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Auditory Detectability of Hybrid Electric Vehicles by Pedestrians who are Blind

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Abstract

Hybrid electric vehicles (HEVs) in low-speed operation may introduce a safety issue for pedestrians. This study compared the auditory detectability of HEVs and internal combustion engine (ICE) vehicles among pedestrians who are legally blind. Independent travelers, with self-reported normal hearing, listened to binaural audio recordings of two HEVs and two ICE vehicles in three operating conditions, and two different ambient sound levels. The operating conditions include: approaching at a constant speed (6 mph); backing out at 5 mph; and slowing from 20 to 10 mph (as if to turn right). The ambient sound levels were a quiet rural [31.2 dB(A)] and a moderately noisy suburban ambient [49.8 dB(A)]. Overall, participants took longer to detect HEVs (operated in electric mode). Vehicle type, ambient level, and operating condition had a significant effect on response time. Candidate countermeasures are discussed in terms of types of information provided (direction, rate of speed change), useful range of detection of vehicles by pedestrians, warning time, acceptability and barriers to implementation.

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1. Introduction

The purpose of this study is to examine how pedestrian performance (response time and accuracy) for three vehicle maneuvers differs for ICE vehicles and HEVs operated in electric mode. In addition, we examined how ambient sound levels affect the ability of participants to detect the vehicles. Three types of vehicle maneuvers with high potential for adverse consequences for blind pedestrians are examined: 1) vehicle approaching at a constant low speed; 2) vehicle backing out (e.g., driveway); and 3) vehicles moving in parallel and slowing (as if to turn right).

Quieter cars such as electric vehicles (EVs) and HEVs can reduce pedestrians' ability to assess the state of nearby traffic and, as a result, may have an adverse impact on pedestrian safety. The primary concern is when HEVs operate using their electric motor systems at slow speeds when other auditory cues from tires and wind noise are less dominant.

Mobility depends in large part on perceiving the characteristics of the immediate surroundings. Traffic sounds provide important cues for pedestrians. The likelihood of perceptual errors by pedestrians is influenced by several factors including absence of information, lack of perceptual or motor skill, inattention, and willingness to take risks (1). Traffic sounds, for example, help blind pedestrians to orient themselves towards the crosswalks, to identify a time to cross, and to travel straight across the street (1, 2). The sound of traffic provides cues that help pedestrians identify vehicle operation (i.e., idling, accelerating, slowing) and vehicle maneuver (going straight, turning right or left). Vehicle operations provide information to assess the state of the traffic flow and to judge how much time they have to cross the street (3, 4). A significant reduction in auditory cues from vehicles may reduce the available information needed by blind and other pedestrians to navigate, and thus impact their ability to travel safely.

NHTSA's National Center for Statistical Analysis (NCSA) documented the incidence rate of pedestrian and bicyclist crashes with HEVs and compared the results to ICE vehicles. The incidence rate of pedestrian crashes is higher for HEVs than the ICE vehicles in the study, and the difference is statistically significant. A total of 8,387 HEVs and 559,703 ICE vehicles were included in the analysis. Seventy-seven HEVs and 3,578 ICE vehicles were involved in crashes with pedestrians. This figure represents 0.9 percent of all HEVs and 0.6 percent of all ICE vehicles in the analysis (5). Incident rates are calculated as the number of vehicles (HEV or ICE) involved in crashes with pedestrians in a particular situation, divided by the total number of vehicles (HEV or ICE) that were in any crash under that same situation.

A series of studies comparing an ICE and a HEV suggest that a HEV traveling at 5 mph is harder to localize when compared to an ICE vehicle. Measures include listeners' ability to identify the direction of a vehicle and the response time for correct detection. Recordings were played to a small number of blindfolded listeners (college students) over headphones in a laboratory. Participants were asked to quickly and accurately identify from which direction (left or right) the vehicle was coming quickly and accurately (6, 7).

In a separate study (published in the course of this present study), the Japanese Automobile Standards Internationalization Centre (JASIC) showed that participants took longer to detect HEVs (in electric mode) than the ICE vehicles tested when the background noise level was low and the speed was about 9 mph or less. The scenarios evaluated included: vehicle stationary and vehicle approaching at low speeds (6.5, 10, 15, and 20 km/h). The results suggest that the situations where it is necessary to improve the perception of HEVs (in electric mode) occur when moving below 20 km/h (approximately 12 mph).The study also suggested that the difference between the two vehicles that is associated with the background noise becomes smaller as the speed of the vehicle increases (8).

The current study, completed by the Volpe National Transportation Systems Center (Volpe Center) and funded by the National Highway and Traffic Safety Administration (NHTSA) expands upon recent work conducted in this area (9).

2. Methods

Each participant listened to binaural recordings of the sounds of various vehicles in three operating conditions or scenarios with either a relatively quiet rural ambient sound or with a moderately noisy suburban ambient sound superimposed. Binaural recordings reproduce the acoustic characteristics of the sound similar to how a human perceives it.[1] The experiment was constructed using the E-Prime system from Psychology Software Tools, Inc. The study setup includes a Toshiba mini laptop computer used by the investigator to run the test; two sets of headphones, one for the participant (Grado Labs Prestige Series SR125) and one for the investigator (Sony Dynamics Stereo MDR-V6); and a full size computer keyboard for participant response.

2.1 Participants

Forty-eight (48) individuals who are legally blind participated in the study (46% male, 54% female). The group includes individuals who are totally blind (42%), blind with light perception (21%), and blind with some usable vision (38%). Participants are all independent travelers who complete streets crossing at least 10 times per week without assistant from another person. Their ages range from 18 to 69 years old (52% were under 50 years old; 48% were between 50 and 69 years old). They all reported to have normal hearing in both ears without hearing aids. Sixty-three (63) percent of the participants use white canes as the primary mobility aid at the time of the study, 33 percent use guide dogs, and four percent do not use canes or guide dogs. Individuals with severe hearing loss, users of hearing aids, and persons who do not travel independently on a regular basis were not eligible to participate. Recruitment information was distributed with the assistance of the Perkins School for the Blind, in Watertown Massachusetts and the Carroll Center for the Blind in Newton, Massachusetts. Participants received a $50 gift card for their participation.

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[1] Binaural recordings were collected for vehicles and ambient sounds, these recordings where then combined for use in this study. Acoustic measurements (including binaural recordings) is a topic unto itself and are described in detail in DOT HS 811 304 (Reference 9).

2.2 Experimental Scenarios

Scenarios were identified based on preliminary crash data and discussions with pedestrian who are blind, and with orientation and mobility specialists. Three of the scenarios were included in the human subject study and are described in this section.

Vehicle approaching at low speed (6 mph passby): The first traveling situation examined includes a pedestrian standing on the curb waiting to cross a one-way street where there may be vehicles approaching from the left. Some trials include a target vehicle and some trials only background noise. The target vehicle in this scenario is traveling from the left at a constant speed of 6 mph. There are vehicles in the background in all trials. The pedestrian must be able to detect a vehicle that would affect the decision about when to start across the street. One of the strategies used by pedestrians who are blind is to cross when the road is quiet. The technique assumes that a vehicle is loud enough to be heard far enough away to determine that it is safe to proceed when no masking sounds are present and no other vehicles are detected (10). This scenario tests the distance and time at which a pedestrian can detect a vehicle approaching at low speed.

Vehicle backing out (5 mph reverse): The second traveling situation includes a pedestrian walking along a sidewalk with driveways on the left side; the pedestrian hears distant vehicles in the background in all trials. This is similar to walking in an area that is a few blocks away from a main road. The target vehicle is a nearby vehicle backing towards the pedestrian at a constant speed of 5 mph. This task is complex for pedestrians since it is difficult to anticipate where there may be a driveway and when a vehicle will move out of a driveway. In addition, a driver's visibility may be limited and the pedestrian may have very limited time to respond to avoid a conflict.

Vehicle traveling in parallel lane and slowing (slowing from 20 to 10 mph): The third and last traveling situation examined in the present study includes a pedestrian trying to decide when to start crossing a street with the signal in his/her favor and a surge of parallel traffic on the immediate left. The sound of slowing vehicles in the parallel street helps blind pedestrians identify turning vehicles. In some trials (no-signal condition), a vehicle continues straight through the intersection at 20 mph, so pedestrians can cross whenever they choose. However, in other trials there is a vehicle slowing from 20 mph to 10 mph as if to turn right into the pedestrian path (target vehicle). The pedestrian must be able to detect when the vehicle is slowing. This scenario tests whether the pedestrian perceives this information when the vehicle is in the parallel street.

2.3 Stimuli

Three independent variables were examined. Vehicle type is tested at two levels (ICE vs. hybrid electric vehicles in EV mode). Four vehicles were included in the test: two hybrid electric vehicles operated in electric mode (2010 Toyota Prius and 2009 Toyota Highlander) and two internal combustion engine vehicles (2009 Toyota Matrix and 2008 Toyota Highlander). These four vehicles were selected from a subset of vehicles recorded based on the potential of HEVs to operate in electric-only mode. Vehicle maneuver, also referred as operating condition or scenario, is tested at three levels: 1) vehicle approaching a constant low speed of 6 mph from the left; 2) vehicle backing out of a driveway at 5 mph from the left; and 3) vehicle moving in the parallel street, but slowing down from 20 to 10 mph as if to turn right. The average sound pressure levels, A-weighted, for each vehicle and scenario are summarized in Table 1. Ambient sound level is tested at two levels: 31.2 dB(A) and 49.8 dB(A).[2] Details of the acoustic measurements including sound pressure levels and spectra characteristics for these and other vehicles are documented in Garay-Vega et.al. (9)

Table 1 Overall A-weighted sound level at the Microphone Location (12 ft)

	Average A-weighted level, $L_{Aeq0.5s}$ (dB(A))			
Scenario	2010 Toyota Prius	2009 Toyota Matrix	2009 Toyota Highlander Hybrid	2008 Toyota Highlander
Approaching at 6 mph	44.7	53.5	53.2	55.5
Backing out (5 mph)	44.2	51.3	45.9	52.7
Slowing from 20 to 10 mph	53.0	54.2	53.0	55.4

2.4 Data Collection

Two dependent variables are examined: missed detection frequency and response time (and corresponding time-to-vehicle arrival and detection distance). Missed detection frequency is defined as instances when the target vehicle is present and the participant fails to respond. Response time is computed as the time from the start of a trial to the instant the participant presses the space bar as an indication he/she detects the target vehicle. From the response time we compute the time-to-vehicle arrival and the detection distance. The time-to-vehicle-arrival is the difference between the duration of a trial and the response time. Detection distance is the longitudinal space between the vehicle and the pedestrian (microphone) location at the instant the participant indicated detection of a target vehicle. All the data was collected in E-Prime.

2.5 Experimental Design

All participants were presented with the same experimental trials (within-participant design) to account for between-participant variability. A total of 144 observations were recorded for each participant. There were three experimental sessions, one for each scenario. Each experimental session included 48 trials. A trial consists of the combination of the sound of a particular vehicle (either ICE vehicle, HEV, or no target vehicle present) executing the maneuver in question and a particular ambient sound (either quiet rural or moderate suburban). Each of the sessions had two blocks, one for each ambient sound level. Each block consisted of 24 trials. Each combination of vehicle maneuver-ambient was repeated six times (four times with and two times without target vehicles). The no-signal condition (e.g., target vehicle not present) was needed to determine the percentage of correct detection and more importantly the frequency of misses or incorrect detection. The presentation order for the vehicle maneuvers and ambient level was counterbalanced across participants. The presentation of vehicle/no vehicle trials and vehicle types was randomly distributed within participants.

2.6 Procedure

Each participant was briefed by a Volpe Center investigator according to the informed consent form as required by the Institutional Review Board with regards to the protection of human participants. The investigator described the traveling situation before each session. Each session

[2] These ambient levels simulate a quiet suburban and a somewhat nosier suburban environment where pedestrians who are blind are likely to travel without assistance.

began with eight practice trials containing examples of the sounds of all of the target vehicles as well as examples with no target vehicle present. The practice session allowed participants to experience the relatively uniform ambient and environmental sounds. The practice session also allowed them to familiarize themselves with the traveling situation and experimental task. The investigator provided feedback during the practice session about whether the participant was making the correct response. Participants were instructed to press the computer space bar only when and if they first heard a target vehicle. Target vehicles include: a vehicle approaching at 6 mph that may affect their decision to cross a street; a nearby vehicle backing out at 5 mph; and a vehicle decelerating from 20 to 10 mph as if to turn right into the pedestrian path. If they did not hear the target vehicle they were instructed not to press the space bar and to wait for the sound clip to end and for the next one to begin. There was a 5-second average transition between trials. A total of 1 hour and 15 minutes per participant was required to complete the study including debriefing.

3. Results

3.1 Missed Detection

Missed detection frequency is defined as the instances when the target vehicle was present and the participant failed to respond.[3] The missed detection rate is computed as the total number of trials where participants missed a target vehicle, divided by the total number of trials with a target vehicle present (for all participants). Each participant experienced 48 trials in each session. A target vehicle was present in 32 out of the 48 trials; 16 with low ambient and 16 with high ambient sound

Vehicle approaching at low speed:

Participants were more likely to miss the Toyota HEVs than the Toyota ICE vehicles approaching at a constant low speed. The missed detection rates in the low ambient condition are: 0.02 for the Prius; 0.01 for the Matrix; 0.03 for the Highlander Hybrid; and 0.0 for the Highlander ICE vehicle. The corresponding values in the high ambient condition are: 0.21 for the Prius; 0.02 for the Matrix; 0.04 for the Highlander; and 0.01 for the Highlander ICE vehicle.

Vehicle backing out:

Participants were more likely to miss the Toyota HEVs than the Toyota ICE vehicles in the backing out session. The missed detection rates in the low ambient condition are: 0.05 for the Prius; 0.02 for the Matrix; 0.10 for the Highlander Hybrid; and 0.02 for the Highlander ICE. The corresponding values in the high ambient condition are: 0.11 for the Prius; 0.0 for the Matrix; 0.26 for the Highlander; and 0.02 for the Highlander ICE.

Vehicle traveling in parallel lane and slowing:

Participants were more likely to miss the ICE vehicles approaching in parallel lane and slowing than the HEVs in the same situation. The missed detection rates in the low ambient condition are: 0.05 for the Prius; 0.31 for the Matrix; 0.03 for the Highlander Hybrid; and 0.17 for the Highlander ICE vehicle. The missed detection rates in the high ambient condition are: 0.05 for

[3] Additional information, including figures summarizing missed detection data, is available in DOT HS 811 304 (Reference 9).

the Prius; 0.35 for the Matrix; 0.03 for the Highlander Hybrid; and 0.17 for the Highlander ICE vehicle.

3.2 Time-to-Vehicle Arrival

Time-to-vehicle-arrival is the time from first detection of a target vehicle, for each of the scenarios described above, to the instant the vehicle passes the microphone line/pedestrian location. A repeated measures analysis of variance (ANOVA) is used to analyze the main and interaction effects of the independent variables; vehicle type, vehicle maneuver and ambient sound level. Considering all three independent variables, there is a main effect of vehicle type [F (2.5, 119.4) = 78.13; p < 0.05], vehicle maneuver [F (1.69, 79.59) = 146.49; p < 0.05], and ambient sound level [F (1, 47) = 94.21; p < 0.05]. Similarly, there are interaction effects between vehicle type and ambient [F (2.68, 125.89) = 4.54; p < 0.05]; vehicle type and maneuver [F (3.818, 179.43) = 137.37; p < 0.05], ambient and vehicle maneuver [F (1.99, 93.31) = 31.71; p < 0.05], and a three way interaction between ambient, vehicle type and vehicle maneuver [F (4.6, 216.50) = 9.673; p < 0.05]. A separate analysis was completed for each scenario; a pair-wise t-test compares each vehicle with the other (ICE vehicle and HEV twins) for each ambient sound level. Time-to-vehicle arrival for each vehicle-ambient condition is shown in Table 2, Table 3 and Table 4 for each of three scenarios.

Vehicle approaching at low speed:

On average, participants took 1.1 seconds longer to detect vehicles in the high ambient sound condition than in the low ambient sound condition. The main effect of ambient is statistically significant [F (1, 47) = 35.0; p< 0.05]. The mean time-to-vehicle-arrival is 5.5 and 4.3 seconds for the low and high ambient condition, respectively. Participants detected both ICE vehicles sooner than the HEV twins. The main effect of vehicle is statistically significant [F (2.13, 99.9) = 106.1; p< 0.05]. The interaction effect of vehicle and ambient is statistically significant [F(2.80, 131.36) = 11.93; p< 0.05]. Table 2 presents the individual differences between ICE vehicles and their HEV twins (i.e., Prius vs, Matrix and Highlander hybrid vs. Highlander ICE); pair-wise comparisons are statistically significant within a given ambient condition.

Vehicle backing out:

On average, participants took longer to detect vehicles in the high ambient sound condition than in the low ambient sound condition. The main effect of ambient is statistically significant [F (1, 47) = 96.64; p< 0.05]. The average time-to-vehicle-arrival is 4.4 and 2.7 seconds for the low and high ambient condition, respectively. Participants took longer to detect both HEVs than their ICE twins. The main effect of vehicle type is statistically significant [F (2.72, 128.0) = 115.0; p< 0.05]. Table 3 shows the individual differences between ICE vehicles and their HEV twins; pair-wise comparisons are statistically significant within a given ambient condition.

Vehicle traveling in parallel lane and slowing:

Table 4 shows the time-to-vehicle arrival and detection distance for the 'vehicle slowing' scenario. Pair-wise comparisons (HEV vs. ICE twin) are statistically significant within a given ambient condition. On average, participants detected HEVs sooner than their ICE vehicle twins. The main effect of vehicle is statistically significant [F (2.04, 96) = 163.85; p< 0.05]. The trend observed in the vehicle slowing scenario (i.e., HEVs are detected sooner than their ICE vehicle twins) may be explained by a noticeable peak in the 5000 Hz one-third octave band for the HEVs tested during this operation. The tone emitted is associated with the electronic components of the vehicles when braking (e.g., regenerative braking).

Table 2 Time-to Vehicle Arrival and Detection Distance for 6 mph Vehicle Passby by Vehicle Type and Ambient Condition

Vehicle	Ambient Sound Level	Time-to-Vehicle Arrival (s)	Detection Distance (ft)
2010 Toyota Prius	Low	4.3	37.9
	High	2.4	20.9
2009 Toyota Matrix	Low	5.5	48.4
	High	4.6	40.5
2009 Highlander Hybrid	Low	5.3	46.6
	High	4.1	36.6
2008 Highlander ICE	Low	6.8	59.4
	High	6.3	55.1

Table 3 Time-to Vehicle Arrival and Detection Distance for Vehicle Backing out by Vehicle and Ambient Condition

Vehicle	Ambient Sound Level	Time-to-Vehicle Arrival (s)
2010 Toyota Prius	Low	4.0
	High	2.5
2009 Toyota Matrix	Low	5.2
	High	3.6
2009 Highlander Hybrid	Low	3.3
	High	1.4
2008 Highlander ICE	Low	5.2
	High	3.3

Table 4 Time-to Vehicle Arrival and Detection Distance for Vehicle Decelerating from 20 to 10 mph by Vehicle Type and Ambient Condition

Vehicle	Ambient Sound Level	Time-to-Vehicle Arrival (s)	Detection Distance (ft)
2010 Toyota Prius	Low	2.0	35.9
	High	1.9	33.8
2009 Toyota Matrix	Low	1.1	18.0
	High	0.8	12.8
2009 Highlander Hybrid	Low	3.0	58.8
	High	2.7	51.6
2008 Highlander ICE	Low	1.5	25.7
	High	1.3	21.8

3.3 Detection Distance

Detection distance is the distance between the vehicle and the pedestrian (microphone) location at the moment the participant indicates detection of a target vehicle. Detection distance for a vehicle approaching at a constant speed is calculated by multiplying the time-to-vehicle-arrival by the vehicle speed (in feet per second). Detection distance for the "slowing vehicle" scenario(Table 4) is calculated according to the following equation: $d = (v_f t) + (½ a t^2)$; where: d = distance at which detection occurred; v_f = velocity at microphone line (i.e., 10 mph or 14.67 ft per sec); t = time-to-vehicle-arrival (i.e., seconds until vehicle passed microphone) and a = deceleration rate (i.e., 1 m/sec^2 or 3.28 ft/sec^2). Table 2 and Table 4 show detection distance for each vehicle-ambient condition for the 'vehicle approaching at a constant speed' and for the "slowing vehicle' scenario, respectively.

One approach to examining the safety risk is to compute the distance to the vehicle at the time it was detected (detection distance). The needed detection distance is computed from the vehicle speed and the pedestrian response time. This approach assumes that only pedestrians respond to a potential conflict. A second approach is to assume that the driver is the one who responds to a potential conflict. The stopping sight distance for a vehicle approaching at a constant 6 mph is 25.5 ft. The vehicle would travel approximately 22.5 ft while the driver reacts. The driver would need another 3.5 ft to stop the vehicle. The stopping sight distance can be compared against the pedestrian detection distance as a measure of risk. In this example, the pedestrian must detect the vehicle (and respond) when the vehicle is at least 25.5 ft away in order to avoid a potential collision. The calculation assumes a brake reaction time of 2.5 s and a constant deceleration rate of 11.2 ft/s^2. A 2.5-second brake reaction time for stopping situations considers the capabilities of most drivers, including older drivers (11).

4. Discussion

In general, HEVs tested are quieter than ICE vehicles below approximately 20 mph; HEVs also tend to have less high frequency content than ICE vehicles at low speeds (9). Response time for each vehicle maneuver depends on ambient sound level and vehicle type. Overall, vehicles are detected sooner in the low ambient condition. ICE vehicles tested are detected sooner than their HEV twins except for the vehicle slowing scenario where HEVs were detected sooner. Table 5 summarizes the average time-to-vehicle arrival by vehicle type and ambient sound level.

Table 5 Average Time-to-Vehicle Arrival by Scenario, Vehicle Type and Ambient Sound

	Low Ambient		High Ambient	
Scenario	**HEVs**	**ICE Vehicles**	**HEVs**	**ICE Vehicles**
Approaching at 6 mph	4.8	6.2	3.3	5.5
Backing out (5 mph)	3.7	5.2	2.0	3.5
Slowing from 20 to 10 mph	2.5	1.3	2.3	1.1

Although the times-to-vehicle-arrival for the HEVs are small, they are usually sufficient for the pedestrian to take some evasive action or raise their white cane to enhance conspicuity. In discussions with participants, one of the most difficult situations are those in which vehicles appears unexpectedly (as in backing out of a driveway or parking space) as opposed to a crosswalk at a street corner.

The experiments in this study mimic the situation in which a blind pedestrian knows there is a high probability of hearing a vehicle within a few seconds and can devote full attention to listening for it (e.g., laboratory environment). It is reasonable to expect that times to-vehicle-arrival for very quiet vehicles would be even shorter than the time-to-vehicle-arrival measured in this study when pedestrians are distracted (e.g., non-laboratory environment).

Preliminary evaluation criteria to compare potential countermeasures include: types of information provided (direction, vehicle speed, and rate of speed change, etc.); pedestrian detection range, warning time, user acceptability, and barriers to implementation. Infrastructure options and pedestrian training can improve safety; however, they cannot directly address the issue that HEVs operated in electric mode are not as detectable as their ICE counterparts in some scenarios. At the present time, the only countermeasures that are useful for HEVs in providing the relevant sound cues needed by pedestrians appear to be synthetic vehicle sounds (9). Relevant information includes auditory cues about vehicle position, speed, and rate of change in speed. Considering the results of this and other recent studies, such sounds are only needed when vehicles are operated at low speeds (generally less than 10 - 20 mph) (8, 9). Groups representing people who are blind have expressed a preference for sound(s) that will be recognized as that of an approaching vehicle so that it will be intuitive for all pedestrians (9, 12). The characteristic sound of a vehicle being started is also desired as it is often the first cue of the presence of a potential threat, for example, in a parking lot. Similarly, the sound of a vehicle accelerating from stop, for example at a traffic signal, provides relevant cues about the state of the traffic flow. Sound content, such as the relative proportions of high and low frequencies, can be manipulated to improve the effectiveness of such alert sounds while reducing the overall community noise impact. Further evaluation is needed to define what kinds of synthetic sound (e.g., broadband, tonal, modulation, or a combination) provide the most useful alert cues for pedestrians.

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