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Traffic Sounds and Cycling Safety: The Use of Electronic Devices by Cyclists and the Quietness of Hybrid and Electric Cars

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ABSTRACT The growing popularity of electric devices and the increasing number of hybrid and electric cars have recently raised concerns about the use of auditory signals by vulnerable road users. This paper consolidates current knowledge about the two trends in relation to cycling safety. Both a literature review and a crash data analysis were carried out. Based on a proposed conceptual model, knowledge gaps are identified that need to be addressed for a better understanding of the relation between limitations on auditory information while cycling. Results suggest that the concerns regarding the use of electronic devices while cycling and the advent of hybrid and electric vehicles are justified. Listening to music and conversing on the phone negatively influence cyclists' auditory perception, self-reported crash risk and cycling performance. With regard to electric cars, a recurring problem is their quietness at low speeds. Implications of these findings in terms of cycling safety are discussed.

1.1. Introduction

Noise emission is one of the main negative environmental impacts from road transport. Road traffic noise disturbs sleep, impairs school performance and leads to emotional annoyance (Stansfeld & Matheson, 2003). However, in some instances, cyclists and pedestrians (especially the visually impaired), presumably rely on or even depend on traffic-related sounds such as pavement, tyre and engine noises (see e.g. Guth, Hill & Rieser, 1989). Therefore, eliminating the source of traffic noise might pose a safety hazard for these road users.

Recently, the rising number of quiet (hybrid) electric cars on the road and the preoccupation with portable electronic media devices among road users, generated interest in and concerns about the use of auditory signals by cyclists and pedestrians. Global sales of electric vehicles more than doubled between 2011 and 2012 (IEA/EVI, 2013) and many European countries aim to increase the number of electric cars significantly in the near future (IEA, 2012). As for electronic devices, for example, in the Netherlands, 48% of the cyclists listen to music while 58% engage in a phone call (Goldenbeld, Houtenbos & Ehlers, 2010; Goldenbeld et al., 2012).

How road users use auditory information to detect and localise approaching cars has only recently become the subject of empirical investigation. Studies in this field have mainly focused on the importance of auditory cues for pedestrian safety. Up until now there has been no systematic research into the role of auditory information for cycling safety.

Cycling safety is a major traffic safety concern in many European countries and in the USA. Cyclists are benefitting less from safety improvements that are reducing the overall number of traffic fatalities (NHTSA, 2012; Steriu, 2012). Although cyclist fatality risk (number of cyclist deaths per distance travelled) may have decreased between 2001 and 2009 in the countries collecting data on the number of kilometres cycled, the decrease is either very slight (Norway), stagnated (the Netherlands) or the risk is still relatively high (Great Britain) (OECD/ITF, 2013; Steriu, 2012). Only in Denmark the fatality risk of cyclists decreased significantly to a very low level. However, in the Netherlands the risk of serious injury among cyclists actually increased over the same period. Cycling is strongly encouraged by governmental policies of many countries (OECD/ITF, 2013) and it is expected to become a central part of the mobility solution in many cities. It is therefore important to identify and address factors that negatively influence cycling safety. Limiting auditory cues from traffic environment may form such a risk.

This paper provides a review of current knowledge regarding the use of electronic devices and the acoustic characteristics of (hybrid) electric cars in relation to cycling safety. This is for the first time that these two aspects are brought together to discuss the potential problem of limiting auditory cues. The objectives of the paper are: (1) to estimate, using literature and crash databases, the extent to which limitations on availability of auditory information while cycling constitutes a road safety hazard and (2) to identify the most important knowledge gaps that need to be addressed for a better understanding of the relation between this potential problem and cycling safety. For that purpose, a proposed conceptual model of the role of auditory information in cycling is used. The paper introduces the conceptual model, describes the methods of literature search and selection and crash data analysis, followed by the results. The most important knowledge gaps and recommendations for future research are presented, and finally the main results and their implications are discussed.

1.2. Conceptual model

Figure 1.1 presents a proposed conceptual model of the role of auditory information in cycling. This integrated model combines the information processing models (Endsley, 1995; Shinar, 2007; Wickens et al., 2004), general driver behaviour models (Fuller, 2005; Hurts, Angell & Perez, 2011) and insights from research in applied auditory cognition (Baldwin, 2012) .

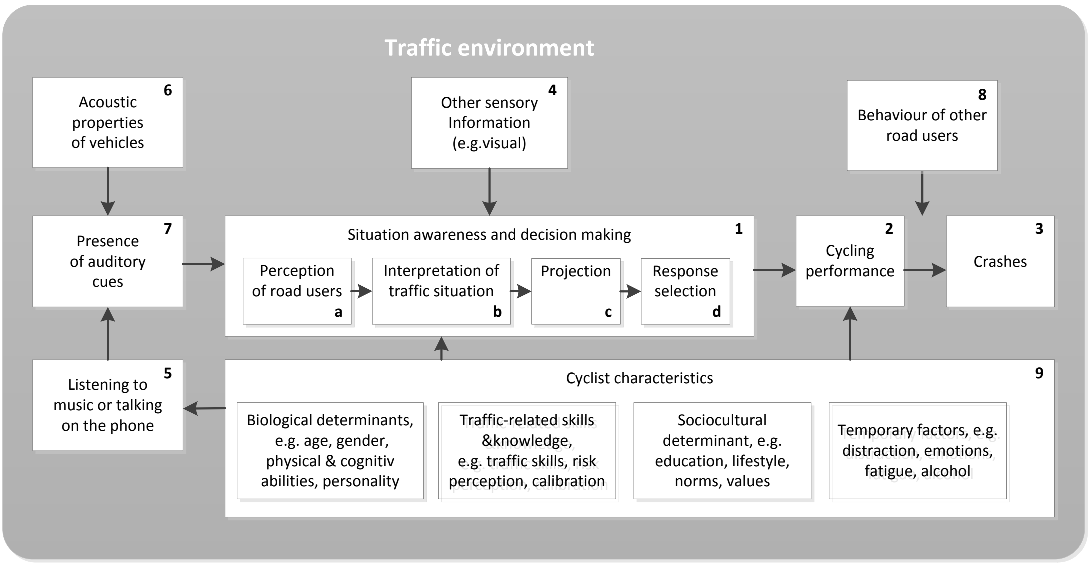

Figure 1.1. Conceptual model illustrating the role of auditory information in cycling safety.

Human beings not only react to physical characteristics of a sound — its pitch, loudness, timbre or duration — by hearing (a sensory process), but a sound is also interpreted (a perceptual-cognitive process) (Baldwin, 2012).Sound perception involves, for example, sound recognition, its identification and location in space. For a cyclist the perception of traffic sound (*box 1a* in *Figure 1.1*) may involve detection, identification of the sound source (as a car, motorcyclist, etc.) and its localisation (e.g. its location, speed), even if it cannot be seen. While acknowledging the relevance of visual – auditory interactions (see, e.g. King, 2009) (*box 4*), the model was specifically designed to address situations in which no visual information is available for cyclists due to visibility obstruction, visual distraction or cyclists' reliance on auditory information. Indeed being able to hear traffic sounds is considered to be especially important for gathering information about approaching traffic from areas outside one's field of view (Ashmead et al., 2012; Mori & Mizohata, 1995).

Auditory information can help cyclists to interpret a traffic situation (*box 1b*) and to project future actions (*box 1c*). Those elements, namely perception (*box 1a*), interpretation (*box 1b*) and projection (*box 1c*), form three levels of cyclist situation awareness (Endsley, 1995) — their awareness of the meaning of dynamic changes in the environment. Cyclist situation awareness forms the basis for response selection (*box 1d*) and cycling performance (box 2), which in turn has consequences for road safety (*box 3*).

The role of auditory information in maintaining one's situation awareness can be reduced by the use of electronic media devices (such as mobile phones or portable music players) while cycling (*box 5*) and also by a low sound emission of vehicles (e.g. electric cars) (*box 6*). Talking on the phone and listening to music may cause auditory distraction by diverting attention away from the traffic task. Traffic sounds may also simply get masked by speech, music or ambient noise. Auditory cues used by a cyclist to detect and localise other road users can then be reduced (*box 7*), affecting cyclists' situation awareness (*box 1*), cycling performance (*box 2*) and road safety in the end. Crashes (*box 3*) can occur if, in the presence of traffic-related hazards, a degraded cycling performance is not compensated by the cyclist himself or other road users involved.

The bottom of the figure shows the importance of cyclist characteristics (*box 9*) influencing this relationship. Cyclist characteristics refer not only to personal characteristics such as age, experience as a cyclist, skills, knowledge, and physical and cognitive abilities but also to temporary conditions such as fatigue or emotional state. Many other factors in the traffic environment can be expected to influence the strength of the relationships shown in *Figure 1.1*, such as bicycle condition, road infrastructure, weather and traffic-related conditions. Given the scope of this paper, we will not systematically address cyclist characteristics and other possible factors.

1.3. The use of devices and electric cars: combined effects

Encountering a quiet electric car may be more dangerous for cyclists who listen to music or phone than for those who "just" cycle. As the sound intensity decreases with increasing distance to the source (Myers, 2006), quiet electric vehicles are likely to be detected later than the more noisy conventional cars. The use of devices is likely to deteriorate the detection of quiet cars even further due to masking effects. Quieter sounds are generally masked by louder sounds. The higher the sound intensity of the masking sound (e.g. music), the higher the intensity level of the masked sound (e.g. car sound) must be before it can be detected (see, e.g. White & White, 2014). Loud music is therefore more likely to mask quiet electric cars. However, the frequency of the masking and the masked sound is also of great importance. Masking is more likely to occur when music contains similar frequency ranges as the car sound (White & White, 2014). In situations where the visual information is not available (due to visibility obstruction or cyclists' reliance on auditory information when making decisions e.g. to turn), approaching cars — particularly quiet electric cars — may be detected far too late by a cyclist who is listening to music or conversing on the phone to provide enough time for the proper reaction.

1.4. Methods

This section presents the methodology adopted for the literature review and the crash data analysis.

1.4.1. Literature review

Relevant literature published up to April 2014 was searched for using scientific databases (Scopus, Web of Science, SafetyLit and the library catalogue at SWOV Institute for Road Safety Research). Since only few studies with cyclists were found, the literature concerning pedestrians was searched for. Although the conceptual model focuses on cyclists, we can assume that it applies to a great extent to pedestrians as they also use auditory cues in traffic. The results among pedestrian should be treated with caution, as obviously there are important differences between cyclists and pedestrians. Cyclists, who typically move around faster than pedestrians, have to deal with aerodynamic noise caused by the head displacement through the air (Defrance, Palacino & Baulac, 2010). Furthermore, cyclists sometimes share the road with cars and they often deal with other traffic situations than pedestrians do.

Search terms "cycling", "cyclist(s)", "cycling safety" or "pedestrian(s)", "pedestrian safety" were included in all searches and combined with "music", "mobile/cell phone(s)", "distraction" or "media devices". Keywords: "electric vehicle(s)/car(s)", "auditory perception" or "traffic sound(s)" were additionally combined with "traffic/road safety". Studies were excluded if they addressed (1) domains other than road safety (e.g. noise annoyance), (2) sounds other than car sounds (e.g. alerts), (3) the effects of combined use of electronic devices (e.g. listening to music and texting) and (4) exclusively added-on sounds of electric vehicles. Furthermore, studies with small non-representative sample sizes were excluded. This resulted in a list of 28 relevant publications. Additionally, the references of relevant publications were analysed, applying the "snowball" method. In total, 33 studies were included (see *Appendix 1*).

1.4.2. Crash data

As almost all relevant studies with cyclists concerned the Dutch situation (see *Appendix 1*), we focused on crashes in the Netherlands. For this purpose, the National (Dutch) Road Crash Register (BRON) was used. BRON is based on all crashes reported and registered by the police. It contains a large number of characteristics of the crash and the drivers and casualties involved. Due to a gradual decline of the registration rate of crashes in BRON, especially from 2009 on, supplemental data from Statistics Netherlands and LMR (the National Medical Registration) were used to account for the missing crashes. Those sources contain data from medical practitioners, hospitals and the district public prosecutor 's offices. The crash data involving cyclists were used to:

1. investigate whether, and to what extent, the use of electronic devices was a factor contributing to crashes, and whether and to what extent those crashes were caused by the lack of auditory cues;
2. compare (hybrid) electric cars with conventional cars as far as the crashes involving cyclists and pedestrians are concerned, and assess whether and to what extent the quietness of the (hybrid) electric car has contributed to the crash.

1.5. Results

The first two results sections, The use of devices and crash risk and Electric cars and crash risk, present findings on crash risk from both the literature review and the crash data analysis. The remaining sections describe the results based on the literature review only. *Appendix 1* provides the details of the studies used. We present the research findings in relation to the specific components of the conceptual model (*Figure 1.1*). The numbers of corresponding boxes are given in brackets. As the studies and crash databases rarely dealt with the direct relationships between components as indicated by the arrows in the model, the indirect relationships are presented as well (see also *Figure 1.2*).

1.5.1. The effects of using devices on cycling performance

Table 1.1a shows that listening to music and conversing on the phone (*box 5, Figure 1.1*) while cycling does not influence the different aspects describing cycling behaviour (*box 2*) equally. Some aspects of cycling performance are similarly affected by both activities. Findings from observational research show that the number of unsafe behaviours (*box 2*) increased and auditory perception deteriorated (*box 1a*) when cyclists were listening to music or talking on the phone.

A field experiment by De Waard, Edlinger, and Brookhuis (2011) shows that only five to about 20% of cyclists using devices heard all bicycle bell sounds as compared with about 70% of cyclists who were not using devices (*box 1a*). The same study indicates that the type of music and the manner of listening are of importance. Moderate volume or moderate tempo music (through normal ear- phones) compromised cyclists' auditory perception of the bicycle bells. High tempo music, loud music and in particular music listened through in-earphones impaired even hearing of loud sounds, that is, horn honking. However, cyclists' auditory perception was not affected when they listened to music using one earphone.

Furthermore, in field experiments cyclists rated both listening to music and talking on the phone as more risky than "just" cycling (*box 1b*). Some aspects of cycling performance (*box 2*) (i.e. the number of traffic conflicts found by observations of cycling behaviour on the road, the position on the road and swerving analysed in field experiments) were not affected by either conversing on the phone or listening to music. Other aspects were influenced by one activity only. Two field experiments show that cycle speed (especially when performing a difficult phone task) and response time (*box 2*) were influenced by phoning (De Waard et al., 2010). By reducing speed, cyclists apparently compensate for the high secondary task demand. Cyclists listening to music, however, were observed to disobey traffic rules (*box 2*) more frequently than those conversing on the phone.

A field experiment by De Waard et al. (2010) shows that visual detection (i.e. a number of noticed objects) (*box 4*) was not influenced by listening to music.

Field experiments investigating visual detection among cyclists on the phone show mixed results. De Waard, Lewis-Evans, Jelijs, Tucha, and Brookhuis (2014) and De Waard et al. (2010) found that a phone conversation — especially a difficult one — negatively affected the number of noticed objects. However, De Waard et al. (2011), using the same difficult conversation task, found no effect. Surprisingly, the effects of having a handheld versus hands-free conversation on cycling performance did not differ much. In the hands-free condition, response time was shorter, probably due to cyclists being able to operate both hand brakes.

1.5.2. Effects of device use on cycling versus pedestrian performance

Comparing *Table 1.1a* and *b*, we can conclude that the effects of listening to music and talking on the phone among cyclists are generally similar to those found among pedestrians — suggesting that similar mechanisms may play a role in performance degradation caused by device use.An interesting aspect investigated by studies with pedestrians is looking behaviour (*box 2*). Research findings are mixed on this aspect. Some observational studies and experiments in virtual environments found no decrease in cautionary looking behaviour (i.e. head turns before crossing the street) while listening to music (Neider et al., 2011; Neider et al., 2010; Walker et al., 2012) or talking on the phone (Neider et al., 2011; Neider et al., 2010; Thompson et al., 2013). However, an observation study by Hatfield and Murphy (2007) and an experiment in virtual environment by Schwebel et al. (Schwebel et al., 2012) found a negative effect of using devices on looking behaviour (Hatfield & Murphy, 2007; Schwebel et al., 2012).

Hatfield and Murphy, who observed decreased cautionary looking behaviour only among females, suggested that females may become more involved in their phone conversations than males, with the result that there is less attention for scanning the traffic situation. An observation study by Walker et al. (2012) also found some gender differences: males listening to music displayed more looking behaviour than those not listening to music, while females showed no differences between the two conditions. This does not have to mean that women who are listening to music are less cautious than men — women may be listening to music at a lower volume than men and may therefore need less compensation.

Table 1.1. a) Summary of the effects of listening to music and phoning on cyclists; b) summary of the effects of listening to music and phoning on pedestrians.

	Music		Phoning	
Effect	**Effect**[1]	**Study type**[2]	**Effect**[1]	**Study type**[2]
(a)				
Missed a bicycle bell	↑ [a]	field	↑ [a]	field
Missed a horn honking	↑ [a]	field	— [a]	field
Speed	— [a,b]	field	↓ [a,b,c]	field
Response/reaction time	— [a]	field	↑ [a]	field
Lateral position *(average position and variation of position)*	— [b]	field	— [b,c]	field
Detected visual objects	— [b]	field	— [a] ↓ [b,c]	field
Risk rating	↑ [a,b]	field	↑ [b,c]	field
Conflicts *(situations where either the observed road user or another traffic participant had to change speed or course to avoid a crash; or near-crash)*	— [b]	obs	— [b]	obs
Disobedience of traffic rules	↑ [b]	obs	— [b]	obs
Unsafe behaviours *(riding in the wrong direction in the bicycle lane, failing to slow down and look for crossing traffic, riding through the pedestrian crosswalk, riding too slow when entering the intersection, causing crossing traffic to brake to allow the cyclist to cross)*	↑ [e]	obs	↑ [e]	obs
Crash risk (self-reported) (music & phoning)		↑ [d,f] survey		

Continued

Notes: Table 1.1a. [1] ↑ = increase; ↓ = decrease; — = no effect. [2] obs = observation (on the road without the intervention by the researcher), field = field experiment (intervention in the real world).

[a] *De Waard, Edlinger & Brookhuis (2011)*

[b] *De Waard et al.(2010)*

[c] *De Waard et al. (2014)*

[d] *Goldenbeld, Houtenbos & Ehlers (2010)*

[e] *Terzano (2013).*

[f] *Ichikawa & Nakahara (2008)*

Table 1.1. Continued

	Music		**Phoning**	
	Effect[1]	**Study type**[2]	**Effect**[1]	**Study type**[2]
(b)				
Speed	— [b] ↑ [i]	obs	↓ [b,h,i,j]	obs, sim
Response/reaction time	— [d]	sim	↑ [d]	sim
Lateral position *(average position and variation of position)*	— [b]	obs	↑ [b]	obs
Detected visual objects	— [b,c,d]	obs,sim, field	↓ [b,c,d]	obs,sim, field
Conflicts *(situations where either the observed road user or another traffic participant had to change speed or course to avoid a crash; or near-crash)*	↑ [e] — [b,j]	sim obs, sim	↑ [c,g] — [b,j]	obs, sim obs, sim
Unsafe behaviours *(not waiting for traffic to stop)*			↑ [h]	ob
Mistakes *(missed opportunities to cross the street/stopping when there is no car present)*	— [c,e,j]	field, sim	↑ [c,g,j]	field, sim
Looking at relevant objects	— [f,p] ↓ [e,i] ↑ [a]	obs, sim sim, obs obs	— [a,i,j,g] ↓ [e,g,h]	obs, sim sim, obs
Injury rate *(number of pedestrian injuries due to mobile phone relative to total pedestrian injuries)*			↑ [f]	crash

Notes: Table 1.1b. [1] ↑ = *increase;* ↓ = *decrease;* — = *no effect.* [2] *obs = observation, sim = experiment in virtual environment, field = field experiment, crash = crash study.*

[a] *Walker et al. (2012)*
[b] *Hyman et al. (2010)*
[c] *Nasar et al. (2008)*
[d] *Neider et al. (2010)*
[e] *Schwebel et al. (2012)*
[f] *Nasar & Troyer (2013)*
[g] *Stavrinos, Byington & Schwebel (2011)*
[h] *Hatfield & Murphy (2007)*
[i] *Thompson et al. (2013)*
[j] *Neider et al. (2011)*

There is no clarity regarding the effects of device use on the number of conflicts. Field experiments, and some experiments in virtual environments, showed an increase in the number of conflicts among pedestrians who listen to music or talk on the phone (Nasar, Hecht & Wener, 2008; Schwebel et al., 2012; Stavrinos, Byington & Schwebel, 2011). Observations and other studies in virtual environments found, however, no effects (Hyman et al., 2010; Neider et al., 2010).

Irrespective of the contradictory results, there are few differences between the effects found among cyclists and pedestrians. However, one difference concerns lateral position: unlike cyclists, pedestrians' lateral position was affected by phoning. The differences between findings do not seem to be related to the use of various research methods, as specific methods cannot be associated with specific results, that is, similar results were obtained with different methodologies, and some studies using similar methodologies obtain contradictory results.

1.5.3. The use of devices and crash risk

The Dutch official crash databases do not record the use of devices as a contributory factor in bicycle crashes (*box 3*). Similarly, no information about the use of electronic devices in crash registration was found in the international literature on cycling safety. Two Dutch surveys among cyclists suggest that the use of devices may have contributed to 7 – 9% of self-reported injury crashes nationally (De Waard et al., 2010; Goldenbeld, Houtenbos & Ehlers, 2010). Also a Japanese survey among students indicates a possible risk-increasing effect from using mobile phones while cycling (Ichikawa & Nakahara, 2008). In this study, the use of a mobile phone while cycling in the past month was related to the experience of a crash or near crash.

Goldenbeld Houtenbos & Ehlers provide a more accurate indicator for the impact of the use of devices on cycling safety levels (2010). While taking into account potentially relevant exposure factors (such as the extent to which cyclists were exposed to hazardous traffic situations), the risk of a self-reported crash for cyclists who used electronic devices on every trip, turned out to be a factor 1.6 higher for teenagers and 1.8 higher for young adults compared with their respective age counterparts who never used devices while cycling. However, for middle-aged and older adult cyclists, no increase in crash risk was found. Both studies (Goldenbeld, Houtenbos & Ehlers, 2010; Ichikawa & Nakahara, 2008) found that the higher the subjective risk ratings of cyclists were, the less often they were involved in a self-reported crash. Those higher ratings of perceived risk found among cyclists who use devices might therefore mean that cyclists are aware of the high secondary task demand and behave more cautiously in traffic.

The only crash study we found involving pedestrians and the use of devices used data on injuries in a representative sample of hospital emergency rooms across the USA (*box 3*). Results showed that an increase in mobile phone subscriptions in the period 2004 – 10 was associated with an increase (from 0.6% to 3.7%) in the share of mobile phone-related injuries among pedestrians relative to all pedestrian injuries. About 70% of the reported injuries related to talking and 9.1% to texting. As texting is considered more distracting than talking, these percentages probably reflect a lower amount of texting than talking while walking.

1.5.4. Hybrid electric cars: detectability and localisation

Studies into the safety consequences of (hybrid) electric cars for vulnerable road users have focused particularly on acoustic characteristics of those cars (*box 6*) and their detectability and localisation (*box 1a*) (see also *Appendix 1*). In those studies hybrid cars (operated in the electric mode[1]) were compared to conventional (Internal Combustion Engine — ICE) cars for various speeds and various ambient noise levels. Only one study (Hong, Cho & Ko, 2013) included a fully electric car — a low speed and light model. Kim et al. (2012a) and Wiener et al. (2006) used conventional and hybrid cars of the same make and model. Other studies do not provide details about the cars used. Comparisons are more conclusive within studies than between them as both the car makes and models used and measurement conditions varied between studies. *Table 1.2* shows that hybrid electric cars were found quieter than conventional ones when stopped or at low speed (*box 1a*). The lower the speed of the cars, the bigger is the difference in the emitted sound level between the two car types. For cars passing by at 10 km/h, the difference ranged from 2 to 8 dB-A. At speeds 15 – 30 km/h hybrid electric cars were found 2 – 3 dB-A quieter than conventional cars. At speeds above 30 km/h, and in some studies already above 15 – 20 km/h, the sound level of two car types do not differ, most likely because of the tyre noise being dominant and not the engine noise.

[1] Mendonça et al. (2013) does not provide information on whether the hybrid car operated in electric mode. Wall Emerson et al. (2011) cannot ensure that the used hybrid electric car was actually driven in electric mode when going at certain speeds.

Table 1.2. Sound level differences between (hybrid) electric (HE) cars and conventional (ICE) cars by speed and ambient sound levels.

Speed	**Ambient sound in dB-A**	**Comparison of sound levels of HE and ICE cars**	**Difference in sound levels in dB-A between ICE & HE cars**
In stationary			
0 km/h[1]	25	H<ICE	20
Forward constant speed			
7−8 km/h[1]	25	H<ICE	7−8
10 km/h[1]	25	H<ICE	6−7
10 km/h[2]	Very low	H<ICE	2−8
15 km/h[1]	25	H<ICE	3−4
15 km/h[5]	Unknown	H<ICE	0.2
15–30 km/h[4]	50.6−54.7	H<ICE	2−5
20 km/h[1]	25	H=ICE	0
30 km/h[1]	25	H=ICE	0
32 km/h[2]	Very low	H=ICE	0
48 km/h[2]	Very low	H=ICE	0
50 km/h[3]	43.7−49	H<ICE	2.3
64 km/h[2]	Very low	H=ICE	0
Reverse constant speed			
8 km/h[2]	Very low	H<ICE	7−10
10 km/h[5]	Unknown	H<ICE	4
Accelerating			
to 30 km/h[3]	43.7−49	H<ICE	8
Slowing down			
From 32 to 16 km/h[2]	Very low	H<ICE	0.7

[1] *JASIC (2009)*
[2] *Garay-Vega et al. (2010).*
[3] *Wiener et al. (2006).*
[4] *Wall Emerson et al. (2011)*
[5] *Kim et al. (2012a)*

When driven at low speeds and in relatively quiet backgrounds, (hybrid) electric cars were more likely to remain undetected longer than conventional cars by both sighted and visually impaired pedestrians (see *Table 1.3*). The study of Hong, Cho & Ko (2013) found a difference between an electric and a hybrid car: the former was detected later when stationary or when driven at 30 km/h. Surprisingly, at 20 km/h, the hybrid car was detected later than the electric car. When in stationary, both car types were detected at very short distances. Furthermore, 80% of the participants passing in front of the hybrid car and 97% of those passing in front of the electric car could not perceive the stationary vehicle sound.

Table 1.3 shows also that hybrid electric cars at low speeds and in higher ambient noise levels were often detected too late to afford safe crossing. Time-to-vehicle-arrival, which is the time from first detection of a target car to the instant the car passes the pedestrian location, was often less than general time needed to cross the street (about 6 – 7 s). In some situations, a hybrid electric car was detected when only an average of 2 – 3 s away. However, even conventional cars were not always detected at distances allowing safe crossing. Once the ambient sound level was above 45 – 50 dB-A or when curves, hills and road- side trees obscured sounds, conventional cars were often detected too late to cross safely (*box 1a*) (Kim et al., 2012a; Wall Emerson et al., 2011; Wall Emerson & Sauerburger, 2008).

Vehicle detection is also significantly affected by vehicle speed, listener 's age and pavement type. Faster travelling cars generate more noise (Garay-Vega et al., 2010) and as speed increased, cars were detected sooner and thus at greater distance (and sooner) (Barton et al., 2013; Barton, Ulrich & Lew, 2012). The worst detectability levels were found among juveniles and older participants (Hong, Cho & Ko, 2013; Mendonça et al., 2013) and on low-noise pavements, that is, asphalt as opposed to cobble stones (Mendonça et al., 2013). Not only detection of cars but also their correct localisation is important for pedestrians when making crossing decisions. Earlier detection of a car does not, however, guarantee that it is more accurately localised in space. To illustrate, although conventional cars were detected earlier than hybrid cars, judgements about whether the car goes straight or turns right were equally accurate but quite delayed for both car types (Kim et al., 2012b).

Finally, auditory localisation of approaching cars, compared to their detection, is to a higher degree influenced by the signal-to-noise ratio: ambient sound level in relation to the car sound output. A laboratory study of Ashmead et al. (2012) found that at higher levels of ambient sound (60 dB-A or more), acoustic output of individual cars are often too low for pedestrians to be able to distinguish between straight and right-turn paths. In the same study, the signal-to-noise ratio needed to distinguish between these paths was higher than the signal-to-noise ratio needed for vehicle detection.

Table 1.3. Detection of (hybrid) electric (HE) and conventional (ICE) cars in relation to time-to-vehicle-arrival and pedestrian crossing time.

Speed in km/h	Ambient sound in dB-A	Car type earlier detected	Time-to-vehicle-arrival in sec.[1] in brackets: crossing time	Study type[2]
In stationary				
0[e 2]	40	ICE*		Field
Forward constant speed				
6.5[a]	45.2	ICE		Lab
6.5[a]	52.6	ICE		Lab
6.5[a]	61.7	ICE = HE		Lab
10[b]	31.2	ICE	C = 6.2; HE = 4.8	Lab
10[a]	45.2	ICE		Lab
10[b]	49.8	ICE	C = 5.5; HE = 3.3	Lab
10[a]	52.6	ICE		Lab
10[a]	61.7	ICE = HE		Lab
15[a]	45.2	ICE		Lab
15[c]	48.7 – 55.1	ICE	C = 8.6; HE = 6.5 (6.9)	Lab
15[a]	52.6	ICE = HE		Lab
15[a]	61.7	ICE = HE		Lab
20[a]	45.2	ICE ≈ HE		Lab
20[a]	52.6	ICE ≈ HE		Lab
20[a]	61.7	ICE ≈ HE		Lab
20[e]	45	ICE		Field
<32[d 3]	52.8	ICE, HE**	*C = 5.5; HE = 2.1-6.7* (6)	Field
30[e]	45	ICE*		Field
30, 40 & 50[f]	62–82	ICE***		Lab
Accelerating				
From stop[g]	unknown	ICE		Field
Slowing down				
32 to 16[b]	49.8	HE	C = 1.1; HE = 2.3	Lab
32 to 16[b]	31.2	HE	C = 1.3; HE = 2.5	Lab
Backing				
10[b]	31.2	ICE	C = 5.2; HE = 3.7	Lab
10[c]	48.7 – 55.1	ICE	C = 10.1; HE = 9.4 (6.9)	Lab
10[b]	49.8	ICE	C = 3.5; HE = 2	Lab

[1] *Mean; median in italics.* [2] *lab = laboratory study, field = field experiment.*

**ICE cars were detected earlier than a hybrid car; the hybrid car earlier than an electric car; **out of three makes of electric cars, two were detected later and one earlier than an ICE car; ***a hybrid car was detected later only when compared with a pickup truck, but not when compared with a small passenger car.*

[a] *JASIC (2009)* [b] *Garay-Vega et al. (2010)*
[c] *Kim et al. (2012a)* [d] *Wall Emerson et al. (2011)*
[e] *Hong, Cho & Ko (2013)* [f] *Mendonça et al.(2013)* [g] *Kim et al. (2012b)*

[2] Erratum: The original version of the article contained an incorrect reference.
[3] Erratum: In the original version of the article, the speed was incorrect.

No studies into the detectability and localisation of (hybrid) electric cars performed with cyclists were found in the literature. Since hybrid cars emit less sound at low speeds, it can be expected that similar differences in detection as for pedestrians will apply for cyclists. However, auditory detection of cars is probably more difficult for cyclists since cyclists, who typically move around faster, have also to deal with aerodynamic noise.

1.5.5. Electric cars and crash risk

It is difficult to determine whether the relative quietness of (hybrid) electric vehicles contributes to a higher risk of crashes involving pedestrians or bicyclists (*box 3*). Due to the limited operating range of the majority of fully electric vehicles (100 – 170 km), electric cars can be assumed to cover lower average annual kilo- metres and to be driven especially in urban areas. Therefore the share of kilometres driven at lower speeds, where their detectability is lower, is likely to be higher for electric cars than for conventional cars. If the lack of sound from the car were a contributory factor to crashes, the differences between conventional and electric cars should be expected to manifest themselves at low speeds.

Some studies show higher incidence of crashes involving (hybrid) electric cars and vulnerable road users (Hanna, 2009; Morgan et al., 2011; Wu, Austin & Chen, 2011). Research in the USA shows that, in the period 2000 – 08, hybrid cars had a higher incidence rate[4] of pedestrian and cyclist crashes (35% and 57%, respectively) (Wu, Austin & Chen, 2011). In situations where cars drive slowly (slowing down, stopping, backing up, and parking manoeuvres) the incidence rate of (hybrid) electric cars involved in pedestrian crashes was twice as high as that of conventional cars. Additionally, the number of bicyclist crashes involving (hybrid) electric cars at intersections or interchanges was significantly higher when compared to conventional vehicles.

Similarly, in the UK Morgan et al. (2011) found that proportionately more (hybrid) electric cars hit pedestrians than conventional cars. It is, however, not possible to conclude that (hybrid) electric cars are more dangerous in terms of crash risk than conventional ones as the absolute numbers of reported crashes involving (hybrid) cars were very small in both studies. Furthermore, the crash rates were not corrected for exposure, that is,

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[4] Incidence rates = the number of vehicles of a given type involved in crashes divided by the total number of that type of vehicle that were in any crashes.

kilometres travelled by each type of car. With higher exposure there is higher chance of crashes. Without exposure data, the available studies addressing the crash involvement of (hybrid) electric cars, do not provide evidence that (hybrid) electric cars pose a higher safety hazard for pedestrians and cyclists than conventional cars (see Verheijen & Jabben, 2010).

Table 1.4. (Hybrid) electric cars versus conventional cars in pedestrian and bicyclist crashes in the period 2007 – 2012 in the Netherlands by speed limit at the crash location.

		Speed limit of the road (km/h)				
Type of passenger car	**Crash opponent**	**15**	**30**	**50**	**<50**	**Unknown**
Conventional	Pedestrian	47	895	3155	362	239
	Cyclist	86	4497	20761	2376	966
	Total (*N* = 33.384)	133	5392	23916	2738	1205
	%	0%	16%	72%	8%	4%
(Hybrid) electric	Pedestrian	1	1	13	4	1
	Cyclist	0	16	56	5	3
	Total (*N 100*)	1	17	69	9	4
	%	1%	17%	69%	9%	4%

Source: DVS (Centre for Transport and Navigation)-BRON.

Quietness of the car as a contributing factor in crashes is not reported in Dutch crash data. *Table 1.4* shows crashes involving a (hybrid) electric car or a conventional car and a cyclist or pedestrian according to the speed limit of the road. Although the number of crashes involving (hybrid) electric cars was low, the distribution of crashes across road types is similar to that of conventional cars. For hybrid cars, it is not known whether or not they were driven in the electric mode at the time of the crash. The majority of crashes involving cyclists and pedestrians occurred in areas with a speed limit of 50 km/h, regardless of car type. In the period 2007 – 12, the percentage of (hybrid) electric cars in the Dutch fleet increased (from 0.15 – to 1.15%) proportionally to crash involvement of these vehicles with a pedestrian or a bicyclist (see *Appendix 2*). However, similar to Hanna (2009) and Morgan et al. (2011), the lack of exposure data and the small number of crashes in which (hybrid) electric cars are involved, makes it impossible to compare the crash risk of (hybrid) electric cars and conventional cars.

1.5.6. Experiences of drivers of (hybrid) electric cars

Two studies investigating the driver perspective (*box 8*) were found: a Dutch survey with drivers of hybrid and electric vehicles (Hoogeveen, 2010) and a field experiment (MINI E) performed in Germany and in France with test drivers driving an electric car (Cocron et al., 2011; Cocron & Krems, 2013; Labeye et al., 2011). The studies suggest that pedestrians and cyclists have problems hearing (hybrid) electric cars when those cars are driven at low speeds. None of the drivers participating in the studies reported a crash caused by the low sound emission of electric vehicles, but a substantial percentage of the drivers in the MINI E study reported noise-related incidents[5] (*box 3*). The Dutch study revealed vulnerable road users getting startled or surprised (*box 3*). In the MINI E study, 35% of drivers identified one or more critical incidents (crucial for traffic safety) and 67% reported less critical incidents involving pedestrians and cyclists and related to the quietness of the electric cars. The reported incidents occurred mainly at low speeds (e.g. at traffic lights, in parking areas or in underground garages) and sometimes while accelerating or in quiet side streets. Similarly, vulnerable road users in the Dutch study got startled predominantly by the vehicles driven up to 25 km/h. Forty-six per cent of the drivers reported observing such reactions among vulnerable road users.

The results also show that a substantial percentage of drivers (31% in the Dutch study and 62% in the MINI E study) do not compensate for the lower sound level of their cars by changing their driving behaviour. Furthermore, the MINI E study shows that as drivers gain experience with an electric vehicle, concerns for pedestrians and cyclists related to low sound emission decrease, most likely because drivers did not encounter as many critical noise-related situations as they might have anticipated. Those who changed their behaviour reported paying more attention (Cocron et al., 2011; Hoogeveen, 2010), actively anticipating and preventing potential hazards, seeking eye contact with pedestrians or even talking to them (Cocron et al., 2011). The lack of behavioural change can indicate that the drivers of electric cars are already relatively careful drivers. Another possible explanation is that they see no reason to adapt their behaviour, for example, because they did not consider driving an electric vehicle to be more dangerous than a conventional vehicle.

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[5] Crashes caused by the low sound emission ¼ situations in which a driver reported having been missed by vulnerable road users resulting in a collision; noise-related incidents ¼ being missed by a vulnerable road user not resulting in a collision.

1.6. Knowledge gaps and recommendations for future research

In line with the second aim of this paper, this section discusses a selection of research gaps in current research that may need to be addressed for a better under- standing of the role of auditory information in cycling safety. To this end, *Figure 1.2* showing which relationships (solid arrows) and which specific aspects have been researched among cyclists and pedestrians is used. Priorities for future research are also provided.

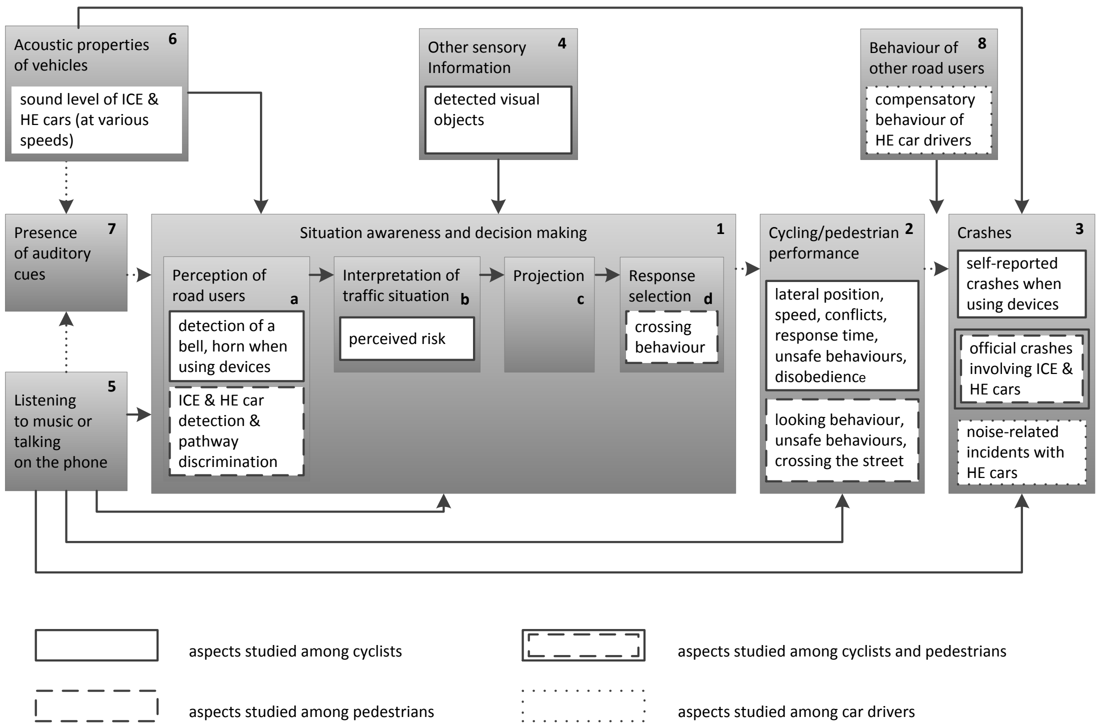

Figure 1.2. Overview of the relationships (solid arrows) examined by the reviewed studies and the specific aspects they dealt with (dashed, dotted and solid boxes).

Relatively little is known about auditory perception (detection and localisation) of traffic sounds (*box 1a*) by cyclists in general and especially when using electronic devices. The traffic sounds used in studies with cyclists were of limited variation (a bicycle bell and a horn). Auditory perception of these sounds may differ from other traffic sounds, e.g. conventional and electric cars. Based on research with pedestrians, electric cars at low speeds can be expected to be detected later than conventional cars. However, due to some important differences between pedestrians and cyclists (see Methods), their use of auditory cues may also differ. Future detection and localisation studies, should therefore be performed with cyclists and include a variety of vehicle sounds. It is also important to explore whether listening to music using one earphone is indeed a safe option for cyclists. This way of listening to music does not seem to impact the detection of auditory stimuli. It can, however, compromise correct localisation of sounds in space for which input from both ears is needed (Grothe, Pecka & McAlpine, 2010) and therefore may yet pose a safety hazard.

It is unknown to what extent the lack of auditory cues from traffic impacts crash risk. There appear to be no objective measures of estimating potential danger (*box 3*) caused by electric cars and the use of electronic devices while cycling. The use of subjective assessments to calculate the crash risk associated with the use of devices while cycling has important disadvantages such as possible non-accurate recall, dishonest reporting, selective non-response bias and does not guarantee a causal relationship. With regard to electric cars, the safety performance of these cars cannot be easily compared to that of conventional cars, primarily due to the lack of exposure data. It is therefore important that future studies collect adequate exposure data necessary to understand crash risk in relation to electric car use and device use while cycling. It is worth mentioning that the reduced sound levels, potentially risky for cyclists today, do not necessarily have to be that risky in the future. A transition from the current fleet to the one containing a substantial share of hybrid and/ or electric cars may cause cyclists to become more aware of their potential presence and behave accordingly. Cyclists may also eventually learn to rely less on auditory information while cycling and listening to music or talking on a mobile phone. They may compensate for the limited auditory input by, for example, increasing visual attention (for other examples of behavioural adaptation in traffic see Rudin-Brown & Jamson, 2013).

The existing crash data in the Netherlands are also not detailed enough to deter- mine whether bicycle crashes involved the use devices, or whether crashes between electric cars and cyclists were caused by compromised auditory perception. There may be some other aspects related to the use of devices or electric cars which make them potentially dangerous: some characteristics of cyclists who use devices (e.g. sensation seeking), characteristics of traffic environment when cycling and using devices (e.g. dense traffic), specific characteristics of drivers of electric cars (e.g. extra concern for the environment especially in case of the early adopters) or car condition (hybrid electric cars are generally much newer than the mix of conventional cars and newer cars meet higher safety standards, Cooper, Osborn & Meckle, 2010)[6]. For this paper, the influences of such potentially relevant factors have not been studied systematically. Future studies should focus more in depth on those factors.

The impact of a phone conversation on visual attention (*box 4*) is an unresolved issue. Although the model proposed in this paper specifically addresses situations in which no visual information is available, it is very important to explore auditory influences on visual perception of cyclists. If speaking on the phone turns out to impair visual perception (as two out of three studies showed), the possible compensation for the missed auditory information provided by the visual information may not occur. Furthermore, it is unknown how the use of devices and quiet cars impact the essential role of auditory cues in orienting visual attention towards the sound source, especially towards approaching vehicles outside of cyclists' visual field of view. Future studies should explore how the auditory and visual systems work together to facilitate cyclists' detection and localisation of other road users. No research about possible compensatory behaviour of car drivers who encounter a cyclist using electronic devices (*box 8*) could be found. Car drivers may, for example, drive more carefully knowing that more and more cyclists are using various electronic devices and therefore compensate for the possible dangerous behaviour of the cyclist.

Finally, not much is known about the use of electronic devices by cyclists in countries outside the Netherlands. Established cycling cities (such as Amsterdam, Utrecht, Copenhagen) differ in terms of cycling behaviour and bicycling infra- structure from cities where cycling is less popular (Chataway et al., 2014). Cyclists in countries where cycling is popular may also be more used to the presence of other "silent road users" (i.e. other cyclists) and therefore rely less on auditory information when detecting and localising other road users. This limitation of "the state of the art" may limit generalizability of the results concerning cyclists using electronic devices to countries in which cycling is less popular. We recommend therefore studying the effects of limitations on avail- ability of auditory information with cyclists in other countries.

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[6] Safety standards in general, but also standards specific for pedestrian protection, such as the design of softer and more forgiving car fronts (see, e.g. www.euroncap.com/home.aspx).

1.7. Main findings and their implications

This paper aimed to review current knowledge on the road safety consequences of using electronic devices while cycling and the effect of lower sound emission of (hybrid) electric vehicles on the behaviour and safety of vulnerable road users. Although for both topics reviewed no objective evidence of increased crash risk was found, there are reasons for concern. Listening to music and speaking on the phone negatively influence auditory perception, cycling performance and self-reported crash risk. With regard to electric cars, the recurring problem is their quietness at low speeds (generally up to 15 km/h). (Hybrid) electric cars are more difficult for vulnerable road users to detect, especially in environments with moderate and high ambient noise. These results have a number of implications. Those implications are potentially greater in situations where cyclists use solely auditory information, for example, when visibility is obscured or cyclists choose not to use the visual information available.

1.7.1. Car speed

Limitations on availability of auditory information seem to especially impact traffic environments where cars are driven at low speeds. Slower cars (both conventional and electric) generate less noise and are detected later and localised less accurately than faster cars. Slower speeds are generally considered safer for vulnerable road users. As speeds get higher, crashes result in more serious injury (Rosén, Stigson & Sander, 2011) and the likelihood of a crash increases (due to the longer braking distance and due to driver 's limited capacity to process information and act on it). However, even at low car speeds, collisions can still have serious consequences for pedestrians and cyclists, especially the elderly and young children. Electric cars at low speeds, due to their low-noise emission and therefore their decreased detectability, seem to pose an even greater risk for vulnerable road users than conventional cars driving at the same low speed.

Not only low car speeds should raise a concern in the discussion on the role of auditory information for cyclists. From the perspective of auditory perception faster moving vehicles seem safer, as both conventional and electric cars at higher speeds indeed offer suitable acoustic cues to other road users. However, cyclist's failure to detect and localise a fast car can increase the likelihood of a fatal injury — speed kills. Listening to music and talking on the phone restrict auditory perception of cyclists and can therefore be expected to lead to detection and localisation failures.

1.7.2. Combined effects: use of devices and electric cars

In the introduction, we have suggested that encountering a quiet (hybrid) electric car may be especially dangerous for cyclists who listen to music or talk on the phone. Research findings presented in this review do not allow hard conclusions, since no studies were found where the use of devices by cyclists was combined with the sound of approaching cars. Based on studies including sounds of a bicycle bell and a horn, we could expect that auditory detection of various types of cars will at least to some extent be negatively affected by the use of electronic devices. The use of devices may, however, turn out to prevent a car sound from reaching the cyclist irrespective of vehicle type, especially when acoustic input of electric and conventional cars does not differ much from each other — which is especially likely at speeds 20 km/h and above.

1.7.3. Add-on sounds

To improve detectability of (hybrid) electric cars, various developments have been set in motion to provide these vehicles with artificial sound (GRB, 2013; NHTSA, 2013). Some government agencies (e.g. in Japan, the USA, European Parliament) are working on standards for a minimum sound level emitted by vehicles (European Parliament, 2013). Add-on sounds may potentially provide some improvement in detectability of electric cars, but at the cost of increased noise levels, which according to Yamauchi et al. (2010) will be unacceptable in urban situations. Even if these new ambient sound levels are realised, some cars will still be too silent. From the traffic safety perspective, negative effects may appear, for instance in the presence of an artificial sound drivers may think that vulnerable road users can hear them and therefore may not drive as carefully as they would without the added sound (Sandberg, 2012; Sandberg, Goubert & Mioduszewski, 2010).

Other solutions to the problem of low detectability can be suggested, e.g. pedestrian/ cyclist detection systems and the use of cobbled pavements in low-speed traffic environment. Cobblestones reach very high detection percentages for both conventional and hybrid cars driven at speeds above 30 km/h across various ambient sound levels (Mendonça et al., 2013). The suitability of cobblestones for ensuring high detectability of vehicles at lower speeds, however, still needs to be explored.

1.8. Concluding remarks

The concerns regarding the potential negative impact of restricted auditory perception among cyclists (and pedestrians) should be taken seriously. Cycling, in recent years strongly encouraged by governmental policies (see OECD/International Transport Forum, 2013), is expected to become a central part of the mobility solution in many cities. Addressing cycling problem areas is therefore of critical importance. Future studies should cover important research gaps for a better understanding of the relation between limitations on auditory information while cycling and cycling safety. Especially transition periods, during which cyclists have to cope with a mix of vehicles characterised by various acoustic properties, seem potentially risky for cyclists.

Appendix 1. Details of the studies included in the literature review

Author (date)	Study type	Location
Details of studies into the use of devices with cyclists		
De Waard et al. (2011)	Field experiment	The Netherlands
De Waard et al. (2010)	Field experiment, observation and survey	The Netherlands
De Waard et al. (2014)	Field experiment	The Netherlands
Goldenbeld et al. (2010)	Survey	The Netherlands
Terzano (2013)	Observation	The Netherlands
Ichikawa and Nakahara (2008)	Survey	Japan
Details of studies into the use of devices with pedestrians		
Walker et al. (2012)	Observation	USA
Hyman et al. (2010)	Observation	USA
Nasar et al. (2008)	Field experiment	USA
Neider et al. (2010)	Experiment in virtual environment	USA
Schwebel et al. (2012)	Experiment in virtual environment	USA
Nasar and Troyer (2013)	Crash study	USA
Stavrinos et al. (2011)	Experiment in virtual environment	USA
Hatfield and Murphy(2007)	Observation	Australia
Thompson et al. (2013)	Observation	USA
Neider et al. (2011)	Experiment in virtual environment	USA
Details of studies into detectability and localisation of (hybrid) electric and conventional cars		
JASIC (2009)	Acoustic measurements, laboratory study with sighted participants	Japan
Garay-Vega et al. (2010)	Acoustic measurements laboratory study with visually impaired participants	USA
Wiener et al. (2006)	Acoustic measurements field experiment with visually impaired participants	USA

Author (date)	Study type	Location
Wall Emerson et al. (2011)	Field experiment with visually impaired and sighted participants	USA
Kim et al. (2012a	Acoustic measurements and field experiment with visually impaired participants	USA
Kim et al. (2012b)	Field experiment with visually impaired participants	USA
Wall Emerson and Sauerburger (2008)	Field experiment with visually impaired participants	USA
Mendonça et al. (2013)	Laboratory study with sighted participants	Portugal
Hong et al. (2013)	Field experiment with sighted participants	Korea
Barton et al. (2012)	Laboratory study with sighted participants	USA
Barton et al. (2013)	Laboratory study with sighted participants	USA
Details of studies into safety of electric cars		
Hanna (2009)	Crash study	USA
Wu et al. (2011)	Crash study	USA
Morgan et al. (2011)	Crash study	UK
Cocron et al. (2011)	Field experiment	Germany
Cocron and Krems (2013)	Field experiment	Germany
Labeye et al. (2011)	Field experiment	France

Appendix 2. (Hybrid) electric cars in pedestrian and bicyclist crashes

(Hybrid) electric cars in pedestrian and bicyclist crashes compared to the share of (hybrid) electric cars in Dutch fleet in the period 2007-2012.

	Year					
	2007	2008	2009	2010	2011	2012
% road crashes[7]	0.08	0.19	0.43	0.35	0.60	1.43
% of Dutch fleet comprising (hybrid) electric cars	0.15	0.31	0.52	0.72	0.89	1.15

Source: DVS (Centre for Transport and Navigation)-BRON (The national road crash register); RDW Technology and information Centre

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[7] Percentage of crashes where a (hybrid) electric car had a collision with a pedestrian or bicyclist out of the total number of crashes where a passenger car of any type had a collision with a pedestrian or bicyclist.

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