

Development of Approaching Vehicle Sound for Pedestrians (VSP) for Quiet Electric Vehicles

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ABSTRACT

Vehicles with electric powertrains emit less noise than internal combustion engine vehicles. These quiet cars have raised concerns about pedestrian safety, especially among the visually impaired community. The primary concern is related to when electric vehicles are travelling at low speeds where tire noise and aerodynamic noise is minimal. In these situations, the EV might not provide an adequate auditory cue for visually impaired pedestrians who need auditory information for navigation and decision making.

A system called Approaching Vehicle Sound for Pedestrians (VSP) has been developed for the 2011 Nissan Leaf EV to help address the potential quiet car concern. This system emits a digitally generated signal from an onboard speaker to provide auditory cues to pedestrians during low speed forward movement and reverse. The auditory cues are designed to help achieve the same detectability performance as internal combustion engine sound. In addition to achieving good detectability performance for pedestrians, the low speed forward movement signal is also designed to help maintain a quiet cabin for the driver and is not intrusive to neighboring communities.

This paper explains the methodology for developing the VSP system, focusing on the forward movement signal. It discusses how the frequency content and temporal structure of the signal are intended for achieving ICE level performance in pedestrian listening tasks, along with good quiet cabin performance and low noise intrusion for neighboring communities. It also presents the results from research laboratory and real world tests that validate the

signal performance as compared to ICE sound. Finally, NVH pass-by and cabin isolation testing results will be discussed.

INTRODUCTION

At low speeds, vehicle tire noise and aerodynamic noise is limited. For ICE vehicles this results in a lower overall sound pressure level (SPL), however a significant level of noise is still emitted from the engine. For EVs, very little noise is emitted by the electric motor, therefore, at low speeds the overall noise level emitted by these vehicles is minimal.

To better understand these conditions, pass-by testing was conducted using an Altima HEV in ICE mode and then in EV mode (engine "off", electric motor "on") to determine the speed at which the SPL of the two modes are the same due to the dominance of tire and aerodynamic noise. Testing occurred at Nissan's proving grounds in Arizona. The results of this testing indicate that the speed at which tire and aerodynamic noise dominate the overall vehicle SPL for Sedan sized vehicles is 25 kph ([Figure 1](#)). As vehicle speed reduces from 25 kph, the SPL gap between EV mode and ICE increases. It can thus be concluded that when travelling at speeds lower than 25 kph, vehicles in EV mode provide less of an auditory cue for pedestrians than ICE vehicles.

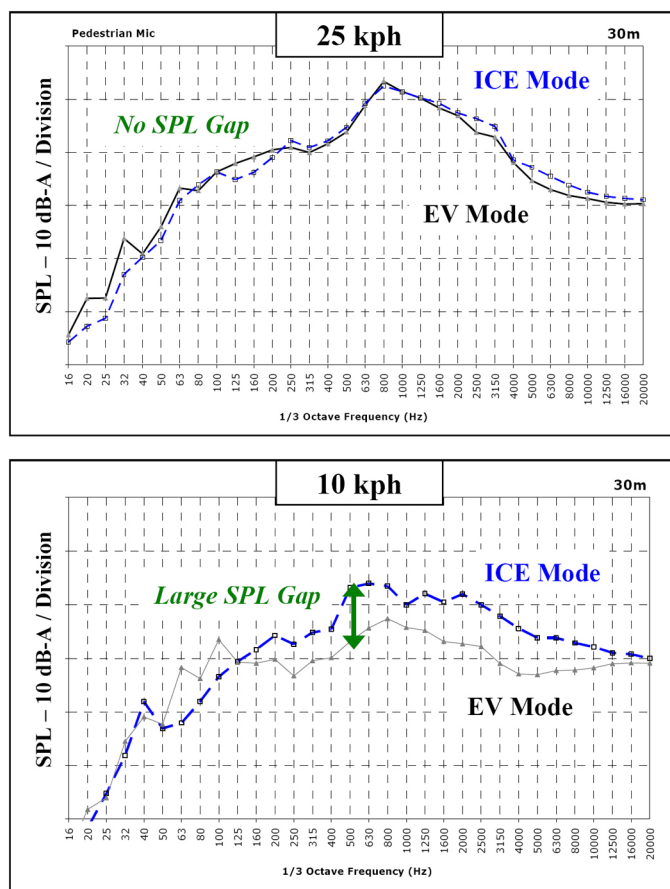


Figure 1. Pass-by testing of an Altima HEV in ICE mode and in EV mode

According to pedestrian crash data this lack of auditory information during low speeds may pose a challenge. NHTSA data from 2000 and later shows that the incident rate of pedestrian crashes was higher in some driving situations for hybrid electric vehicles compared to ICE vehicles [1]. In general most crashes involving HEVs occurred in areas with speed limits less than 56 kph. Subjective information gathered from visually impaired pedestrians by the National Federation of the Blind (NFB) is consistent with the NHTSA crash data - the most challenging situations for pedestrians, especially those with visual impairment, is traffic at low speeds (in particular when vehicles are turning, reversing and/or moving out of a drive way or parking lot) [2].

This issue of quiet cars is likely to grow in the future as the population of people with visual impairment increases. Today, approximately 4.3 million people in the US live with visual impairment - characterized by either "low vision" or "legal blindness" [3]. Most cases of visual impairment are age related, therefore, most of this population is over the age of 60 years. In 2030, the percentage of people in the US who are 65 years and older is projected to be about 20% (compared to 12% in 2005) [4]. In the future, the population

of visually impaired is expected to be even larger due these demographic trends.

To address the concerns of this growing population, in 2007 the NFB started lobbying the US Congress to introduce legislation for studying how to resolve the quiet car issue with new safety standards. In response, SAE formed the "Vehicle Sound for Pedestrians Committee" that is focusing on drafting evaluation methodology for VSP systems (J2889-1), while taking a neutral position on technology solutions [2]. NHTSA initiated its own research efforts for studying the quiet car issue - Phase I of "Quieter Cars and the Safety of Blind Pedestrians" was completed in 2010 [5]. The NHTSA report focuses on defining the critical safety scenarios, studying the acoustic characteristics of vehicle and ambient noise, and the examination of potential countermeasures. NHTSA initiated Phase II in 2010 to start developing guidelines for future VSP systems. At the end of 2010, Congress passed the bill "S.841: Pedestrian Safety Enhancement Act of 2010," requiring NHTSA to establish a set of rules for an alert sound that will allow pedestrians to "reasonably detect a nearby electric or hybrid vehicle" [6].

METHODOLOGY

In response to the above mentioned activities in the US and similar activities in Japan, Nissan started development of a VSP system in 2007. Meetings were held with the visually impaired community and expert researchers in Japan to understand fundamental needs. The feedback was used to develop a design for the basic hardware: digital sound synthesizer connected to an onboard speaker mounted behind the vehicle's front fascia. Also the basic logic, or sound control, was developed for the system. Several potential VSP signal candidates were created for low speed forward movement and reverse.

The prototype hardware and software was sent to the US for further refinement and validation. In November 2009 and January 2010, demonstrations were held with the Detroit Institute of Ophthalmology (DIO) where visually impaired members critiqued the system and VSP signal candidates in various real world pedestrian scenarios. The feedback from these demos was used to refine the sound control of the VSP system. Comments from DIO members also gave insight into which types of signals would be most effective for detectability in real world scenarios. It was made clear that the VSP signal performance as an auditory cue needed to be at least as good as ICE in order to be useful for visually impaired pedestrians.

To achieve ICE level performance, making a recording of an ICE and playing it through the onboard speaker seemed like a reasonable potential solution. However, the fact that VSP would be digitally generated presented an opportunity to design a signal that achieves ICE level detectability

performance and also improves performance in other areas. Current ICE sounds are clearly audible for the driver and passengers inside the cabin and the sounds contribute to growing environmental noise pollution problems. Also, EVs are on the cutting edge of mobility, therefore, implementing an ICE sound would diminish the EVs futuristic image. In developing the VSP signal the challenge was to not only achieve ICE level detectability but also better than ICE level cabin noise isolation performance and lower noise intrusion for neighboring communities, while matching the futuristic image of EV.

To develop VSP signal candidates that balance these attributes, a research collaboration was initiated in 2010 including Acoustic Psychology experts at the Vanderbilt University Medical Center (VUMC) and a Hollywood based Sound Designer. The Sound Designer created over 100 signals based on recommendations on how to optimize detectability performance. Nine signals then went through detectability testing to identify the signal that performs the best in real world representative ambient noise conditions. Next a series of tests were performed by Nissan in an anechoic chamber to evaluate quiet cabin performance. A final VSP forward signal was selected based on a balance between good noise isolation and detectability performance.

To validate the final signal in real world pedestrian scenes, a collaboration was also initiated with Western Michigan University (WMU) experts in mobility for the visually impaired. A group of visually impaired participants performed several listening tasks in critical pedestrian scenarios. An ICE vehicle was compared to an HEV with a prototype VSP system installed (set to achieve the same SPL at low speeds). The test results were analyzed to confirm that EV mode with VSP achieves similar performance as ICE, when set at equivalent SPL.

Finally, to set the Leaf VSP forward signal volume at an appropriate level, a series of pass-by tests were performed at Nissan's Arizona test track according to SAE's J2889-1 methodology. SPL and frequency spectrum were measured to confirm that Leaf with VSP achieves the same SPL as a comparable sized ICE vehicle at low speeds. Also, cabin noise was measured to confirm that Leaf with VSP achieves better than ICE quiet cabin performance.

SOUND DESIGN GUIDELINES

In determining sound design guidelines, first the frequency content and temporal structure of current ICE sound were considered. ICE sound has very broadband frequency content. It is also characterized by a distinct time domain modulation, or rhythm. Throughout development, ICE sound was treated as a reference point to which all VSP signals were compared.

Based on review of existing scientific literature on acoustic psychology and real world study, Nissan adopted 3 key design guidelines (in relation to ICE sound at the same dB-A level) for the evaluation and selection of VSP signals [7]:

1. Increase peak frequency content between 600 and 800 Hz to improve detectability for aging pedestrians with high Hz hearing loss
2. Increase peak frequency content between 2000 and 5000 Hz to improve detectability for pedestrians with normal hearing
3. Reduce frequency content at around 1000 Hz to avoid noise intrusion in neighborhood communities and provide a quiet cabin

INCREASE PEAK FREQUENCY CONTENT BETWEEN 600 AND 800 HZ

Approximately 70% of the visually impaired people in the US are 60 years old and older [3, 8]. People who are 60 years and older have relative hearing loss of over 20 dB between 2000 and 4000 Hz compared to a young adult with normal hearing (Figure 2). In order for a signal to be detectable for the elderly and majority of visually impaired pedestrians it should include significant content between 600 and 800 Hz: the frequency range that is most perceivable for those with high Hz hearing loss.

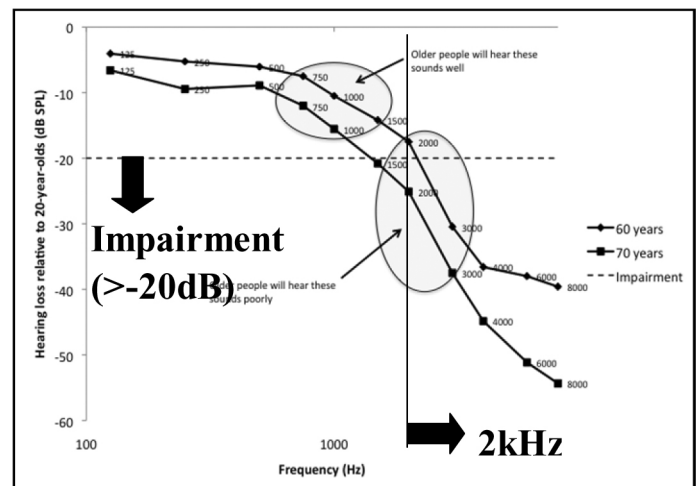


Figure 2. Hearing loss due to aging (compared to a 20 year old with normal hearing) [9]

INCREASE PEAK FREQUENCY CONTENT BETWEEN 2000 AND 5000 HZ

For addressing the needs of younger adults and children, Nissan believed that it was also important for the signal to include significant content in the higher frequency range. For persons with normal hearing, the ear is most sensitive to