Development of Nissan Approaching Vehicle Sound for Pedestrians

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Abstract—Electric Vehicles are very quiet at low speeds therefore people (especially the visually impaired) have difficulty recognizing that these vehicles are approaching. To address this concern, Approaching Vehicle Sound for Pedestrians system development has been discussed worldwide. In Japan, USA, Europe and China, government regulation is currently under study. As a solution to meet this concern, Nissan has developed the VSP (Approaching Vehicle Sound for Pedestrians) system for implementation on Nissan's first mass production Electric Vehicle. Nissan VSP emits a futuristic sound to satisfy 3 key stakeholders' concerns; for pedestrians to provide detectability, for drivers and neighborhoods to maintain a quiet environment. The sound emitted during forward motion has a "twin peaks and one dip" frequency signature, with modulation (or rhythmic structure) to accommodate human-beings ear frequency sensitivity, hearing loss due to aging and ambient noise conditions. Additionally, special emphasis is placed on the forward sound emitted when the vehicle is "taking-off"(starting forward motion)" to notify pedestrians that the vehicle is about to move, in response to real world feedback gathered in surveys with visually impaired in Japan and USA. The system also includes a reverse motion or "backing up" sound that has an easy to recognize cadenced(or rhythmic structure) characteristic.

Keywords— "electric vehicle, hybrid electric vehicle, approaching vehicle sound, pedestrians, safety"

1. Background

Electric Vehicles are very quiet at low speeds (see Figure1), therefore pedestrians (especially the visually impaired) have difficulty recognizing that these vehicles are approaching. In Japan, USA, Europe, and China, regulation is currently under study. The Japanese government published VSP guide-lines in February 2010, and USA National Highway Traffic Safety Administration published a research report "Quieter Cars and the Safety of Blind Pedestrians: Phase I" in April 2010. [1] [2]

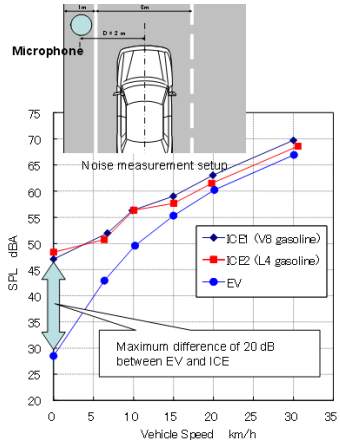


Figure 1: Vehicle noise level comparison EV vs. ICE (Internal Combustion Engine) vehicle[1]

2. Solution by Nissan

As a solution to meet this concern, Nissan has developed the VSP system for implementation on Nissan's new mass production Electric Vehicle. This system addresses 3 key stakeholders' concerns; for pedestrians to provide good detectability, for drivers and neighborhoods to maintain a quiet environment.
The design concept of Nissan VSP is as follows (from 1 to 3 are followed by Japanese guideline):
1. Sound is recognized as a vehicle
2. Sound pitch is proportional to vehicle speed
3. Similar sound level as ICE (Internal Combustion Engine) vehicle
4. Sound has a futuristic image
5. Easily audible for pedestrians (young and elderly) under various ambient sounds, yet maintains a quiet environment for driver and neighborhoods

2.1 Sound characteristics

2.1.1 Frequency characteristic

In order to achieve this concept, Nissan considered the following information related to sound frequency in the sound design and selection process:

A. Human-beings ear frequency sensitivity

People with normal hearing are sensitive to frequencies between 2 and 5 kHz due to the resonance of the ear canal and the transfer function of the ossicles of the middle ear.

Therefore VSP sound should include a peak between 2 and 5 kHz (see Figure 2). Additionally, the ear sensitivity difference to frequency levels increases as the sound volume level decreases. Due to this phenomenon, high frequency sound (i.e. 2.5 kHz) can be heard from much longer distances than lower frequency sound (i.e. 200 Hz).

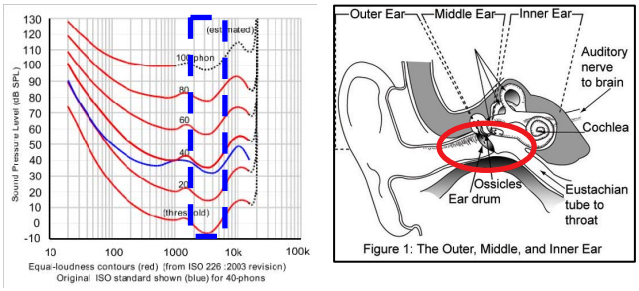


Figure 2: Human-beings ear structure and frequency sensitivity [3]

B. Hearing loss due to aging

People who are older than 60 years have difficulty detecting sound higher than 1 kHz due to age related hearing loss. More then 70% of visually impaired people are over 60 years old [4]. As a result VSP sound should include another peak lower than 1 kHz (see Figure 3).

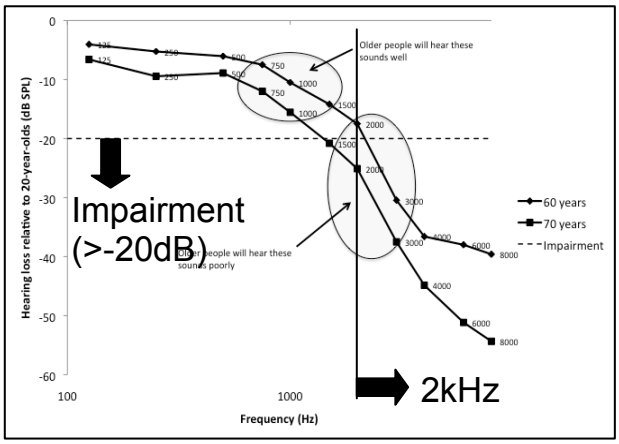


Figure 3: Hearing loss due to aging (comparison between 20 and 60,70 year olds) [5]

C. Ambient noise frequency characteristic

Ambient noise measured at busy intersection, neighborhoods near busy intersection, etc. consistently peaks at around 1 kHz. Therefore VSP sound should peak at the shoulders of 1 kHz (see Figure 4).

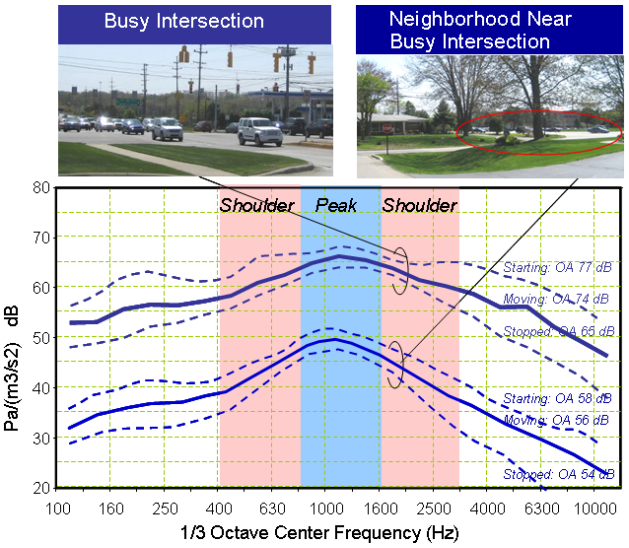


Figure 4: Ambient noise measured at busy intersection and neighborhood near busy intersection in Detroit USA

In summary, Nissan VSP sound has a " twin peaks and one dip" frequency profile (see Figure 5), including peaks at 0.6kHz and 2.5kHz, and a dip at 1kHz. The 2.5 kHz peak is intended to accommodate normal hearing. The 0.6 kHz peak is intended for elderly with high frequency hearing loss. Lastly the 1 kHz dip is for maintaining a low sound pressure level that is acceptable for neighborhoods.

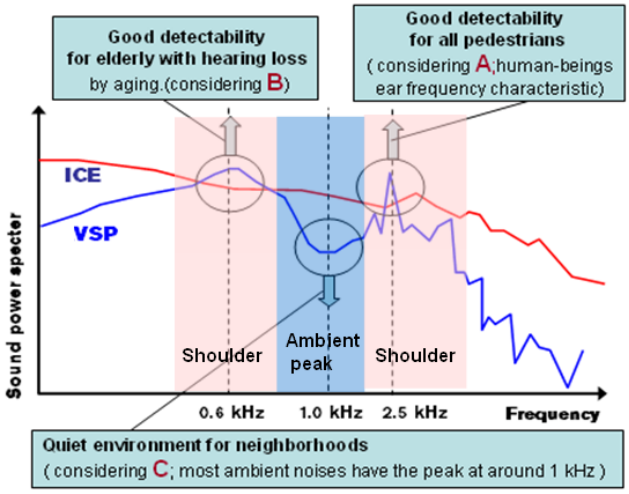


Figure 5: "Twin peaks and one dip" frequency sound characteristic explanation of Nissan VSP

2.1.2 Time domain characteristic

It is well known that sound with modulation (or rhythmic structure) stands out in ambient noise more than sound without modulation. To support the detectability of the VSP sound, subtle modulation of 0.6k Hz peak is included in the design. The time domain sound characteristic of Nissan VSP is shown in Figure 6. Another important time domain sound characteristic is "sound pitch proportional to vehicle speed". This is an important factor that helps make it possible for pedestrians (especially the visually

impaired) to detect the approaching vehicle's behavior (accelerating or decelerating) and to recognize the sound as a vehicle .

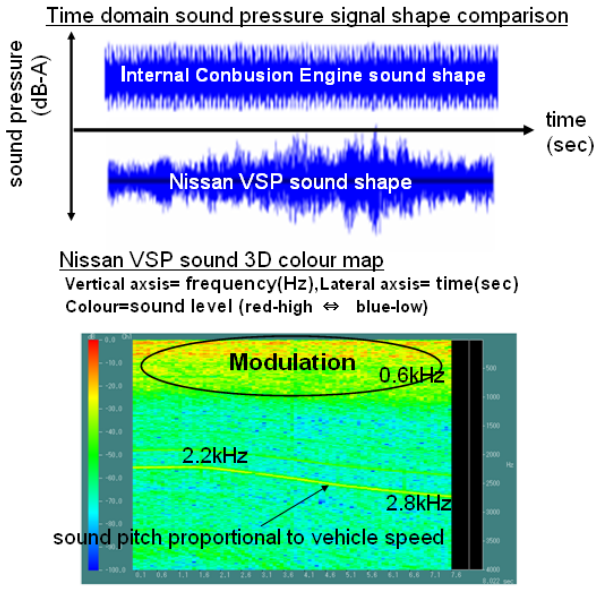


Figure 6: Time domain characteristic of Nissan VSP

2.1.3 Evaluation of sound

9 sample sounds and 1 ICE vehicle sound were evaluated for detectability (through subjective testing) and driver ear position quietness (by dB-A measurement). The sound candidates with high frequency white noise character (#3,#4,#5) were quiet inside the vehicle but the detectability was poor. The low frequency sounds with strong modulation (A,B,D) resulted in good detectability but were considerably louder inside the vehicle. The sound with 1kHz peak and medium level modulation (C,E), and the sound with twin peaks and a 1kHz dip (#1) resulted in good balance of quietness and detectability as compared to ICE sound. Taking real world ambient noise conditions (peak at 1 kHz) and other design guidelines into consideration, it was concluded that the twin peaks sound with 1 kHz dip (#1) would be most appropriate for the VSP system (see Figure 7).

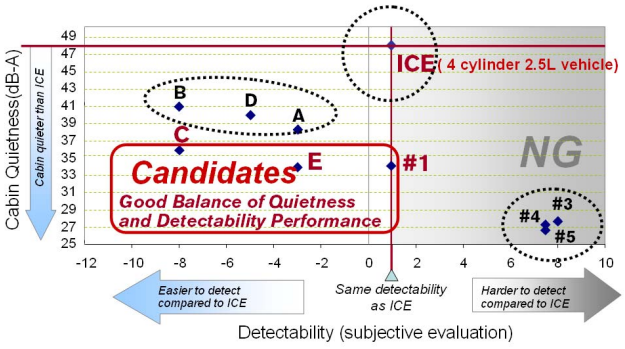


Figure 7: Detectability vs. Cabin Quietness evaluation result for 9 sample sounds

2.2 Sound volume level

The SAE J2889-1 pass-by measurement procedure was used to set the VSP forward signal sound pressure level (SPL) as measured in dB-A. First, 7 different Nissan US market vehicles were measured including 5 ICE, one Nissan HEV and one Nissan full electric vehicle when travelling at 10 kph. The results were consistent with what is shown in Figure 1 - there is a clear difference in SPL between ICE and EV vehicles.(see Figure 8) Even smaller segment vehicles such as the Nissan 1.8 L ICE vehicle2 have considerably higher SPL for pedestrian detectability as compared with vehicles in electric mode. Therefore, Nissan VSP has been set to achieve equivalent SPL as Nissan 1.8 L ICE vehicle2 at 10 kph. The actual SPL is 55 dB-A.

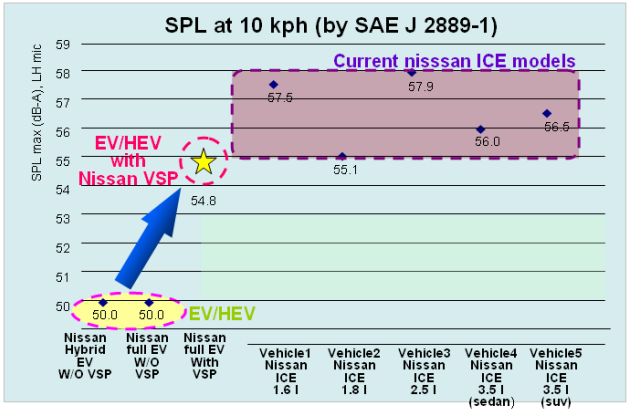


Figure 8: Comparison of SPL at 10kph (by SAE J2889-1)

Testing in a hearing research laboratory and real world testing with the visually impaired has confirmed that Nissan full EV with VSP setting 55dB-A achieves the same or better performance than Nissan vehicle2(high sales volume ICE model in the US) in all Approach Detection and Turning Perception listening tasks. Therefore Nissan VSP will achieve equal or better performance than ICE at equivalent SPL in the two key pedestrian listening tasks. (Figure 9)

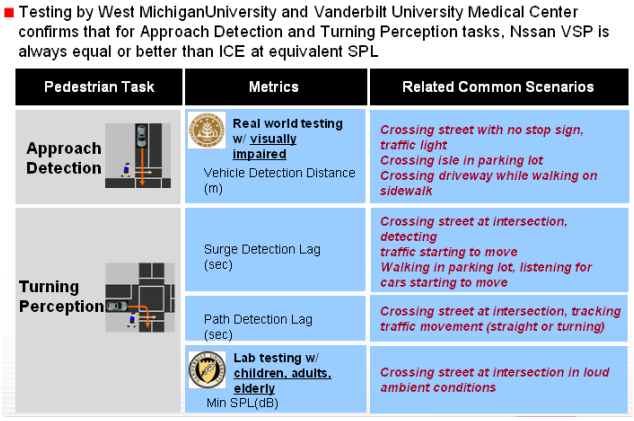


Figure 9: Real world testing of Approaching detection and Turning perception of Nissan VSP

There currently is no study indicating that low speed pedestrian crash risk is higher for vehicles with SPL similar as Nisan vehicle2, as compared to noisier ICEs (i.e. vehicles with SPL at 60 dB-A and higher). Therefore the

direction to set the Nissan VSP sound at the same level as Nissan vehicle2 is reasonable. To verify that Nissan vehicle2 SPL does not pose additional pedestrian crash risk over noisier vehicles, a statistical analysis is being performed of actual pedestrian crash data.

One other consideration is the difference in difficulty between pedestrian listening tasks in terms of how loud the sound needs to be for good performance. Testing with Vanderbilt University Medical Center revealed that the Turning Perception task (perceiving if a vehicle is moving straight through an intersection or turning right into the pedestrian's walking path) is significantly more difficult than Approach Detection. The test results show that turning perception requires approximately 11 dB-A more SPL than detection in a typical 60 db-A ambient noise condition. Therefore design elements such as time domain and activation features are very important for addressing the usefulness of VSP in motion perception tasks.(Figure 10)

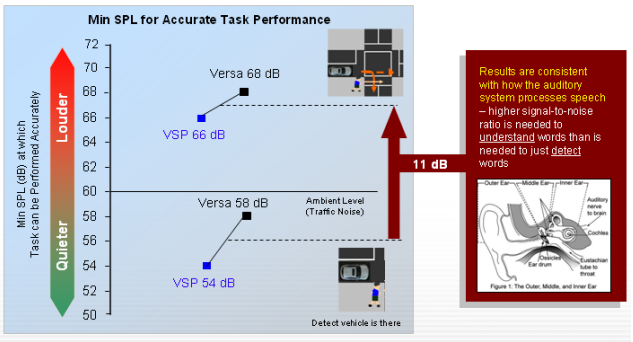


Figure 10: Minimum SPLs at which approaching detection task and turning perception task can be performed accurately

2.3 Sound activation procedure

The VSP system emits sound during low speed forward movement and reverse (see Figure 11). The reverse sound, or "cadenced backing up sound" and the "emphasized taking-off sound" were included in the final design based on feedback gathered in real world survey with visually impaired in Japan and USA.

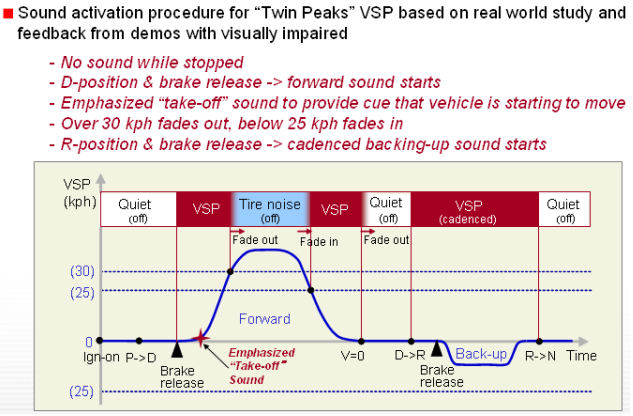
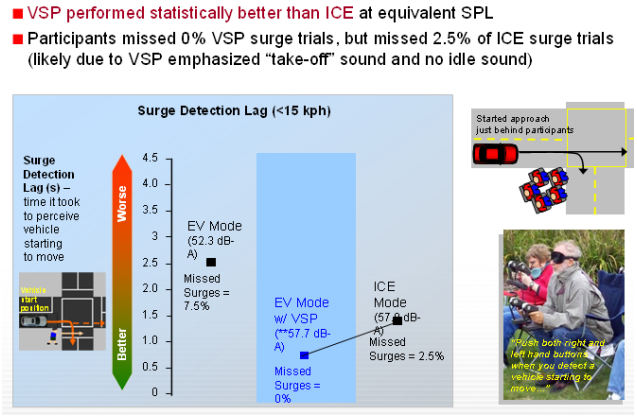


Figure 11: the Sound activation procedure of Nissan VSP

2.3.1 Sond during idle and take-off

Nissan VSP does not have idle sound, instead it has an emphasized take-off sound (starting forward motion) to clearly notify pedestrians that the vehicle is about to move. This decision is based on testing in real world pedestrian scinarios with visually impaired participants in collaboration with Western Michigan University. We tested surge detection lag (time it makes to recognize that a vehicle has started to move from a stopped position) of EV mode with VSP compared to ICE. The result show that the VSP emphasized take-off sound helps to shorten the time lag as compared to ICE. (Figure 12)

Moreover we found that no idle sound condition of VSP contributed to the shortened lag because of the noticeable gap in sound level from stopped condition to take-off condition. This is critical because a pedestrian failing to detect a vehicle surge at an intersection may increase the risk of an accidental collision in situations where the vehicle is making a right turn into the pedestrian's crossing path. Although implementing an idle sound may prevent startling a pedestrian at an intersection, it was decided to not include sound at idle to address the risk of collision.(Figure 13)



.Figure 12: Surge detection lag comparison test result

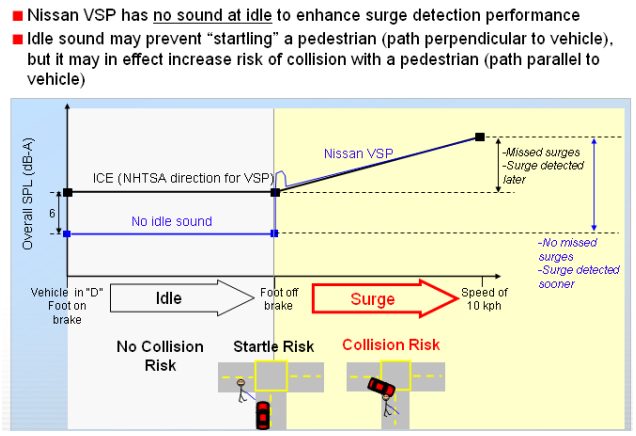


Figure 13: Explanation why no sound at idle VSP can reduce the collision risk at intersection

2.3.2 Back-up sound

The sound level is set by same SPL as ICEs at the pedestrian position in the rear. This is about 15dB smaller

than SAE J994 back-up alarm standard type E (according to SAE J994 definition, loudest type A ; 112dB-A at 1.2m distance point, type B; 107dB, type C; 97dB, type D; 87dB, and the smallest SPL type E; 77dB-A). And continuous cadenced with reverberation characteristics is added to enhance the motion perception(different sound from forward motion) and less annoyance(different sound from typical annoying backing alarms), in response to real world feedback gathered in surveys with visually impaired in Japan and USA. And nissan VSP back-up sound characteristic is supported very strongly by the visually impaired in France and USA to compare with continuous ICE like back-up sound characteristic. (Figure 14) There is an opinion that the enhancedced reverse sound might cause drivers less attention to pedestrians. But VSP is a kind of ADAS(Advanced Driver Assist System) like the back view monitor system or the pedestrian detection auto brake system. Although someone might concern that such reverse sound increase the noise intrusion to neighbourhood, but nissan back-up sound is within ICE vehicles sound pressure levels and much smaller than the typical aftermarket alarm systems.

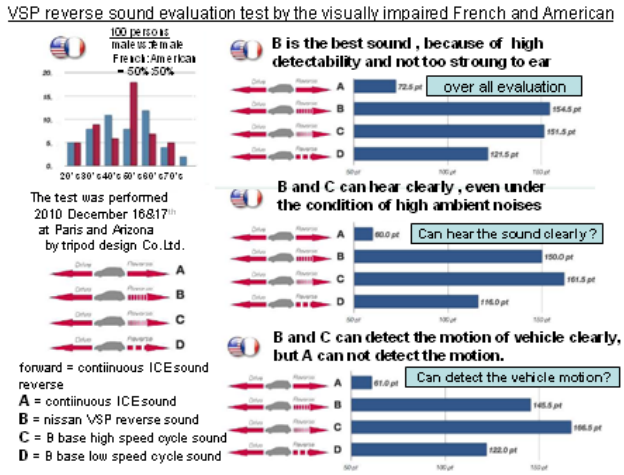


Figure 14: Nissan VSP reverse sound evaluation test by French and American visually impaired

2.4 System Configuration and diagram

The actual system applied to the Nissan new mass production electric vehicles is shown in Figure 15 and Figure 16.

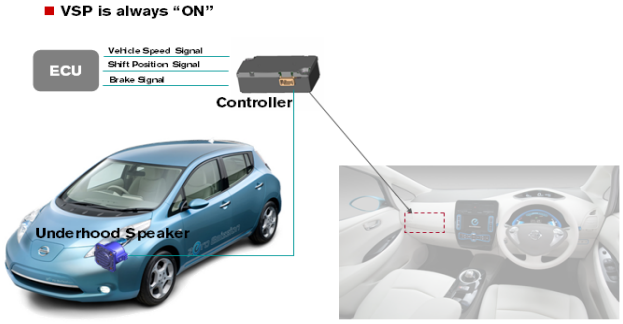


Figure 15: the System Configuration of Nissan VSP

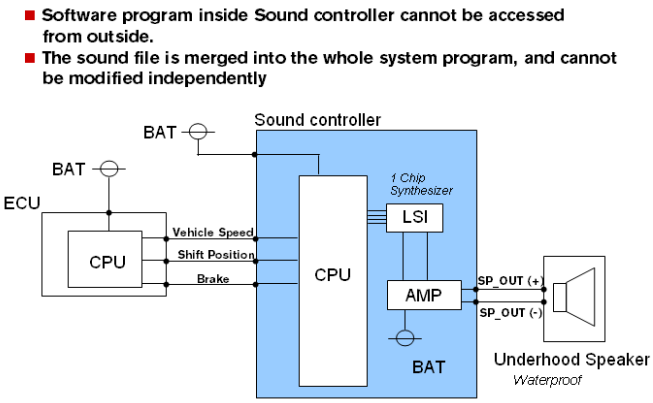


Figure 16: the System Diagram of Nissan VSP

3. Real world survey with visually impaired

Key feedback points from real world survey with the visually impaired includes: "sound should have a low pitch in order to intuitively recognize an approaching vehicle" and "distinctive sound when a vehicle is backing up and taking off (starting forward motion) helps raise awareness for motion perception and surge detection (recognizing that the vehicle has started to move from the stopped position)" (Figure 17).

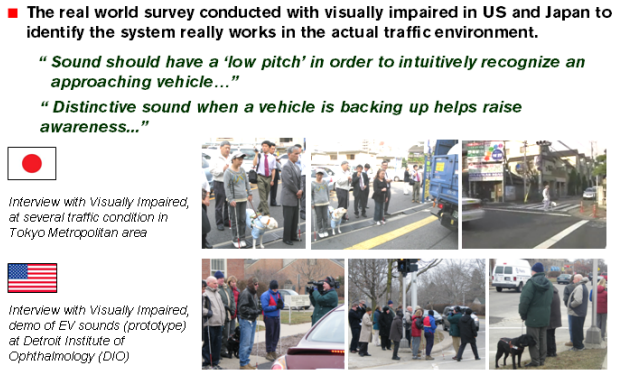


Figure 17: The result from real world survey with visually impaired in Japan and USA

4. Smart sound as a future solution

In the future this quiet electric vehicle issue should be solved by using "Pedestrian detection technology". There is discussion that the VSP sound volume should be higher up to the old fashion noisier vehicles' level like 60-65dB-A to be able to detect in the very noisy ambient conditions. But this is impossible, because 60-65dB-A level sound brings unpleasant noise intrusion into car cabin and neighborhoods. Future Pedestrian detection by radar/camera on vehicles, by ITS (for example, pedestrians keep signal transmitter) will make future smarter sound system possible. Only when the system detects pedestrians and dangerous conditions should emit louder sounds, otherwise emitts smaller sounds. This is the Smart sound concept. In the future, not only pedestrian detection technology but also conditions detection techmology, like detection of high ambient noise, blind corner, dangerous turning at intersection, may be installed on vehicles. (Figure 18)

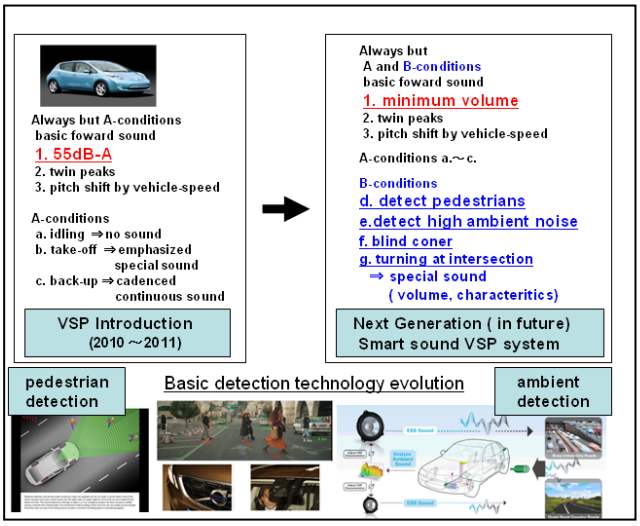


Figure 18 : Smart sound as a future solution

5. Conclusion

As research to support VSP development progressed, it became clear that the solution was much more complicated than just adding a sound effect or artificial engine noise to electric vehicles. The challenge was to provide detectability and recognition for all pedestrians, including the visually impaired, older hearing impaired adults and young children. The signals needed to be acceptable for neighborhood communities, so as not add to noise pollution, while at the same time offering a pleasant , non-intrusive sound for drivers and passengers. The final Nissan VSP system includes a unique forward driving sound with "twin peaks and one dip" frequency signature (see Figure 19). The system also includes a distinctive cadenced sound for reverse backing. With quiet cabin performance, the system is pleasing drivers and passengers, yet it also offers good detectability for all pedestrians, along with low noise intrusion for neighboring communities.

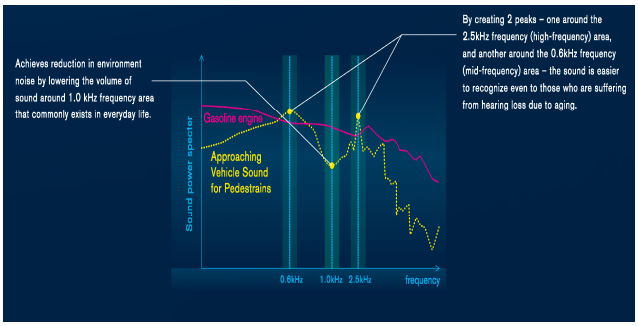


Figure 19: The final Nissan VSP system frequency signature

6. References

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