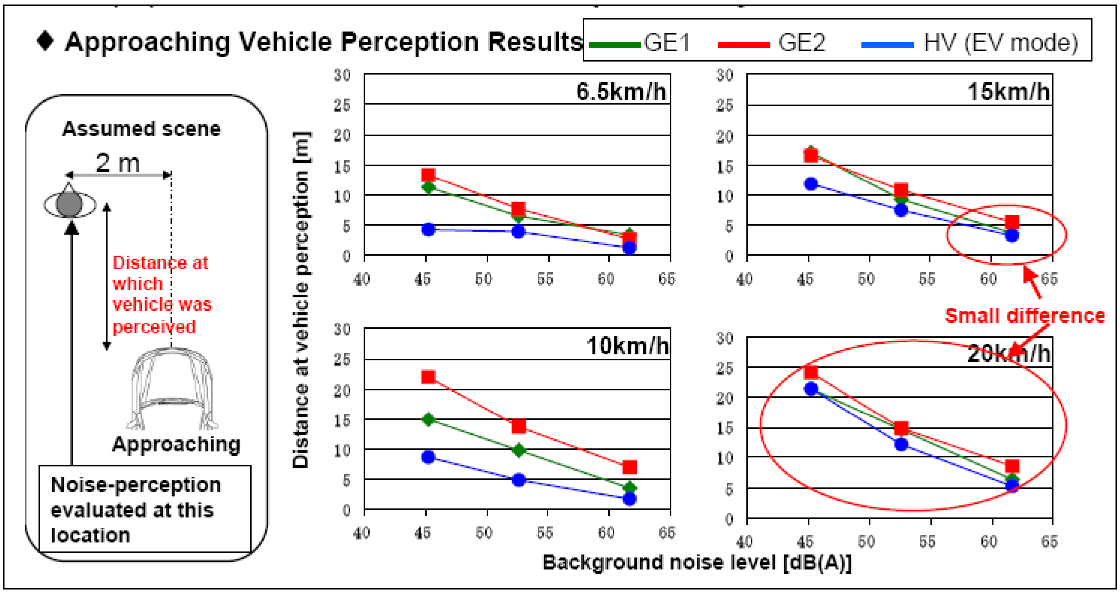

Figure 3. Results of a study on perception of sound from an approaching HEV car, compared to two ICE cars in Japan for three sites with different background noise 45-62 dB. From [JASIC, 2009-1].

NOISE LEVELS OF QUIET VEHICLES COMPARED TO "CONVENTIONAL" VEHICLES – DATA FROM BRRC

BRRC tested a Toyota Prius in the summer of 2010 together with some ICE cars, using speeds around 20 km/h. It appeared that there was almost no difference for the Prius between its two modes of operation at 20 km/h, even though its tyres seemed to be exceptionally quiet. Therefore, it was concluded that in both the electric and the ICE mode, at 20 km/h, the Prius emits mainly tyre/road noise.

BRRC tested a Volvo V50 with a 2.0 liter turbo diesel engine from 2004 with tyres Goodyear Efficientgrip 205/55 R16 91V in two driving modes: (1) constant speed at 20 km/h on the 2nd gear, and (2) coasting at 20 km/h, with the engine idling. The result was that the coasting condition, which should have given only tyre/road noise, was only 1 dB(A) quieter than the constant speed condition on the 2nd gear. The same tests for a Renault Espace with a 3.5 litre V6 petrol engine from 2004 with tyres Michelin Pilot Primacy 255/55 R17 101W, gave the same result; i.e. approximately 1 dB(A) difference between the two modes. The conclusion is that for these two ICE cars, one medium-sized and one large, engine noise at constant speed is far below tyre/road noise at 20 km/h (1 dB of difference corresponds to 6 dB of difference between tyre/road noise and engine noise) and would be almost impossible to hear. Note that one of the cars had a diesel engine.

NOISE LEVELS OF "CONVENTIONAL" VEHICLES – DATA FROM THE VENOM MODEL

VENOM by TUG and VTI

In a project at VTI about the effects on noise emission of Ecodriving, conducted in 2000-2001, VTI and TUG collected data on vehicle noise emission for light vehicles driven at over 80 different conditions per vehicle (various speeds, gears, and driving conditions). Based on these data, TUG with some assistance from VTI developed a **Ve**hicle **No**ise **M**odel – "VENOM". The model is based on 8 light vehicles, ranging from small, and medium to large, one SUV and one light truck. One of the 8 vehicles was a motorcycle. One of the vehicles had automatic transmission (5-speed); the others had manual 5-speed transmission. The year models were

2000-2001, plus one from 1997; measurements were made in 2001.

All data were recorded at each metre along a 50 m vehicle pass-by location with full third-octave-band spectra per metre. The total number of measured data therefore was enormous. The vehicles were in used but close to new condition, except one which was 4 years old, and they used original equipment tyres. The test track surface was an old DAC 11 in good condition as it did not carry regular traffic, the noise characteristics of which were measured to be approximately 1 dB quieter than the virtual reference surface for noise prediction proposed in [Sandberg, 2006].

VENOM is partly described and applied in [Ejsmont & Ronowski, 2005].

Explanations related to the presented data

The data in Figures 4-8 were obtained as follows:

- All presented noise levels are A-weighted maximum sound levels recorded during a pass-by or coast-by (although also single-event Leq:s over 50 m were calculated). The microphones were at 7.5 m from the centre of the vehicle path and 1.2 m above the pavement.
- "Coast-by" means tyre/road noise with the power unit (engine) switched-off. All other curves show total vehicle noise with the engine in operation; including also coast-by noise (i.e. these curves show power unit noise plus tyre/road noise).
- Data have been averaged for the seven light vehicles that were tested, excluding the motorcycle but including the SUV and the light truck; also coast-by noise is the average for the same vehicles; i.e. for the seven different tyre sets.
- Figure 5 contains only the data for the three quietest cars, by intention.
- Figure 7 contains data for 6 light vehicles. This is because in this special driving condition data are irrelevant for the automatic transmission vehicle.
- Data are shown only for the speed range 0-50 km/h and for the three lowest gears. However, data are available also for higher speeds and higher gears, but these are not of interest in this paper.
- Broken lines denote data that have been extrapolated from the other speeds (knowing reasonably well how noise levels depend on speed).
- Dotted lines show cases where noise at idling (standstill) of the cars have been included at 0 speed and the dotted (straight) lines connect the 0, 10 or 20 km/h points by adding noise at idling to coast-by noise. This corresponds to vehicle operation when the transmission is disengaged and engine rpm runs down to idling, as is necessary at deceleration at very low speeds.
- In the model development some smoothing of data has been made to obtain data that may be described without discontinuities. The data in these figures are only marginally affected by this.

Noise levels versus speed according to VENOM

First, Figure 4 shows the vehicle noise levels from VENOM when the seven tested light vehicles were driven at constant speed; i.e. at cruising. Note that the coast-by curve shows only tyre/road noise, while the other curves show tyre/road noise plus power unit noise. Engines are idling when approaching zero speed.

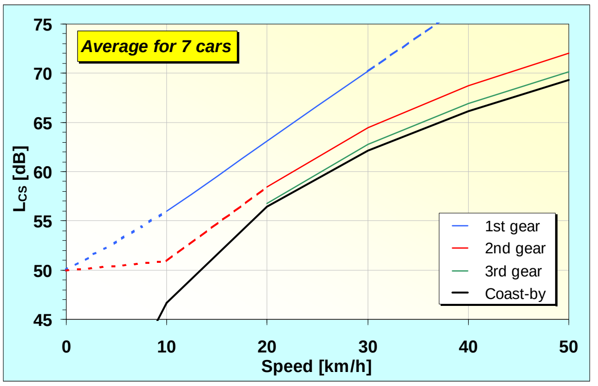

Figure 4. Noise levels versus speed, averaged for the 7 cars tested. Driving condition is cruising (constant speed) at the lowest 3 gears. See further the text.

Figure 5 shows the same as Figure 4, but here only the three quietest cars were included (also for coast-by). Figure 6 is a variant of Figure 4, where it is assumed that the vehicle drives at a speed over 30 km/h, but between 20 and 30 km/h the transmission is put in neutral and the engine slows down to idling. This causes less power unit noise at the speeds when idling occurs. This driving condition is meant to correspond to a case where the driver sees something coming up that may force him to stop and he/she therefore prepares for this by pushing the clutch. It may for example be an intersection far ahead where light is shifting to red.

Figure 7 is a variant of Figure 4, where it is assumed that the vehicles are driven with a moderate deceleration caused by using the engine brakes; i.e. by releasing the accelerator pedal. This is probably the most common way of slowing down ahead of a pedestrian crossing, a stop light or of an intersection.

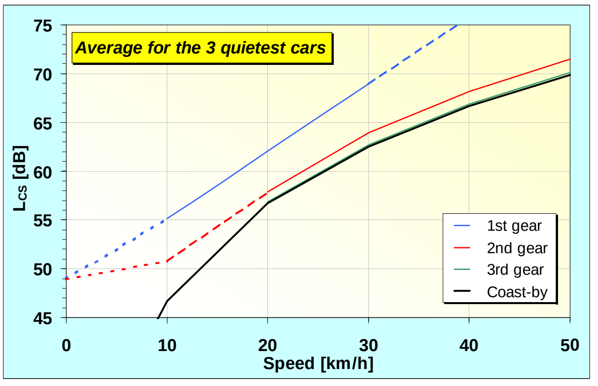

Figure 5. Same as Figure 4, but averaged for only the 3 quietest cars tested.

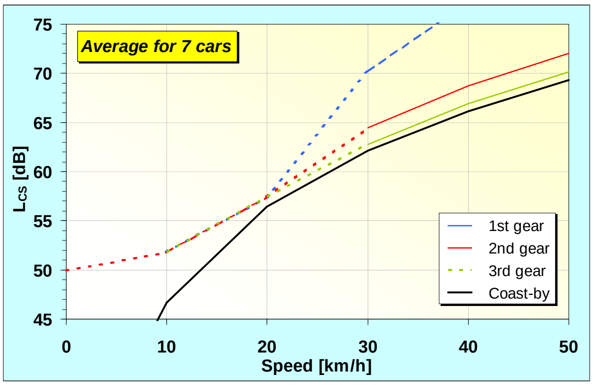

Figure 6. Same as Figure 4, but at speeds 20 km/h and below the transmission is in neutral and the engine is idling.

This causes some extra power unit noise emission, but it also causes some extra tyre/road noise, so the difference between power unit noise and tyre/road noise stays approximately the same as in Figure 4.

Finally, Figure 8 represents the case when vehicles are accelerated moderately at a level of 0.5 m/s^2. It is intended to be typical of accelerating from standstill without using full throttle operation.

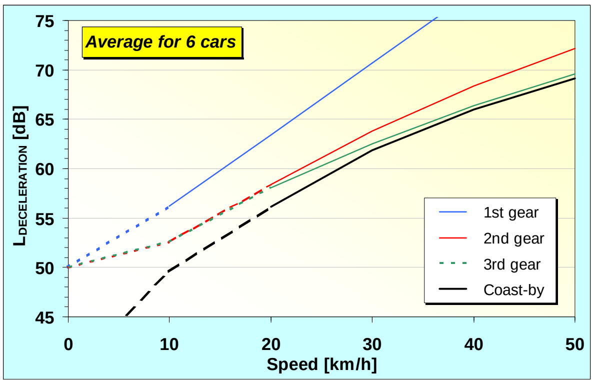

Figure 7. Same as Figure 4, but for a driving condition when the vehicle is decelerating by using the engine brakes.

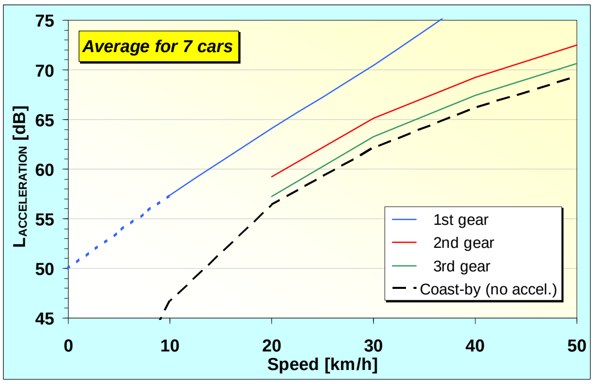

Figure 8. Same as Figure 4, but for a driving condition when the vehicle is accelerating moderately (0.5 m/s^2).

Summary of the data

Note that in all these diagrams, the tyre/road noise is included in the vehicle noise curves shown. It means that if the vehicle noise curves are less than 3 dB above the coast-by (i.e. tyre/road noise), the power unit noise is lower than tyre/road noise.

It follows from the diagrams that power unit noise has a higher noise level than tyre/road noise for all cases where the first gear is used, but it never happens when using the third gear. When using the second gear it happens only at the following conditions:

- Acceleration at 0.5 m/s^2 and above; although at 0.5 m/s^2 it is a border case.
- Deceleration when using the engine brakes at 10 km/h and below.
- Below 15 km/h when the engine is idling or close to idling.
- At constant speeds below about 15 km/h.

However, in the range 10-15 km/h, other than when accelerating harder than at 0.5 m/s^2, the power unit noise and tyre/road noise have noise levels close to each other, which means that power unit noise is not expected to be clearly heard. The first gear would normally be used above about 10 km/h only at acceleration.

The results of this study are consistent with the Japanese studies mentioned earlier, but our results are more comprehensive and cover more vehicles.

How does this affect hearing hybrid vehicles in comparison to conventional vehicles?

It is assumed that a vehicle driven in electric mode emits only tyre/road noise and that tyres are similar to those that are used by ICE vehicles. The masses of hybrid vehicles are normally not lower than of same-size ICE vehicles; rather the manufacturers attempt to keep the mass at the same level as for other similar vehicles, so the assumption of similar tyres is reasonable.

Assuming that it is difficult to hear power unit noise when it is similar to or lower than tyre/road noise (Yamauchi et al showed that artificial engine noise needed to be several dB above background noise to be safely perceived; see below) it appears that only vehicles driven on the first gear would be easy to perceive from their power unit noise. Vehicles driven in the second gear would be perceived based on power unit noise when accelerating a little faster than the "moderate" acceleration of 0.5 m/s^2 used in our study. At constant speeds or deceleration in 2nd gear, speeds need to be 10 km/h or lower in order for power unit noise to reach a level which can be expected to be perceived without serious problems.

At all other conditions, ICE vehicles of the semi-modern models tested here (around year 2000) would not have power unit noise loud enough to be safely perceived. It is probable that the ICE vehicles of year models 2010 would have lower rather than higher power unit noise levels than those of one decade earlier, if different at all, as this has been a commonly accepted (although weak) time trend.

The above is valid if background noise can be neglected. If background noise is not negligible, it will further reduce the cases when power unit noise can be perceived.

When light vehicles drive at 10 km/h or lower, the vehicle noise level at 7.5 m from the vehicle centre is mostly below 55 dB(A), according to Figures 4-8. 55 dB(A) at 7.5 m corresponds to approximately 49 dB(A) at 15 m and 43 dB(A) at 30 m in a free field. In an urban location it is very rare that background noise is below about 45 dB(A).

The overall conclusion is that in several common traffic conditions, perhaps even a majority of urban traffic situations, ICE vehicles have since many years ago emitted power unit noise so low compared to tyre/road noise that it has been very common in traffic that pedestrians have not heard anything more than tyre/road noise when these vehicles have approached them. It is only at speeds below 10 km/h, or at heavy acceleration, combined with very low background noise, when power unit noise would be easy to perceive.

Therefore, the feared problem of quiet vehicles is something that we have had for years, and nothing new that has been introduced with electrified vehicles.

NOISE EMISSION FROM OTHER VEHICLES THAN CARS, VANS, BUSSES AND TRUCKS

Not only road vehicles may be of an exceptionally quiet type at some operating conditions. Other vehicles that could potentially pose a hazard to pedestrians are bicycles and Segways. There are also electric scooters that are quiet. All of them may operate at speeds around 20-30 km/h and collisions with pedestrians or bicycle-to-bicycle may cause serious injuries. Since bicycles and Segways mostly operate on the same pathway as pedestrians, or very close to it, they are potentially extra big threats to pedestrians; not the least to blind people. Also some electric trams may be this quiet.

If artificial sound needs to be added to EV:s and HEV:s it would be equally justified to do so also for bicycles, Segways and electric scooters. Not doing so would seem illogical.

In fact, almost all light road vehicles and many heavy road vehicles except diesel-driven vehicles and sporty versions (diesel engines often give pronounced idling noise) are equally quiet as EV:s and HEV:s at coasting (engine idling), which is a common driving condition for example when approaching a pedestrian crossing. This would mean that virtually *all* road vehicles should have artificial sound generators fitted if the electric vehicles would be equipped with such devices.

SOLUTIONS TO THE PROBLEM

Artificial sound and its effects

Adding artificial sounds is of course a solution which potentially may provide some improvement in safety, although these authors believe that the improvement will be very small if any at all. But this will be paid by a poorer acoustical environment, which is both a matter of life quality and health. It may even be counterproductive since it may overestimate expectations of increased pedestrian and bicyclist safety.

The type of artificial sound preferred by [Yamauchi et al, 2010], among several very different types, was "quasi-engine sound"; i.e. a sound produced to simulate the engine of an ICE petrol-driven vehicle.

It appeared in a study with subjects listening to various artificial sounds in various background noise situations, that in a background of 60 dB(A) L_{Aeq}, the artificial sound needed to produce a level of at least 64 dB(A) (probably at the receiver position) to be observed with consistency [Yamauchi et al, 2010]. In higher background noise levels the artificial sounds could in the best cases have a level equal to the background and yet be perceived. Levels of (say) 60 dB(A) at the receiver position would be created only if cars are running at speeds above approx 20 km/h (see below).

But Yamauchi and his colleagues also concluded that in louder backgrounds the artificial sound needed to be substantially higher to be effective, and it would be necessary to use an artificial sound source emitting approx 76 dB(A) at the receiver in the second quietest environment tested by [Yamauchi et al, 2010]. It was recognized that this would mean a serious conflict between safety and acceptable noise in an urban situation. The authors would characterize this as an acoustical disaster if it happens.

It seems that the artificial sound solution is hard to accept in an acoustical environment typical of urban areas where substantial efforts are generally made to reduce noise; rather than to increase it.

Non-acoustical solutions

If needed, alternative solutions to artificial sound production are suggested here:

In public campaigns, in driving schools and in each quiet vehicle, the following information should be given:

- Make it clear to drivers of quiet vehicles that their vehicle may not be heard when approaching pedestrians at low speed.
- Make it clear to drivers of quiet vehicles that blind people are especially exposed to dangers if they cannot hear an approaching vehicle.
- Emphasize especially for drivers of quiet vehicles that the driver is always responsible for avoiding collisions with pedestrians, no matter how inappropriate the pedestrians behave.

An alternative way of improving pedestrian safety, in particular for the visually impaired, is to equip quiet vehicles with a chip which sends out a radio signal within a very limited range, which can be identified by a pedestrian if he/she has a receiving unit for such signals. It should be possible in such systems to distinguish between approaching and non-approaching vehicles, as well as displaying some kind of speed indication. This is in practice possible already today if the political will exists. This may be made useful also for hearing-impaired people as such signals may be sensed also as vibrations. Not the least, this may be effective even for pedestrians who have chosen to neglect ambient sound by wearing earphones connected to music-producing systems.

In backing operations, a possibility is to equip quiet vehicles with a simple radar device or an "Ultrasonic Auto Reverse Safety Device" that can detect moving objects behind the vehicle. Many vehicles are already equipped with "parking radars" to facilitate parking operations, and there are already products on the market that offer protection against backup on small children and other pedestrians. The authors have seen some devices offered at low prices and if the volume of such products will increase drastically and be part of the new vehicle, the price will go down substantially.

Some modern cars are already equipped with pedestrian detection systems; for example, Volvo S60 was the first car equipped with such a detection system [Pdd, 2010]. So far they are quite expensive but in the future the cost is likely to decrease. In Sweden, this system is part of an optional "safety system" which costs EUR 1800 extra [DN, 2010]. It is not known how much of this that is due to the pedestrian detection system. The Volvo approach utilises both radar and camera technology. The aim is to identify pedestrians and alert the driver so that he or she can take the necessary action to avoid a collision. If the driver does not react in time, the system automatically brakes the vehicle [Volvo, 2010]. Journalists who tested this system recently reported that it effectively stopped the Volvo C60 in front of a dummy without any driver action [DN, 2010].

Toyota Crown Hybrid is a car currently offered only on the Japanese market (?) with a night view system and which highlights pedestrians and presents them in a box on an LCD display in front of the driver [Wikipedia, 2010].

For particular use among blind people, it is easy to imagine a system which the person can carry and which would detect any object that moves towards the observer at a speed above a threshold. For example, there are IR detectors using a technology similar to that of many burglar alarms that have operating ranges of 100 m or more. In order to block out other pedestrians and the person's own movement, there should be a threshold speed of (say) 7 km/h, which is a little above normal walking speeds. This would offer protection not only against hybrid cars but also against any road vehicle, plus bicycles and Segways. If there would be a market for it, compact and inexpensive systems would rapidly become available.

In relation to these electronic devices, some of which are using already known technology, adding artificial sound to quiet vehicles appears to the authors as a "stone age measure", with much less potential to improve safety than the non-acoustical devices mentioned above.

Finally, it is pointed out that the best way to make quiet vehicle sounds heard is to reduce the masking by other sounds, i.e. to reduce the noise emission of the noisy vehicles. In especially North America, heavy trucks and busses are exceptionally noisy, meeting much less stringent limits than in Europe, Japan and many other countries, so there is much to gain here.

FURTHER COMMENTS

An important argument against adding artificial sound to quiet vehicles is that some drivers will think that pedestrians will hear them and they will therefore not be as careful as they would be if they would know that the pedestrians may not hear them. That might (incorrectly) seem to transfer some of their own responsibility to the pedestrians. The same argument may perhaps apply to some other alerting systems suggested by the authors.

The driver should never rely on his/her vehicle being heard. For example, children will not always react logical in traffic and whatever sound that they will or will not hear, a child may suddenly run out into the road or street or behind a parked vehicle.

In April 2010, a New Work Item Proposal "Measurement of minimum noise emitted by road vehicles" was approved by the ISO noise subcommittee. The intention is to work out an ISO standard for measurement of "minimum noise". The work will be carried out by a subgroup under ISO/TC 43/SC 1/WG 42. A first draft is already available, which is based on an SAE (Society of Automotive Engineers) draft.

There is also a proposal for Pending Legislation in the US Congress - HR 734. The summary reads [HR734, 2009]:

> Pedestrian Safety Enhancement Act of 2009 - Directs the Secretary of Transportation to study and report to Congress on the minimum level of sound that is necessary to be emitted from a motor vehicle, or some other method, to alert blind and other pedestrians of the presence of operating motor vehicles while traveling.

In Japan, there is also a proposal for similar action in a study committee at the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) [JASIC 2009-2].

The authors feel that these extremely fast and concerted actions (US Congress, SAE, Japanese MLIT, ECE and ISO), still without confirmed traffic safety effects, may be more politically than scientifically based.

RECOMMENDATIONS AND CONCLUSIONS

No records of traffic safety or accidents indicate that quiet vehicles cause accidents with pedestrians to such an extent that it has been observed to be significant. The exception is a study in USA, but the authors argue that this study may be biased and not sufficiently reliable.

Nevertheless, the potential safety problem of quiet vehicles not being heard in due time in traffic situations should be studied more.

Without present confirned evidence of a traffic safety hazard, it seems premature to suggest such a dramatic measure as adding artificial sounds to quiet vehicles to counteract a problem that may not even exist. This is especially unfortunate as that type of measure would eliminate the breakthrough in power unit noise reduction offered by the exchange from IEC to HEV and EV vehicles that has just started.

If it is needed at all, there are a number of alternative solutions to adding artificial sound which are suggested by the authors as options:

- In public campaigns, in driving schools and in each quiet vehicle, special information about the problem should be given.
- Equip quiet vehicles with a chip which sends out a radio signal within a very limited range, which can be identified by a pedestrian if he/she has a receiving unit for such signals.
- Equip quiet vehicles with an Auto Reverse Safety Device or "parking radar". This would work when the vehicle transmission is set in R position. However, if such a system may be made insensitive to normal objects in front of the vehicle, this safety device should operate also in the front direction.
- State-of-the-art would be a system like the Volvo C60 pedestrian detection system or the Toyota Crown Hybrid night view system; connected with some automatic collision avoidance system.

The alternative solutions that the authors propose seem to have a much higher potential of improving safety as they would potentially apply to a much wider category of pedestrians.

Whether quiet vehicles constitute a traffic safety hazard or not, it is a fact that many blind people feel unsafe due to them. Blind people have essentially only the acoustical information to rely on. One should consider means of reducing such worries; irrespective of the safety issue. The authors think that chip and receiver option would be the best solution.

Further, it is pointed out that the best way to make quiet vehicle sounds heard is to reduce the noise emission of the noisy vehicles. This would have a clear positive environmental effect in addition to a possible safety effect.

An important argument against adding artificial sound to quiet vehicles is that some drivers will believe that pedestrians will hear them and they will therefore not be as careful as they would be if they would know that the pedestrians may not hear them. They would transfer some of their own responsibility to the pedestrians. The same argument may perhaps apply to some other alerting systems suggested by the authors.

Most environments in urban areas are so contaminated with noise emission from various transportation modes, by industries, by shops and by people themselves, that acoustical clues from road vehicles are useless as they are masked by other sounds, unless they are very loud.

In some cities, areas that are so quiet that an acoustical distinction can be made between EV:s and ICE vehicles do not exist anywhere except indoors or inside yards or walls, or in parks, and in such cases pedestrians would not be subject to dangers from the street.

Other vehicles than road vehicles are potentially equally or more dangerous due to low noise emission that EV:s or HEV:s. These are bicycles and Segways (in some countries

Segways are considered to be bicycles). To require artificial sounds from quiet road vehicles but not from bicycles and Segways is illogical.

More and more pedestrians, in some situations a majority of them, wear some kind of system producing music or speech in earphones, which often effectively makes sounds of approaching vehicles totally obscured. It may then be impossible even to hear warning sounds. Under such circumstances, adding artificial sounds to quiet vehicles will fail for a large proportion of pedestrians.

The choice this group of pedestrians has made to block out acoustical cues is their own choice, the safety effects of which would be interesting to study.

OVERALL CONCLUSIONS

For at least over a decade, people in Europe, USA and Japan have lived in an acoustical environment in which it is common that it is impossible to hear anything else than tyre/road noise from an approaching light vehicle. This is not very different from today, or even more the future, when a large proportion of the vehicle fleet is driven in electric mode.

This means that if quiet vehicles are a safety problem today, we have lived with this problem for a very long time already. During all these years, there have not been many complaints about quiet vehicles, and safety problems due to them have not been reported anywhere, as far as known to the authors.

Therefore, there is not enough justification for equipping our future vehicles with extra artificial noise or warning sounds. When quiet vehicles now suddenly are assumed by some as a potential safety problem, this seems to be unjustified fears.

Adding artificial sound to electrified vehicles will mean very little to improving possibilities to hear such vehicles when they approach a pedestrian. There will be situations when this could improve perception, but then speeds would be so low (at or below 10 km/h) that they are close to walking speeds at which a vehicle can be stopped within about 5 m.

Heavy accelerations would also be a case when perception may be increased by added artificial sound. However, all pedestrians should be careful at locations when heavy accelerations occur and such locations would normally be only in connection to a signalized intersection. Finally, reversing out from a parking lot may be a case where artificial sound may have a potential safety effect.

Nevertheless, fears of the blind are well documented and shall be taken seriously, even if they have lived with similar situations for many years without really realising it (?). Therefore, one should consider solutions that would solve their fears. But such solutions should have a potential for providing real added safety and not just provide a placebo effect. Such solutions, relying on innovative and non-acoustical designs, some of them already existing, are suggested in this paper.

If introducing systems intending to prevent collisions between vehicles and pedestrians and bicyclists, one must try to avoid that drivers get an impression that the responsibility to avoid collisions with pedestrians or bicyclists is shifted towards the pedestrians.

ACKNOWLEDGEMENTS

It is acknowledged that the own data reported here were collected by means of funds provided by:

A model called VENOM, developed by TUG and VTI, based on data collection conducted within the projects "Influence of EcoDriving on Noise Emissions" funded by the Swedish Road Administration (SRA), and "Noise emission from road traffic", sponsored by the Swedish Agency for Innovation Systems (VINNOVA). VINNOVA also funded extra modelling work. Most of the VENOM model development took place at the TUG, using funds from the Technical University of Gdansk.

Production of this paper has been leisure time work by the authors.

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