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PROJECT FINAL REPORT

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0. Executive Summary

The “Advanced Radar TRAcking and Classification for enhanced road safety” (ARTRAC) research project contributed to the Road Safety Programme 2011-2020 concerning improved safety for vulnerable road users (VRU). The main objective was to develop a novel 24 GHz radar sensor to protect VRUs in general and reduce the number of fatalities in particular.

The European commission described the ambitious goal in 2001 to reduce the number of fatalities by 50% in a ten years time frame. This requirement has not completely met so far, however a significant progress could be observed when the number of fatalities has been reduced by 25% in the last 10 years due to several technical assistance procedures and techniques. For the period from 2011 to 2020 again the goal is to reduce the number of fatalities on European roads by 50% [1]. The technical challenge of ARTRAC was to develop a 24 GHz radar sensor product in high volume series cars, as they are already applied in high-end limousines. Current sensor systems (cameras and radar sensors) show already excellent performance in target detection for driver assistance and comfort system functionality. However, the new ARTRAC radar sensor has also a target recognition feature integrated. This functionality distinguishes between radar echo signals from pedestrians, bicyclists, vehicles and static objects and is able to classify these different objects. Thereby as a reaction upon a critical situation an extended functionality like automatic deceleration, steering recommendation and driver warning is performed. The system developed consists of a 24 GHz radar sensor, a risk assessment and a vehicle control procedure. This safety system has a high potential to be launched because the majority of all components belong already to standard equipment in series cars.

There are a number of systems to detect pedestrians in the market. However, these combine radar and optical sensors and thus come with a high cost and therefore are available in middle class to high-end cars only. At the end of the project, the ARTRAC system was the first to use radar only allowing implementation also in compact cars. The demonstration vehicles used were a Volkswagen GTI and a Fiat 500L.

The ultimate highlight of the project was the Final Event held at the proving ground of Volkswagen in Ehra near Wolfsburg. About 50 persons, many of whom were from the production sector in addition to research oriented participant were presented with an overview of the work in the project and subsequently had the chance to take a test ride on the two demonstration cars. A video of the event and the test rides is available on the project web site.

1. The ARTRAC Project Context and Objectives

The European Union launched a programme in 2001, “Halving the number of road accident victims in the European Union by 2010: A shared responsibility”. Despite numerous safety initiatives and activities, it is clear that this ambitious target is still far from being met. There are a number of reasons for that. One of them is that the deployment of Intelligent Vehicle Safety Systems (IVSS) has not been as fast was anticipated in the 1990s. This, in turn, is due to a number of factors. Besides user awareness and outreach issues, a major problem has been the performance of the Advanced Driver Assistance Systems (ADAS) in all driving situations and the high cost of the applications. When drivers had a possibility to try out different ADAS, they have almost exclusively approved of them. However, they were willing to invest only modest amounts of money in advanced safety systems.

The work towards realising the ARTRAC vision is a logical continuation of activities from the late 1980s such as Prometheus and the DRIVE I project (Framework Programme 2), where incident detection based on environment perception and information systems for transport & traffic, guidance and cooperation between the vehicles were ranked among the core R&D areas in the years to come.

Today, safety technologies such as ESC (Electronic Stability Control) have shown outstanding capabilities for supporting the driver in hazardous situations. Despite their effectiveness, currently available lateral and longitudinal control systems are typically implemented as independent functions. This results in multiple expensive sensors and unnecessary redundancy, limiting their scope to premium-class vehicles. Vehicle safety technology is not democratic today.

The large Integrated Project PReVENT by major European safety technology developers recently showed the feasibility of a concept called the “electronic safety zone” surrounding a vehicle, which has considerable potential for enhanced road safety. Here again, the need for further developments was in improving the performance in all scenarios, integrating the different functions, and providing commercially feasible solutions. In this context, in addition to further enhancing ADAS performance and reducing the number of sensors used, ARTRAC needs to address the issue of making safety systems affordable and accessible to all drivers.

Traffic fatality risk has been significantly reduced in recent years for those inside vehicles through the use of initially *passive* measures such as seat belts, stiff passenger cell, and more recently *active safety* systems that incorporate sensors such as airbags for protection and anti-lock braking systems (ABS) and electronic stability control (ESC). Important to this development has been the development of mass production low-cost sensors making such safety systems affordable in the mass market vehicle range.

Much of the above has also improved safety of vulnerable road users (VRUs), but it is recognised that more can be done. The attention of vehicle manufacturers and regulatory authorities is now much more focused on the protection of road users outside the vehicle, particularly in urban scenarios where all traveller groups interact. This is turn builds on initiatives such as the so-called *two phases* of pedestrian safety in the European Union with the goal to halve the number of pedestrian fatalities from what they were in 2001 by 2010.

Research in the field of pedestrian protection has been undertaken for more than two decades. It is now being driven by parallel regulatory initiatives by the European Union and also globally: in 2002 pedestrian protection was introduced in the compendium of the UN regulatory forum of UN-WP29 (Working Party 29 of the United Nations). So far approaches have been to engineer those parts of the car that come into contact with a pedestrian in such a way as to minimise impact e.g. through specially adapted bonnets and bumpers. Other passive means include use of daytime running lamps to improve visibility. But in both cases it is the driver or the pedestrian respectively who has to take action. Sensing technologies, however, provide a means for automated collision avoidance. The challenge is to provide a reliable means of detection coupled with a fast reaction time for the vehicle.

Although there continues to be much research in this area, and especially on materials and the engineering of the vehicle body, this passive safety system approach is really not the ultimate solution: the vehicle should be prevented from hitting the pedestrian or cyclist in the first place. The goal of ARTRAC is to achieve a breakthrough in deployment of Intelligent Vehicles Safety Systems (IVSS) that will provide the function of *collision avoidance as well as collision mitigation.*

To achieve IVSS that will get market acceptance means in practice providing an extremely *reliable detection system*, *a link to actuation* of the vehicle to provide the appropriate response in a form that is *affordable*. Regulation can of course make safety features mandatory, but this is a slow process. If the aspirations of the European policies towards improving the road safety of all users are to be met quickly, then IVSS which can be easily integrated into all types of vehicles, perhaps even those already on the road, offers the best way forward.

The key element to achieve an Intelligent Vehicle Safety System which acts as a driver assistant to protect vulnerable road users is the obstacle detection system. The choice of technology and approach needs to take into account the requirements for achieving the low cost needed for mass market penetration of all vehicle classes, small size and robustness.

The consortium will develop a totally new safety system for the protection of vulnerable road users by means of advanced environment perception technology and active intervention by vehicle braking and steering. Decision strategies for active safety and driver-vehicle-interaction will be developed. The objective is significantly to improve current ADAS, and it requires major breakthroughs in system intelligence and decision making. In particular, three areas will be addressed by the project:

- New techniques for the dynamic prediction of a safe trajectory ahead.
- Decision strategies able to balance human and system interventions, keeping the driver in the control loop as far as possible.
- Advanced actuation system combining both emergency steering and braking.

To enable a novel VRU-safety system, a more advanced environment perception technology is needed. For this purpose, the consortium will also develop a novel 24 GHz radar sensor including a new transmit/receive antenna and multichannel receiver that helps to open up the Advanced Driver Assistance System market and broadens the range of possible automotive applications by achieving the low cost needed for mass market penetration of all vehicle classes.

Currently two main frequency bands are relevant for automotive radars, 24 GHz and 77 GHz. Radars in both bands are available in serial vehicles. The 24 GHz band is regulated for ISM (industrial, scientific and medical) purposes and has a band width of 250 MHz (frequency spectrum from 24.000 GHz up to 24.250 GHz). The radars operating in the 24 GHz band are highly attractive because of their low-cost-perspective. Two different technologies are currently considered and have already been introduced into commercial cars, namely 24 GHz narrow band (NB) solutions and 24 GHz ultra-wide band (UWB) systems. The NB technology fits exactly into the regulations of the ISM band; corresponding European Norms are EN 300 440 and EN 302 858. This is one of the reasons why the consortium is of the opinion that this technology will have many advantages and potential for future applications.

To reach the required safety function, the following six major scientific and technical objectives are defined:

1. *Develop a generic detection system for vulnerable road users and vehicles.* The novel system must be capable of detecting and classifying different types of obstacles and road users: this road environment perception system detects pedestrians, cyclists, and other vulnerable road users as well as vehicles. The system needs to have an ability to:
    - Measure target position and radial velocity.
    - Measure target 2d velocity vector in typical urban traffic conditions.
    - Cover a sufficiently wide observation area so that all relevant objects can be detected.
    - Target resolution (separation) capability in range, velocity and azimuth angle.
    - Distinguish between objects which can be driven over (because of their small height) and really relevant objects.

   To achieve these, the core of the development will be the design of a generic multipurpose radar sensor system with broad 60° coverage in azimuth direction.

2. *The system also needs to have a capability to monitor road surface conditions*. The possibility of detecting low-friction road sections caused by water, ice or snow on asphalt can be used for warning or adapting the vehicle's electronic control systems such as ESC and Collision Avoidance Systems (CAS) for changed friction conditions. The unique advantage of the radar-based system is that the sensor measures the friction ahead of the vehicle. Driving dynamics can then be adapted – a highly important feature for the optimisation of vehicle actuation like steering and braking able to offer extra protection to VRUs.
3. *Develop an electronically controllable brake and steering force system to be able to slow down the vehicle and provide a supported evasive manoeuvre.* Numerous studies show that in an emergency situation the driver's reaction to a hazard is too often stereotypic, slow and furthermore, the evasive manoeuvre is either insufficient or erroneous. Consequently, the goal is to extend the range of possible crash scenarios and the usability of ADAS by two integrated functions and active interventions to address vulnerable road users, too (two-wheelers and pedestrians). This objective implies the coupling of longitudinal and lateral vehicle controls, with a focus on joint steering and braking actuations. As a result, the effectiveness of collision avoidance can be significantly increased.
4. *Provide the required driver assistance and actuation*. ARTRAC is proposing a totally new safety function based on automatic braking and system-initiated steering recommendation to avoid accidents, or at least mitigate their impact in the event of an unavoidable crash due to physical limitations. Moreover, the increased radar sensor sensitivity permits several functions to be

integrated into the sensor system aside from obstacle detection, pedestrian recognition and road condition estimation based on radar measurements.

5. *Validate and demonstrate the system functionality by means of pre-defined test scenarios*. The novel VRU-safety system prototype functioning will be demonstrated within some "basic" safety applications on a demonstrator vehicle as follows:
    - Pre-crash braking. If a traffic situation is extremely dangerous and a collision is unavoidable, system-initiated braking will reduce the collision speed and with it the injury level of VRUs. In addition to this hard braking, pre-conditioning measures of the brake will be triggered as well. This is a measure to mitigate collision severity.
    - Pre-crash steering recommendation. If the predicted trajectory of an observed VRU is directed to the right or left corner of the vehicle front, a pre-crash steering recommendation to left or right respectively is provided to the driver. The steering recommendation will be a superposed steering moment on the steering wheel. This mechanical moment will be an intuitive warning signal, which supports the driver in performing an evasive manoeuvre.
    - Investigations into VRU warning. In addition to the braking and steering recommendation measures mentioned above, concepts of driver warning in the event of critical situations with VRUs will be considered. The goal is to avoid collisions between VRUs and vehicles. If collision avoidance is not possible due to the traffic constellation, collision mitigation measures take over.
    - Road condition information. By analysing reflected signals from the radar's side lobe, some information about road surface condition can be provided to the driver. This is an interesting topic for a suitable HMI (Human Machine Interface) solution and optimising the ADAS performance.

6. *Promote the deployment of VRU safety technologies among relevant bodies and stakeholders with end-users included*. Since the project is partly funded by European money, it is important to set as one major goal promoting the development of safety technologies all possible channels. This goal is achieved by means of the following activities:
    - Contribute to standardisation for cost-effective and rapid market introduction of new ADAS safety technologies for VRUs.
    - Disseminate the project results among all relevant parties.
    - Make use of the results in the subsequent product development work.
    - Carry out the validation and testing in a manner able to generate knowledge on user perspective and reactions to a novel VRU protection system.

Main S/T Results and Foregrounds

The project could be divided into three consecutive milestones. The first milestone was the analysis of accident statistics, preceding projects and their activities and current sensor technology. From this, the requirements for the development of the radar sensor and the VRU safety system where derived and specified.

In the next phase, the sensor hardware and algorithms were developed, so were the on-board system interfaces and software. The second milestone was reached with the successful integration of the sensor into the demonstrator vehicles and first proof of the functionality.

In the last project phase, an in-depth testing and evaluation programme for all system parts has been specified and performed. The last project milestone was reached by finalizing the test runs and documenting the test results.

The following subchapters present the results of each particular phase.

User Needs and Requirements for VRU Safety

For enhancing road safety, like proposed by the EC, accident analysis is fundamental to develop valuable and effective countermeasures. Therefore, this chapter identifies factors affecting injury and fatality especially in pedestrian-vehicle-collisions. Further we derive relevant traffic scenarios and technical attributes to determine system parameters for the project target of active VRU protection. The project did an in-depth analysis of accident statistics and scenarios, in the following we concentrate on the resulting requirements for varios system components.

General high level requirements

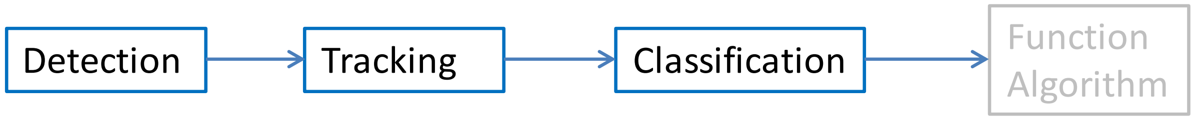
The analysis of accident statistics and scenarios led to general requirements for the radar sensor for VRU detection:

- The radar sensor system shall consist of one or max. two radar sensors. A total field of view of 60° (+-30°) shall be covered with one or two sensors.
- The radar sensor system shall determine the position of reflectors. While the detection algorithms work in a polar co-ordinate system, the tracking algorithms shall provide Cartesian coordinate data.
- The radar sensor system shall determine the relative speed vector of reflectors.
- The radar sensor system shall have a max. range of 50 m on pedestrians, 280 m on passenger cars.
- The radar sensor system shall be able to detect many reflectors simultaneously.
- The radar sensor system shall be able to separate stationary from moving reflectors.
- The radar sensor system shall have a cycle duration of ~40 ms.

- The radar sensor system shall be able to determine an over- or under driveability for reflectors. This shall reduce the number of false collision alarms from driving under bridges and gantries as well as from driving over small reflectors having low height above the road surface.

- The radar sensor system shall detect oncoming traffic. This is required to take evasive actions when a pedestrian is detected and a collision shall be avoided by automatically selecting an alternative driving path around the VRU.

The signal processing path consists of four logical blocks and is shown below. The function algorithm is not part of the radar signal processing but is implemented on the next higher level of the VRU system.



In the following text the requirements for the individual logical blocks are given, as far as they can be specified at this time.

Detection requirements

Each single radar sensor shall be able to detect VRU in its field of view. Secondly it shall detect all other moving traffic; including oncoming traffic (and such traffic in particular at long enough distance) to make the overall system capable of calculation an evasive course around the VRU should this be possible. Stationary reflectors shall also be detected.

Because of the physics of radar detection, this part of the signal processing is working in polar coordinates. The detection algorithms are run cycle by cycle, do not contain any model based algorithms and have no memory, i.e. every cycle is measured completely independent of the previous cycle.

Detection algorithms will – in addition to the basic reflection information per target: range, radial speed, angle and level – provide additional reflector information to be used for a later classification processing. The type of such additional reflector information still need to be defined (TUHH).

The specified range separation of 1.0 m translates into a modulation bandwidth requirement of 150 MHz.

The radar sensitivity is mainly defined by the given max. range on the specified reflectors: pedestrian, equal to -3 dBm² radar cross section, to be detected at 50 m; as well as passenger car, equal to 10 dBm² radar cross section, to be detected at 280 m max. range. For both types of reflectors a minimum signal to noise ratio of 20 dB shall be assumed. In the overall radar sensitivity calculation a transmit power budget of 20 dBm or 17 dBm (final value to be confirmed during project) needs to be considered.

The required radar parameter specifications on raw target detection level are collected in the summary table below.

Parameter	Value	Unit
Max. Range on Pedestrian	50	m
Max. Range on Passenger Car	300	m
Minimum Range	0.5l	m
Range accuracy	Typ. < +-3% or < +-0.3m (bigger of)	%, m
Range separation	1.0*	m
Radial speed interval	+-40	m/s
Radial speed accuracy	Typ. < +-0.28	m/s
Radial speed separation	0.16**	m/s
Angle interval	+- 6(El.); +-30 (Az.)***	degree
Angle accuracy	1.0	degree
Angle separation	6.0**	degree
Update time	<= 40	ms
Number of reported targets	<= 64	

Table 1: VRU Radar detection requirements.

* At short range < 1.5m, only presence detection is available.

** Bin to bin distance is given here.

*** Total field of view, 3dB field is more narrow.

Tracking requirements

The next signal processing block – object tracking – will filter the detection results over time. It will have a data base of objects; such objects representing Kalman filter based models for the physical objects to be detected: pedestrians, vehicles and stationary clutter. Detection data are either associated to existing objects or will initiate new objects in the data base.

The tracking algorithms shall be capable of processing the incoming detection data of one or two radar sensors. A data fusion of such multiple sensors will be possible. Whether one or two sensors will be required needs to be evaluated during the course of the project, in particular at the time when detailed antenna simulations will show first results and will proof if the total required field of view of 60 degree can be achieved with just one sensor, while providing the high azimuth angle separation and pedestrian classification performance at the same time.

Because of the filtering over time, the tracking is capable of calculating the speed vector of any object, based on the individual detection locations and radial speed components associated to an object during multiple measurement cycles. Object data will be calculated in a Cartesian coordinate system.

For over- and under driveability decisions, for all stationary reflectors information will be collected and filtered which will eventually allow to determine that an obstacle is placed on the road and must be regarded a danger or it can be over- or under driven.

Along with the standard information for each object, further data per object (features) will be collected and filtered which supports object classification in a subsequent processing stage. Not only detection features are filtered over time but also new features may be calculated based on the statistical information available for each object.

The radar system should have a long range to detect oncoming traffic early. Hence the tracking algorithms shall have provisions to filter even such long range reflectors.

To facilitate tracking, a data compensation of the vehicle ego motion is performed for all objects in real time. This can be regarded as a data fusion between the vehicle dynamics data of the radar equipped vehicle and the object tracking data base.

Parameter	Value	Unit
Number of sensors processed	1 or 2*	
Filter models	Pedestrian, vehicle, stationary clutter	
Number of reported objects	<= 64	
Tracking delay (time to report object after first detection)	<= 10	cycles
Update time	<= 40	ms

Table 2: VRU Radar tracking requirements.

* Needs to be determined during the project.

Classification requirements

Following object tracking, classification algorithms are next and will be implemented in order to distinguish between pedestrians, stationary clutter, vehicles and other types of objects.

The classification is implemented straight forward with the steps feature extraction (from detection algorithms and from the tracking), usage of a training data base and the calculation of a classification matrix based on pre-calculated coefficients. As a result there will be probabilities for each of the object classes from the training data base, and a decision about an object class can be made.

Requirements for the classification signal processing stage are collected in the summary table below.

Parameter	Value	Unit
Classes	Pedestrian, vehicle, stationary, other	
Targeted classification performance (true positive)	95	%
Number of classified objects	<= 64	

Classification delay (time to classify object after first detection)	<=12	cycles
Update time	<= 40	ms

Table 3: VRU Radar classification requirements.

Antenna requirements

The required field of view is specified in earlier sections of this document with 60 degree total field of view. The second key parameter is the angular separation performance, specified with 6 degree. Generally an even better angular separation capability is desirable, as it will improve the performance of the VRU radar system. However given the selected frequency band and the required antenna aperture a compromise needs to be found to allow an antenna system being still small enough to be integrated in a vehicle but still performing good enough to fulfil the VRU detection, separation and classification requirements.

While the details of the antenna system still need to be worked out as part of the development work in the project, a possible tentative antenna setup is shown in the figure below. It comprises a transmit antenna system which can be physically switched to one of four subsections of the total field of view. In this example, the TX antenna is switched in the position -15, -5, +5, +15 degree. The receive antenna system comprises a number of individual receive antennas each covering the depicted interval. Depending on the number being finally selected (which could be 8, 12 or 16 receive antennas), as a rule of thumb the total angular interval can be divided into 8, 12 or 16 digitally formed receive beams which finally define the separation performance. In the depicted example, in the case of 16 RX antennas, each of the four (~16degree wide) TX sections would be subdivided into four RX beams in that interval.

If the antenna would be designed as depicted in the following detailed design phase, two sensors would be required to cover the total 60 degree field of view.

Parameter	Value	Unit
Number of physical antenna systems	1 or 2*	
Angle interval	+- 6(El.); +-30 (Az.)***	degree
Angle accuracy	1.0	degree
Angle separation	6.0**	degree

Table 4: VRU Radar antenna requirements.

* Needs to be confirmed during the project.

** Bin to bin distance is given here.

*** Total field of view, 3dB field is more narrow.

Basic requirements

Other basic requirements for the ARTRAC sensor(s) are collected in the table below.

Bandwidth and RF transmit signal power are indirectly specified by the selected frequency band of 24.0 to 24.25GHz. While the available bandwidth is 250MHz, the occupied bandwidth must be >= 150MHz.

The most important international frequency regulations which need to be taken into account are listed below. Depending on the final radar configuration, transmit signal power and bandwidth will be selected such that the VRU radar would be possible for usage in the listed regions.

EU: EN 300-440-1; 300-440-2

US: FCC part 15.209, 15.245

Canada: RSS-210

Japan: Cat. Y; Article 49.14(4).

Again, most other general requirements regarding the VRU radar sensor are collected in the summary table below.

Parameter	**Value**	**Unit**
Environmental		
Ambient Temperature	-40 ... +85	° Celsius
IP	67	
General		
Power Supply	7 ... 32	V DC
Frequency Band	24.0…24.25	GHz
Bandwidth	< 250	MHz
Transmit Power (EIRP)	<=20	dBm
Physical data interface	CAN V2.0b (passive)[V]	

Table 5: VRU Radar other requirements.

Road friction estimation sensor requirements

The road friction estimation system is planned to be an additional functionality to the same sensor system used for VRU detection. The following general additional requirements for the radar system are set by the road surface friction detection capability:

- *The radar sensor needs to measure the road surface using at least two polarisations to utilise polar metric data*
- *The antenna(s) needs to have a beam or beams pointing downwards towards the road surface*
- *The radar needs to be able to do range gating to isolate the scattering from the road surface from reflections originating elsewhere*

The basic operational steps of the road friction estimation system are illustrated in Figure 1.

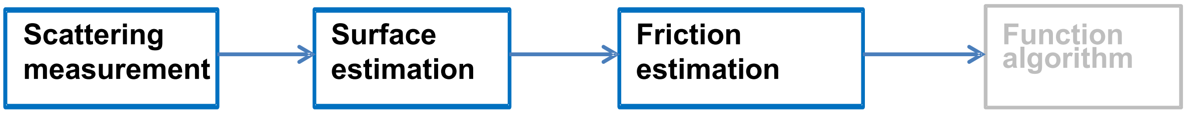


Figure 1: Road friction estimation system.

In the following the requirements of the road friction estimation system parts are discussed further. Most of the parameters and specifications can be determined only later in the project when more information on the friction estimation is obtained.

Scattering measurement

The backscattered power has to be measured at both horizontal and vertical polarisation – transmitting and receiving at both linear polarisations. Alternatively, circular polarisation can be transmitted and both linear polarisations are received. The road surface measurements in the feasibility study indicated that the minimal backscattering level is -55 dBm^2 [Vii09]. Considering the VRU detection specification that -3 dBm^2 radar cross section is detected at 50 m distance with the signal to noise ratio of 20 dB, the same signal to noise ratio for the road surface is obtained at ranges up to about 2.5 m. Thus transmit power of +20 dBm is preferred over +17 dBm to maximise the S/N and the road surface scattering is measured at short ranges, i.e. below 3 m.

Road surface scattering measurement algorithms need to perform range gating to filter out reflections originating from larger distances to eliminate unwanted radar echoes. The relation of the received scattered power at different polarisations is computed.

Surface condition estimation

The surface condition estimation block will filter the scattering measurements over time. A suitable algorithm utilising also the past measurements to determine the current scattering power ratio for the road surface with reduced uncertainty due to random deviations in the signal strength.

Friction estimation

The scattered power ratio at different polarisation is used to classify the road surface conditions to different classes, e.g. dry, wet, icy or snowy – and if possible, to sub-classes corresponding to different properties of the surface (smooth, rough, thick / thin layer on top, etc.). Electromagnetic properties of the surface are used to estimate the corresponding physical properties: road surface material, covering layer material and thickness etc. Based on the classification of the road surface the predetermined typical friction coefficient for such a surface is used as an estimate for the road surface friction coefficient.

The ARTRAC Sensor

General system architecture

The general objective of the ARTRAC project is to increase the safety of vulnerable road users (VRUs). VRUs have to be detected and identified by a radar sensor. These detection results will be reported to the top level application which will react in case of a possible collision.

To ensure the ability to recognise and classify VRUs under traffic condition a powerful automotive radar system is needed. The ARTRAC sensor combines therefore a multichannel receiver hardware and a digital signal processing board providing high computational resources.

Requirements and specification are given in deliverable D2.1 [MEI12] and D3.1 [ROH12]. The general system architecture is given in the following figure.

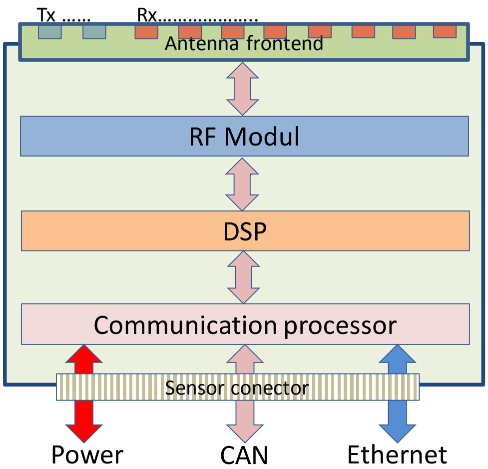


Figure 2: System architecture of the ARTRAC sensor

Antenna Frontend

Following the requirements, a total field of view of 60° (+-30°) is covered. The antenna design is chosen to include 2 transmit antennae and 8 receive antennae. Figure 3 shows the overall antenna diagram.

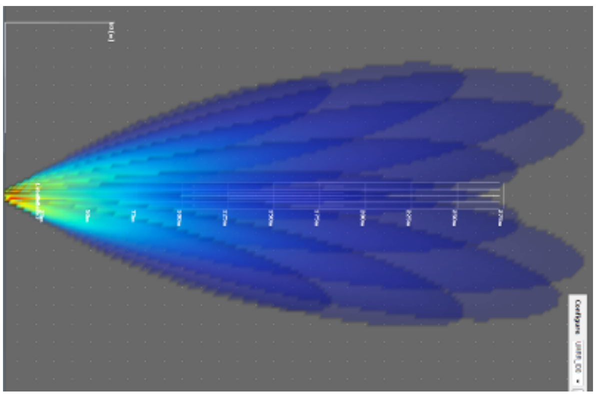


Figure 3: Antenna diagram

DSP board

The DSP board is linked to the RF-Modul. The receive signal is converted to the digital domain and processed by a powerful digital signal processor.

A microcontroller is used to interface the signal processor to the vehicle.

The DSP board includes also the power supply for all sensor parts. The operation range is designed to work with vehicle power supply 12V/24V.

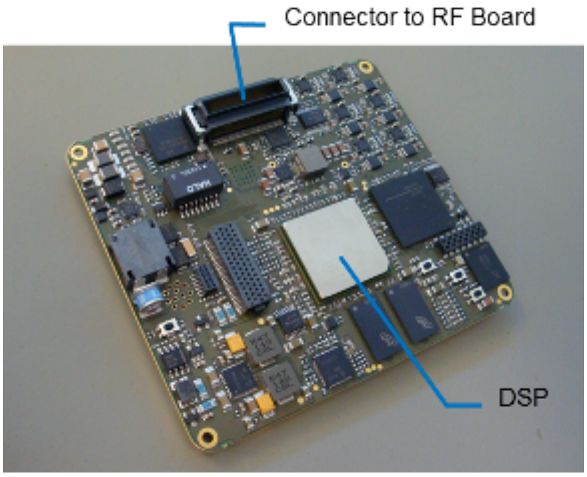


Figure 4: DSP Board

Sensor Housing

The hardware solution of the ARTRAC sensor was developed under the condition of possible implementation in the front of the passenger cars used for the ARTRAC results demonstration. The one of the important restrictive condition was the sensor dimension. And although the applied solution was foreseen only as a prototype the sensor was developed with the view for the further adaptation to the packaging requirements the car manufacturers.

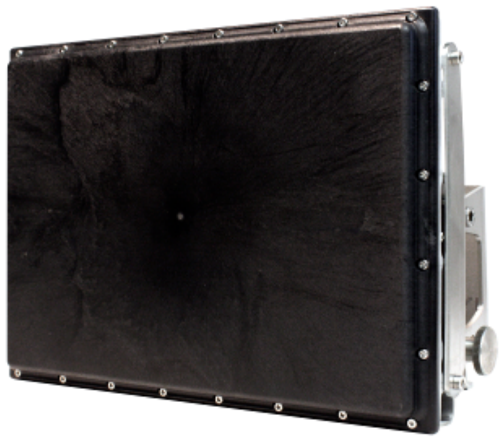


Figure 5: ARTRAC VRU Sensor

Sensor Testing

The RF board and the DSP board were first tested separately and found to be working properly.

The complete sensor hardware was tested in an anechoic chamber with a target simulator. Basic detection functionality like measurement of range, speed and angle was tested and showed promising results.

Further tests on a proving ground have been carried out and proved the desired performance of the sensor.

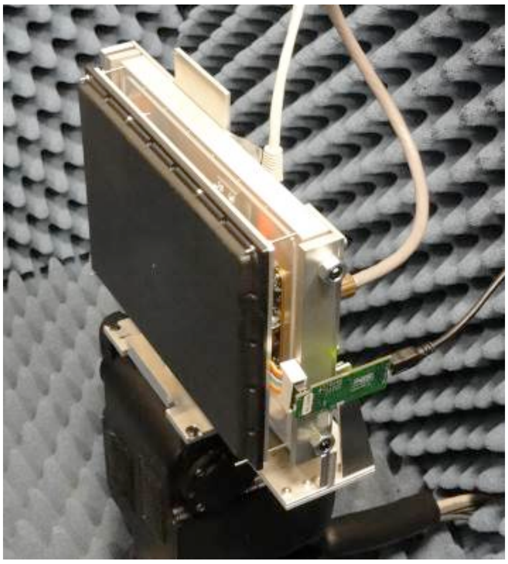


Figure 6: Sensor under test (anechoic chamber)

Radar Waveform

24GHz radar sensors allow a simultaneous and unambiguous measurement of target range R and radial velocity v_r even in multiple target situations. This is achieved in a specific transmit waveform. Typically maximum ranges of several hundred meters are reached using 24GHz radar sensors for automotive applications with a range resolution smaller than one meter. The maximum velocity measurement covers a wide range of up to 250 km/h with a very high velocity resolution. Azimuth angular measurement and resolution is also available using a certain antenna design.

The ARTRAC radar sensor uses the Rapid Chirp waveform scheme with 8 receive signals. With this waveform, only frequency measurements are used to estimate range and radial velocity, which results in more accurate measurement estimation compared to MFSK. By using additional receive antennas, an azimuth resolution is available.

Target Classification

Pedestrian classification is done in a specific signal processing part inside the radar sensor where the radar echo signal of an object is analysed. It can distinguish between longitudinally and laterally moving vehicles, pedestrians and static objects. Therefore, a feature extraction is implemented which is based on a target recognition model analysing the radar echo signal on the specific velocity profile and range profile for each object separately.

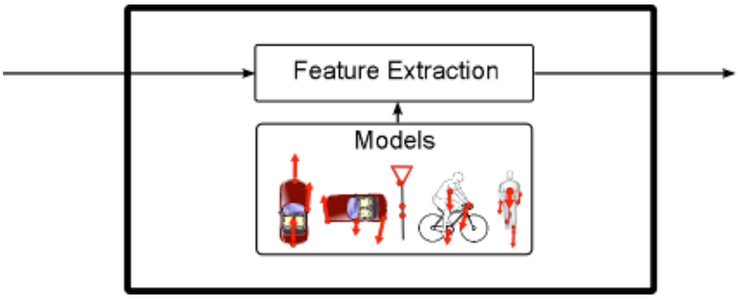


Figure 7: Feature Extraction Signal Flow.

In the case of a pedestrian, different reflection points at the torso, arms and legs are characteristic in radar propagation. An extended velocity profile will be observed in the radar measurement, as the velocity resolution Δv of the radar sensor is higher than the occurring velocities. Considering the range profile, a point shaped range profile will occur as the physical expansion is small compared to the range resolution of ΔR. In contrast, the radar echo signal in case of a vehicle shows mainly a point shaped velocity profile and an extended range profile. This is due to several reflection points spaced in several range cells with a uniform motion.

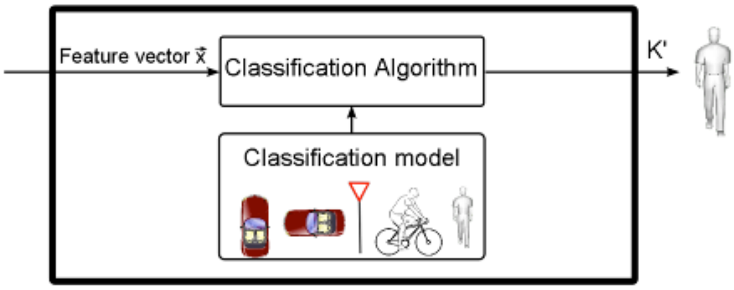


Figure 8: Classification process

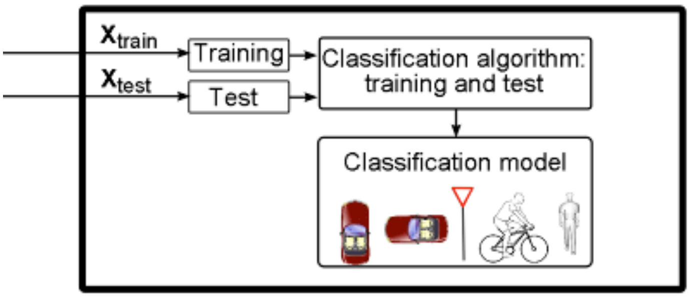


Figure 9: Training phase

Also, using the tracker feedback and a lateral velocity estimation approach, additional features can be extracted to distinguish between lateral moving vehicles and pedestrians.

Road Condition Estimation

The road condition affects the friction between the tyre and the road surface. The motion of the vehicle is controlled via this road-tyre interface. The friction in this interface is highly important for advanced VRU safety applications such as automatic braking for collision mitigation and steering recommendations to avoid the collision. The friction coefficient depends both on the road surface and on the tyres – the exact value of the friction coefficient cannot be thus determined by knowing just the road surface properties. Nevertheless, knowing the road condition allows the estimation of the approximate friction coefficient between the surface and tyres.

In this Chapter, the principle of detecting the road surface condition using 24 GHz radar backscattering measurements is described. Radar backscattering studies based on electromagnetic simulations and scattering models are described. The measurement system developed for measuring the backscattering for different asphalt surfaces is described and measurement results are presented.

Road Surface Condition Detection Principle

The friction coefficient between the road and the tyres is a valuable and useful input for the safety applications protecting the vulnerable road users – such as collision avoidance and mitigation. In principle, the road surface can be asphalt, cobbled stone or gravel but for simplicity only asphalt surfaces are considered within ARTRAC.

Asphalt surface and the friction coefficient

Asphalt is the most common pavement material in urban environments. The friction in the road-tyre interface is mainly determined by the road surface condition i.e. by the material of the road surface and its properties. Figure 9 illustrates the basic structure of the road surface. On top of the asphalt there can be a top layer of ice, snow or water or their mixture.

The icy road surface structure is in electromagnetic sense a rather complicated structure consisting of three materials: two dielectric materials with varying complex permittivity with unknown layer thicknesses with rough interfaces between the layers and the air above the top layer. The case of water on the asphalt is slightly less complicated as the electromagnetic properties of water at 24 GHz are well-known and the water surface is mostly smooth and flat. For clear asphalt, the electromagnetic properties depend on the moisture content and the backscattering depends also strongly on the surface roughness.

Figure 9: Asphalt road surface structure.

Road condition detection

The friction coefficient correlates with top layer material and with the layer thickness on top of the asphalt. Therefore, to estimate the friction, primarily the top layer material and the layer thickness need to be known. Secondarily, the properties of the surface such as the surface roughness and temperature affect the friction. The basis of the road surface friction estimation is the detection of the road surface condition – clear dry, wet, snowy or icy road.

The road surface condition is detected by measuring the polarisation properties of radar backscattering from the road surface. A feasibility study was carried in [VII09] where it was discovered that different road surfaces have a different backscattering level at different polarisations.

Road surface friction coefficient

The friction coefficient correlates with top layer material and with the layer thickness on top of the asphalt. Therefore, the basis of the road surface friction estimation is the detection of the road surface condition – clear dry, wet, snowy or icy road.

Figure 10 shows the correlation between the top layer thickness for water, ice or snow, and the friction coefficient obtained in ROADIDEA project where road weather models were developed by the Finnish Meteorological Institute.

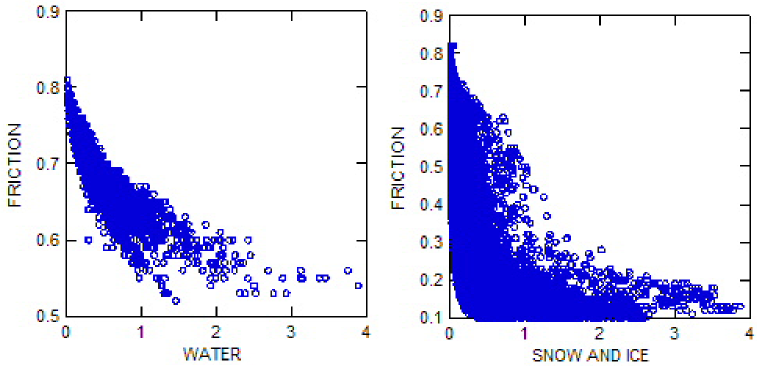


Figure 10: Friction coefficient for different layers on top of asphalt; layer thickness in millimetres [HIP10].

Two approaches to determine the road surface friction coefficient can be identified. Firstly, a systematic approach can be used where the road surface top layer material is identified and the layer thickness is estimated so that the friction coefficient can be then estimated using a friction model. This method is similar to optical method called ellipsometry, where the polarisation of the reflected or scattered light is used to determine the thickness and permittivity of thin films. The material can be identified based on its complex permittivity. Secondly, an empirical approach can be used to develop a classifier that estimates the friction coefficient by classifying the road surface conditions to a few classes using the backscattering ratio with their associated typical friction coefficients. The classifier is trained with backscattering data from different road surfaces.

Measurement Set-Up

The measurement set-up is based on a customised version of 24 GHz radar module by IMST GmbH [IMST] – the integrated antenna was replaced with 50 Ω connectors enabling different antennas to be connected. The module has two receiver (RX) channels and one transmitter (TX) channel which were connected to in-house designed and fabricated planar antenna arrays. The RX antennas are linearly polarised and the TX antenna is circularly polarised allowing measurement of the backscattering polarisation ratio as the ratio of the received powers of the receiver channels. Figure 11 shows the radar module and the antennas.

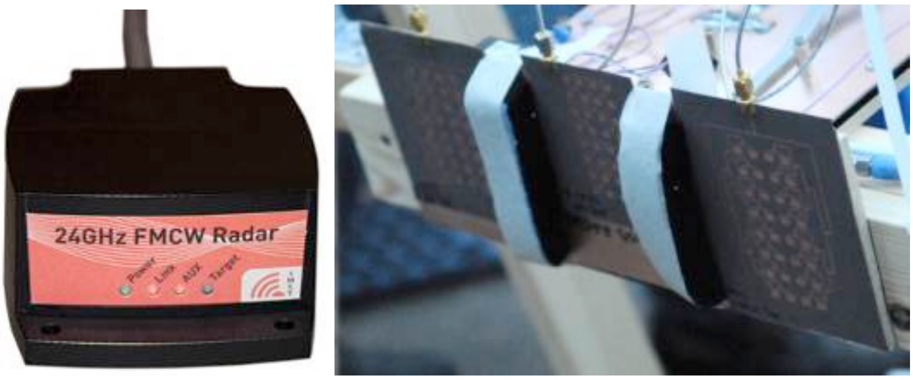


Figure 11 The 24 GHz radar module and the antennas.

Using the software supplied with the radar module measurements of bursts up to 200 chirps can be done which limits the measurement duration to below 10 s. The measurement set-up is mounted on the cart and the measurement time of up to 10 s allows a few metre long tracks on asphalt to be measured at the time.

Conclusions

Road surface friction affects the collision avoidance and mitigation in the VRU safety applications – the friction coefficient determines e.g. the braking distance needed and the minimum turning radius of the vehicle. The friction coefficient depends on the properties of the road surface and the tyres. By detecting the road surface condition, dry, wet or icy, the friction coefficient can be estimated as the typical friction of the surface in question.

The asphalt surface friction can be determined using existing friction models if the top layer material and thickness can be estimated. In principle, by measuring the polarisation of the backscattered radar signal at different incidence angles the surface layer thickness and permittivity can be estimated. The permittivity is different for each material in question, air, water or ice, so the material can be identified based on the permittivity. Simple parameter to measure is the ratio of the received power at the vertical linear polarisation to the received power at the horizontal polarisation (called backscattering polarisation ratio) when a circularly polarised wave is transmitted.

To better estimate the feasibility of the road surface condition detection using 24 GHz automotive radar outdoor measurements on road surfaces were carried out. The radar used was radar module by IMST GmbH connected to in-house designed planar array antennas at both linear polarisations (reception) and at circular polarisation (transmission). This set-up represents the actual situation in the vehicle; the antennas are planar with lower gain and higher sidelobes, and the incidence angle is determined from the radar range bins and measurement geometry (antenna height).

Driving Intervention Actuation System (CTAG)

Based on the environmental detection, the ARTRAC system solution to avoid or mitigate a collision with a VRU in critical situations has been defined with two different approaches which will mainly provide two different reactions in the two vehicle demonstrators: frontal collision warning and automatic braking in the demonstrator from Centro Ricerche Fiat (CRF) and automatic braking and system-initiated steering recommendation in the demonstrator from Volkswagen (VW). However, the global control strategy in both of them has the same basis.

Global control strategies

In the chapters bellow collision warning, deceleration actuation and steering recommendation, as part of the system solution, will be presented separately. In this chapter the general global control strategy which has a common basis for both vehicle demonstrators is presented.

First of all, the measurement data from the sensor is used within the environment detection module to reconstruct the actual traffic scene and to check whether VRUs are present in the scene or not. Then, an obstacle selection module identifies the main obstacle to be taken into account as possibly provoking a potentially risky situation. A risk assessment unit, based on different strategies in each demonstrator estimates a collision risk (CR) that indicates how hazardously the situation is, if an accident is imminent, where is the predicted point of impact (POI) in a vehicle-pedestrian collision, etc.

With the CR as input, a decision making which safety strategy in the current traffic constellation is activated takes place. In this sense, the strategies followed in the two demonstrators diverge: the CRF strategy is based on different areas to define the final system reaction: frontal collision warning or automatic braking and in the VW demonstrator, a strategy based on the time to collision (TTC) and the evaluation of the scene selects the actuation between automatic braking and system-initiated steering recommendation.

The global control strategy for each demonstrator will be detailed in the subchapters below.

CRF Demonstrator solution

If a VRU has been detected by the ARTRAC system, it shall check if the object is in the warning area (defined zone where a warning will be given to the driver in case the pedestrian has a lateral velocity and the predicted trajectory of the pedestrian collides with the trajectory of the vehicle) or in the intervention area (defined zone where an automatic brake intervention will be processed).

If a VRU is in the warning area and the CR is over a threshold (a POI is predicted but the VRU is currently outside of the impact zone and all the function operative conditions are verified) a warning will be displayed to the driver and the Pre-Fill will be requested.

Moreover, if the intervention condition (IC) is over a threshold (the driver is not braking or the driver is not braking with enough deceleration to avoid the collision) the ARTRAC system will automatically intervene on the brakes in order to avoid the collision or if not possible to at least reduce the impact speed.

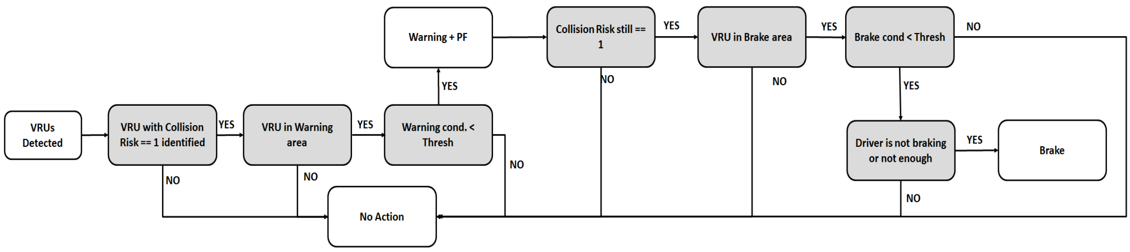


Figure 12: CRF demonstrator global strategy.

The actuation unit in CRF ARTRAC vehicle is implemented into a dSPACE MicroAutoBox 1401/1511 ECU (MABX).

The overall functionality is a composition of three sub-functionalities: Warning: to advise the driver about the presence of a dangerous pedestrian, Pre-Fill: to precondition the vehicle brake system optimizing brake performances in case of driver or autonomous braking, and Autonomous Brake: to brake autonomously (or enhance a driver initiated braking) in order to avoid/mitigate the impact.

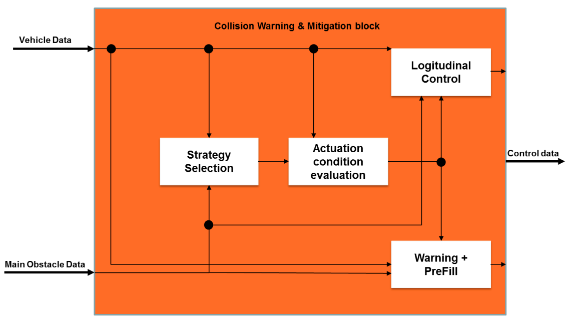


Figure 13: Block diagram of actuation unit in CRF Demonstrator.

VW Demonstrator solution

If a VRU has been detected by the ARTRAC system in the vicinity of the host vehicle and the CR is over a threshold (corresponds to a probability that indicates how hazardously the situation is and if an accident is imminent) the system deploys the actuators under determined considerations.

If the IC is under a threshold (based mainly on a TTC) and the contact with VRU is not avoidable by steering (the POI is predicted to be in the centre of the bumper or oncoming traffic in the near side lane) the ARTRAC system applies a braking maneuver with increasing brake pressure.

If the IC is below a threshold, the collision is avoidable by steering (the POI is predicted to be at the edge of the front bumper) and there is an obstacle in the nearside lane the ARTRAC system applies a braking maneuver with increasing brake pressure. If there is no obstacle in the nearside lane the ARTRAC system applies a steering recommendation to the driver.

If the IC is over a threshold the ARTRAC system applies a braking maneuver with full pressure.

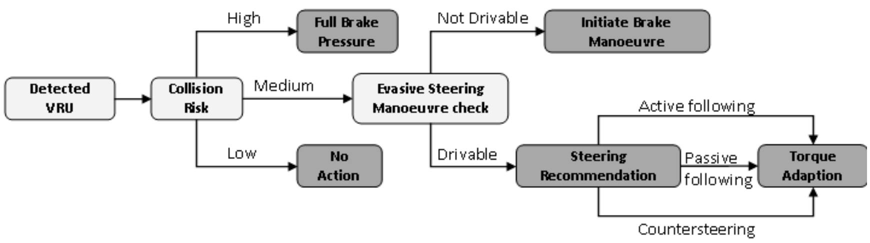


Figure 14: VW demonstrator global strategy.

The ARTRAC sensor is feeding, via sensor fusion algorithm and risk assessment algorithms, a vehicle actuation unit. The Volkswagen demonstrator will have a MABX as a main actuation unit, which has the possibility of switching between two different submodels. These submodels are alternative implementations of control strategies developed by the project partners CTAG and VW.

The actuation unit makes a decision on what kind of vehicle safety actuation is activated. This decision is based on information delivered by vehicle data (e. g. host vehicle motion parameters), detected object data (e. g. object position, velocity vector, object class, etc.) as well as the previously calculated CR.

Inside of the actuation unit different further calculations are conducted. Firstly the vehicle's path is predicted into several time steps in the future. Depending on the CR, the received object list is parsed and an object selection is performed. This selected object (what is the endangered pedestrian) is considered for the intervention decision making concerning longitudinal or lateral intervening. The output of the actuation unit directly controls brake and steering torque of the vehicle.

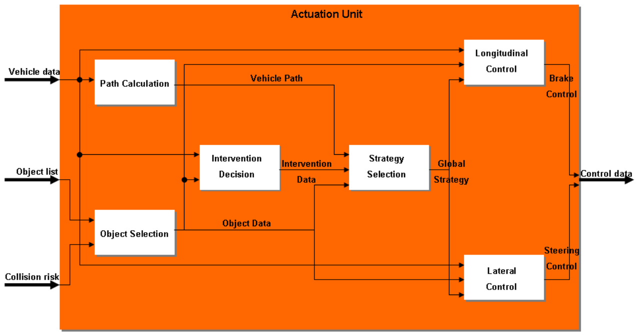


Figure 15: Block diagram of actuation unit in VW Demonstrator.

Development of specific SW for the warning and actuation

General description of the software for the on board system is given in the following.

CRF Demonstrator solution

As before mentioned, The CRF actuation strategy is based on two defined areas: a warning area and a brake area (brake corridor) that have been defined in order to trigger the brake only if the VRU is inside this corridor and the warning if the VRU is in danger but outside the brake corridor.

The Brake corridor width is wider than the vehicle width and is currently defined as Veh_width + Delta.

In the following picture an example is reported:

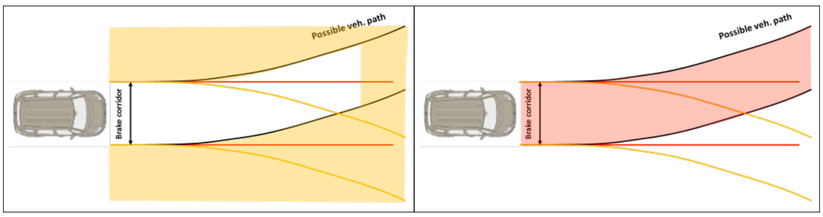


Figure 16: Example of brake corridor (red) and warning area (yellow).

Among all the obstacles detected by the sensor the one with CR equal to 1 is passed to the Warning and brake logics. If the Warning or Brake conditions are verified than the Warning (+PreFill) and the Brake are triggered.

Warning strategies

The warning functionality is triggered using different strategies according to the lateral velocity of the object. If the object is laterally static (vy=0) only the longitudinal movement is used to calculate the TTC. On the contrary, if the object is laterally moving (vy<>0) both the longitudinal and lateral TTC are considered. Notice that the longitudinal TTC deeply depends on the vehicle speed while the lateral TTC mainly depends on the vy of the VRU.

To calculate the TTC Lat & Long the intersection between the VRU movement path and the Brake corridor is evaluated than the TTC needed to the VRU to reach the Brake corridor edge is calculated.

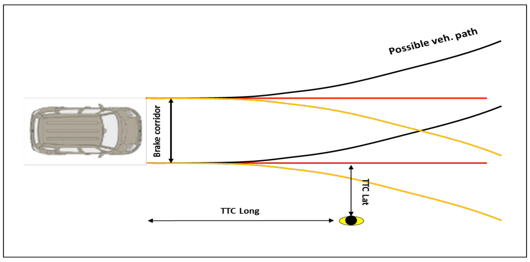


Figure 17: TTC Lat and TTC Long explanation.

Automatic braking strategies

The braking intervention actuation depends on the scenario around the demonstrator, on the dynamics of the vehicle demonstrator and on the dynamics of the obstacle selected as the most dangerous one. The function shall be able to identify dangerous situations and properly provide the brake actuation.

The required final expected result is to reach vehicle speed equal to zero and final distance from pedestrian over a certain threshold in the whole functionality speed range (20-60 Km/h). A maximum deceleration profile depending on the vehicle speed has been defined.

The logic represented in Figure 18 is applied in the brake control to reach the expected results: the distance needed to accomplish the maneuver reaching the expected results (final vehicle speed/ final distance vehicle-pedestrian) is calculated and if the actual relative distance between the pedestrian and the vehicle is different from the expected one to accomplish the maneuver than the deceleration level is modulated. Due to functional safety the initial deceleration applied is limited to A_max (< 1g) if the vehicle speed is over a certain threshold.

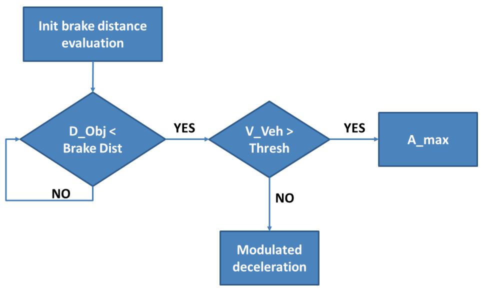


Figure 18: Deceleration profile definition logic.

VW Demonstrator solution

In the following paragraphs the function implemented into the VW demonstrator will be described.

The longitudinal control strategy and the lateral control strategy are fed by a CR module able to identify between all the VRUs detected by the ARTRAC sensor the most dangerous one. The logic takes as input the coordinates (x,y) of the VRU and its speed component (vx,vy).

Longitudinal control

One very effective design criterion is to apply full brake pressure only in situations where the collision is unavoidable by driver actions, it means that the CR is over a CR threshold, and the IC is over an IC threshold. If the collision is avoidable, the CR is still over a CR threshold but the IC is under an IC threshold, the strategy is to increase steadily the brake pressure to smoothly reduce vehicle speed. This increasing pressure strategy allows either driver reaction, given that TTC is still enough, either automatic full brake pressure once IC gets over IC threshold. See Figure 19.

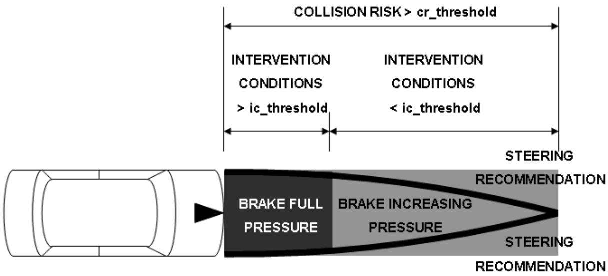


Figure 19: Longitudinal control strategy.

The automatic braking results in a deceleration of the vehicle. When the control system applies a braking maneuver with full pressure, the maximum deceleration value is set to -6.0 m/s2. When the control system applies a braking maneuver with increasing pressure, the deceleration profile is based on the distance travelled and the velocity as shown in Figure 20.

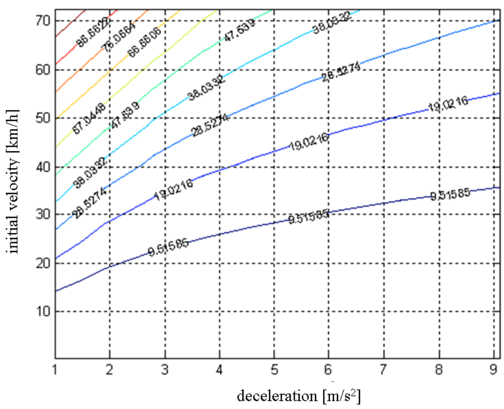


Figure 20: Deceleration profile.

Lateral control

The goal of the lateral support is to control the vehicle on an evasive maneuver which has a trajectory like an S-curve. The S-curve is required to add some lateral motion without changing the vehicle's driving direction after the intervention. So, the vehicle is parallel translated in lateral-direction, it has the same heading as the inertial head was. That control strategy guarantees that the vehicle will not drive into another direction as it did before the maneuver, minimizing another conflict with other traffic participants.

The Volkswagen approach for lateral control follows a geometric trajectory planning strategy. Idea of this approach is to assemble the trajectory of a set of principle geometric functions. The number of geometric functions is high which provides some degree of freedom in the optimization process. Due to the fact that in many countries roads are laid out based on clothoids this function seems to be a well suited candidate for these calculations. The curvature of a clothoid increases linearly. This enables a linear turning speed of the steering wheel and results in jerk-free driving dynamics.

A sigmoid function is used to define an evasive trajectory instead of a clothoid. While the sigmoid function $y(x) = \frac{B}{2} \cdot \left(1 - \tanh\left(a \cdot \frac{x-c}{2}\right)\right)$ has more parameters, it can be easier adapted to the required shape.

Test and Evaluation Programme (VW)

In the final phase of the project all the developments have been evaluated against their specification. The following paragraphs provide a brief overview about test results of all components considered. The entire test programme can be found in Deliverable D7.1, the test results are summarized in D7.2.

Sensor Tests

The radar sensor developed was tested in an anechoic chamber first. In this chamber a corner reflector was used to represent a well-defined reflector target. This target was movable in longitudinal direction (refer Figure) to do investigations about sensors behaviour in different distances to targets.

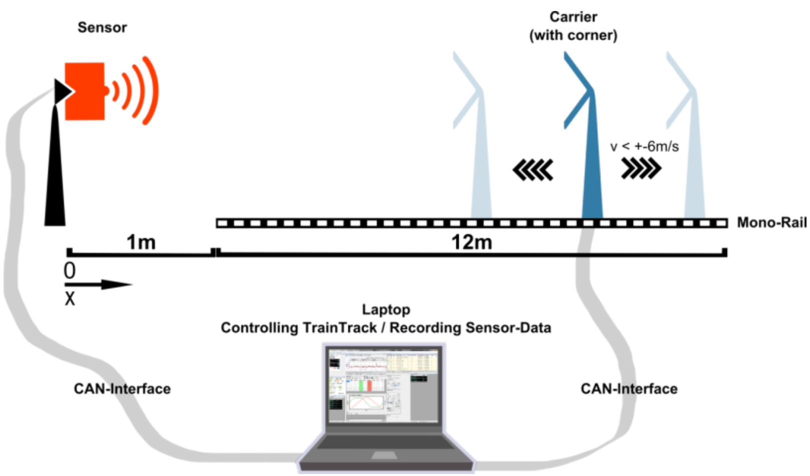


Figure 21: Train Track System

Furthermore some free field test have been conducted. They all showed impressive results in terms of detection probability, position accuracy as well as radial speed information. The lateral speed information cannot be measured with radar directly but was derived by a tracking algorithm.

An example of these kind of measurements is provided in Figure. In this scenario a pedestrian is passing in front of a parked car in a distance of 1 m and is crossing the host vehicle's path. The following figure shows the position of the track of a crossing pedestrian. It can be seen clearly that the detecting probability is very high.

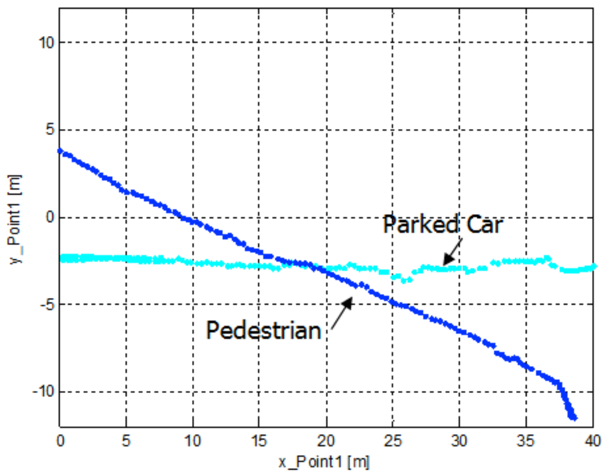


Figure 22: Crossing Pedestrian

Tests on the work bench show good detection results for raw targets in terms of accuracy in range and speed and angular separation. Also with vehicles and pedestrians in the real world a good detection performance can be achieved using the advantages of a fast ramp waveform and signal processing using a 2D-FFT.

Pedestrians entering the scenario from an obstructed view were reported by the sensor with a delay which is caused by the validation phase of the tracking. For safety systems reaction capability should be fast and therefore further improvements in this topic should be made.

The classification algorithms have been proven by fast and good results. Further investigations to handle special cases could follow.

Overall the ARTRAC sensor shows the capability to report a high resolution image of the situation in front of the vehicle which is important for pedestrian detection in order to improve pedestrian safety.

Target Recognition/ Classification

The team of TUHH did research in the area of pedestrian classification. The classification result distinguishes between classes "pedestrian" vs. "non-pedestrian". The classification bases on features taken from radar detection spectrum. One very important feature in this contect is the Doppler extension of those targets. The resulting confusion matrix for a single measurement of 65 ms is depicted in the following table.

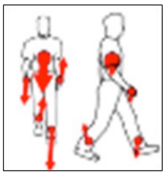
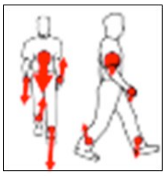
		Classification Result	
			
True Label		92%	8%
		7%	93%

Table 23 Confusion matrix for sample set in a single measurement 65ms (no tracking)

The developed target recognition algorithm is able to correctly classify pedestrians, both walking radially and tangentially to the vehicle, in a single measurement. The false classification rate of 7% for a single measurement is acceptably low and can be reduced below 1% when observing consecutive measurements.

Limitations are observed when laterally driving vehicles pass through the measurement area and when measuring static objects in non-straightforward driving situations. These limitations can partly be avoided with additional signal processing steps but are out of scope for the ARTRAC project.

CRF Demonstrator Evaluation

The demonstrator vehicle Fiat 500L of CRF has been evaluated in dedicated scenarios intensively. In Table the corresponding test scenarios are shown.

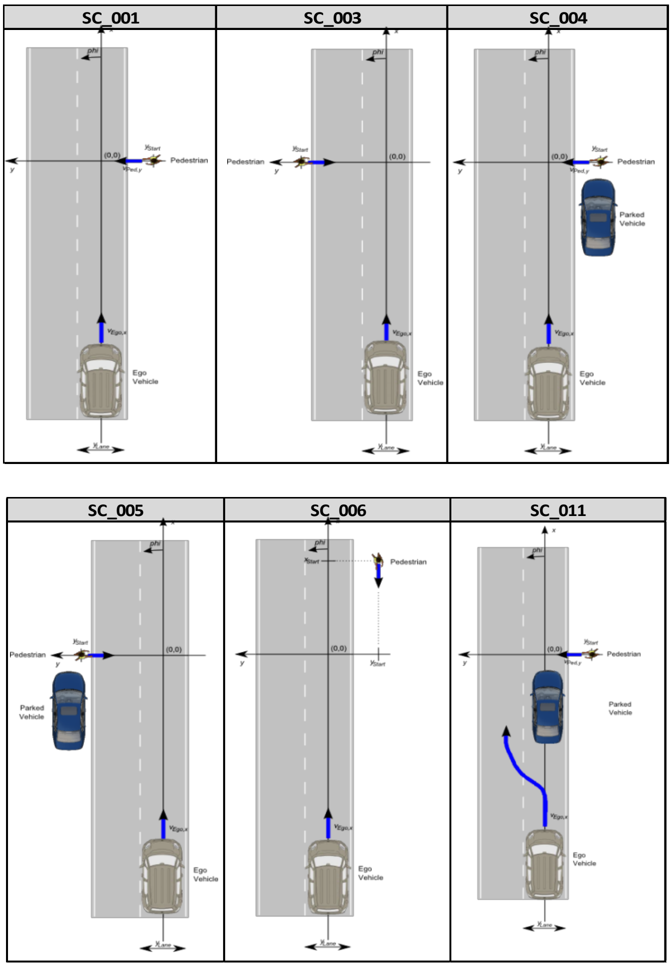


Table 23: CRF Test scenarios overview

Below an example of plots coming from data analysis of scenario SC_005 is given. These tests have been conducted with the Fiat 500L vehicle.

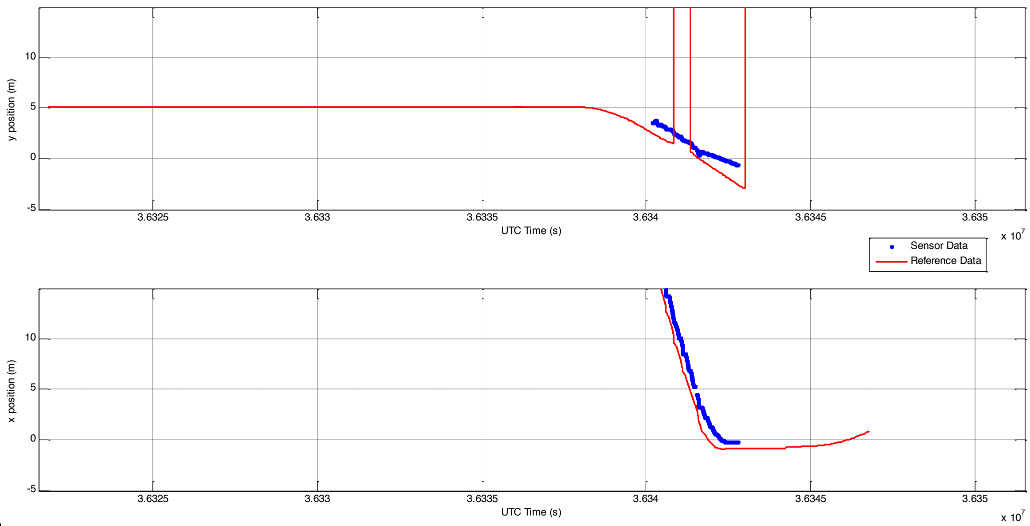


Figure 24: Pedestrian x and ,y position

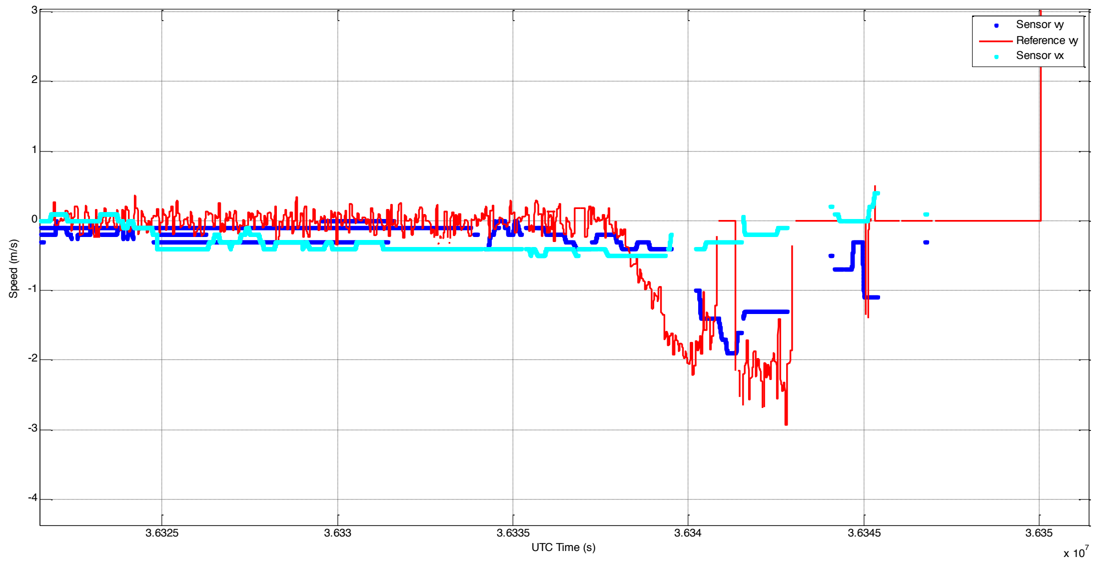


Figure 25: Pedestrian x and y speed

In the following table CRF test results obtained in SC_005 are reported.

Test Number		Test Conditions						Test Results																	
Scenario	Test Run	Ego Speed [km/h]	Pedestrian Speed [km/h]	Pedestrian Heading Angle [°]	Lateral Position of Pedestrian at t_0 [m]	Pedestrian/ Dummy	Obstruction	Sigma_x [m]	According to Spec	Sigma_y [m]	According to Spec	Sigma_vy [m/s]	According to Spec	Sigma_vx [m/s]	According to Spec	First Detection TTC [s]	According to Spec	Sensor Delay [ms]	According to Spec	Classification Result	Warning	Brake	Comments	Overall Test Case performance	Test Result
SC_005	1	20	-8	-90	5,5	Dummy Adult	Parked vehicle	-		-		-				0,98	☹			Not evaluated	NO	NO	No tracking	☹	Impact
SC_005	2	20	-8	-90	5,5	Dummy Adult	Parked vehicle	0,27	🙂	0,75	🙂	0,90	☹	0,50	☹	1,36	🙂	580	😐	Not evaluated	YES	YES		🙂	Avoidance
SC_005	3	20	-8	-90	5,5	Dummy Adult	Parked vehicle	0,84	🙂	0,56	🙂	0,27	🙂	0,12	🙂	1,20	🙂	279	🙂	Not evaluated	YES	YES	Late tracking	😐	Mitigation
SC_005	1	30	-8	-90	5,5	Dummy Adult	Parked vehicle	-		-		-				1,27	🙂			Not evaluated	NO	NO	No tracking	☹	Impact
SC_005	2	30	-8	-90	5,5	Dummy Adult	Parked vehicle	0,62	🙂	0,62	🙂	0,34	☹	0,24	🙂	1,17	☹	540	😐	Not evaluated	YES	YES		🙂	Avoidance
SC_005	3	30	-8	-90	5,5	Dummy Adult	Parked vehicle	0,55	🙂	0,58	🙂	0,28	☹	0,16	🙂	1,04	☹	550	😐	Not evaluated	YES	YES		🙂	Avoidance
SC_005	1	40	-8	-90	5,5	Dummy Adult	Parked vehicle	0,33	🙂	0,66	🙂	0,55	☹	0,49	☹	0,97	☹	580	😐	Not evaluated	YES	YES		🙂	Avoidance
SC_005	2	40	-8	-90	5,5	Dummy Adult	Parked vehicle	0,48	🙂	0,53	🙂	0,51	☹	0,52	☹	1,01	☹	490	😐	Not evaluated	NO	NO	Brake on parked vehicle	☹	
SC_005	3	40	-8	-90	5,5	Dummy Adult	Parked vehicle	0,58	🙂	0,56	🙂	0,32	☹	0,24	🙂	1,33	🙂	387	😐	Not evaluated	YES	YES		🙂	Avoidance
SC_005	1	50	-8	-90	5,5	Dummy Adult	Parked vehicle	0,53	🙂	0,34	🙂	0,34	☹	0,16	🙂	1,68	🙂	450	😐	Not evaluated	YES	YES		🙂	Avoidance
SC_005	2	50	-8	-90	5,5	Dummy Adult	Parked vehicle	0,84	🙂	0,54	🙂	0,41	☹	0,37	☹	1,26	🙂	430	😐	Not evaluated	YES	YES		🙂	Mitigation
SC_005	3	50	-8	-90	5,5	Dummy Adult	Parked vehicle	1,03	☹	0,43	🙂	0,44	☹	0,36	☹	0,87	☹	351	😐	Not evaluated	YES	NO	Brake not active	🙂	Mitigation
SC_005	1	60	-8	-90	5,5	Dummy Adult	Parked vehicle	0,45	🙂	0,45	🙂	0,46	☹	0,47	☹	1,50	🙂	324	😐	Not evaluated	YES	YES		🙂	Mitigation
SC_005	2	60	-8	-90	5,5	Dummy Adult	Parked vehicle	0,65	🙂	0,60	🙂	0,51	☹	0,51	☹	1,29	🙂	480	😐	Not evaluated	YES	YES		🙂	Mitigation
SC_005	3	60	-8	-90	5,5	Dummy Adult	Parked vehicle	1,00	☹	0,72	🙂	0,97	☹	0,45	☹	0,99	☹	330	😐	Not evaluated	YES	YES		🙂	Mitigation
							Mean Values	**0,63**	🙂	**0,56**	🙂	**0,48**	☹	**0,35**	☹	**1,19**	😐	**444**	😐						

Table 26: Test Results of Fiat 500L in Scenario SC_005.

The overall performances of the sensor are satisfying the specifications regarding the accuracies on x and y, some enhancement are needed for the accuracies on the speed. Due to the requirement to the sensor to properly track the pedestrian and give as output all the data about x, y, v_x, v_y and classification a long evaluation time between detection and tracking is needed (mean 500 ms) this value a little higher than specifications and should require further development for its reduction to lower value, for the same reason the performances in obstructed scenarios are lower than in free scenarios.

The overall performances of the system (sensor + functionality) are good, in 75% of the case the final results is good or acceptable, in the 25% is out of specification but must be considered that the 63% of the not acceptable results are coming from the SC_011 with lane change distance 20 m that is a very hard scenario to be covered.

Regarding the classification the results is good, better results occur in pedestrian crossing than in pedestrian walking longitudinally to the vehicle. Once correctly classified the object-pedestrian is maintained with the correct classification until it is detectable.

In conclusion, the sensor tests conducted on CRF prototype shown acceptable performances of the sensors and of the functionality, good results have been obtained for the classification algorithm.

VW Demonstrator Evaluation

The demonstrator vehicle VW Golf has been evaluated in dedicated scenarios intensively. In Table the corresponding test scenarios are shown.

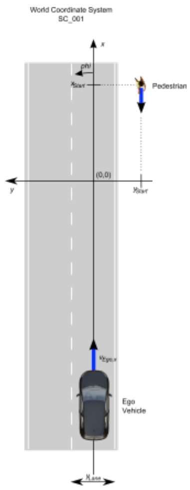
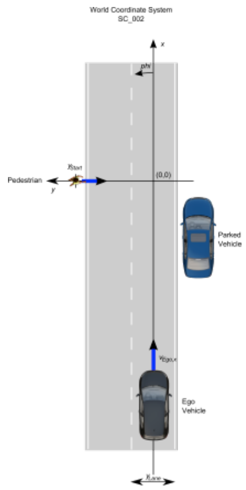
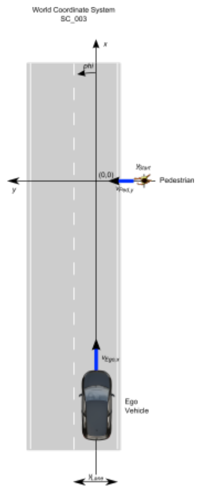
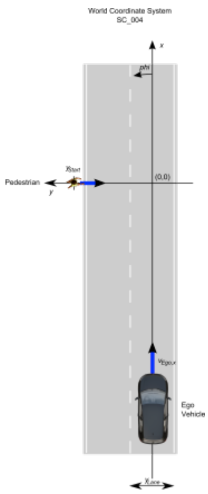
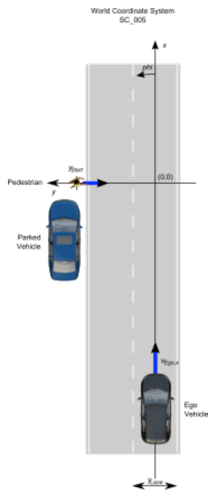
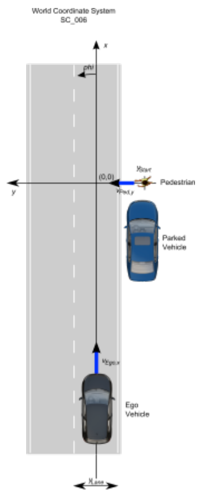
Scenario SC_001	Scenario SC_002	Scenario SC_003
		
Scenario SC_004	**Scenario SC_005**	**Scenario SC_006**
		

Table 27: General test scenarios for Volkswagen demonstrator

The following table provides an overview about test results in the VW Golf in scenario SC_005.

Test		Conditions							Results						
		Ego	Target				Road	Sensor				Function			Overall Rating
									Accuracy						
# ID	Trial	Speed	Speed	Heading	Impact	Type		Tracking	Position	Speed	Class	Expected	Reaction	Safety	
SC03_01	1	30	Walking	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CA	Accept
SC03_02	2	30	Walking	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CA	Accept
SC03_03	3	30	Walking	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	N	None	Denial
SC03_04	1	40	Walking	270	50	FGA	Dry	Delayed	Accept	Accept	/	Brake	B	CM-05	Denial
SC03_05	2	40	Walking	270	50	FGA	Dry	Partly	Accept	Accept	/	Brake	B	CM-10	Denial
SC03_06	3	40	Walking	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CM-15	Accept
SC03_07	1	50	Walking	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CM-15	Accept
SC03_08	2	50	Walking	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CM-20	Accept
SC03_09	3	50	Walking	270	50	FGA	Dry	Partly	Denial	Accept	/	Brake	B	CM-30	Accept
SC03_10	1	30	Running	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CM-10	Accept
SC03_11	2	30	Running	270	50	FGA	Dry	Missing	Denial	Denial	/	Brake	N	None	Denial
SC03_12	3	30	Running	270	50	FGA	Dry	Missing	Denial	Denial	/	Brake	N	None	Denial
SC03_13	1	40	Running	270	50	FGA	Dry	Delayed	Accept	Accept	/	Brake	B	CM-05	Denial
SC03_14	2	40	Running	270	50	FGA	Dry	Delayed	Accept	Denial	/	Brake	B	CM-05	Denial
SC03_15	3	40	Running	270	50	FGA	Dry	Delayed	Accept	Denial	/	Brake	B	CM-05	Denial
SC03_16	1	50	Running	270	50	FGA	Dry	Delayed	Accept	Accept	/	Brake	B	CM-15	Accept
SC03_17	2	50	Running	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CM-10	Accept
SC03_18	3	50	Running	270	50	FGA	Dry	Permanent	Accept	Accept	/	Brake	B	CM-20	Accept
SC03_19	1	30	Walking	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S	CA	Accept
SC03_20	2	30	Walking	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S	CA	Accept
SC03_21	3	30	Walking	270	25	FGA	Dry	Delayed	Accept	Denial	/	Steer	B	CM-05	Denial
SC03_22	1	40	Walking	270	25	FGA	Dry	Permanent	Accept	Denial	/	Steer	S/B	CA	Accept
SC03_23	2	40	Walking	270	25	FGA	Dry	Permanent	Accept	Denial	/	Steer	S/B	CA	Accept
SC03_24	3	40	Walking	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S/B	CA	Accept
SC03_25	1	50	Walking	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S/B	CM-20	Accept
SC03_26	2	50	Walking	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S/B	CM-15	Accept
SC03_27	3	50	Walking	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S	CA	Accept
SC03_28	1	30	Running	270	25	FGA	Dry	Delayed	Accept	Denial	/	Steer	B	CM-05	Denial
SC03_29	2	30	Running	270	25	FGA	Dry	Missing	Denial	Denial	/	Steer	N	None	Denial
SC03_30	3	30	Running	270	25	FGA	Dry	Delayed	Accept	Denial	/	Steer	B	CM-05	Denial
SC03_31	1	40	Running	270	25	FGA	Dry	Delayed	Accept	Accept	/	Steer	B	CA	Accept
SC03_32	2	40	Running	270	25	FGA	Dry	Delayed	Accept	Accept	/	Steer	N	None	Denial
SC03_33	3	40	Running	270	25	FGA	Dry	Delayed	Denial	Accept	/	Steer	N	None	Denial
SC03_34	1	50	Running	270	25	FGA	Dry	Permanent	Accept	Accept	/	Steer	S/B	CM-10	Accept
SC03_35	2	50	Running	270	25	FGA	Dry	Delayed	Denial	Accept	/	Steer	B	CM-05	Denial
SC03_36	3	50	Running	270	25	FGA	Dry	Delayed	Accept	Accept	/	Steer	B	CM-10	Accept

Table 28: Test Results of VW Golf in Scenario SC_005.

The overall performance of the radar sensor in VW Golf almost met the specifications regarding the accuracies on *x* and *y*. The accuracy in lateral velocity has also been improved while there is still a need for further investigations concerning safety critical application (like automatic braking or steering recommendation). Unfortunately there is no physical effect that provides the lateral speed information directly. Therefore it has to be derived from an effective object tracking. In contrast to that, the longitudinal speed information is very reliable.

In case of occlusion the track initialisation of a crossing pedestrian was often delayed about 1 s. This is definitely an important parameter which has to be improved for better overall performance of the safety measure triggering.

The overall performance of the safety system (what includes both, sensor and safety function) is satisfying. In 79.8% of all tested scenarios the system did correct detections and correct interventions into driving dynamics. As expected the performance was much better in non-occluded scenarios (SC_001, SC_003, SC_004), namely 88.1%. In these tests no false alarms have been observed. Due to the resolution of the sensor the detection and tracking in scenarios with occlusion (SC_002, SC_005, SC_006) have been much more challenging with strong influence to the risk assessment unit. On the other hand the movability of a pedestrian is very high such that we choose a conservative trigger strategy to reduce false positive. As a consequence the aim to avoid a collision in the majority of our test cases could not be met. Instead the impact speed was reduced by at least 10 km/h.

The classification was tested in SC_001 only, because this scenario does not have provide any danger for the pedestrian under test. All other tests (SC_002 … SC_006) have been conducted with a pedestrian dummy which does not provided the same radar signature as a real human body. In test scenarios SC_001 the sensor achieved a 100% correct classification rate. In urban test the classification rate was also high, but cannot be quantified because of missing ground trough information.

In conclusion, the sensor tests conducted on Volkswagen prototype car shown acceptable performances of the sensors and of the functionality, good results have been obtained for the classification algorithm.

Road Surface Estimation Radar

The road surface condition detection testing is based on comparing the road surface condition determined with the radar to the road condition measured with reference devices or to controlled road condition. Road surface measurements are carried out under different conditions on selected test tracks. The measurement cases correspond to the basic test scenarios with clear dry, wet and icy asphalt surfaces. In addition to the measurements on test tracks, measurements in controlled conditions are done. The measurements are done to build a data library of backscattering properties to obtain test and training data for the road surface condition classification. Figure shows exemplary results on road with different conditions.

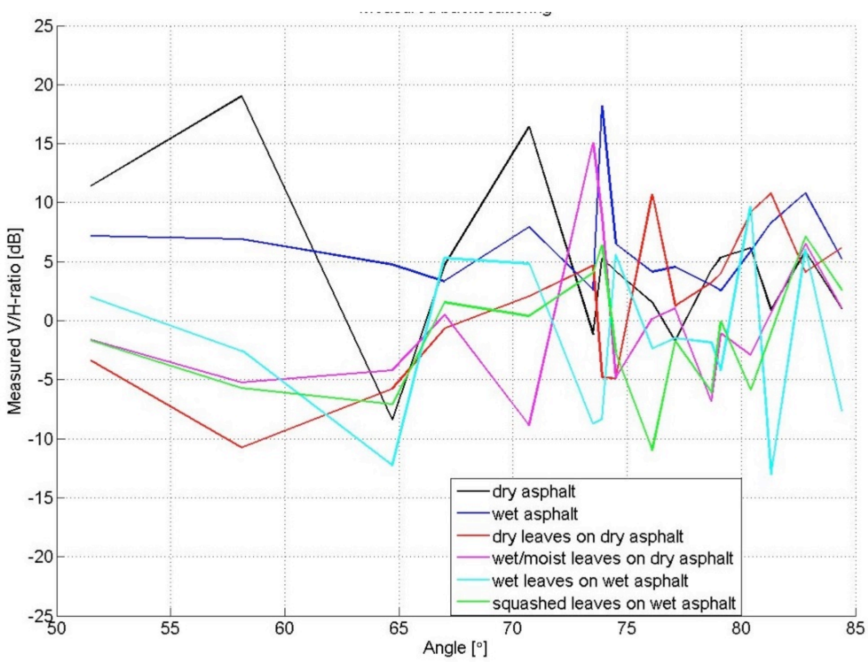


Figure 29: Measured backscattering polarisation ratio for different asphalt surfaces.

The motion of the vehicle is controlled via the road-tyre interface and the friction in this interface is critical for braking and turning the vehicle. Thus road friction information is valuable for the vulnerable road user protection – the friction coefficient determines the needed braking distance and turning radius for collision avoidance and mitigation. The friction coefficient depends on the road surface condition, which can be detected by measuring the surface backscattering polarisation ratio.

Radar backscattering polarisation measurements of different road surfaces were carried out to investigate the possibilities to detect the road surface condition and to estimate the road friction coefficient. Measurements of dry, wet, icy and leaf covered asphalt were done in controlled environments. The friction coefficient can be estimated as the typical value for the road surface class (dry, wet, icy, etc.) in question and the estimate can be used as an input in the VRU protecting applications.

The feasibility of detecting the road surface condition was investigated with simple k-nearest neighbour (kNN) classifier tests. Measured backscattering from dry and wet asphalt was classified with the kNN-classifier using the averaged measurement result for each surface as the model in the classifier. Wet asphalt was correctly classified as wet asphalt in all of the test measurements but dry asphalt was correctly classified with 50 % success rate – in 50 % of the test cases the dry asphalt was mistaken as wet asphalt. For leaves on asphalt, the simple kNN-classifier identified the leaf covered asphalt from dry and wet clear asphalt with 100 % success rate. The variation in the measured backscattering polarisation ratio from dry asphalt is large due to the surface roughness which is large in relation to the wavelength at 24 GHz. This variation makes the surface classification more difficult for dry asphalt surfaces.

To collect a large amount of measurement data a vehicle mountable automated measurement system consisting of multiple radars and reference measurement equipment (e.g. road condition monitor, accelerometer based friction meter) was designed. This ambitious development was seen necessary at the beginning of the project to develop research tools for estimating the friction coefficient from the radar measurements – the friction coefficient estimation for VRU protecting safety applications extended the original scope of the research in ARTRAC. Due to technical difficulties in the radar development, full functionality of the measurement system was not achieved. This limited the number of measurements that could be done.

The results obtained in the classification tests indicate that road surface condition can be identified from the backscattering polarisation ratio and the corresponding friction coefficient can be estimated. However, to improve the reliability of the surface classification more data from different asphalt surfaces is needed – a larger number of measurements of different road surfaces should be used to train the classifier. The classifier should be also optimised to maximise the classification success rate.

Socio Economic Impact

The key result of the ARTRAC project is a safety system to protect vulnerable road users (VRUs) designed to be economically viable in the volume vehicle market. The safety system consists of both, actuators for controlling vehicle driving dynamics and the perception component for the vehicle's surroundings. It was tested on two vehicles that pose the biggest hazard to VRUs in urban settings, namely compact cars.

However, the issue of market penetration is of major importance and this is very much an issue of cost. This has so far been the main barrier to the results of many previous funded projects bearing fruition in terms of widespread adoption of the technology, and it is only through widespread adoption that inroads into reducing road casualties will be achieved.

In turn, ARTRAC has supported the objectives of the Road Safety Programme 2011-2020 adopted by the Commission in July 2010. Here there is a commitment to '*promoting the use of modern technology to make traffic safer*' (Objective 5) and to do more to '*protect vulnerable road users'* (Objective 7). It is the goal of ARTRAC to achieve breakthrough systems in support of the latter by means of the former.

<u>Establishing market acceptance for ADAS systems for VRUs – the price issue</u>

The development of ADAS has reached the stage where both longitudinal and various lateral control support systems are entering the market. However, the penetration level of these systems is still very low, and currently there is no prospect of them becoming standard for all vehicles due to their high price level, so they are restricted to the high end of the market For any kind of VRU safety enhancement to make a difference to overall safety the cost issue has to be addressed, and ways found for ADAS to become affordable for the small to medium class segments. As shown in Figure 3.1, 56% of all accidents are caused by cars belonging to the subcompact[1] – compact[2] range, and the total rises to 83% if we include mid-size cars[3]. These segments are unfortunately literally untouched by current ADAS and active safety systems. Even the penetration of D segment by these systems is still very low.

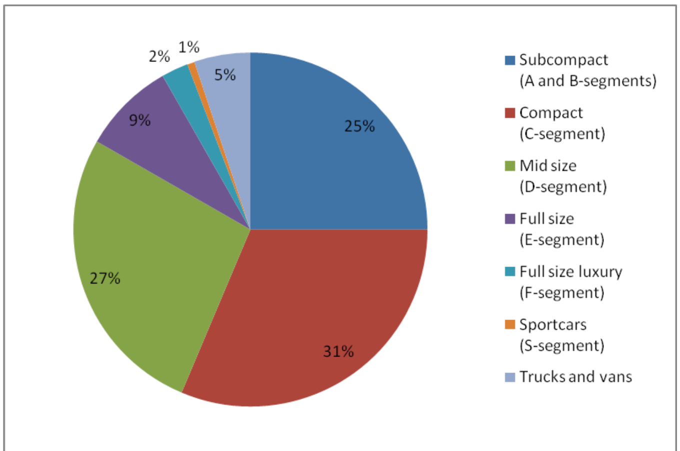


Figure 30. Accidents distributed by car segment[4].

[1] E.g. Opel Corsa, VW Polo, Ford Fiesta, Skoda Fabia, Audi A2, FIAT Punto, Ford Fusion, Honda Jazz

[2] E.g. VW Golf, Opel Astra, Ford Focus, Mercedes A-Klasse, Audi A3, Skoda Octavia, Toyota Corolla

[3] E.g. Audi A4, VW Passat, Opel Signum, Ford Mondeo, Honda Accord, Mazda 6, Škoda Superb, Volvo S40/S60

[4] AUTOTECH CAST Europe, Harris Interactive 2006, European Consumer Advanced Automotive Technologies Report

Figures 3.2a and b show by way of example results of a study undertaken by AUTOTECH[9] on customer perceptions of the value of various types of ADAS functions, based on measuring attitudes of the desirability of a function before and after a price was revealed. What holds the key for market penetration is the perception that something is "good value". True consumer behaviour is always difficult to predict and such studies are open to interpretation, but the conclusion about price sensitivity is backed up by current consumer behaviour and their unwillingness to pay for functions already on the market. The analysis does show, on the other hand, a perceived value in pedestrian protection and sensing.

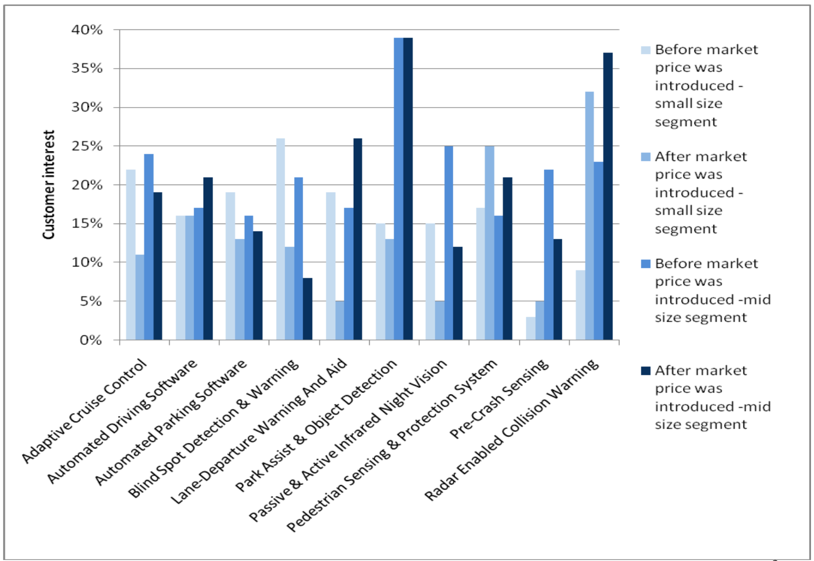


Figure 32 ADAS – user interest in targeted size vehicle segments[9]

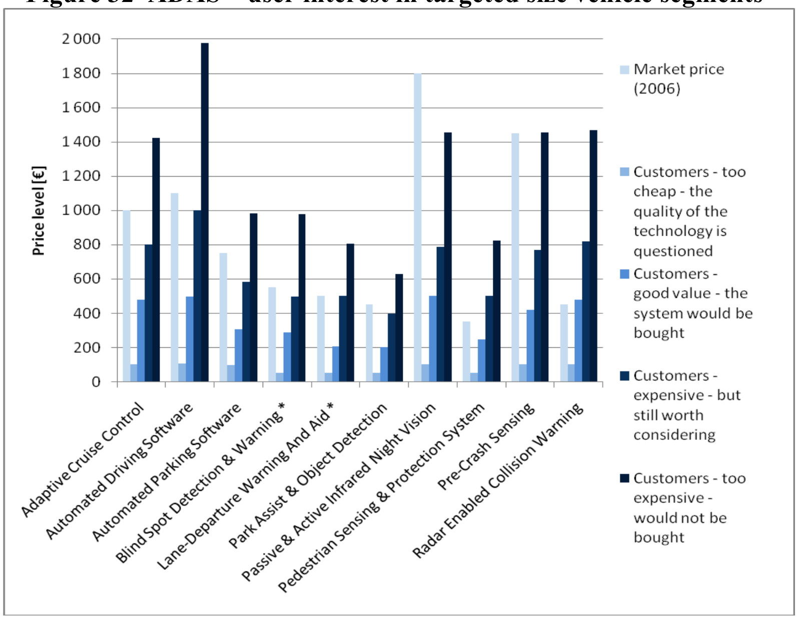


Figure 33 Comparison of market price and customers' ideas of the pric[9]

Since, price is an issue ways need to be found to implement ADAS functions more economically. This is core to the ARTRAC detection system, a novel radar-based system that is small and lightweight in order to enable an easy integration in the vehicle design. To meet the tough cost parameters, the system design incorporates existing controllable components, especially actuators, in serially produced vehicles.

Addressing VRUs by analysis of accident types

The second core issue concerns the ability of the ARTRAC development to deal with typical accident types involving VRUs. Accident types, their frequency and whether they are addressed by ARTRAC are listed in Table 3.1.

Table 34: Accident types for cars.
Possible driver assistance systems and potential for systems based on ARTRAC radar.

Accident type	Description	Frequency	Possible ADAS function	ARTRAC potential
1	Longitudinal collision	3%	FCW, Pre-crash, AEB	Yes
2	Longitudinal collision	19%	FCW, Pre-crash, AEB, ACC, S&G	Yes
3	Lateral collision	3%	LCW, LCA	Yes
4	Longitudinal collision	10%	FCW, Pre-crash, AEB	Yes
5	Intersection collision	20%	Intersection assist	Yes for urban situations
6	Pedestrian collision	18%	Pedestrian protection	Yes
7	Longitudinal collision	1%	FCW, Pre-crash, AEB	Yes
8	Lane departure	14%	LDW, LKA	No
9	Lane departure	10%	LDW, LKA	No
10	Misc. collisions	2%	-	No
		100%		**54%-74%**

Four main accident types represent the vast majority of all the accidents: frontal crash-related accidents can be considered types 1, 2 and 4 in Table 3.1 with a total share of 32%. These accidents can be avoided or at least partially mitigated by a pre-crash system.

The second group of accidents is related to running off the road. These are the categories 8 and 9 with a total share of total 24% of the accidents. To handle these types of accidents, functions similar to lane departure warning (LDW) are required. The ARTRAC of a system will not be able to be used for lane deviance monitoring. These types of accidents are therefore beyond the scope of this project.

The third group is somehow related to intersections and junctions. To this group belongs the category 5 of accidents displayed in 4 with approximately 20% of the accidents.

The fourth group of accidents is hitting pedestrians (accident type 6). With a total percentage of 18% of all accidents, the need of using pedestrian protection system for the demonstrator passenger car is obvious.

Pedestrian and other VRU fatalities are more common within urban areas than outside, since the pedestrian density is higher in cities than outside. Therefore ARTRAC is primarily addressing urban situations.

Furthermore, in Figure 35, it can be seen how the vast majority of accidents happen in urban areas below the speeds 50 km/h, and furthermore, 80% of all accidents take place up when vehicle speed is not exceeding 30km/h.

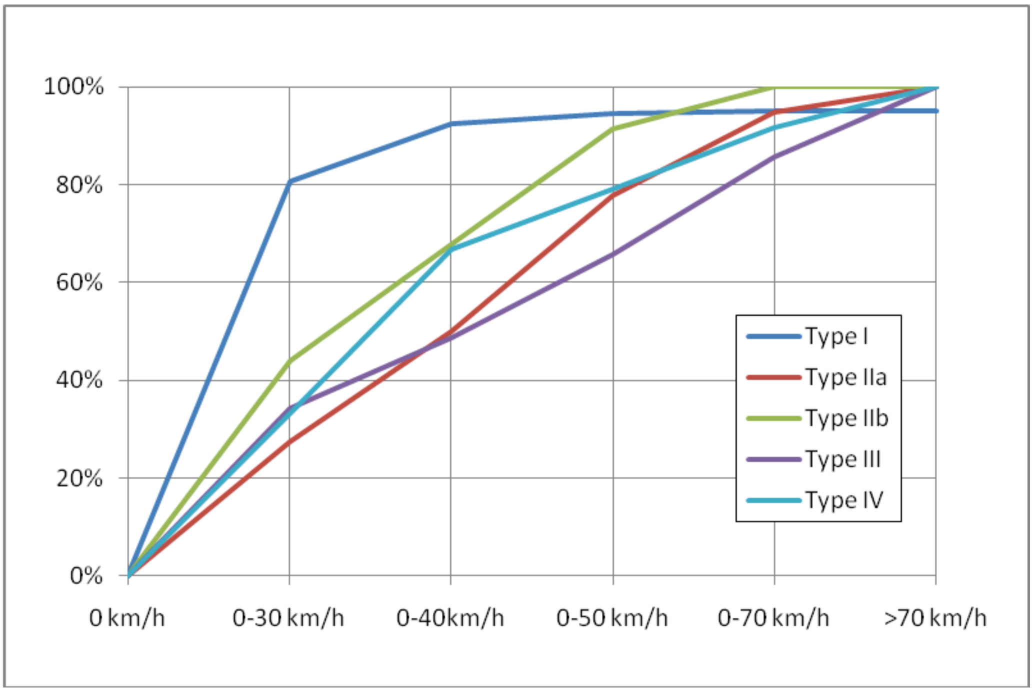


Figure 35 Pedestrian accidents by type of accident and speed (compare Table 3.1).

It can be seen in Table 3.1 that dealing with accident types I and II addresses the consequences of almost 90 % of pedestrian related accidents. In practice it is difficult to cover all cases of these, however. For example, it may be impossible to prevent an accident in cases where the pedestrian suddenly appears on the road: the degrees of freedom of a VRU's motion and the motion of ego vehicle are so large that it is very difficult to predict a collision sufficiently ahead of time for the vehicle to react (or at least not in such a way that it would cause false alarms). The physics of the dynamics of motion mean that an imminent collision can only be detected 500 msec before crash. Accident type IV, and Type IIb, where the visibility is reduced by an obstacle, are also extremely challenging to deal with. Nevertheless, even without coverage of these scenarios, more than 65% of pedestrian accidents could be covered.

Addressing regulatory testing

Developing the sensor system and verifying its function alone was not sufficient to ensure its acceptability as a safety component. The ARTRAC partners recognised the need for the development of independent test procedures and standards. Traditional vehicle safety is largely has been evaluated by mechanical tests, so-called crash-tests. Pre-crash systems like ARTRAC will require new test methods to be developed.

The development of testing standards is beyond the scope of this project since it would be presumptuous of a handful of players in the automobile sector to impose their view on what has to be a process that needs a much broader stakeholder approach. However, the subject of testing is addressed as part of Work Package 7 and outputs from this can contribute to the definition of test standards for pre-crash detection systems. Through the VRU Safety Regulation Review Work Group defined in the management structure ways will be found to pass on on-going results that may support standardisation work.

Summarising the impact

ARTRAC offers a complementary approach to hitherto passive safety approaches in the structural design of cars that have been developed to meet existing and emerging regulations. It will not make such developments obsolete, but it offers a genuine breakthrough in the development of active safety systems to protect VRUs.

In conclusion, ARTRAC created a breakthrough technology to achieve the goals of the **Road Safety Programme 2011-2020** which include again the objective to halve the number of road deaths. Perhaps ever the project could help to push the boundaries further towards the 'zero-fatalities' scenario.

Dissemination

The success of the project for the partners means public and regulatory acceptance of the ARTRAC sensor and associated safety features. Therefore there was a willingness in the ARTRAC consortium to share information and to disseminate to the public the project achievements and findings in the course of the project.

A web site was designed and activated containing information about concepts, vision, objectives and expected outcomes as well as public documents. The web site also provides access to project internal document management and collaborative work functionalities.

The overall dissemination was carried out using internet, social media, presentations at targeted events, workshops as well as the provision of public domain reports and printed material.

Two public workshops were organized during the project. One was targeted at VRU specialists, the other to experts from radar solutions. In addition, a session on ARTRAC and its concept was included in the IRS 2013 conference in Dresden, where additionally the Volkswagen demonstration car was presented.

TuTech created a project flyer, which was distributed at several events and furthermore served as material introducing the project and its concept to interested persons.

Furthermore VW's demonstrator vehicle was presented on several occasions.

A concluding workshop in connection was held at the end of the project in Volkswagens proving ground in Ehra where participants were presented with a project overview and were presented with the opportunity to take test drives with both demonstration cars.

A detailed list of dissemination activities is part of a table below.

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