Development of a next-generation audible pedestrian alert system for EVs having minimal impact on environmental noise levels – project eVADER

David QUINN[1]; Josh MITCHELL[1]; Paul CLARK[1]

[1] Nissan Technical Centre Europe, United Kingdom

ABSTRACT

The silent operation of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs), at low speeds, has provoked significant concern regarding increased risk to pedestrian safety. Conversely, the relative silence of EVs is seen by others as a positive feature and a rare opportunity to reduce environmental traffic noise levels. The prevailing solution to the pedestrian safety concern is to add artificial sounds to EVs, in order to improve their detection by pedestrians and other vulnerable road users. However, this approach may not satisfy the need to reduce environmental traffic noise pollution levels, unless a solution can be found which satisfies these conflicting requirements.

eVADER (electric Vehicle Alert for Detection and Emergency Response) is a European Commission, part funded, project which is developing a next-generation audible alert system solution for EVs and HEVs. The prime objective of eVADER is to develop a practical solution whereby effective audible alert systems added to EVs can have minimal impact on environmental noise levels.

This paper describes the eVADER pedestrian alert system concept and practical installation of the system into a Nissan LEAF demonstrator car, together with initial results of system performance.

Keywords: Sound, Pedestrian, Detection, Alert, Quiet, EV, Electric

I-INCE Classification of Subjects Number: 13.2.1

1. INTRODUCTION

There is significant concern that the relative silence of EVs and HEVs will result in increased risk to pedestrian safety, as has been reported by the US Department of Transportation (1). With little or no audible sound from some Evs, it is possible that road users may not be aware of the presence of an EV in their vicinity. This issue is of particular concern to visually impaired pedestrians because they rely heavily on audible cues from cars and other traffic to help them navigate a safe path when crossing the road. Legislators and OEMs have responded to these concerns and the prevailing solution is to add artificial sounds to EVs and HEVs.

Conversely, the relative silence of EVs is seen by many as a positive feature, which provides a rare opportunity to significantly reduce environmental traffic noise levels. However, this opportunity could be severely compromised or even negated by the addition of artificial sounds to EVs and HEVs, unless a way can be found whereby audible alerts will have minimal impact on environmental noise levels. The eVADER system has been developed by a consortium of OEM's, R&D Centres, Universities, Tier 1 Suppliers and the European Blind Union. The eVADER consortium has developed a next-generation intelligent audible alert system for EVs, which has the potential to satisfy the conflicting requirements of adding audible pedestrian alerts to EVs with minimal impact on environmental noise levels.

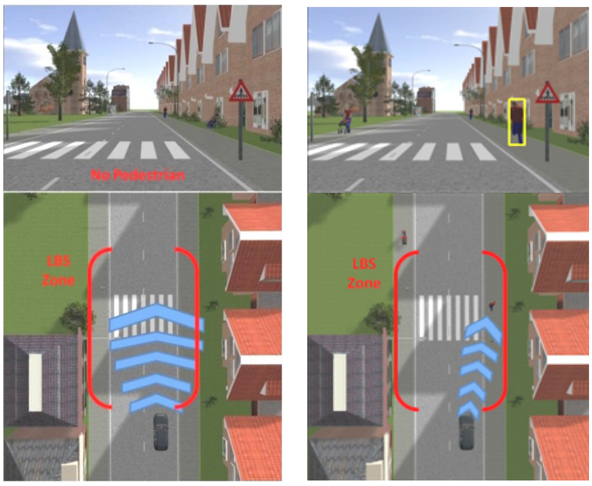
2. eVADER SYSTEM DESCRIPTION

2.1 System concept

The eVADER objective is to develop an effective audible pedestrian alert system for quiet EVs, which also has minimal impact on environmental noise levels. The eVADER system emits an optimised alert sound from an acoustic beamforming loudspeaker array mounted at the front of the vehicle. The alert sound can be directed towards any detected vulnerable road user (VRU) at an appropriate sound level when required. Detection of VRUs is achieved by an Environmental Perception System (EPS) incorporating a windscreen-mounted stereo camera and front chassis-mounted radar, which are based upon existing Advanced Driver Assistance System (ADAS) technology.

In addition to the EPS, there is a Location Based System (LBS), which uses GPS position, time of day and a database of hotspots, critical areas and speed limits to support risk estimations when no VRU is detected. The system default condition, when no VRU is detected, is to emit a low level alert sound in all directions forward of the vehicle. When the EPS camera detects a VRU, the alert sound is directed toward the VRU and sound beam becomes spatially narrower and increased in sound level (dependant upon the collision risk estimation value). Figure 1 illustrates the ‘default’ and ‘pedestrian detected’ conditions. In addition, the loudness of the alert sound can be adjusted in response to the prevailing ambient noise level, as measured by the vehicle on-board microphones. The level adjustment is constrained within defined limits to avoid generating extreme noise levels.

Default condition:
Wide sound beam at lower sound level.

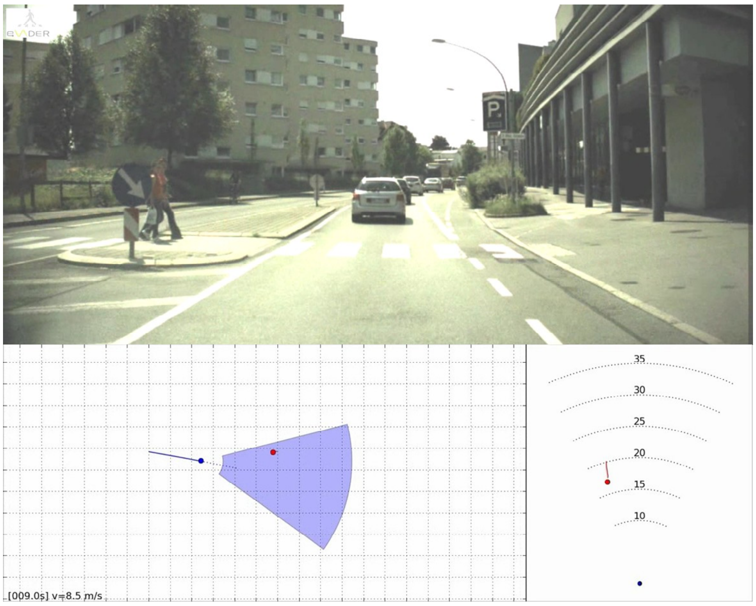


Pedestrian detected:
Narrow sound beam, directed toward pedestrian, sound level increased dependant upon collision risk estimation and ambient noise level.

Figure 1: eVADER alert sound can be directed toward a detected VRU
(Source eVADER consortium member Continental)

Figure 2 illustrates a typical view from the eVADER EPS camera. The lower part of the graphic shows a pedestrian detection simulation result made during system development. The two pedestrians to the left of the upper image were detected by the software at 20 meters distance and their paths relative to the car were also tracked. These types of data are used by the eVADER system to direct an appropriate alert sound towards any ‘at-risk’ pedestrians.

EPS camera image:
Showing two pedestrians approaching a crossing.



Simulation result:
The pedestrians were detected from 20 meters distance and their path traced relative to vehicle motion (red dots on lower right image within detection zone).

Figure 2: eVADER EPS camera view & pedestrian detection simulation result
(Source eVADER consortium members AIT and Continental)

2.2 eVADER system architecture

The eVADER pedestrian alert system is comprised of a number of sophisticated sub-systems, which inter-communicate via a dedicated eVADER CAN-bus. To minimise the risk of interference with other vehicle systems the eVADER CAN-bus receives a one-way stream of vehicle data, such as vehicle speed, steering angle and braking effort from the Nissan LEAF vehicle CAN-bus. By also taking into account the influence of driver reactions the eVADER system will continually evaluate the potential risk of collisions with any detected VRU. Figure 3 illustrates the main software blocks implemented within the eVADER system, these software modules are realised within the three hardware processors illustrated in the schematic in Figure 4 and described below:

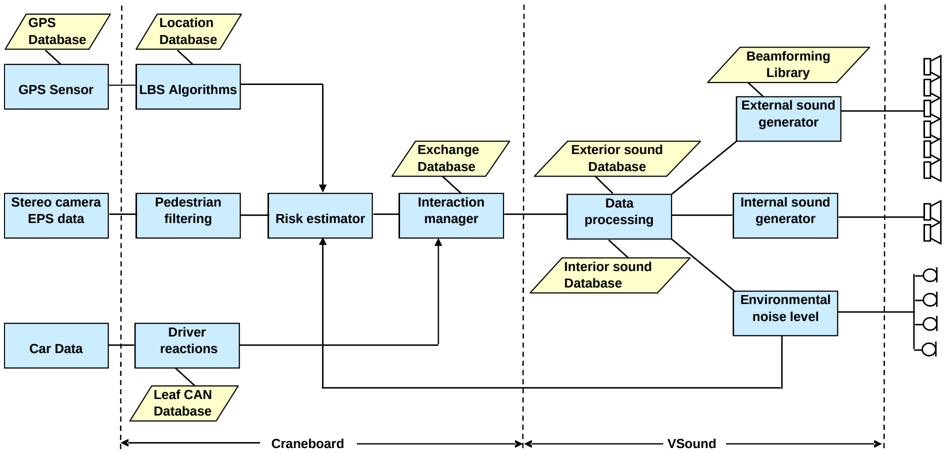


Figure 3: Main software blocks of the eVADER pedestrian alert system
(Source eVADER consortium members Continental, TNO & Nissan)

- Processor 1: EPS camera system utilising proprietary ADAS hardware and software of consortium member Continental. This unit passes polar coordinate information for each detected VRU to the collision risk estimator processor, via the eVADER CAN-bus.
- Processor 2: Craneboard PC, this unit continually monitors the EPS and vehicle data and calculates the collision risks of each detected VRU. It passes this information to the Interaction Manager software, also running on the Craneboard. The Interaction Manager sends commands to Processor 3 (VSound) for the required alert sound beamforming direction, sound level and interior warning sound as required.

Processor 1

Processor 3

Processor 2

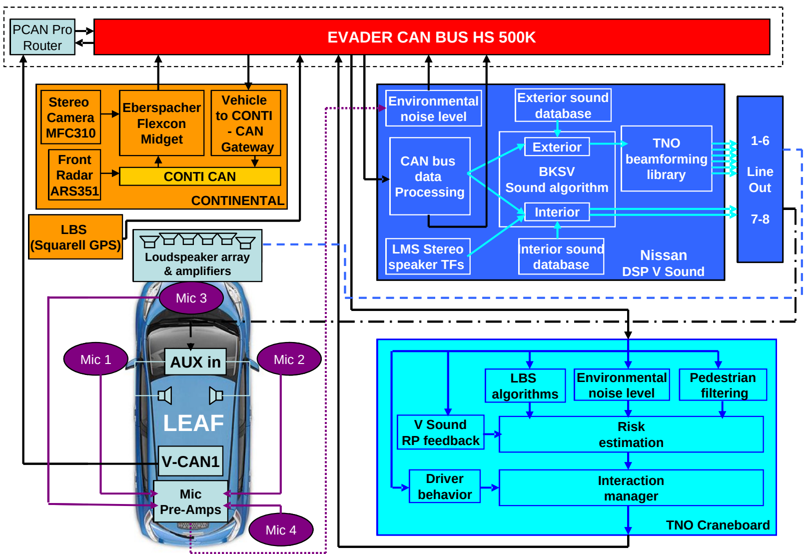


Figure 4: Schematic of eVADER processors and interconnectivity
(Source eVADER consortium member Nissan)

- Processor 3: VSound DSP, is a hardware processor supplied by B&K and running custom eVADER software. VSound manages all of the sound processing for the beamforming loudspeaker array and internal driver alert sounds. VSound also monitors environmental noise levels via four external body mounted microphones and sends this data to the Craneboard for calculation of the required alert sound output level.

The eVADER system only produces an alert sound when the vehicle speed is below 35 kph, above this speed road and tyre noise will be dominant and additional synthetic sounds are not required. In addition to speed dependency the alert sound generation will have different behaviour dependant upon whether or not a VRU is detected, or if the immediate vicinity is flagged by the LBS as higher risk e.g. close to a school or other area of increased risk. When a VRU is detected, the alert sound will also change in response to the calculated level of risk of collision. The complete list of Use-Cases for the eVADER system alert sounds and driver warnings is shown in Table 1. The icon referred to in the table is a small internal display mounted on the instrument panel. This will flash whenever a high collision risk is encountered to alert the driver and, in addition, there is an audible internal alarm for the case of highest collision risk.

Table 1- Complete table of eVADER alert sound Use-Cases
(Source eVADER consortium members Continental & TNO)

<table>
<tr><th>Car speed</th><th>Pedestrian</th><th></th><th>Hot spots (0= low risk; 1=high risk)</th><th>Date & time (0= low risk; 1=high risk)</th><th>Use Case</th><th>Supposed Risk</th><th>External warning</th><th>Interior warning</th></tr>
<tr><td>over 35Kmh</td><td>--</td><td>--</td><td>--</td><td>--</td><td>UC0</td><td></td><td>No sound</td><td>no</td></tr>
<tr><td rowspan="12">under 35Kmh, no speeding</td><td rowspan="5">NO Pedestrian sensor</td><td rowspan="4">Location Based System (LBS) OK</td><td>0</td><td>0</td><td>UC1</td><td>Low</td><td>Full forward, low warning sound</td><td>no</td></tr>
<tr><td>0</td><td>1</td><td rowspan="2">UC2</td><td rowspan="2">Medium</td><td rowspan="2">Full forward, medium warning sound</td><td rowspan="2">no</td></tr>
<tr><td>1</td><td>0</td></tr>
<tr><td>1</td><td>1</td><td>UC3+</td><td rowspan="2">High</td><td rowspan="2">Full forward, high warning sound</td><td>icon</td></tr>
<tr><td>NO LBS or speeding</td><td>--</td><td>--</td><td>UC3</td><td>no</td></tr>
<tr><td rowspan="5">Pedestrian sensor OK, NO Pedestrian detected</td><td rowspan="4">Location Based System (LBS) OK</td><td>0</td><td>0</td><td rowspan="3">UC4</td><td rowspan="3">Low</td><td rowspan="3">Full forward, low warning sound (no sound in future)</td><td rowspan="3">no</td></tr>
<tr><td>0</td><td>1</td></tr>
<tr><td>1</td><td>0</td></tr>
<tr><td>1</td><td>1</td><td rowspan="2">UC5</td><td rowspan="2">Medium</td><td rowspan="2">Full forward, medium warning sound (no sound in future)</td><td rowspan="2">no</td></tr>
<tr><td>NO LBS</td><td colspan="2">--</td></tr>
<tr><td rowspan="2">Pedestrian detected</td><td>Low conflict Probability</td><td colspan="2" rowspan="2">--</td><td>UC6</td><td>Medium</td><td>Directional if possible Medium warning sound</td><td>icon</td></tr>
<tr><td>High conflict probability</td><td>UC7</td><td>Highest</td><td>Directional if possible Highest warning sound</td><td>icon + Sound, directive if possible</td></tr>
</table>

2.3 System integration into Nissan LEAF

It was important that the eVADER system components integrated seamlessly within the existing Nissan LEAF vehicle architecture and did not have any adverse impact on the normal operation of the existing vehicle systems. Figure 5 illustrates the main eVADER system components and their locations within the vehicle.

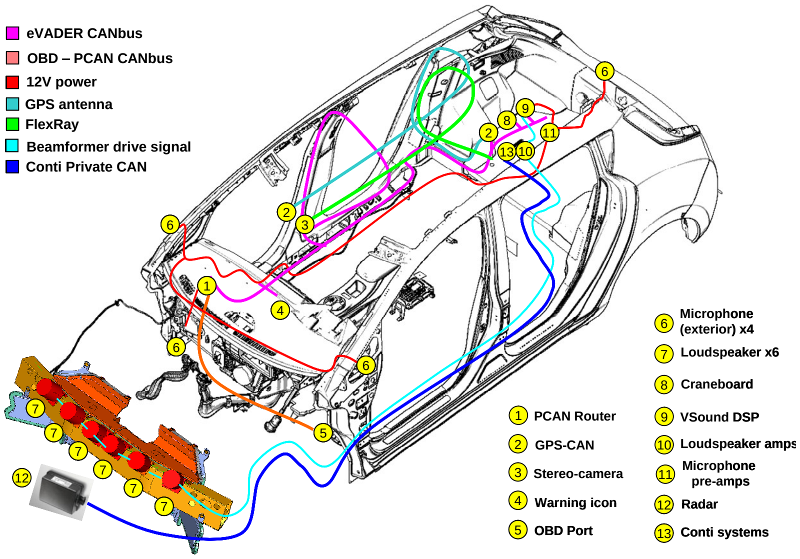


Figure 5: Illustration showing locations of main eVADER components
(Source eVADER consortium member Nissan)

All system wiring was concealed behind trim panels or carpets in order to maintain good visual appearance of the vehicle. The main processor units and power supplies were located in the vehicle trunk for convenience and ease of access for development and maintenance. Figure 6 shows the completed eVADER demonstration vehicle; the six beamforming array loudspeakers can be seen on the front bumper.

Figure 6: eVADER demonstration vehicle
(Source eVADER consortium member Nissan)

3. ALERT SOUNDS AND PSYCHOACOUSTICS

3.1 Requirements of alert sounds

The prevailing requirement to add artificial sounds to EVs and HEVs raises the obvious question ‘what sound should an EV make?’ There is no simple answer to this question and this is an area of much debate. In the US the Department of Transportation issued notice of proposed rule making (NPRM), (2) which specified minimum sound levels in a range of 1/3 octave bands. However there has been strong comment from the Alliance of Automobile Manufacturers (3) and others critical of a number of aspects of the NPRM including the nature of their proposed sounds.

There are however, some general requirements that many agree should be satisfied such as:

- Alert sounds should be easily detected by pedestrians and other vulnerable road users.
- The road user should be able to easily localise the source of the alert sound.
- Alert sounds should have minimal impact on environmental noise levels.
- Alert sounds should be recognisable as vehicle sounds.
- Alert sounds should not be annoying – i.e. the sound should not deter potential customers from adopting EVs.
- The pitch of the sound should increase and decrease in step with vehicle speed for the perception of vehicle acceleration / deceleration.

There is also general agreement that EVs should not sound like any animal, or like any natural sound, such as running water or breaking waves. The requirement that artificial EV sounds should be ‘recognisable as a vehicle’ is open to interpretation. At a basic level, this could be construed as meaning EVs should produce artificial sounds, which imitate existing internal combustion engine (ICE) vehicle sounds. However, this interpretation misses two important opportunities. As was found within the eVADER psychoacoustic studies, summarised in section 3.2 of this paper, it is entirely possible to define sounds which have excellent detectability and which also have significantly lower sound levels than sounds emitted by conventional ICE powered cars. Secondly, there is growing evidence that customers of EVs do not want their cars to sound like a conventional ICE car, but would rather it had a sound more appropriate to the new technology it embodies. The use of new sounds, which are unlike existing ICE vehicle sounds, raises the question of whether it will be acceptable to require road-using populations to become familiar with a range of new EV sounds and this is an area of debate and possible research. Additionally, if new non ICE sounds are to be allowed it will require new standards and rules to be developed in order to set clear boundaries for their definition to satisfy legislators.

3.2 eVADER psychoacoustics experiments

Prior research on dynamic sound source localisation was found to be limited, therefore, to improve our understanding and to try to develop some guiding principles for effective vehicle alert sound design, the eVADER consortium carried out a series of jury listening studies to investigate fundamental characteristics of potential alert sounds. This work was lead by consortium member INSA-Lyon (4,5,6) and supported with jury evaluations carried out by consortium members LMS, PSA, TUD and Nissan with excellent support from consortium member European Blind Union whose members kindly agreed to take part in many of the jury listening experiments.

It is beyond the scope of this paper to go into the detail of the psychoacoustic experiments carried out by eVADER; more information will be found by following the references at the end of this paper. However, a summary of the eVADER psychoacoustic experiments and some of the key findings is provided below.

Three aspects of possible vehicle alert sounds were investigated by the eVADER consortium in a series of jury listening experiments:

Experiment 1: Detectability of sounds and the influence of three timbre parameters:
- Frequency content, by way of harmonic complexity (from 3 – 9 harmonics)
- Frequency modulation
- Temporal (amplitude) modulation

Experiment 2: Ability to judge speed / distance from vehicle sound only

Experiment 3: Unpleasantness / annoyance of sounds

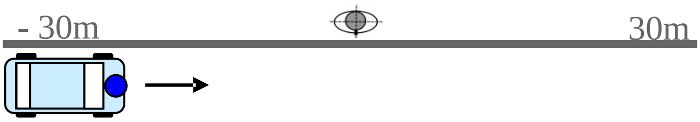


Figure 7: Waiting to cross scenario used for the listening experiments
(Source eVADER consortium member INSA-Lyon)

Nine experimental sounds were created by applying three levels of each of the three timbre parameters to arrive at a Taguchi fractional design for the nine stimuli. Each sound was then layered onto a recording of an EV vehicle to produce a set of sound files representing different vehicles passing the listener, as if standing at the kerb-side waiting to cross, as illustrated in Figure 7. The sounds were presented to jury members via headphones. For experiments 1 and 2 background traffic noise was added, sometimes with additional rain noise, as this can present added difficulty for visually impaired pedestrians when trying to discern vehicle behavior from sound only.

Two reference sounds, a diesel car and an electric vehicle, without alert sound, were included in each experiment giving in total 11 experimental sounds. Vehicle ‘passing speed’ for experiments 1 and 3 were 20kph and for experiment 2 passing speeds of 20 kph and 30 kph were applied.

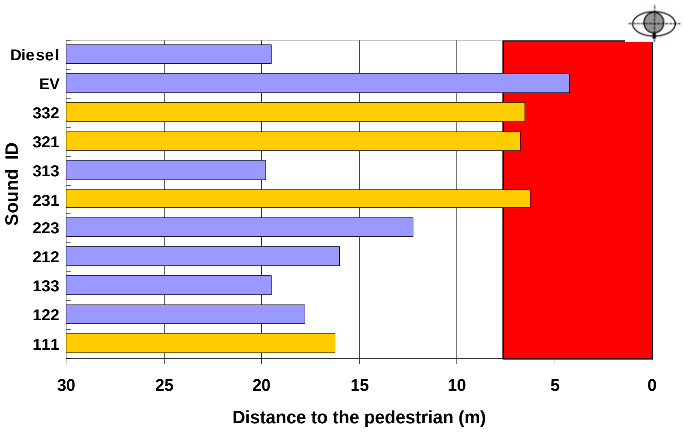


Figure. 8: Comparison of ‘detection distance’ for eVADER psychoacoustic experiments.
Orange coloured bars indicate the least-unpleasant synthetic sounds (equal to diesel)
(Source eVADER consortium member INSA-Lyon)

It is worth noting that the best performing synthetic sound for detectability (sound 313 in Figure 8) had a sound pressure level 6.5 dB(A) lower than the diesel car sound. Unfortunately, this sound was also judged to be more unpleasant than the diesel car sound. However sound 111 was no more unpleasant than the diesel car sound, had good detectability and was also 6 dB(A) quieter than the diesel car sound. This shows that there is potential to develop synthetic sounds, which can be detected by road users and have lower impact on environmental noise levels than conventional ICE cars. Table 2 gives a summary of the key findings from the eVADER psychoacoustic experiments.

Table 2 - Summary of key findings from eVADER psychoacoustic experiments for alert sounds (Source eVADER consortium member INSA-Lyon)

	Task	Objective	Key Findings
Experiment 1	Detect the car as soon as possible, identify the direction of the car (left/right).	1) Detectability of various alert sounds within typical traffic noise scenario 2) Influence of sound timbre characteristics	> No difference in response time for detection between visually-impaired and sighted subjects. > Some alert sounds were as easy to detect as the diesel car > No relationship to sound pressure level for detectability Timbre parameters which tend to improve detection: > Small frequency range / low number of harmonics > Temporal modulation
Experiment 2	Indicate when you think it is no longer safe to cross the road while this car is approaching.	Is it possible to judge approaching vehicle speed / distance just from its sound	> Visually Imapired participants were on average 0.5 sec quicker to decide 'unsafe to cross' to approaching vehicle sounds > Speed effect as expected. People feel unsafe sooner for cars travelling at 30 km/h compared to 20 km/h. > No effect of alert sound modulation frequency. > Surprising effect of pitch: higher pitch sounds tended to result in later judgement of 'unsafe to cross'.
Experiment 3	Listen to the sound then move the slider to indicate how unpleasant the sound was, listen to the sound as often as you want before deciding [Slider scale: not at all unpleasant - to - extremely unpleasant]	1) To establish how annoying / unpleasant each sound is 2) Influence of sound timbre characteristics on unpleasantness	> The EV was judged the least-unpleasant sound. > Four of the synthetic sounds were judged equally unpleasant as the diesel > All other synthetic sounds were judged more unpleasant than the diesel > Temporal fluctuation tended to increase unpleasantness > Increasing the number of harmonics tended to lower unpleasantness

4. PERFORMANCE OF eVADER BEAMFORMING ARRAY

A key feature of the eVADER system is the ability to direct an alert sound toward any detected VRU to mitigate the risk of collision but also to minimise unwanted noise radiation in all other directions. The evaluation and selection of the most appropriate beamforming strategy and algorithm was carried out by consortium member TNO (7,8). This work concluded that a six loudspeaker beamforming array with non uniform loudspeaker spacing, coupled with a sound-power minimisation beamforming algorithm, would provide the best directivity for the eVADER system. A real-time implementation of the beamformer algorithm has been programmed into the VSound DSP sound processor.

During development of the eVADER system inertial mass shakers, mounted directly to the inside of the LEAF ABS front bumper structure were considered as acoustic drivers for the Beamforming array.

The use of panel shakers has some strong advantages:

- Invisible ‘loudspeaker’ – no interference with aesthetic design features
- Good protection against environmental influences (weather, water, cleaning agents)
- Easy installation
- Capable of high quality sound output and a wide sound dispersion angle

However there are also disadvantages to the use of shakers:

- Low efficiency factor compared to standard loudspeakers (more powerful amplifier required)
- Other vehicle parts in contact with the excited surface may cause disturbing noise or unwanted noise transmission into the cabin
- Acoustic performance strongly dependent upon material, dimensions and shape of the excited panel, potentially requiring significant panel shape tuning for optimum performance.

Whilst it would be possible to find engineering solutions for all of the above disadvantages it was felt to be outside the scope of the eVADER project and therefore a conventional loudspeaker array was selected for practical reasons of ease of fitment and predictable good performance. The selected loudspeakers were off-the-shelf 50mm diameter drivers mounted into 0.47 litre sealed enclosures. A moderate level of environmental protection of the loudspeakers was achieved by the addition of waterproof breathable membranes mounted in front of each loudspeaker grille.

Figure 9 shows typical results for the eVADER beamforming array performance. The plots show normalised dB(A) sound pressure levels measured at different steer angles of the array from -60 degrees to +60 degrees. The measurements were made at 5m radius from the centre of the front grille of the vehicle, angular resolution of the measurements was 6 degrees. Overall performance is generally good with around 10 dB(A) attenuation away from the lobe maximum and up to 20 dB(A) attenuation behind the vehicle, effectively minimising unnecessary noise radiation into the environment.

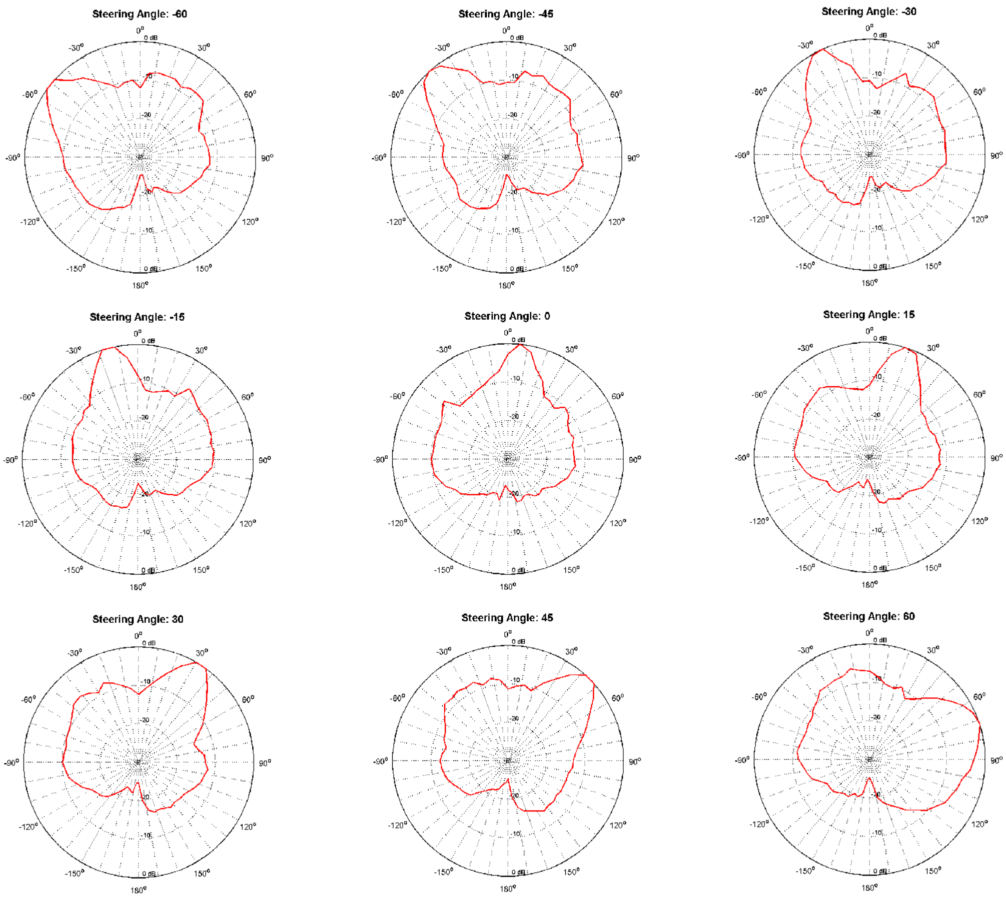


Figure 9: Typical beamforming loudspeaker array performance shown as normalised dB(A) levels at steer angels from -60 degrees to +60 degrees (Source eVADER consortium member Nissan)

5. VALIDATION TESTING

The next stage of the eVADER project is to carry out validation testing of the complete system performance. For these tests a mix of normally sighted and visually impaired pedestrians will interact with the vehicle in various scenarios and manoeuvres which are known to be higher risk for pedestrians.

It is planned to carry out some of the validation tests in controlled conditions at the consortium member IDIADA proving ground in Spain. Additionally, discussions are progressing with Barcelona City Authority to carry out real world evaluations at specific locations within Barcelona.

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Roger Williams - Brüel & Kjær

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