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Acoustic Characteristics of Hybrid Electric Vehicles and the Safety of Pedestrians who are Blind

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Abstract

Quieter cars such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) may reduce auditory cues used by pedestrians to assess the state of nearby traffic and, as a result, their use may have an adverse impact on pedestrian safety. In order to document differences in the sound levels of HEVs and internal combustion engine (ICE) vehicles, the authors measured the sound pressure level in one-third octave bands of three HEV and three corresponding ICE vehicles for the following operating conditions: idle, backing up at 5 mph; approaching at a constant speed (6, 10, 20, 30, and 40 mph); accelerating from stop, and slowing from 20 to 10 mph at 3.28 ft/s^2. Sound level results comparing the HEVs and ICEs are presented. In general, HEVs have lower sound levels than ICEs for operating conditions below 20 mph, but above 20 mph, the sound from road-tire interactions dominates and the sound levels of the two vehicle types converge.

1. Introduction

As cars and other vehicles become quieter due to new and improved technologies, there is the potential to reduce noise pollution in our cities and urban living areas. However, the decrease in the noise emitted from quieter cars may pose a safety problem for bicyclist and pedestrians, in particular blind pedestrians (Reference 1), who rely on auditory cues to assess the state of nearby traffic and to navigate their environment. For example, blind pedestrians use auditory cues from vehicles to determine the position of vehicles relative to themselves, to determine a vehicle's trajectory, and to determine a vehicle's speed and if it is accelerating. Auditory cues from vehicles also facilitate pedestrian orientation tasks such as establishing alignment before and while crossing a crosswalk.

The reduction of auditory cues from vehicles is particularly a concern for electric vehicles (EVs) and hybrid-electric vehicles (HEVs) operating in electric only mode at low speeds where other auditory cues from tires, wind, etcetera are less dominant. In such cases, there may be a difference in the sound level and character of these vehicles compared to typical internal combustion engine (ICE) propelled vehicles. While the number of visually impaired is increasing from today, where there are about 3.3 million Americans over the age of forty who are blind or have low vision to about 5.5 million by the year 2020 (Reference 2), the level and details of the impact of EVs and HEVs on the safety of blind pedestrians is not well known.

This paper provides a brief summary of the acoustic measurements and results for vehicles operating under conditions representative of critical safety scenarios identified during the first phase of the National Highway Traffic Safety Administration's (NHTSA's) study to examine the safety risk associated with quieter cars for blind pedestrians and to investigate appropriate countermeasures (Reference 3). The purpose of the measurements was to document acoustic differences between HEV and ICE vehicles as well as to acquire recordings of HEV and ICE vehicles for evaluation during human performance testing. The human performance testing is a topic unto itself and is described in the paper, "Auditory Detectability of Hybrid Electric Vehicles by Pedestrians who are Blind" (Reference 4).

2. Critical Safety Scenarios for Pedestrians who are Blind

In order to determine under what operating conditions vehicles should be measured, it was important to discuss the issue with those most concerned about the issue of cars becoming quieter. Therefore, a series of critical safety scenarios were identified based on discussions with pedestrians who are blind and with orientation and mobility specialists. Scenarios were defined by combining pedestrian-vehicle environments, vehicle type, vehicle maneuver / speed / operation, and ambient sound level. The risks for various pedestrian-vehicle interactions were considered. These included vehicles approaching at a constant speed, vehicles turning into the pedestrian's path, and vehicles backing out into the pedestrian's path. In addition to these risks, pedestrians who are blind identified information used to facilitate navigation. This information included: vehicle presence;

vehicle position relative to the pedestrian; vehicle direction of travel; and vehicle rate of acceleration or speed. This information is used to judge how fast the vehicle is moving or how soon the vehicle may reach the pedestrian position or travel path.

Based on these considerations, the following scenarios were identified as critical safety scenarios: vehicle backing out; traveling in parallel and slowing; approaching at low speed; accelerating from stop; and idling. For the purposes of this paper, a vehicle is considered to be idling if it is not moving, but would be capable of imminent movement without any additional auditory cues. For example an ICE could have the engine running and either have the brake depressed or have the transmission in park. An EV would be "on", but with no power directed to the motor. These scenarios are described in more detail below.

2.1 Vehicle Backing Out

There is a concern that EVs and HEVs operated in EV mode may not be detectable when backing out. This is a complex detection task 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. Thus, the pedestrian may have very limited time to respond to avoid a conflict.

2.2 Vehicle Traveling in Parallel and Slowing

Pedestrians who are blind often need to distinguish between a vehicle moving through an intersection and a vehicle turning into their path. The pedestrian needs to perceive this information when the vehicle is in a parallel street, before it turns into their path. The sound of slowing vehicles in parallel streets helps pedestrians identify turning vehicles. A quieter car slowing may not be as detectable.

2.3 Vehicle Approaching at Low Speed

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. Preliminary studies have shown that HEVs approaching at low speed (less than 12 mph) may not be detectable (References 5 and 6). A quieter car approaching at low speed may not be detected until it is too close to the pedestrian.

The difference in sound levels between HEVs and ICE vehicles may become smaller as the speed of the vehicle increases. Both the electric motor and engine are used to propel HEVs at higher speeds and tire / road noise begins to dominate at higher speeds as well. This study includes acoustic data for vehicles approaching at low (6 mph, 10 mph) and moderate speeds (20 mph, 30 mph, 40 mph) to examine how the acoustic characteristics of HEVs and ICE vehicles differ as a function of vehicle speed.

2.4 Vehicle Accelerating from a Stop

Pedestrians who are blind use the sound of traffic in parallel streets to establish alignment and to identify a time to cross. The sound of accelerating vehicles in parallel streets indicates, for example, that the perpendicular traffic does not have the right of way and thus a crossing opportunity is available. A safety concern is that quieter cars may not be heard during initial acceleration. Pedestrians may initiate their crossing as soon as they detect the surge of parallel traffic or may delay the decision to make sure traffic is moving straight through the intersection and not turning into their path. A significant delay in detecting the surge of parallel traffic may impact a blind pedestrian's ability to complete a crossing within the designated walking interval.

2.5 Vehicle Idling

Finally, there is a concern that a quieter car may not be detected when it is idling. The sound of vehicles idling provides important cues to pedestrians who are blind. For example, in the far lane it gives cues about the width of the road (number of lanes), conveying information about the distance to walk, and the time required to cross a road. A quieter car may not be detected when it is idling at intersections or in parking lots and it may start moving suddenly at the same time the pedestrian crosses its path. Previous studies suggest that an idling HEV is not detectable even when the background noise is moderate (Reference 6).

3. Experimental Procedure and Setup

SAE has developed a draft test method "Measurement of Minimum Noise Emitted by Road Vehicles" (Reference 7) to measure the acoustic characteristics of vehicles at low speed and idle. This method was reviewed to assess its suitability for collecting vehicle acoustic data for critical safety scenarios. In general the SAE method was well suited to the needs of this current study. However, because the goal of this study was not to document vehicle acoustics under the *minimum noise emitted* but rather vehicle acoustics for *critical safety scenarios*, a modified method was required that considered the location of the pedestrian and expanded the set of operations. This study follows recommendations of the SAE draft method with regard to instrument settings, calibration, meteorological monitoring, etcetera; however, it deviates from the SAE method with respect to operating condition, data measured, as well as height, distance, and orientation of the microphones.

For this study, the sounds emitted by HEVs and ICE vehicles were measured and recorded under operating conditions representative of the previously identified critical safety scenarios[1]. The operating conditions were as follows: (1) vehicle backing up at 5 mph (mimicking a vehicle backing out of a driveway); (2) vehicle slowing from 20 to 10 mph (mimicking a vehicle preparing to turn right from the parallel street); (3) vehicle approaching at a low constant speed (6 mph and 10 mph); (4) vehicle accelerating from a

[1] The SAE test method covers only two operating conditions: stationary vehicle and 10 km/h (6 mph) constant speed passby.

stop; and (5) vehicle idling. Additionally, measurements were collected for vehicles approaching at moderate constant speeds (20 mph, 30 mph, and 40 mph) in order to document the convergence, if any, of HEVs and ICEs at higher speeds.

Data were measured with a Type 1 sound level meter (SLM) using a fast time weighting and included the minimum A-weighted level (L_{AFmin}), one-half second equivalent A-weighted level ($L_{Aeq0.5s}$), maximum A-weighted level (L_{AFmax}), and one-half second equivalent unweighted one-third octave band sound levels over the range from 50 Hz to 20 kHz[2]. Each measurement was made for each operating condition. For stationary operating conditions, a 1-minute interval was measured, for accelerations the measurement interval was terminated 2 seconds after passby, and for all other tests, the measurement interval included 10 seconds prior to passby.

The sound level meter's monaural microphone was located 12 feet from the center line of the vehicle's travel path[3]. This location was chosen as the best approximation for an average pedestrian waiting to cross an intersection. The microphone was positioned 5 feet above the ground, again to approximate the location of a typical pedestrian's ear. Finally, the free-field microphone was oriented such that it pointed upwards, perpendicular to the ground surface. This was done so that the same microphone correction could be applied regardless of the location of the vehicle along the approach path as it was desired to measure the vehicles as they approached the measurement location, not just when they were at the measurement location. In addition to the monaural measurement microphone, a binaural dummy head system was also utilized for recording each event. These recordings were later culled and processed for use in the human performance testing described in References 3 and 4. Temperature, relative humidity, and wind speed were monitored using a portable meteorological system.

3.1 Experimental Setup

Test vehicles included three HEVs: a 2009 Honda Civic, 2010 Toyota Prius, and 2009 Toyota Highlander and their ICE twins: a 2009 Honda Civic, 2009 Toyota Matrix, 2008 Toyota Highlander. Five of the six vehicles were new 2009-2010 vehicles while the 2008 had low mileage. Vehicles were in good operating condition and did not generate noticeable sounds due to any defect in the condition of the vehicles. Tires had a tread depth considered sufficient for safe operation, were evenly worn or had no wear, and were representative of standard OEM tires. Tires were inflated to the manufacturers' recommended pressure and debris in the treads was removed prior to testing.

Since background noise can affect the ability of a measurement to accurately quantify the sound levels of quieter vehicles due to contamination, significant efforts were made to locate a measurement site with a very low background level. Even so, some HEVs were

[2] The SAE test method focuses on L_{AFmin}, occasionally uses L_{AFmax}, and does not include one-third octave band measurements.

[3] The SAE test method specifies 2 m (6.5 ft) from center line, 1.2 m (4 ft) above the ground.

not measurable under some operating conditions due to the extremely low sound level of vehicles operated in electric-only mode relative to the existing background. Such cases were noted during the measurements and analysis.

The measurement site was located at NHTSA’s Vehicle Research and Test Center, at the Transportation Research Center in East Liberty, Ohio (Reference 8). Sound measurements were conducted during the night (with no other vehicles operating at the test facility) to guarantee the quietest possible background levels at the site and to obtain the highest quality recordings possible. Two sub-sites were used at TRC. Sub-site 1 was used for measuring idle and acceleration measurements (see Figure 1), while sub-site 2 was used for all other measurements (see Figure 2). Sub-site 1 was closer to the staging area and allowed for quicker vehicle exchanges but had a shorter useable road length so was not appropriate for the operations that required greater run lengths.

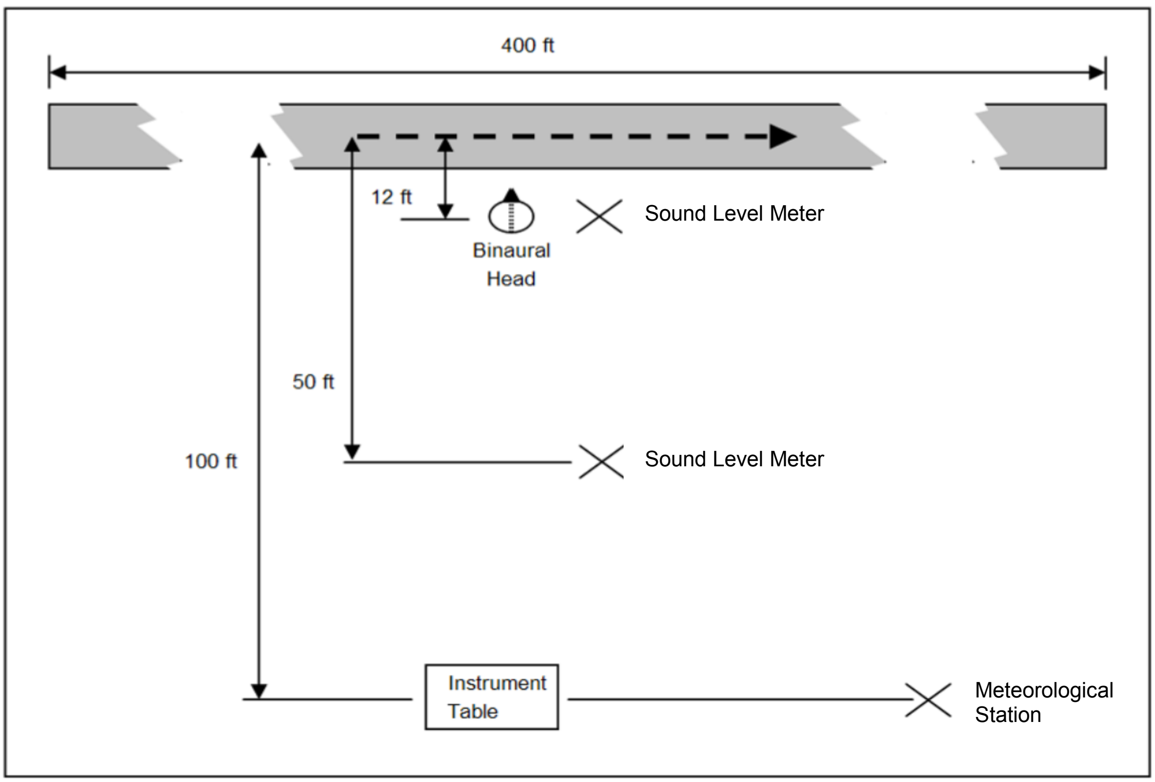

Figure 1. Vehicle Measurement Equipment Layout, Sub-Site 1. Note, although a 50 foot microphone position is indicated in this site diagram, the data from this position are not reported in this summary paper; for details on these data, refer to Reference 3.

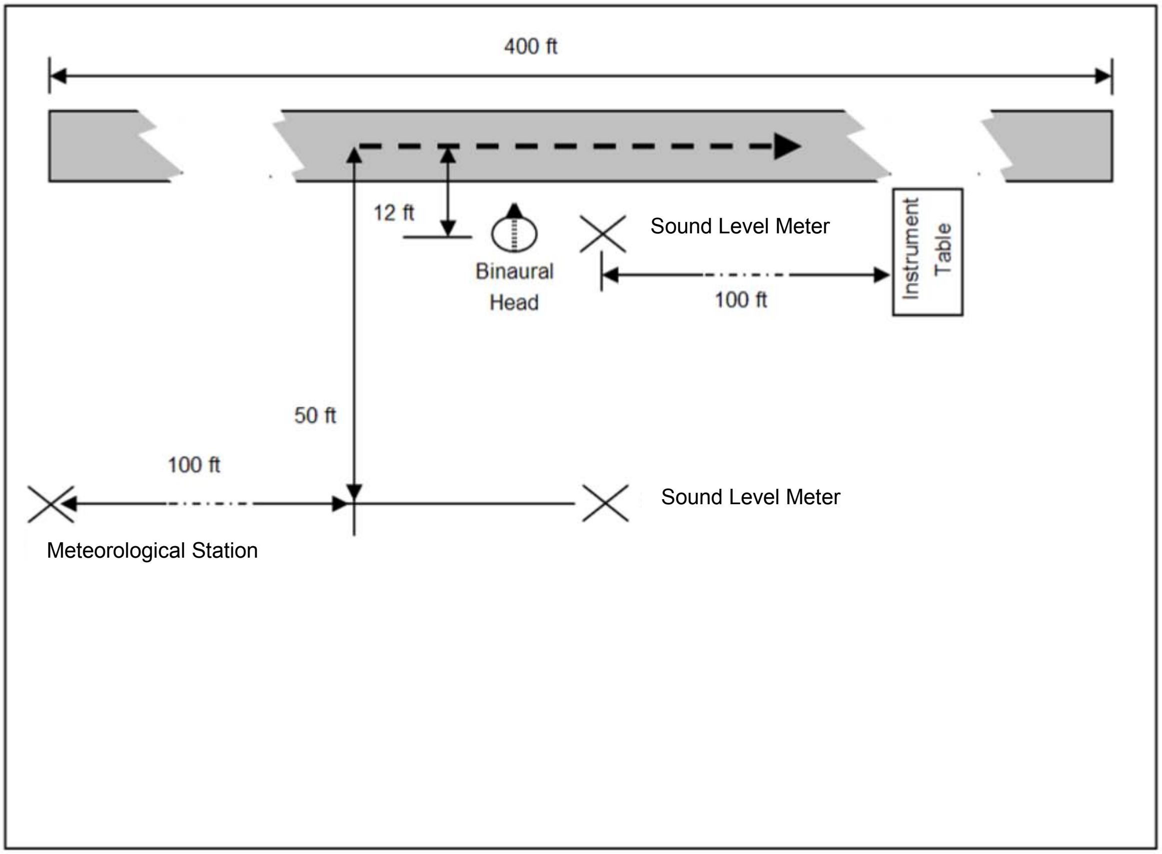

Figure 2. Vehicle Measurement Equipment Layout, Sub-Site 2. Note, although a 50 foot microphone position is indicated in this site diagram, the data from this position are not reported in this summary paper; for details on these data, refer to Reference 3.

3.2 Experimental Procedure

A protocol was developed for the tests, the details of which are described in Reference 3. In order to minimize changeover times, the general procedure was to test a given car for all operating conditions prior to switching to another vehicle. However, each vehicle was tested on multiple days in order to avoid any time dependent biases. For some operations, HEVs needed to be taken out of the testing cycle in order to recharge their batteries so that they could continue to operate in EV mode for testing. For both HEVs and ICE vehicles all practicable attempts were made to operate vehicles with accessory devices, such as cooling fans, off. In addition, both Toyota HEVs were able to be measured while operating in EV only mode for all runs except those greater than 20 mph; in contrast, the Civic Hybrid's engine was on during all operations. For all operating conditions except idle, a minimum of four repetitions for each operating condition were measured for the purpose of obtaining at least one clean recording (e.g., a recording suitable for human subject testing). For the idle measurements, a minimum of 1 continuous minute was measured and recorded. Details of the test procedure for each operating mode are described below.

3.2.1 Constant Speed Passby Measurement Procedure

Six constant speed passby operating conditions were tested. All vehicles were tested at 5 mph traveling in reverse, 6, 10, 20, and 30 mph traveling forward, and the Toyotas, because of their stronger electric motor systems, were also tested at 40 mph traveling forward. Target speeds were attained prior to entering the measurement zone, which was marked using flashing lights along the road. The target speeds were maintained within a tolerance of +/- 1 mph by a professional test vehicle operator. After passing the microphone line, the test speed was maintained for at least 100 additional feet. For HEVs all practicable attempts were made to maintain electric motor only vehicle operation and the propulsion mode was documented in the measurement log for each passby. Options include ICE only, Electric Motor only, and ICE and Electric Motor mix.

3.2.2 Accelerating Passby Measurement Procedure

For the acceleration tests, the vehicle started at rest at a distance of 200 ft from the microphone line and then accelerated at a constant rate to a speed of 20 mph. The professional test vehicle operator attempted to accelerate at the same rate for each vehicle for each repetition.

3.2.3 Decelerating Passby Measurement Procedure

For the deceleration tests, the professional vehicle operator accelerated the vehicle to a constant speed of 20 mph outside the measurement zone, again marked by flashing lights along the road. Once the driver reached a position 100 ft from the microphone line, the vehicle was decelerated at a constant rate of 3.28 ft/s^2 (1 m/s^2) in order to attain a vehicle speed of 10 mph at the microphone line.

3.2.4 Idle Measurement Procedure

For the idle measurements, the vehicle started and remained at rest for the entire measurement. For HEVs the vehicle power was on, but the engine and all accessory devices, for example, compressors, cooling fans, etcetera were off. (Note: during testing, it was not possible to get the Honda Civic hybrid to operate with the engine off for any extended period.) For ICE vehicles, the engine was running at idle speed with the vehicle in park and all accessory devices, for example, compressors, cooling fans, etcetera were off.

4. Results and Discussion

A summary of the data analysis is presented in this section in order to highlight key results of this study. Because many of the source measurements in this study were close to the background sound levels, care was needed to identify and account for the energy due to the noise and due to the vehicle's emissions for each measurement. The SAE procedure for measuring the minimum sound level of road vehicles, SAE J2889-1, indicates that for measurements that are within 3dB there is not sufficient confidence to accept these measurements (Reference 7). When such results were found in this study, the results were labeled as “background” to indicate that they were not sufficiently above the background level. The SAE procedure further indicates that for measurements that are between 3 to 10 dB of the ambient, a correction to the measurement is needed to accurately account for the vehicle's contribution to the measurement. The correction is as follows:

$$SPL_{corrected} = 10\log_{10}\left(10^{(SPL_{measured}/10)} - 10^{SPL_{background}/10}\right)$$

The average background level during the measurements was 31.2 dB(A). According to the SAE procedure, measurements that were at least 10 dB greater than the background do not need a correction. Of the final data analyzed, 13.5% were within 10 dB or the background, with 8.3% at least 6 dB above the background, 1.3% between 3 and 6 dB above the background, and 3.8% were too low to be corrected. The only data that were too low to be corrected were idle measurements for the Prius and Highlander Hybrid. The remainder, 86.5% of the data did not require corrections. Once all data had been corrected for background levels, the one-third octave band spectra and A-weighted levels were compared amongst vehicles for the different operating conditions.

4.1 One-Third Octave Band Spectra

Sounds at the same A-weighted level may be more or less detectable depending on the spectral content of the sound. Sample unweighted one-third octave band spectra are shown in Figure 3 for vehicles traveling in reverse at 5 mph. These spectra provide a means for making general comparisons of spectral characteristics of the various vehicles. Specifically, there is a slight trend for ICEs at low speeds to have less high frequency content relative to the total A-weighted sound pressure level. An exception to this is a spectral peak that was evident in the Toyota vehicles in the 5000 Hz one-third octave band. The strength of this peak depended on the specific operation and was most noticeable while decelerating / braking. The source of this tone was clearly due to the electric motor system, although it was not determined whether it was due to the motor, inverter, etcetera. Spectral results for other operating conditions were consistent with those of the sample shown in Figure 3 and can be found in Reference 3.

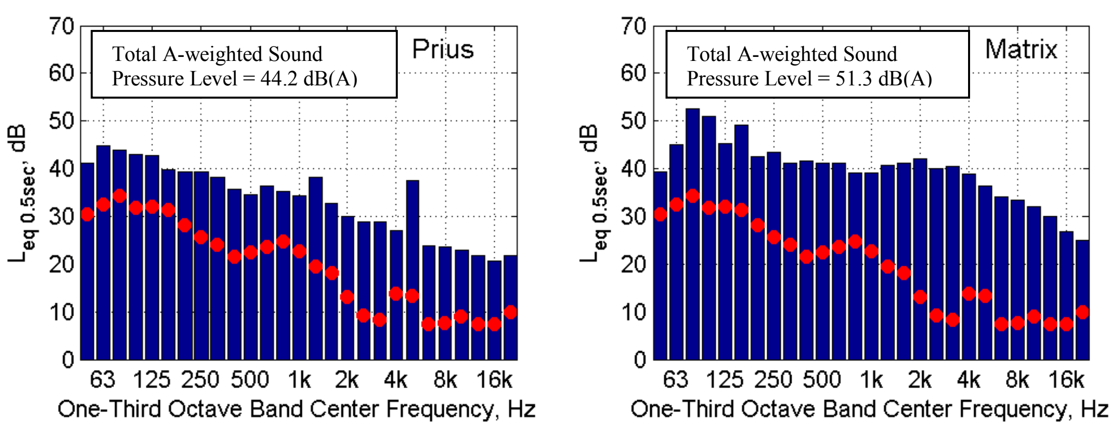

Figure 3. Sample One-Third Octave Band Spectra for Reverse 5 mph Constant Speed Passby at 12 ft Microphone Location (Note, total level in the figure is A-weighted, while the one-third octave bands are unweighted.) Bars indicate vehicle level. Circles indicate background level.

4.2 Broadband Metrics

Three metrics computed over all frequencies are presented for four sample operations: idle, deceleration, 5 mph reverse, and 6 mph forward in Table 1 through Table 4. In general, the HEVs tested had lower A-weighted sound pressure levels for all low speed operations. Table 1 shows the levels for idle, where levels for the Toyota hybrids were too low to be recorded for the background condition present. (Recall the average background level during the measurements was 31.2 dB(A).) These low levels stemmed from the absence of any engine related noise from these vehicles at idle. The A-weighted sound pressure level for ICE vehicles when idling ranged from 46 to 48 dB(A) while the civic hybrid was 45 dB(A). Note, that the Civic Hybrid's engine was running during the measurement. Thus there was a clear distinction between vehicles at idle with engines running and those with just the electric motor enabled.

As shown in Table 2, the A-weighted sound pressure levels of HEVs do not differ considerably from the levels of their ICE twins in the deceleration maneuver. As will be shown in section 4.3, this is due to the relatively high initial speed, 20 mph, and moderately high final speed, 10 mph, for the deceleration maneuver. At these speeds the differences are small to negligible. However, although the A-weighted sound pressure levels were similar, it was observed that the 5 kHz tone associated with the Toyota hybrids was much more noticeable during deceleration than any other operation.

Table 3 shows the passby levels for 5 mph reverse constant speed passby events. Here, the A-weighted sound pressure levels for HEVs were 7 to 10 dB(A) lower than the levels for their ICE vehicle twins. Table 4 shows the levels for vehicles approaching at a constant speed of 6 mph in the forward direction. The A-weighted sound pressure levels of HEVs here are 2 to 8 dB(A) lower than the levels of their ICE vehicle twins. Because the speeds are similar between the reverse and forward operations presented here, it is reasonable to expect that the relative difference should be similar. This is the case for the high end of the measurement speeds, however, the forward operation had a smaller difference at the low end. This may be due to differences in gears used for forward and reverse operations, or it may be due to a greater contribution of exhaust noise from ICEs in the reverse direction.

Results for 10 mph, 20 mph, 30 mph, 40 mph, and acceleration are not included here due to space constraints but are listed in Reference 3.

Table 1. A-weighted Sound Levels by Vehicle for Idle

Vehicle Type	L_{AFmin}	$L_{Aeq0.5sec}$	L_{AFmax}
Prius	Background	Background	Background
Matrix	47.6	47.8	48.1
Civic Hybrid	44.6	44.8	45.1
Civic	45.8	46.0	46.4
Highlander Hybrid	Background	Background	Background
Highlander	47.9	48.1	48.5

Table 2. A-weighted Sound Levels for Deceleration Passby

Vehicle Type	L_{AFmin}	$L_{Aeq0.5sec}$	L_{AFmax}
Prius	52.2	53.0	53.4
Matrix	53.8	54.2	54.6
Civic Hybrid	55.7	56.6	57.2
Civic	54.8	55.0	55.3
Highlander Hybrid	52.2	53.0	53.7
Highlander	54.9	55.4	55.8

Table 3. A-weighted Sound Levels for Reverse 5 mph Constant Speed Passby

Vehicle Type	L_{AFmin}	$L_{Aeq0.5sec}$	L_{AFmax}
Prius	43.7	44.2	44.8
Matrix	51.2	51.3	51.5
Civic Hybrid	48.5	48.5	49.0
Civic	58.0	58.2	58.9
Highlander Hybrid	44.6	45.9	48.6
Highlander	52.3	52.7	53.1

Table 4. A-weighted Sound Levels for 6 mph Constant Speed Passyby

Vehicle Type	L_{AFmin}	$L_{Aeq0.5sec}$	L_{AFmax}
Prius	44.4	44.7	45.1
Matrix	53.0	53.5	54.2
Civic Hybrid	49.2	49.3	49.5
Civic	51.8	52.0	52.6
Highlander Hybrid	52.5	53.2	54.9
Highlander	55.2	55.5	55.9

4.3 Level versus Speed

One question that arises when considering the differences in level between ICEs and HEVs is whether or not the A-weighted sound pressure levels of the two types of vehicles converge at higher speeds due to the dominance of tire noise. In order to document the convergence at higher speeds, maximum A-weighted levels at passby are shown in Figure 4 through Figure 6 as a function of speed for the three pairs of vehicles (similar results were observed for minimum A-weighted levels and one-half second equivalent A-weighted levels).

The sound level for the Toyota hybrids is between 1.4 and 8.8 dB(A) lower than that for the ICE vehicle twins at speeds lower than 10 mph. The Prius converges with the Matrix after 20 mph, while the Highlander hybrid converges with the ICE vehicle twin after 10 mph. For both Toyota models, hybrid idle sound levels were too low to be accurately measured and are therefore not shown in these figures. The Honda Civics did not show as great a difference in sound level at low speeds; however, during the experiments it was not possible to get the hybrid Civic to operate in EV-only mode. Therefore, all measurements of the Honda Civic hybrid include engine noise. The Honda Civic hybrid is still noticeably quieter at 6 mph but converges with its ICE vehicle twin after 10 mph. In all three cases the Hybrids are quieter for at least some low speed operations, but all converge with their ICE twins by about 20 mph.

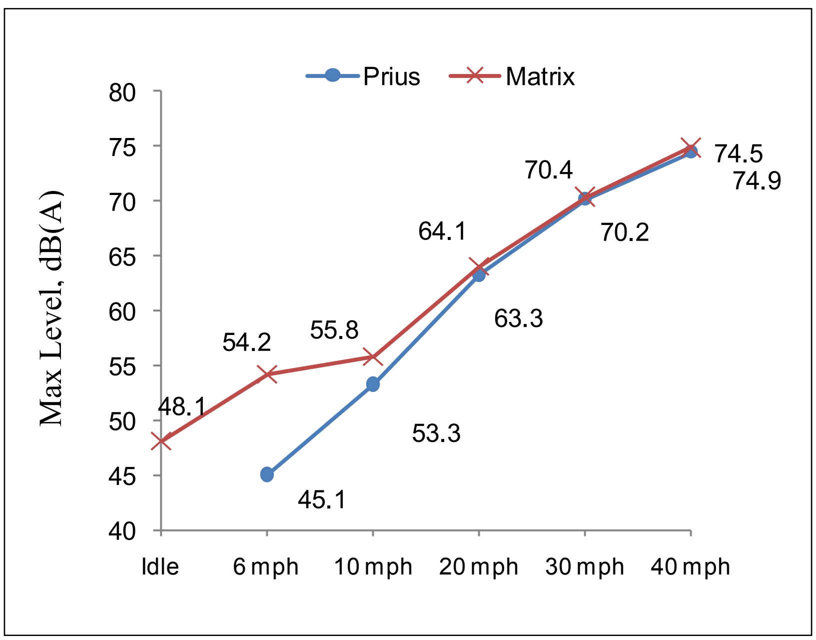

Figure 4. Maximum Levels in dB(A) for the Prius (●) and Matrix (✕)

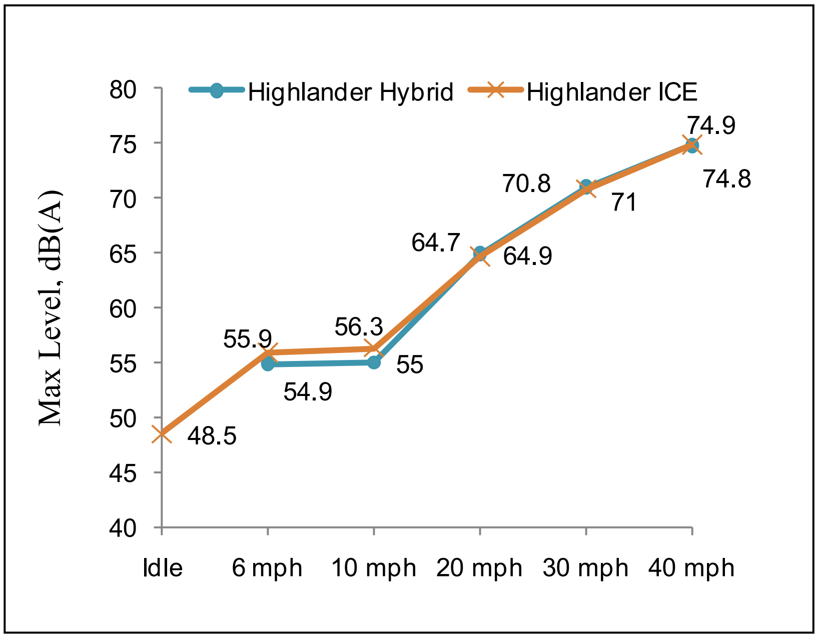

Figure 5. Maximum Levels in dB(A) for the Highlander Hybrid (●) and ICE (✕)

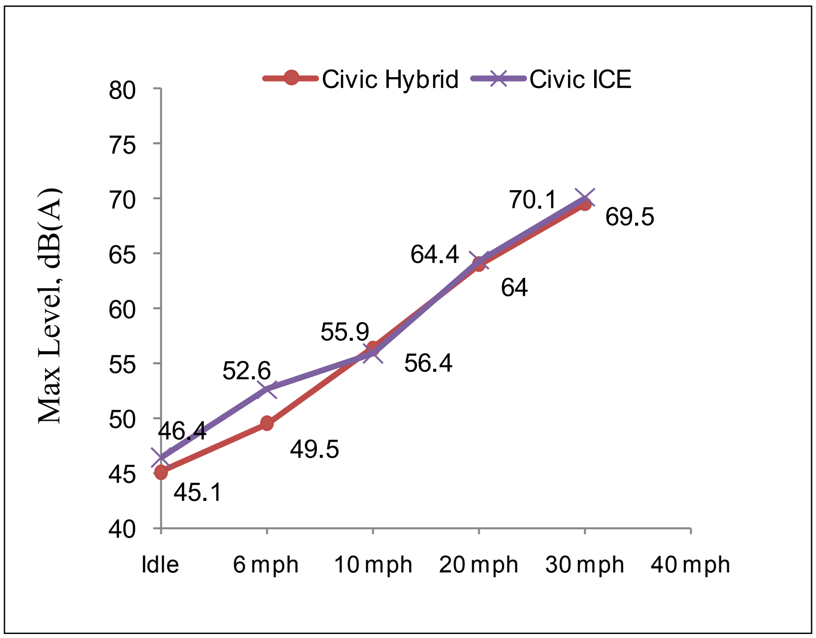

Figure 6. Maximum Levels in dB(A) for the Civic Hybrid (●) and ICE (✕).

5. Summary

Six vehicles were tested under nine different operating conditions including, idle, accelerating, decelerating, and constant forward speeds from 6 to 40 mph and one reverse speed, 5 mph. The operating conditions were relevant to the understanding of five critical safety scenarios of concern for pedestrians who are blind. Three vehicles were hybrid electric vehicles and where possible were operated in electric motor only mode during the tests. The other three vehicles were equivalent internal combustion-only vehicles. In general, hybrid electric vehicles were quieter below approximately 20 mph, above which either engines turned on, tire / road noise became dominant, or both. Hybrid vehicles also tended to have less high frequency content than internal combustion engines at low speeds. Further details and results from this study can be found in the National Highway Traffic Safety Administration report DOT HS 811 304 (Reference 2).

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