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Executive summary

This state of the art report comprises information on three types of systems which are essential to achieving the objectives in the eVADER project:

- Interior warning systems
- Exterior warning systems
- Environmental perception systems

The main objective of eVADER is to design and demonstrate a selective warning system for a passenger car to reduce the potential accident risk due to the low audibility of electric drive vehicles like hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs) at speeds below 50 km/h. The main idea is to use a selective, targeted acoustic warning device emitting carefully designed signals while at the same time making the car driver aware of the situation. In order to keep noise pollution as low as possible, the signals should only be emitted when necessary and should be directed at the endangered pedestrians. For this reason both appropriate interior and exterior warning systems as well as an environmental perception system is necessary, which allows to evaluate and assess the danger of the situation.

Advanced interior warning systems are usually part of Advanced Driver Assistance Systems (ADAS), which are designed to provide crucial information to the driver while managing complex situations. They are designed to quickly provide clear information about the diagnosed risk and about possible and recommendable actions. Correctly implemented, the combination of visual, acoustic and haptic stimuli can be used to trigger the correct actions quickly and reliably. Acoustic warning signals need to be audible, distinctive and unambiguous. A typical choice is represented by sound with frequency modulation over a large bandwidth.

Exterior acoustic warning systems installed on an electric drive vehicle are designed to alert pedestrians of its approach. Due to the current legislation, guidelines and recommendations in Japan, the US and Europe electric and hybrid car manufacturers like Nissan or Toyota are developing and implementing exterior acoustic warning systems. The recommended signals are specified with respect to their loudness, locatability, directivity and other properties. This report gives an overview about systems which are already installed or are currently being developed. In addition, guidelines for similar auditory warning systems in other fields are discussed.

Environmental perception systems based on sensor technology using laser, radar, microwave or infrared radiation provide a substantial input for ADAS and exterior warning systems. Data fusion technologies even allow combine inputs from several sensors to take advantage of their respective strengths. Environmental perception systems enable the car systems to recognize pedestrians and estimate their speed relative to the car, which makes it possible to recognize dangerous situations. This can be used for decisions on the use of exterior acoustic warning signals.

In summary this report reviews the state of the art in three technological fields which will be important for the implementation of the eVADER project.
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1 Introduction

This deliverable focuses on collecting the existing experience with acoustic warning systems including information not only from road traffic but also from related fields of application (e.g. rail, occupational applications). An inventory of the applied technologies and strategies is then presented.

Following the organization of work package 4, this deliverable includes 3 main sections that are reported hereafter:

- Strategies for interior warning
- Strategies for exterior warning
- Environmental perception systems.

This document documents the stat of the art as related to the objectives of eVADER and specifically to work package 4. The eVADER project aims at developing and demonstrating an acoustic warning device for electric drive road vehicles, which enables pedestrians to perceive the approach of an electric vehicle and to avoid dangerous situations and accidents. The acoustic warning is supposed to compensate for the lack of engine noise in electric vehicles, which makes them less perceptible at travelling speeds below 50 km/h. While the purpose of the signal is to achieve a sufficient audibility, it is not intended to supersede other auditory signals in the way an emergency signal like a car horn does. Nevertheless the experience and design recommendations from classical warning and emergency signals will be used. An additional challenge of eVADER is to develop warning systems that do not contribute more than necessary to the overall noise pollution, which makes it necessary to target the signal and restrict its use to relevant situations as much as possible. In order to achieve this objective, required properties for the involved systems and strategies for their use need to be defined.

The exterior warning system will be focused mainly on making pedestrians aware of the approach of the car, whereas the interior warning systems work in the way of ADAS (advanced driver assistance systems) which are already available for other purposes in modern cars. The environmental perception system is intended to provide input to the algorithms controlling both warning systems by providing the necessary information to categorize and evaluate the current situation and take the appropriate actions. This document therefore focuses on presenting the current state of the art for these systems, which will be essential for further work in work package 4.

Work package 4 cooperates with the other eVADER work packages by using information from work package 1 on the concept definition and system requirements, from work package 2 on the psychoacoustic aspects and selection of the warning signals, and from work package 3 on the warning signal generators to be used. It will provide information to work package 5 for the design and construction of the warning device and work package 6 for the vehicle implementation, as well as subsequent validation and demonstration phases in work packages 7 and 8.
2 Strategies for Interior warning

Modern cars have a wide range of sensors, which monitor the cars performance and constantly check for problems. In most of the case, the way they tell the driver of any problems is through dashboard telltales. As a rule orange lights mean that the problem should be checked at the earliest convenience and red lights indicate a problem that should be checked immediately. Next pictures are presenting typical dashboard telltales.

![Engine Warning or Malfunction Indicator Light](image1)

**Figure 1 Engine Warning or Malfunction Indicator Light**

![Battery and Charging Light Indicator](image2)

**Figure 2: Battery and Charging Light Indicator**

![Anti-Lock Braking System Indicator Light](image3)

**Figure 3: Anti-Lock Braking System Indicator Light**

More recently the development of Advanced Driver Assistance Systems (ADAS) has generated a real technological break.

In general, Advanced Driver Assistance Systems (ADAS) are expected to mitigate specific driver deficits, reduce driver’s workload and thus increase driving comfort and safety. Systems like Lane Departure Warning, Adaptive Cruise Control or Blind Spot Detection have successfully been launched by several car manufacturers into a growing market. Apart from challenges related to sensor development and data processing one crucial aspect for the success of ADAS is the design of the human machine interface. For many current ADAS which do not take over any form of vehicle control the effect of the ADAS intervention is entirely dependent on the driver’s reaction to the system output which often takes the form of warnings.

**Warning Objectives**

In general, warnings must be noticed, be read or heard, be understood and accepted by the user. In order to reach these goals with ADAS the warnings need to effectively draw the driver’s attention. It should ideally inform the driver about the diagnosed risk and about possible and recommendable actions in case they are not obvious. However, in a highly dynamic task like driving a vehicle there is usually little time to convey all these elements of a warning message. Therefore, it is essential for ADAS warnings to be easily perceived and quickly interpreted in the correct way in order to trigger the correct response in time. In addition, the style of the warning must be accepted by drivers (even in the case of false warnings). Otherwise there is a risk that drivers just switch off an annoying warning system.
Although the implementation of warning signals is often highly dependent on the nature of the task, system, and display, some general findings should be taken into account when designing new warnings. In practice, three sensory channels can be effectively deployed to communicate a warning message:

- The acoustic
- The visual
- The haptic channel

In the automotive domain all three modalities have been used either alone or in combination. There has been a long debate about whether one modality is better than another for warning signals. Early studies (1,2) compared auditory and visual signals on reaction time to a visual target. The authors reported that an auditory warning signal (a brief tone) reduced reaction time more than a visual warning signal (a brief light) particularly when the fore period was short. However, recent experiments (3) question this effect and show that this was mainly caused by using different locations for the visual warning and the visual target. Visual warnings presented very close or on top of the visual target can be equally effective in terms of reaction time. The peripheral FOV is very sensitive for dynamic changes. Movements in the peripheral FOV have even a signal function which triggers an automatic allocation of drivers’ glance and attention. According to these evidences, dynamic warning signals (like flashing LEDs) in the peripheral FOV could be effective for visual in-vehicle warnings. Haptic warnings in the form of vibration and force feedback have also been investigated for various ADAS (4) as an alternative warning modality if the visual and the auditory ones are less adequate or overloaded. Dynamic tactile stimuli (with a rapid onset) have been shown to elicit even quicker reactions than auditory or visual signals (5). On a more general level, uni-modal warning signals (same modality as target) seem to facilitate responding more than cross-modal signals (different modality as target). This effect has been replicated and referred to as the modality shift effect. In order to combine advantages of single warning modalities, multi-modal warnings have been discussed and introduced for many applications including ADAS. Multi-modal warnings are expected to be more robust since they are less likely to be masked by noise signals. Moreover, they seem to be more effective than uni-modal warnings if they come from roughly the same spatial location. Spatial information can be integrated in most warning modalities to further facilitate their interpretation: For lane departure warning systems haptic or acoustic feedback was implemented either coming from the left or right side depending on which side the vehicle is leaving the road. For blind spot warnings visual indicators at both side mirrors have been used to visually indicate the direction of the potential hazard.

2.1 Visual warnings

Thus, it is recognized that the optimal design of warnings is one of the crucial aspects for the effectiveness and acceptance of ADAS. According to research findings on uni-modal and spatial warning signals a more advanced visual warning concept can be developed and implemented in a driving simulator. In some applications, for example, LED based visual warning indicators are placed at specific positions in the vehicle interior in order to guide the driver’s visual attention to the direction of a particular hazard. The warning system has been experimentally compared against conventional visual warnings on the instrument cluster in a driving simulator study. Results indicate a clear advantage of distributed warnings: The frequency of collisions could be reduced; driver reacted quicker to the warning stimulus and subjectively rated the distributed warnings to be more useful than the visual warning on the
instrument cluster. The results confirm the hypothesis that spatially distributed visual warnings can improve the effectiveness and acceptance of ADAS warnings.

### 2.1.1 Distributed visual warning concept

Advanced Driving Assistance Systems aim to communicate possible hazards in the immediate surroundings in order to make drivers react in the most appropriate way. When entering the safety-critical stage of the warning process one key element is to guide the driver’s visual attention to the detected hazard. Based on the findings on uni-modal warnings this could be effectively accomplished by visual warning signals being presented close or on top of the visual target. Inside the vehicle visual targets (e.g. pedestrians or other traffic participants) are mainly perceived through the front windscreen and through mirrors (side and rear-view mirrors) which would require to present visual warning signals at exactly these positions. Therefore, areas around the vehicle could be mapped to positions of visual warnings inside the car.

Objective and subjective results indicate a clear advantage of distributed warning signals inside the vehicle. Spatially distributed visual warnings could prevent more collisions and trigger faster brake reactions. In the literature, subjects have reported to react better with distributed warnings and found them more helpful to guide visual attention to the target. Surprisingly, the subjective assessment of the brake reaction after the central warning was even rated “below normal” although more accidents could be avoided compared to the control condition. This issue points towards some general drawbacks of centrally displayed warnings in critical situations. The results of the experiment are in line with findings in the literature about the potential advantage of unimodal warnings (6) and the requirement to present the visual warning signal very close or even on top of the visual target (7). For experimental reasons the frequency of hazards and warnings was very high in the driving simulator which is not realistic for everyday driving conditions. Although learning effects were controlled by the experimental design future work should especially focus on driver behaviour after unexpected and infrequent warnings. The distributed visual warning system that was used for the experiment worked well under the lighting conditions in the driving simulator. It still needs to be tested if light intensities of LED arrays are high enough to effectively guide visual attention also in real (sun-) light conditions. However, with current high performance LEDs this seems to be possible with reasonable cost and effort.

### 2.2 Haptic warning signals

Through last years, all developed Advanced Driver Assistance Systems (ADAS), have been attempting to increase road safety and to reduce the number of traffic deaths and injuries all over the world, supporting users and enhancing safety to all drivers. This is the case of Forward Collision Warning systems (FCW) or Lane Departure Warning (LDW), alert systems aimed to give support to drivers when an obstacle is found inside vehicle trajectory, and when the vehicle is stepping over lane boundaries, respectively. Most work done regarding that matter, investigates obstacles like vehicles found in front of driver’s car, pedestrians, even cyclist, and finally, driver alertness and behavior while driving. However, there is limited knowledge of which modality, whether acoustic, haptic or visual, is more appropriate to warn and induce drivers to apply steering maneuvers if necessary, and what characteristics should those warnings have to achieve maximum efficacy.

Closed environment using road simulators have been used to gather information regarding objective performance of users while driving and subjective user feelings. The object of study has been a haptic acceleration pedal as a new warning channel.
Tests have been reported in the literature using a haptic pedal as an alert system for a Frontal Collision Warning (FCW). Other tests used the pedal as an alert complement of a Drowsiness Detection System (DDS), with participants in different sleep conditions.

In the FCW test, the results demonstrated that haptic stimuli decrease reaction times, speed variation and also vehicle approach, in contrast with visual alarms. The best performance was achieved with vibration torques of 1.60 Nm, and in the frequency range between 5 and 10 Hz.

As a complement for a DDS, this device was evaluated as a secure element with a great predilection upon visual and acoustic signals. A set of physiological variables were also recorded in order to correlate the effects of several warning strategies and driving performance. These results contribute to solve the key dilemma of how to balance the efficacy of a warning signal with user acceptance.

2.3 Acoustic warning signals

2.3.1 Introduction

Signals of various modalities may be used as warning signals which inform people of dangerous happenings. Among them, auditory signals have advantages that they are non-directional and can be transferred in wide areas. It would be desirable to meet the following requirements in order that the auditory warning signals used in dangerous situations should be effective:

- They are easily detected in noisy situations
- They are easily detected by people of any generations
- They are easily universally recognized as a warning signal

Previous research results concerning the aspect of having an easily universally recognized signal as a warning signal suggest that there is a cross-cultural difference in the impression of some signals and that, generally speaking, frequency modulated sounds are perceived as being dangerous by all people.

On the basis of these results, herein we present the effects of frequency components and temporal factors on the impression of dangerousness with systematically controlled synthetic sounds.

2.3.2 Stimuli

As an example, in this type of studies, systematically controlled synthetic sounds can be used as stimuli. The stimuli can consist of sounds of a certain duration which is repeated several times with or without off-time. The frequency can be shifted from low to high in various octaves.

Figure 1 shows a sound structure based on the important parameters that affect interior noise warning perception by the driver. It depicts a sound with a spectra basically made up of an intermediate frequency band that defines the limits of the frequency sweep and a lower frequency band of constant limits. The relative value of the limits of such bands determines attributes of the sound such as:

- Loud
- Deep
- Frightening
This attributes can be associated to a given sound by, for example, pair comparison of samples in a jury test.

**Figure 4: The main structure of a suitable interior noise warning signal for a driver**

The speed of the frequency modulation is also another parameter to be taken into account. In general the general behavior of drivers has been found that the stimuli with the wider and higher frequency content are perceived as more dangerous, exciting, powerful, tense and unpleasant.

Also there is a relationship between the adjective scale value “safe-dangerous” and off-time value. This suggests that the sound appears more dangerous as the off-time becomes shorter (see figure 2).

**Figure 5: The relationship between off-time in a warning signal and the perception “Safe-Dangerous” associated**
There is tendency that the impression of danger becomes stronger as the frequency becomes higher. The phenomena also occur if the stimuli contain a wide frequency range.

The combination of a high frequency band and a low frequency significantly increases the perception of danger. This fact also indicates that the sounds with wide frequency range are appropriate as warning signals.

### 2.3.3 Conclusions

The signal whose frequency shifts from low to high over a wide range gives the impression of dangerousness and the impression becomes more dangerous as the off-time becomes shorter. Signals with this property are appropriate for the auditory interior warning signals. When the signal consists of a wide frequency range and the frequency sweeps from low to high, it would be difficult to be masked in noisy situations and can be detected by the people who have some usable hearing to identify the signal in some frequency region.

![Diagram](image)

**Figure 6:** The effect of increasing the frequency bandwidth of stimuli on the perception “safe-Dangerous”
3 Strategies for Exterior warning

**Electric vehicle warning sounds** are a series of sounds designed to alert pedestrians to the presence of electric drive vehicles such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs) travelling at low speeds. Their purpose is because vehicles operating in all-electric mode produce less noise than traditional combustion engine vehicles and can make it more difficult for pedestrians, the blind, and others, to be aware of their presence.

Japan issued guidelines for such warning devices in January 2010 and the U.S. approved legislation on December 2010(8,9). Several automakers have developed electric warning sound devices, and as of December 2010 advanced technology cars available in the market with manually activated electric warning sounds include the Nissan Leaf, Chevrolet Volt, Nissan Fuga Hybrid/Infiniti M35, and the Toyota Prius (Japan only)(10). Models equipped with automatically activated systems include all Prii family cars to be introduced in the United States, including the standard 2012 model year Prius, the Toyota Prius v, and the Toyota Prius Plug-in Hybrid (11).

### 3.1 Background

As a result of increased sales of hybrid electric vehicles in several countries, there have been concerns about the noise reduction when those vehicles operate in all-electric mode, as blind people or the visually impaired consider the noise of combustion engines a helpful aid while crossing streets and feel quiet hybrids could pose an unexpected hazard (12).

This problem is not exclusive to electric vehicles. In 2007 research at the Technical University Munich showed that ordinary vehicles in background noise are often detected too late for safe accident avoidance. The researchers measured the distances of 35 approaching vehicles to a pedestrian in the moment when they just got audible in a stationary background noise. These distances were then compared to the stopping distances of the respective cars and an algorithm was proposed to estimate them based on auditory masking (13,14).

Research conducted at the University of California, Riverside in 2008 found that hybrid cars are so quiet when operating in electric mode (EV mode) that they may pose a risk to the blind, small children, the elderly, runners, cyclists, and other pedestrians, as they may have only one or two seconds, depending on the context, to audibly detect the location of approaching hybrid cars when the vehicles operate at very slow speeds. This research project was funded by the National Federation of the Blind (15,16).

The experiment consisted of making audio recordings of a Toyota Prius and combustion engine Honda Accord approaching from two directions at 5 miles per hour (8.0 km/h) to assure that the hybrid car operated only with its electric motor. Then test subjects in a laboratory listened to the recordings and indicated when they could hear from which direction the cars approached. Subjects could locate the hum of the internal combustion engine car at 36 feet (11 m) away, but could not identify the hybrid running in electric mode until it came within 11 feet (3.4 m), leaving just less than two seconds to react before the vehicle reached their position. In a second trial, the background sounds of two quietly idling combustion engine cars were added to the recordings to simulate the noise of a parking lot. Under this condition, the hybrid needed to be 74 percent closer than the conventional car before the subjects could hear from which direction the cars approached. Subjects could correctly judge the approach of the combustion car when it was about 28 feet (8.5 m) feet away. This result means that under closer to normal environmental noise, a pedestrian would not be able to correctly determine the hybrid’s approach until it was one second away( 17,18).
A separate 2008 study from Western Michigan University found that hybrids and conventional vehicles are equally safe when travelling more than about 20 miles per hour (32 km/h), because tire and wind noise generate most of the audible cues at those speeds. Hybrid cars were also tested safe when leaving a stoplight and it was found that under this condition they do not pose a risk to pedestrians. All Prius models used in the study engaged their internal combustion engines when accelerating from a standstill and produced enough noise to be detected (16).

A 2009 study conducted by the U.S. National Highway Traffic Safety Administration found that crashes involving pedestrians and bicyclists have higher incidence rates for hybrid electric vehicles than internal combustion engine (ICE) vehicles in certain vehicle maneuvers. These accidents commonly occurred in zones with low speed limits, during daytime and in clear weather. The study found that a HEV was two times more likely to be involved in a pedestrian crash than was a conventional ICE vehicle when a vehicle is slowing or stopping, backing up, or entering or leaving a parking space. Vehicle maneuvers were grouped in one category considering those maneuvers that might have occurred at very low speeds where the difference between the sound levels produced by the hybrid versus ICE vehicle is the greatest. Also the study found that the incidence rate of pedestrian crashes in scenarios when vehicles make a turn was significantly higher for HEVs when compared to ICE vehicles. Similarly, The NHTSA study also concluded that the incidence rate of bicyclist crashes involving HEVs for the same kind of maneuvers was significantly higher when compared to conventional vehicles (17).

In September 2010, Volvo Cars and Vattenfall, a Swedish energy company, issued a report regarding the results of the first phase of the Volvo V70 Plug-in Hybrid demonstration program.[11][12] Among other findings, before the trial drivers participating in the field testing were concerned about being a danger to pedestrians and cyclists due to the quietness of the electric-drive vehicle. After the test several of them change their opinion and said that this issue was less of a problem than expected. Nevertheless, some test drivers said they experienced incidents of not being noticed while others said they had taken extra care in their driving with regard to this issue (18,19).

3.2 Regulation

Since 2009 the Japanese government, the U.S. Congress and the European Commission are exploring legislation to establish a minimum level of sound for plug-in electric and hybrid electric vehicles when operating in electric mode, so that blind people and other pedestrians and cyclists can hear them coming and detect from which direction they are approaching. Tests have shown that vehicles operating in electric mode can be particularly hard to hear below 32 km/h (20 mph) (8,20,21,22).

3.2.1 Japan

Beginning in July 2009 the Japanese government began assessing possible countermeasures through the Committee for the Consideration of Countermeasures Regarding Quiet Hybrid and Other Vehicles, and in January 2010 the Ministry of Land, Infrastructure, Transport and Tourism issued guidelines for hybrid and other near-silent vehicles (8).
3.2.2 United States

The Pedestrian Safety Enhancement Act of 2010 was approved by the U.S. Senate by unanimous consent on December 9, 2010 and passed by the House of Representatives by 379 to 30 on December 16, 2010 (9,23,24). The act does not stipulate a specific speed for the simulated noise but requires the U.S. Department of Transportation to study and establish a motor vehicle safety standard that would set requirements for an alert sound that allows blind and other pedestrians to reasonably detect a nearby electric or hybrid vehicle, and the ruling must be finalized within eighteen months(9,10). The bill was signed into law by President Barack Obama on January 4, 2011(25).

3.3 On the basic characteristics of the warning sound

Requirements according to the informal Group on Quiet Road Transport Vehicles

Following the QRTV guidelines as closely as possible, this document sets out to define, optimize and harmonize a QRTV warning device’s sometimes conflicting performance requirements for safety and for the environment. The essential characteristic of the warning sounds is to its audibility, localability and directivity. From an environmental point of view, the important points are its directivity, the attenuation and the acceptability.

Audibility

The audibility of a warning device in a background noise is a function of its loudness (phon). It has been proposed that a warning device should have a sound pressure level (SPL) equal to that of a typical ICE vehicle at the same distance, but the decibel is not a measure of loudness. Only by defining the frequency content and determining the loudness of a QRTV warning device will it be possible to arrive at the required SPL in dBA.

The following considerations need to be taken into account:

1. For equal overall SPLs, each doubling of the frequency bandwidth requires 3 dB lower SPL. Consider e.g. a warning device with a bandwidth of 1 kHz and a warning device with a bandwidth of 8 kHz which have equal overall SPLs. Because the total energy in the wider 8 kHz band equals that in the 1 kHz band then the SPL in the 1 kHz band will be 9 dB greater than the SPL in each of the eight 1 kHz bands which combine together to make up the full 8 kHz band (10 log 8 = 9).

2. Older age groups progressively lose audibility of higher frequencies. Therefore if a warning device depends largely on its higher frequencies, this will disadvantage elderly people.

For optimal audibility a frequency band from 0.5 kHz to 3.5 kHz is recommended.

Loudness Level

The following is a procedure to measure the dB(A) levels of an ICE and a warning device which are equally loud. It is not possible to measure (perceived) loudness using a sound level meter with a dB(A) scale. To measure loudness we can use either a phon meter or the following subjective procedure:

1. Select a range of typical ICE passenger cars to provide a loudness reference for QRTV warning devices.
2. In turn run the engine of each of these cars at RPMs typical of 20 kph.

3. Record the sound generated by each ICE and measure its SPL in dB(A) at a specified distance, e.g. 3 m.

4. Perform the following action in an open field:
   a. Replay the recorded ICE sound and the QRTV warning device
   b. Compare the loudness of the recorded ICE sounds and the warning device at a distance of 3 m.
   c. Adjust the warning device volume to the loudness of the ICE sounds.
   d. Measure the warning device’s SPL (dBA) at a distance of 3 m.

This gives the A-weighted SPLs of the ICE and the warning device when they are of equal loudness.

Alternatively, a warning device can be attached to an ICE vehicle and the two are listened to one after the other, adjusting the level of the warning device to give equal loudness with the ICE. This will not require recording. If suitable equipment is available a similar result can be achieved by direct measurement of the loudness level (phones) of each ICE vehicle and adjusting the warning device to the same phone level. At this level the A-weighted SPL of the warning device will be measured.

Note: Studies have shown that, for equal loudness level, the A-weighted level of a broad band sound is around 5dB lower than that of a sound containing a limited number of components over a restricted frequency range.

**Locatability**

For optimal locatability, a frequency band from below 0.5 kHz to above 4 kHz is recommended, as this band covers the main frequency regions which contribute to the locatability.

**Directivity**

The transformation of electric energy into acoustic energy presents certain limitations in terms of energy efficiency and the spatial characteristics of the radiated field. Normally this spatial characteristic of acoustic radiators is defined in terms of its directivity which defines the relative level of the sound pressure around the source at any given frequency.

The radiation characteristics of a typical acoustic source are shown in Figure 8. This figure shows the sound field in space, the directivity pattern and the 3D-directivity pattern versus frequency respectively.

At low frequencies (for values so that \(2\pi f a/c < 1\)), the disc radiates sound equally well in all directions. As shown in the second example in Figure 8, sound waves radiating the disc spread out evenly in all directions. This behaviour is primarily why the location of a subwoofer does not really matter; one can place it anywhere and still fill the room with sound.

At higher frequencies (so that \(2\pi f a/c > 1\)) the disc becomes directional. This means that the sound energy produced by the source becomes channelled into preferred directions and very little energy is radiated at other directions. In the last example the radiated sound is basically
contained within a cone of 55º from the centre of the axis. Also from the darkness of the contour shading (darker means higher pressure), one can see that the radiated sound field is strongest right in front of the disc and weakens as you move to other side.

As the frequency becomes even higher (so that $2\pi f a/c \gg 1$) the sound field radiated by the disc becomes even narrower and side lobes appear. Now the main lobe of radiated sound is limited to about 20º on either side of the central axis, and the pressure amplitude falls off rapidly as you move away from the central axis. Notice that the side lobes are much lower in amplitude than the main lobe (the darker the contour the higher the pressure - louder the sound). Also notice that the sound waves in the side lobes have the opposite phase as the sound wave in the main lobe.

The physical behaviour of acoustic radiating devices presented above shows that an important challenge in this project is to develop innovative acoustic sources that can concentrate and project the acoustic energy in a narrow beam so that the warning sound can be 'located' in the desired point in space which would correspond to an area around the VRU (vulnerable road user) heads. This technical challenge will present technical and physical problem and limitations that will have to be overcome. Multi-array sources or ultrasonic array sensors can be developed in order to provide this narrow beam performance. Physical orientation of the array could also add additional capabilities to the system in order to increase its space selectivity.

eVADER will face the challenge of designing an optimized driver and, especially, pedestrian warning signal spectrum and level with a suitable directivity that will maximize pedestrian selectivity in-close-to-accident situations with increasing urban noise annoyance.

Too much or too little directivity are not good for safety and environmental reasons respectively. If the sound is too narrowly focused, pedestrians to the side of a QRTV travel path will not receive the full warning signal. If the sound radiates equally in all directions, including to the rear, then a QRTV passing a pedestrian will mask the sound from a following QRTV.

Uniform radiation all around the vehicle is undesirable, for safety and environmental reasons. An SPL guideline reduction of 3 dB at +/- 45º and up to 10 dB at +/- 90º is suggested to provide audibility at a safe distance outside the edges of the vehicle’s wheel print. Additionally, the sound should fall off rapidly to the side and rear of the vehicle. This avoids masking the sound of a following vehicle.

For optimal directivity, a frequency band from below 1-KHz to above 3-KHz is recommended. As an example of a simple directivity pattern, the figure below shows an A-weighted directivity plot to the front of a vehicle. In practice, the higher frequencies are more directive than the lower frequencies and high frequencies are attenuated to the side of the vehicle.
Figure 7: Example of omnidirectional pattern with an almost spherical geometry
Figure 8: General directivity patterns for a loudspeaker at different frequencies
Attenuation
The wider the frequency band, the greater the attenuation with distance, as higher frequencies attenuate and scatter more readily. For optimal attenuation, a frequency band from below 1 kHz to above 5 kHz is recommended.

Acceptability
The characteristics of the warning device should be chosen to produce minimum deterioration of the soundscape. This implies a sound which presents its warning characteristic in an inoffensive manner.

Frequency Bandwidth Essentials
The frequency bands associated to the most important aspects defined for a warning signal are presented in the following table:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Frequency Band (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audibility</td>
<td>0.5 – 3.5</td>
</tr>
<tr>
<td>Locatability</td>
<td>0.5 – 4.0</td>
</tr>
<tr>
<td>Directivity</td>
<td>1.0 – 3.0</td>
</tr>
<tr>
<td>Attenuation</td>
<td>1.0 – 3.0</td>
</tr>
</tbody>
</table>

Comparison of the different requirements:

1. Audibility:
   a. Lower end of audible frequency range: Most elderly people retain lower frequency audibility (500 – 1K).
   b. Higher end of audible frequency range: Higher frequencies are progressively lost with increasing age and many elderly people will have lost frequencies above 2 kHz (matches the critical range defined in ISO 7731).
   c. Wide frequency range: Those with specific hearing-impaired frequency bands will still hear the unimpaired frequencies.

2. Locatability: The minimum/desirable frequency band width for locatability matches that for the above proposed for audibility.
   a. 0.5 – 1.5 kHz provides interaural phase differences - indicates angle from centre line
   b. Up to 3 kHz provides interaural SPL differences - indicates left or right
   c. 3 kHz and above contributes to HRTF (Head Related Transfer Function) - indicates front or rear

3. Maximum frequency preferably below 5 kHz because overall audibility will be limited for those, generally the elderly, with progressive hearing loss of higher frequencies.

4. Directivity: At any given distance:
   a. Maximum 3 dB(A) reduction 45° from centre line SPL
   b. Minimum 5 dB(A) maximum 10 dB(A) reduction 90° from centre line SPL
OEM Personalization

Tones
Tones are permitted but the level of a tone should not be greater than 5 dB above the level of the 1/3rd octave band adjacent to that within which it lies.

Sound familiarity
Recognition as engine sound. It is recommended that the sound contains qualities make it reminiscent of an ICE.

Other items
Technology is available for the warning device continuously to self-adjust its SPL to a predetermined variant from ambient SPL. This can be higher or lower than ambient SPL. The warning device should continuously self-adjust its SPL according to acceleration or deceleration and the vehicle speed. It is desired, particularly by the blind, that the warning device continues to sound when the vehicle is temporarily stopped and ready to move again, e.g. at traffic lights. In the case of a warning device containing a tone(s), the frequency(ies) could be varied, e.g. 500 up to 1000 Hz for 0 up to 20 kph. The environmental effect should be considered before selecting this option. Thus, fluctuation should be an important factor since sound without fluctuation is easy to be masked by background noise and also makes the sound more detectable. On the other hand, sound fluctuation can be associated with vehicles as conventional engine sound has fluctuation

3.4 Specific systems

3.4.1 Enhanced Vehicle Acoustics

Enhanced Vehicle Acoustics (EVA), a company based in Silicon Valley, California and founded by two Stanford students with the help of seed money from the National Federation of the Blind, developed an after market technology called “Vehicular Operations Sound Emitting Systems” (VOSES). The device makes hybrid electric vehicles sound more like conventional internal combustion engine cars when the vehicle goes into the silent electric mode (EV mode), but at a fraction of the sound level of most vehicles. At speeds higher than between 20 miles per hour (32 km/h) to 25 miles per hour (40 km/h) the sound system shuts off. The system also shuts off when the hybrid combustion engine kicks in.[19][20] VOSES uses miniature, all-weather audio speakers that are placed on the hybrid's wheel wells and emit specific sounds based on the direction the car is moving in order to minimize noise pollution and to maximize acoustic information for pedestrians. If the car is moving forward, the sounds are only projected in the forward direction; and if the car is turning left or right, the sound changes on the left or right appropriately.[19] The company argues that chirps, beeps and alarms are more distracting than useful, and that the best sounds for alerting pedestrians are carlike, such as "the soft purr of an engine or the slow roll of tires across pavement.”[8] One of the EVA's external sound systems was designed specifically for the Toyota Prius.[20]
3.4.2 ECTunes

ECTunes is developing a system that utilizes directional sound equipment to emit noise when and where it is needed. According to the company, its technology sends audible signals only in the direction of travel, thus allowing the vehicle to be heard by those who may be in the car’s path, without disturbing others with unwelcome noise. Energi Horsens, a Danish firm, has provided a significant investment to help ECTunes fully develop its technology (28). The ECTunes system, and most others so far disclosed, use a control box, with software, digital amplifiers and weather-friendly external speakers. ECTunes’ system connects to the car, and reads speed and acceleration, shutting down when the car reaches approximately 20 miles per hour (32 km/h), at which point the tires and wind are making noise of their own. The company is testing its sounds in a Citroën C1 electric car and a Mega Van, at the University of Warwick in the U.K (29).

3.4.3 Fisker Automotive

Figure 11: The Fisker Karma will incorporate an automatic warning sound generator.

Figure 12: The 2011 Chevrolet Volt includes a manually activated warning sound.

Fisker Automotive is in the last stages of developing a sound-generator to be incorporated in its Fisker Karma luxury plug-in hybrid electric vehicle, scheduled to begin sales in February
According to the carmaker, the sound is designed to both alert pedestrians and enhance the driver experience, and the warning noise will be emitted automatically. The Fisker Karma will emit a sound through a pair of external speakers embedded in the bumper. According to a company spokesman the sound is a mix between a "Formula One car and a starship" (21, 31,32).

The developing process took between nine months to a year, and three sound companies sent in synthesized WAV file samples that were evaluated by Fisker employees and executives. The prospective sounds were studied in an audio chamber to allow engineers to evaluate the sounds without other noise interfering. After testing the candidate sounds in different locations relative to the vehicle, Fisker will fine-tune the final sound with its own equipment (31,33).

3.4.4 Ford

The 2012 Ford Focus Electric will include warning sounds for pedestrians. Ford Motor Company developed four alternative sounds, and in June 2011 involved the electric car fans by asking them to pick their favourite from the four potential warning sounds through the Focus Electric Facebook page (34).

3.4.5 General Motors

General Motors' first commercially available plug-in hybrid electric vehicle, the Chevrolet Volt, introduced in December 2010, includes warning sounds for pedestrians (35, 36, 37). GM's system is called Pedestrian-Friendly Alert System and it is manually activated by the driver, but future generations probably will include an active system (38, 39, 40). The automaker conducted a test with a group of the visually challenged at Milford Proving Grounds in order to evaluate the audible warning systems on the Volt when a pedestrian is in the car's proximity. The system uses the car's horn to emit a series of warning chirps, like a low tone of a horn, enough to provide an alert but not to startle. According to GM engineers, the biggest challenge is "developing an active system that can distinguish a pedestrian from another vehicle"; otherwise, the sound will go off frequently, producing noise pollution instead (38,39).

3.4.6 Hyundai

Hyundai developed a warning noise for called the Virtual Engine Sound System (VESS). The system, which was introduced in September 2010 on its test fleet of BlueOn electric hatchbacks, provides synthetic audio feedback mimicking the sound of an idling internal combustion engine (41, 42).

The 2011 Hyundai Sonata Hybrid is the first mass production car manufactured by Hyundai to include the warning sound system. In 2010 the carmaker decided to have a button on the Sonata Hybrid's instrument panel to turn the VESS on and off, but after the enactment of the Pedestrian Safety Enhancement Act of 2010, signed into law by President Obama in early 2011, and learning that the U.S. National Highway Traffic Safety Administration would not allow such switches to avoid the noise device to be turned off, Hyundai decided not to install the button, and the first Sonata Hybrids destined for the U.S. market had to be altered to remove the switch (43).
3.4.7 Lotus Engineering

Lotus Engineering, a consultancy group of British sports carmaker Lotus Cars, partnered in 2009 with Harman Becker, a producer of audio systems, to develop and commercialize a synthetic automotive audio systems. Lotus has worked on a number of hybrid and electric vehicles and its engineers thought they would be safer if these vehicles made a noise while moving around the factory. Originally developed to cancel out intrusive noises inside a car, the noise canceling system was adapted so that it could also simulate engine sounds that change with speed and use of the throttle, providing audible "feedback" to drivers of vehicles with a silent engine. At the same time, and through the addition of external speakers, the sound system allows pedestrians to hear the noise too, but optionally there can be a different sound within the car from the one that is emitted for the outside. Lotus used a Toyota Prius to demonstrate the device but did not reveal if it intended to bring this technology to market.

Lotus' synthetic sound system was incorporated in the Lotus Evora 414E Hybrid, a concept plug-in hybrid unveiled at the 2010 Geneva Motor Show. The system, called HALOsonic Internal and External Electronic Sound Synthesis, is a suite of noise solutions that uses patented technologies from Lotus and Harman International. The audio system generates engine sounds inside the vehicle through the audio system. The system also generates the external sound through speakers mounted at the front and rear to provide a warning to increase pedestrian safety. The system comes with four driver-selectable engine sounds, two of which have been designed to have characteristics of a multi-cylinder conventional V6 and V12 engine.

3.4.8 Nissan

![Image of Nissan Leaf]

Figure 13: The 2011 Nissan Leaf includes different warning sounds for forward and reverse motion.

**Vehicle Sound for Pedestrians** or VSP is a Nissan-developed warning sound system in electric vehicles. The Nissan Leaf was the first car manufactured by Nissan to include VSP, and the electric car includes one sound for forward motion and another for reverse. VSP will also be used in the upcoming Nissan Fuga hybrid, due in 2011. The system developed makes a noise easy to hear for those outside to be aware of the vehicle approaching, but the warning sounds do not distract the car occupants inside. Nissan explained that during the development of the sound they studied behavioral research of the visually impaired and worked with cognitive and acoustic psychologists, including the National Federation of the Blind, the Detroit Institute of Ophthalmology, experts from the Vanderbilt University Medical Center and a Hollywood sound design studio.

Nissan's Vehicle Sound for Pedestrians is a sine-wave sound system that sweeps from 2.5 kHz at the high end to a low of 600 Hz, a range that is easily audible across age groups. Depending on the speed and whether the Leaf is accelerating or decelerating, the sound system will make sweeping, high-low sounds. For example, when the Leaf is started the sound will be louder, and when the car is in reverse, the system will generate an intermittent
sound. The sound system ceases operation when the Nissan Leaf reaches 30 kilometres per hour (19 mph) and engages again as the car slows to under 25 kilometres per hour (16 mph). The driver can turn off sounds temporarily through a switch inside the vehicle, but the system automatically resets to "On" at the next ignition cycle. The system is controlled through a computer and synthesizer in the dash panel, and the sound is delivered through a speaker in the front driver's side wheel well (20, 47, 49). Nissan said that there were six or seven finalist sounds, and that sound testing included driving cars emitting various sounds past testers standing on street corners, who indicated when they first heard the approaching car.[13]

The Leaf's electric warning sound had to be removed for cars delivered in the U.K., as the country's law mandates that any hazard warning sound must be capable of being disabled between 11:00 pm and 6:00 am, and the Leaf's audible warning system does not allow for such temporary deactivation (50).

3.4.9 RocketAudio Traffic

RocketAudio Traffic is developing a sound system based on modern synthesizer technology. It can simulate any petrol based motor sound that is pre-recorded and designed with its tools. The software is platform independent and is currently running on lightweight ARM based systems (dimension 70mmx70mmx15mm, power consumption 2 watts max) and PC for evaluation purposes. Its authentic motor sound, its flexibility in integration (CAN Bus / Sensors via ADC) and simple generation of new sound events are its main advantages. Currently it is tested on electric carts and scooters. Videos with sound examples are available on their website (51).

Since the system is fully programmable it can switch sounds, do starting and stopping sounds, fade out when reaching a certain speed, produce a softer motor sound for interiors and produce more sounds for special events like driver notification on closing the door for example. The goal of this flexibility is to assure compatibility with customer needs and future changes in legislation. RocketAudio Traffic GmBH is a German company which formed in 2011.

3.4.10 Toyota

![Toyota Prius](image)

**Figure 14: Since August 2010 in Japan a warning device for retrofitting the Toyota Prius is available.**

Toyota Motor Company teamed up with Fujitsu Ten to develop an automatic warning system for hybrids and electric vehicles to alert pedestrians when the car is propelled by its electric motor. The companies also studied the development of a system that would change the alarm's tune and volume with the assistance of obstacle detection radar (52, 53).
On August 2010 Toyota began sales of an on-board device designed to automatically emit a synthesized sound of an electric motor when the Prius is operating as an electric vehicle at speeds up to approximately 25 kilometres per hour (16 mph). The device will be available in Japan through authorized Toyota dealers and Toyota genuine parts & accessories distributors for retrofitting on the third-generation Prius at a price of ¥12,600 (~US$150) including the consumption tax. The alert sound rises and falls in pitch according to the vehicle's speed, thus helping indicate the vehicle's proximity and movement to nearby pedestrians. Toyota is planning to use other versions of the device for use in gasoline-electric hybrids, plug-in hybrids, electric vehicles as well as fuel-cell hybrid vehicles planned for mass production. The device meets the 2010 government regulations issued for hybrid and other near-silent vehicles.[1]

Toyota's Vehicle Proximity Notification System (VPN S) will be introduced in the United States in all 2012 model year Prius family vehicles, including the Prius v, Prius Plug-in Hybrid and the standard Prius. The system is being introduced to comply with the Pedestrian Safety Enhancement Act of 2010 (11, 54).

### 3.4.11 Other carmakers

Tesla Motors and Think Global, both manufactures of electric cars already in the market, are assessing this safety issue.[31] Ford Motor Company is developing a system for emitting external sounds to future hybrids and electrics, including its Focus BEV, scheduled for 2011, and a next-generation hybrid and plug-in hybrid vehicle planned for 2012. Nancy Gioia, Ford's Director for Global Electrification commented that "car companies should consider standardizing tones from future hybrids and electrics to avoid a cacophony of confusion on the streets (53)."

### 3.4.12 Criticism and controversy

After Nissan's new sounds were publicized, the U.S. National Federation of the Blind issued a statement saying that "while it was pleased that the alert existed, it was unhappy that the driver was able to turn it off."[13] The NFB approves the Nissan Leaf's forward motion sound, but it said the forward noise should also be used for reversing because the "intermittent sound is not as effective as a continuous sound" and that the car should emit warning sounds when it is idling, not only when it's moving slowly. Nevertheless, their main complaint is that they don't think the driver should be able to switch the sound off (20). Several anti-noise and electric car advocates have opposed the introduction of artificial sounds as warning for pedestrians, as they argue that the proposed system will only increase the noise in the environment. They also opposed U.S. pending legislation that would require generated warning sounds with no off switch for the driver (55).

Robert S. Wall Emerson of Western Michigan University has argued that several high-end gasoline-powered luxury cars are already quieter than hybrids, and according to his most recent studies, hybrid SUVs were noisier than many internal-combustion vehicles. He concludes that pedestrian safety is not a hybrid issue but rather "a quiet car issue"(16).
### 3.4.13 Market availability

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Powertrain type</th>
<th>Sound activation</th>
<th>Type of sound</th>
<th>Launch date</th>
<th>Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Nissan Leaf</td>
<td>All-electric</td>
<td>Automatic with manual turn off</td>
<td>Forward: continuous Reverse: intermittent</td>
<td>December 2010</td>
<td>Japan and the U.S.</td>
</tr>
<tr>
<td>2011 Fisker Karma</td>
<td>Plug-in hybrid</td>
<td>Automatic</td>
<td>Continuous</td>
<td>July 2011</td>
<td>U.S. and Europe</td>
</tr>
<tr>
<td>2011 Hyundai Sonata Hybrid</td>
<td>Hybrid electric</td>
<td>Automatic</td>
<td>n.a.</td>
<td>March 2011</td>
<td>U.S.</td>
</tr>
<tr>
<td>2012 Toyota Prius v</td>
<td>Hybrid electric</td>
<td>Automatic</td>
<td>Continuous</td>
<td>October 2011</td>
<td>U.S.</td>
</tr>
<tr>
<td>2012 Toyota Prius Plug-in Hybrid</td>
<td>Plug-in hybrid</td>
<td>Automatic</td>
<td>Continuous</td>
<td>2Q 2012</td>
<td>U.S.</td>
</tr>
<tr>
<td>2012 Toyota Prius</td>
<td>Hybrid electric</td>
<td>Automatic</td>
<td>Continuous</td>
<td>2012</td>
<td>U.S.</td>
</tr>
</tbody>
</table>
3.5 Examples of auditory warning systems from other fields

3.5.1 Public spaces and work areas

Warning and emergency signals for public spaces and work areas serve to enable the exposed persons to recognize the danger and take appropriate actions. Required actions can include e.g. maintaining awareness of dangerous situations or locations, removal of the danger if possible, rescue operations and evacuation of the dangerous area. Adequate acoustic warning signals will induce the appropriate reactions without creating startle responses or fright reactions. This is especially important and difficult in areas where hearing protection is necessary or even mandatory even in normal operation, like e.g. in machinery halls.

Regulations for acoustic warning signals going beyond the general requirements of section 2.3 can be found e.g. in the international standard ISO 7731 (56). There three types of danger signals and required reactions are distinguished:

- Auditory emergency evacuation signal: immediate evacuation of the danger zone required
- Auditory emergency signal: urgent action for rescue or protection required
- Auditory warning signal: preventative or preparatory action required

The auditory danger signals need to exceed the effective masked threshold depending on the ambient noise situation in the reception area in order to be clearly audible and incite the expected responses. Additionally they need to be distinctive, i.e. sufficiently different from similar signals in the reception area, and unambiguously recognizable as danger signals.

To ensure audibility, ISO 7731 requires a minimum sound pressure level of 65 dB(A) of the danger signals in the whole reception area. Moreover, they need to exceed the overall A-weighted sound pressure level of the ambient noise by at least 15 dB. Alternatively, the effective masked threshold must be exceeded by at least 10 dB in one octave band or by 13 dB in one third octave band, making narrow-band signals viable. However, the use of visual warning signals instead of purely acoustic ones is advised, if the ambient noise already exceeds 100 dB, and danger signals should never exceed 118 dB(A) in the reception area. The standard also requires a periodic re-evaluation of the effectiveness of the signals.

In the design of the warning signals overall sound pressure level, spectral and temporal characteristics will be used. For the frequency content, two dominant components between 500 and 1500 kHz are recommended, which should differ as much as possible from the frequency characteristics of the ambient noise. Concerning the temporal characteristics, pulsating signals with repetition frequencies between 0.5 and 4 Hz are preferable, with lower frequencies to be used in areas with high reverberation times. The duration of the warning signal should coincide with the occurrence or possibility of the actual danger to avoid false alarms.

Examples for suitable choices are given in ISO 7781 for different types of machinery. For an approaching shuttle conveyor an intermittent signal of 84 dB(A) with 0.5 Hz repetition frequency and peaks at 1 and 2 kHz are chosen in the presence of constant fan noise. A similar situation is that of an approaching crane, where a high-frequency bell signal at 90 dB(A) with low repetition rate is chosen to distinguish it from traffic noise. Quite a different
situation is presented in the case of a rolling mill where there is already a very high ambient broadband noise of 80 dB(A) and the indication of lacking oil in the mill needs a narrow-band continuous horn signal at 1000 Hz and 100 dB(A) to be audible.

In general the warning and danger signals used in public spaces or work areas require relatively high sound pressure levels, but benefit from the situation that the reception area is usually well defined and the background noise sources and levels are known, which makes an adapted design of the warning signals possible. Warning signals emitted from a moving source like a car which is traversing potentially quite different reception areas do not have this advantage. On the other hand, the objective of ISO 7781 is to make the warning signals clearly audible above all other possible signals, to clearly indicate the danger. This is more comparably to the function of a horn on a car as prescribed in UNECE Regulation 28 (57). If the objective is to make an electric car just as audible as one with an internal combustion engine, the overall levels can be lower, while the other requirements will still be relevant.

3.5.2 Railway warning signals

Warning signals for trains are typically designed to indicate the approach of a train to the railway crossing of a road or a similar location where the crossing of the tracks by pedestrians or other vehicle is to be expected. Nowadays railway crossings often have additional warning and protection devices like traffic lights, bells, and barriers or gates, however, a significant portion of the low-level roads have ungated railway crossings. In such cases the train is required to emit a warning signal when approaching the crossing well in advance of its actual arrival.

The performance of train horns is regulated in UIC 644 (58), which determines the form of the signal as two single tones at the frequencies of 370 +/- 10 Hz and 660 +/- 15 Hz. The overall sound pressure level at a position in front of the horn along its symmetry axis at a distance of 5 m should be between 120 and 125 dB(A). The minimum distance from the railway crossing where the train driver needs to start signalling is determined by the train speed and the local conditions and is regulation in national laws and standards.

![Figure 15: Railway crossing relying on the train warning signal](image)

However, due to the effects of sound diffraction, absorption and shielding along the propagation path it is quite difficult to ensure audibility for all vehicle drivers and pedestrians, in addition to masking sounds from the surroundings. Especially for modern cars with very good sound insulation, auxiliary devices, air conditioning and radio, the chances to hear the train signals with closed car windows can be substantially diminished (50).
With respect to eVader, the conclusion can be drawn that for the reliable warning of other car drivers even very high noise levels may not be sufficient. Therefore a combination of interior and exterior warning systems together with environmental perception systems may be necessary to ensure sufficient warning.
4 Environmental perception systems

The past few years have seen increased awareness of the plight of vulnerable road users at the national and EU level. In 2003, the EU passed Phase 1 of Directive 2003/102/E on pedestrian protection, focusing on passive safety, i.e. meaning to reduce injury levels upon impact, by specifying various maximum impact criteria (e.g. head, leg). More recently, June 2008, the EU Parliament approved the Phase 2 draft legislation, which specifies a combination of passive and active safety technologies. In particular, Phase 2 requires new passenger cars to be fitted with Brake Assist Systems (BAS). Pedestrian protection is meanwhile also a major theme for consumer rating groups like Euro NCAP.

The table below presents an overview of the fatalities Vs. user types. Of all traffic fatalities, the proportion of pedestrian fatalities is about 17 to 18%. However, differences between countries are large. It varies from 10% in Belgium and the Netherlands to 35% in Poland (60).

The deployment of EV and HEV has no reason to change these numbers. In fact the due to the EV and HEV specificities there is a risk to increase them. Then the technological solutions that are currently studied and begin to be implemented within conventional vehicles can be easily foreseen for EV and HEV.

Figure 16: Road accidents statistics in Europe (Sources CARE, April 2007)

Within passive and active safety technologies the sensor system is an essential part of the environmental perception systems. The sensor must be capable of distinguishing pedestrian or other vulnerable users from other objects within complex environments and also assessing the relative velocity of the pedestrian.

The sensor types can be broadly categorized into active and passive sensors. Passive sensors depend only on radiation emitted naturally by the human body. For example, in visible spectrum (350 nm to 750 nm up to 850 nm for NIR), or infrared (heat) and millimetre wave (between 7 to 14 µm for non-cooled FIR cameras; between microwave and IR on the frequency spectrum). However, this radiation may be affected by time of day, weather conditions and location. Furthermore, human infrared emission is shielded to some extent by clothing and may difficult to distinguish in hot ambient situations. Human skin is a strong emitter in the millimetre wave frequency and this emission has the advantage of being unaffected by clothing. However, the technology for millimetre wave detection is not currently mature as for infrared detection.

Additionally passive sensors also involve impact sensors in the front section of the vehicles and vehicle structures (e.g. bonnet, bumper) that expand during collision in order to minimize impact of the pedestrian leg or head hitting the vehicle. For example, Mercedes-Benz introduced the active bonnet as standard for the new E-Class(2009). The system includes three impact sensors in the front section as well as special bonnet hinges pre-tensioned by powerful springs. Upon impact with a pedestrian, the rear section of the bonnet is pushed upwards by 50 millimetres in a fraction of a second, thus enlarging the deformation zone. The system is reversible and can be reset manually by the driver. Although important, passive pedestrian safety measures are constrained by the laws of physics in terms of ability to reduce collision energy and thus injury level. Moreover, passive measures cannot account for injuries sustained in the secondary impact of the pedestrian hitting the road.
Figure 17: Daimler active bonnet © Daimler

For active technologies, a signal is emitted into the surroundings and reflected off a target, for example laser, radar, active Infrared. These have the advantage of providing accurate range information. However they may have health and safety implications to be addressed, especially in case of laser and microwave emissions. Considerations must also be given to the problem of interference if the number of such units on the road increases. Such systems are particularly valuable when the driver is distracted or visibility is poor. Nevertheless, Pedestrian detection with such technologies is a difficult problem for a number of reasons. The objects of interest appear in highly cluttered backgrounds and have a wide range of appearances, due to body size and pose, clothing and outdoor environmental conditions. Of course, passive and active technologies can also be combined to provide better accuracy and robustness for pedestrian detection. Several technologies have been foreseen to perform pedestrian detection. The most typical are introduced hereafter.

<table>
<thead>
<tr>
<th>Active</th>
<th>Passive</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADAR</td>
<td>Monoscopic camera</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Stereoscopic camera</td>
</tr>
<tr>
<td>Time of Flight</td>
<td>Cameras for Night vision: FIR</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>LASER scanner</td>
</tr>
<tr>
<td>Active NIR</td>
<td></td>
</tr>
</tbody>
</table>

Figure 18: technologies for Pedestrian/obstacle detection

In parallel to laboratories research activities and industrial technological development, many researches on pedestrian protection have been conducted in several EU projects like for example: PROTECTOR (2000-2003), SAVE-U (2002-2005), WATCH-OVER (2005-2008), HAVE-IT (2008-2011), the German AKTIV-SFR (2006-2010) project, the French projects DO30 and LOVE.
4.1 Camera Based technologies

Pedestrian detection has attracted an extensive amount of interest from the computer vision community. Many techniques have been proposed in terms of features, models and general architectures. There are four major challenges with pedestrian detection that require special technical development:

- **Figure size:** Distant pedestrians appear very small in the image. For example, with VGA resolution and 36° vertical FOV (field of vision), the figure of a child 1 m tall at 30 meters is only 25 pixels long. The lateral figure dimension is even smaller.
- **Fast dynamics:** The detection latency must be small, and decisions must be obtained within a few frames.
- **Heavy clutter:** Pedestrian detection is typically taking place at urban scenes with a lot of background texture.
- **Articulation:** Pedestrians are non-rigid objects, spanning high variability in appearance and cause tracking difficulties.

The following overview will only focus on the most representative systems currently in production or nearby production.

4.2 Monoscopic cameras

4.2.1 Mobileye pedestrian collision warning (PCW)

Mobileye’s is currently the only mono-camera automotive pedestrian detection system in production. PCW runs on EyeQ2 based systems. Mobileye’s approach to pedestrian detection lies in using advanced pattern recognition and classifiers with image processing and optic flow analysis. Both static and moving pedestrians can be detected to a range of around 30m using VGA resolution imagers. As higher resolution imagers become available, range will scale with imager resolution, making detection ranges of up to 60m feasible.

Mobileye’s first production for Pedestrian detection systems was in 2009 on for industrial powered vehicles where 8 EyeQ2 based monocular cameras provide a 360deg all-round Pedestrian Detection system to a range of 15 m and will warn the vehicle operator via Audio/Visual warnings of pedestrian in the vehicles path. In late 2009 Mobileye added the Pedestrian detection warning functions to the next generation of consumer product line systems – called C2-270. In mid-2010 Mobileye launched a world’s first application of full emergency braking for Collision Mitigation with pedestrians on the Volvo S60 and V60 vehicles. In this system, Vision is the key technology and lead sensor for pedestrian detection. Today’s system is operation in Daytime only (based on Mobileye’s core day-night decision mechanism), but development is underway to extend this to dusk environments, and moving forward and based on NIR filtering on the imager, Mobileye is developing nigh time pedestrian detection for 2014 SOP (61).
4.3 Stereoscopic cameras

4.3.1 DAIMLER

The pedestrian detection based on stereoscopic vision has attracted since a couple of years a strong focus from Daimler that has developed a full concept. The detection component consists of a cascade of module, each utilizing different visual criteria to successively focus on relevant image regions, carefully balancing robustness and efficiency considerations, this includes the generation of the Depth based Region of Interest (ROI), a shape based localization, a texture based pattern classification and a dense stereo verification. Then, the tracking component aggregates per-frame detections to trajectories by a tracking module. Finally, the risk assessment and warning/control component evaluates the probability of collision. Pedestrians are detected in a range of 5-25 m and up to 4 m lateral, on each side of vehicle. It does so at processing rates of 7-15 Hz, allowing vehicle speeds up to 50 km/h. Late 2012 beginning 2013 a first generation of Mercedes vehicles will be commercialized.

Figure 20: Operational field of view for Daimler stereoscopic vision

4.3.2 Continental

Continental has also invested a lot in the development of stereoscopic vision technologies for pedestrian detection. The principles of this concept and characteristics are very similar to those of Daimler. It combines mono vision approaches with distance information issued from the stereoscopic vision and makes also use of six dimensional information (distance, flow).
Figure 21: Continental stereoscopic vision system

Continental aims to commercialize this product late 2012, beginning 2013.

4.3.3 BLAXTAIR from ARCURE

ARCURE company is commercializing BLAXTAIR that is a ready to use pedestrian detection system for all environments dedicated to industrial vehicles. **BLAXTAIR is a warning system that allows mitigating the collisions between industrial vehicles and pedestrians.** In case of a pedestrian is located in a predetermined area (danger area) around the vehicle, the driver is warned by an audio or visual alarm. Several levels of alarms can be foreseen depending on the risk level the vehicle type and the safety policy of the owner. The stereoscopic vision algorithms have been provided by the French research organization CEA LIST.

Blaxtair allows detection of obstacles higher than 1.4 m in a range from up to 20 m around the vehicle depending on the lenses focal. It allows obstacle identification in less than 300ms. This product has been specially designed to be used in severe environments (63).

Figure 22: BLAXTAIR stereovision from ARCURE
4.4 Time of flight sensors

New developments are currently on going with new generation of Time Of Flight cameras (TOF) called PMD (Photonic Mixer Device). TOF cameras measure the time needed for light to travels from the camera to the object and back again. Typically, the phase shift between sent and received modulated signal is measured and converted into a range value. TOF cameras provide 3-D range images that not only enables fast and accurate object segmentation and but also provides useful information such as distances to the pedestrians. TOF images needs the design of specific algorithms for the information extraction and classifications (e.g. Support Vector Machine-SVM…) (64)

4.5 Cameras for night vision

Accident statistics in OCDE countries demonstrate that nocturnal driving twice the risk of an accident as compared to day driving. According to estimates, approx. 560,000 people are injured in the dark in Europe and some 23,000 are killed. The darkly dressed jogger in the half light, the insufficiently lit cyclist at night, the increased risk to pedestrians poses one of the biggest safety problems in the dark.

There are today two different technologies on the market for night vision systems:
- Far Infrared (FIR) also called Passive Infrared
- Near Infrared (NIR) also called Active Infrared.

The NIR system beams infrared radiation into the area in front of the vehicle. The infrared beamers are often incorporated in the headlights. The infrared radiation is reflected by objects, the road and human beings and converted to an image. FIR technology registers the differences in heat, or infrared radiation, emitted by objects and human beings. It does not need a separate light source from the vehicle.

Many experiments proved that FIR could detect pedestrians and obstacles sooner than NIR that is highly dependent on the power of the infrared beamers. FIR systems are not affected by light and there is no risk that the driver is blinded by oncoming headlights or other light sources. Furthermore FIR systems only provide comprehensive image about heat difference while NIR gives a complete image of the road needing additional processing to extract pertinent information. Nevertheless, despite their high performance potentialities, FIR technologies remain still expensive for automotive application.

4.5.1 FLIR thermal camera: PathFindIR
FIR technology from FLIR is based on the observation of heat or thermal radiation. Any object that has a temperature above absolute zero (0 degrees Kelvin) emits radiation in the infrared region. The warmer the object, the more infrared radiation it emits. Infrared energy coming from an object is focused by the FIR camera optics onto an infrared detector. The detector sends the information to sensor electronics that translates the data into an image that can be viewed on any standard LCD. Based on the temperature differences of objects, a thermal imaging camera can produce a comprehensive image on which the smallest of temperature differences can be seen. Contrary to other technologies, such as e.g. light amplification that needs at least small amounts of light to generate an image, thermal imaging needs no light at all.

Traditionally FIR technologies have been applied for military applications and vehicles allowing them to see without being seen. Other applications are foreseen for civil vehicles like emergency vehicles, truck and buses as well as metros and trains. The PathFindir is a not cooled micro bolometer technology with 320x240 pixels with a large field of View of about 36°. The detection range of the system is about 300m (65).

![FLIR thermal camera](image)

**Figure 24: FLIR thermal camera**

4.5.2 BMW FIR night vision

The core of the "BMW Night Vision system" is a FLIR Systems thermal imaging camera. The aim of this system is to detect living objects, such as pedestrians and animals, which are not illuminated in total darkness.

At speeds below 80 km/h, the wide horizontal field of view (36°) of the thermal imaging camera assures that not only the road can be seen but also the areas at the side of the road and surroundings. (bicyclists, pedestrians, children, wild animals, ...) At a high speed the field of view is automatically narrowed to 24°. At the same time, the field of view follows the turning of the road up to 6° left or right. This so called panning movement is controlled by the parameter “steering of the wheels”. A digital zoom can be activated which displays objects at further distance in a 1.5:1 enlargement. The 320 x 240 pixels image is directly displayed on the centrally placed on-board monitor in the dashboard. It is installed in conjunction with the navigation system.

BMW started marketing its Night Vision systems as an option on BMW 7-series models by the end of 2005. More recently, the Night Vision system can be ordered as an option on our 7-, 6- and 5-series models.

4.6 Laser technologies

4.6.1 Jaguar

Jaguar Cars is exploring the use of Micro-Epsilon displacement sensor, which uses a laser-optical sensor that operates using the triangulation measurement principle to determine displacement, with post-test differentiation analysis to determine speed (65).
4.7 Data fusion approaches

Several companies have foreseen the possibility to fuse information from different sensing device to detect pedestrian. Most of them include an association between camera and radar technologies that allows taking profit of the advantages of both technologies: Distance, localization and depth measurement from the radar and recognition and classification from the camera.

4.7.1 TRW forward looking

TRW's forward-looking pedestrian detection system fuses sensor information from a scalable video camera with its 24 GHz radar data, in combination with electronic stability control (ESC), to automatically brake a vehicle and help reduce the severity of a potential pedestrian impact. If a pedestrian is detected in front of the vehicle by the camera and confirmed by the radar, risk assessment algorithms are employed to determine the probability of a collision. The scalable camera provides the capability to detect and track pedestrians at distances of over 40 m, even in challenging urban scenarios – such as multiple pedestrians in crowded cross walks or pedestrians using umbrellas in the rain. By adding a radar device via sensor fusion, the enhanced performance allows full braking of the vehicle at higher speeds."

TRW's forward-looking pedestrian collision mitigation system is scheduled for production in 2014 with full braking functionality (67).

4.7.2 Volvo pedestrian detection

The Volvo pedestrian detection system uses wide-angle radar that detects objects and monitors their speed and distance from the car, and a camera fitted near the rear view mirror. Using this information it is possible to identify the objects and determines if they are on a collision path. At speeds below 35 km/h a collision is prevented, while at higher speeds it may not be possible to avoid a collision but the impact and subsequent injuries are reduced. The Collision Warning with Full Auto Brake and Pedestrian Detection system fitted in the 2011 models XC60, S60 and V60.
4.7.3 Bosch pedestrian protection based on combined sensor systems

Bosch roadmap of Electronic Pedestrian Protection (EPP) provides three sensor system generations for pedestrian protection:
- a contact sensor system (EPP1),
- a system combining contact sensors and ultrasonic sensors (EPP2),
- a system combining ultrasonic sensors and video sensors (EPP3).

EPP2 uses synergy effects with ultrasonic systems (e.g. USS4 from parking aid) that are well-established on the market, in order to enhance the classification performance. USS4 has a detection range of about 0.25 m to 3 m (related to a 7 cm-tube). In the EPP2 system, the ultrasonic sensor subsystem generates a feature vector which carries ultrasonic as well as geometric properties. This feature vector is combined with that of the contact sensor subsystem, which gives information about the mechanical object properties “stiffness” and “impact energy” of the object. The combination of the feature vectors leads to an improved and robust classification, allowing the use of an irreversible actuator.

In the EPP3 system, the video subsystem (512x256 pixels) accomplishes pedestrian recognition in a mid-range ahead of the car. Camera range is up to 25 m ahead of the bumper at aperture angles of 50° horizontally and 35° vertically. Video-based pedestrian recognition is achieved by contour analysis, while tracking of pedestrians is carried out by applying an extended Kalman filter to active-shape representations of pedestrian contours.
Any time the video subsystem predicts a pedestrian to enter the ultrasonic field-of-view, information concerning direction of movement and velocity of the respective pedestrian plus an estimate of the time-to-impact is transferred from the video subsystem to the ultrasonic subsystem. The main task of the ultrasonic subsystem is to verify or reject the hypothesis of pedestrian presence delivered by the video Subsystem.

Test performed by Bosch demonstrated that in comparison to EPP2, EPP3 provides a significant gain with respect to the forewarn time. According to our experiments, for a closing velocity of 30 kph, a final decision concerning the triggering of an actuator can be taken 150-200ms (i.e., 1-2 m) before the actual beginning of a collision (68).

4.7.4 Combined Capacitive and Ultrasonic Distance Measurement for Automotive Applications

Graz university of technology has worked on a concept based on fusing information from capacitive and ultrasonic sensors for pedestrian pre-crash distance measurement in automotive applications. Although ultrasonic sensors are a well-accepted technology for distance sensing applications, they reveal drawbacks in the immediate vicinity of a vehicle. Capacitive sensors are suited for distance measurements from 0 to 0.3 m and may also provide information about the approaching object itself. The measurement range of the proposed fusion concept reaches up to 2 m whereby blind spots are avoided and means for object classification are provided.

4.7.5 Volvo CISS

Volvo has developed a vehicle safety system that could reduce the number of cyclists killed or injured by lorries on busy city streets. The Cooperative Intersection Safety System (CISS) development is part of the EU-funded Intersafe 2 project. The system uses laser scanners and ultrasound sensors positioned at the front and on the passenger side of the truck to monitor a driver’s blind spot. This information is processed using on-board computers, which output a bird’s-eye view of the lorry and its immediate surroundings on a TV monitor inside the cabin. The CISS system can also reduce the chances of drivers failing to notice pedestrians at a crossing. A radio receiver fitted on the roof of the truck communicates wirelessly with nearby traffic lights to monitor whether the lights are red or green, or whether someone has pressed the pedestrian crossing button. If the system determines a cyclist or pedestrian is at risk, warning lights or sound are activated to warn the driver of a possible collision. At this stage Intersafe 2 is merely a research and development project, and that there are currently no plans to introduce CISS in the real world (69).

4.8 Sensor networking

The Department of Computer Science in Trinity College, Dublin, (TCD) is proposing a technique based on a large scale wireless sensor network of “cat’s eyes” augmented with cheap embedded processing and communication capabilities. In this pedestrian detection system, reflective armbands or night vision jackets worn by pedestrians are equipped with communication capabilities that send radio signals periodically. These beacons are received by the cat’s eyes placed along the road and can be used to infer, thanks to the strength of the signals, the presence and approximate position of pedestrians. This information is forwarded from cat’s eye to cat’s eye allowing vehicles to be informed about the pedestrians’ presence beyond their drivers’ line of sight. The approach of requiring pedestrians to carry tiny, self-contained devices with radios seems reasonable to Trinity College researchers, as wearable computing moves from research laboratories to the real world. For instance, digital avalanche transceivers are today integrated into apparel, helmets, protection gear or boots,
### 4.9 Requirement comparison

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Note: most of the commercialized systems propose a typical maximum operating speed between 35 and 50 km/h to carry out accident mitigation.
5 Conclusions

In this document the current state of the art concerning interior warning systems, exterior warning systems and environmental perception systems has been reviewed. In the eVADER project a link between these three systems will be provided by the algorithms that determine the necessary actions based on the evaluation of the current situation. The overall objective is to achieve sufficient perception of the electric vehicle by pedestrians and awareness of the driver for the use of acoustic signaling in potentially hazardous situations.

For the use of Advanced Driver Assistance Systems (ADAS), which represent highly developed interior warning systems designed to help drivers react to complex situations and risks. Ideally they provide clear information about the diagnosed risk and about possible and recommendable actions. Interior warning systems can use the visual, acoustic and haptic channels to transmit information. The combination of more than one channel into multimodal warnings and the inclusion of spatial information make the warning more robust and elicit quick and reliable reactions. Haptic stimuli have been determined to lead to very low reaction times. Acoustic warning signals need to fulfil the requirements of audibility, distinctiveness and unambiguousness. Sounds which include frequency modulation over a wide bandwidth from low to high frequency are most appropriate as warning signals, because they are perceived as dangerous and unpleasant and avoid masking more easily.

Exterior vehicle warning signals are designed to alert pedestrians to the approach of an electric drive vehicle in all-electric mode. Guidelines and legislation for such signals have been issued in Japan and in the U.S. Car manufacturers like Nissan, Toyota or Chevrolet have responded by integrating manually or automatically activated warning sounds into their electric drive models. The UNECE informal Group on Quiet Road Transport Vehicles has also issued requirements for such a warning signal pertaining to its audibility, locatability and directivity. These specify a signal with sufficient loudness in the frequencies from 0.5 kHz to 4 kHz with high forward-facing intensity lobe of approximately 45° width. While the sound should be recognizable as an engine sound, a certain degree of OEM personalization may be possible. The challenge for practical implementation is to integrate emitters meeting the requirements into the car while avoiding disruption of other systems and functions. Realizations of specific systems are discussed in section 3.4. Principles for auditory warning systems for public spaces, work areas and railway crossings and their implications for exterior car warning systems are discussed in section 3.5.

Environmental perception systems are designed to enable the automatic detection of pedestrians and warning of the driver in hazardous situations. The challenge lies in distinguishing pedestrians from other objects and assessing their velocity relative to the car. Passive sensors use infrared radiation emitted from human bodies, while active sensors emit laser, radar, microwave or infrared signals and detect the reflected radiation. Camera-based systems rely on computer vision technology for image analysis. Challenges are the smallness and variability of the human images, the multi-textured urban surroundings and the required small detection latency. Groups of systems are monoscopic cameras, stereoscopic cameras, time-of-flight systems, cameras for night vision or laser triangulation. Additionally data fusion techniques allow the combination of information from more than one sensor and taking advantage of their individual benefits.

To sum up, the exterior and interior warning systems as well as environmental perception systems constitute fields of on-going development of advanced systems. In all three fields systems are available that will be accessible to the eVADER consortium, which is necessary to achieve the eVADER objectives.
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