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TNO report

TNO-033-HM-2010-00695/IP

**Pre-development of a Vulnerable Road Users
(VRU) airbag. Phase 1; preparation.**

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Summary

In the Netherlands, annually about 185 cyclists are killed in road accidents. Half of this number results from a collision with a passenger car. Furthermore, the annual number of pedestrian fatalities in the Netherlands is about 65 in the last years. The number of cyclist and pedestrian fatalities has remained constant over recent years, while the total number of road accident fatalities shows a clear decreasing trend.

In projects commissioned by the Dutch Cyclists' Union and the Dutch Ministry of Transport, TNO investigated the specific properties of collisions between cars and cyclists and what measures can be incorporated in the car to increase the safety of cyclists and pedestrians. These most promising measures are:

- Systems for automatic braking or brake assistance
- An airbag that covers the car's windshield, to protect against harsh head impacts.

This report describes phase 1 of a project, to come to an evaluated prototype of a VRU airbag, following the approach as given in TNO report *TNO-33-HM-2009-00741 An approach towards a dedicated windshield airbag; Improvement of the safety of vulnerable road users: Pedestrians and cyclists*. The current project is commissioned by the Dutch Ministry of Transport.

Overall objective of the project is a prototype airbag system -evaluated according to the Beyond NCAP protocols of Euro NCAP- which is available in 2012.

Phase 1 of the project is carried out by TNO, in close cooperation with the Dutch Cyclists' Union, Autoliv Sweden and Centraal Beheer Achmea. This cooperation will be continued in phase 2 of the project.

The main goal of phase 1 of the project is to set-up specifications for the development and evaluation of a Vulnerable Road Users (VRU) airbag, including sensor system, that protects pedestrians and cyclists. To set up these specifications the following activities are carried out:

- WP 1.1 Data analysis / Chapter 2
 - Accident data concerning pedestrian and cyclist accidents is collected and analysed. Databases from the Netherlands, Sweden and Germany are used.
- WP 1.2 Effectiveness study / Chapter 3
 - Based on the accident data the potential effectiveness of three countermeasures to increase VRU safety: autonomous braking, a pedestrian airbag and a VRU-airbag, is defined. A summary of this study is presented in this report, the complete study is presented in TNO report: TNO-033-HM-2010-00695/2.
- WP 1.3 Computer simulations / Chapter 4
 - The possible kinematics of a cyclist during 1 to 3 second prior to an impact is studied using computer simulations. This information is essential to predict a potential impact using pre-crash sensor information.
- WP 1.4 accident reconstruction tests / Chapter 5
 - A number of typical impacts between a vehicle and a cyclist is reconstructed in the crash laboratory. The main objectives are to gain insight into the kinematics of the dummy and to investigate the in-crash (accelerometer) sensor in the vehicle bumper.
- WP 1.5 Functional specifications / Chapter 6
 - Based on the results of the previous activities functional specifications for airbag and sensor system are drafted.

- WP 1.6 Specifications Sensor Field Test / Chapter 7
 - A main part of the development of the sensor development is a Sensor Field Test to collect data from the real live traffic situation. The specifications for such a field test, to be carried out during phase of the project, are developed.
- WP 1.7 Specifications final System evaluation / Chapter 8
 - The prototype airbag and sensor system will be evaluated according to the Euro NCAP protocol during phase 2 of the project. Detailed specifications for this evaluation are set up in this phase of the project.
- WP 5 Dissemination activities
 - During the project the objectives and status of the project are presented to various stakeholders. The used presentations and related articles are presented in report: TNO-033-HM-2010-00695/3

The conclusions of phase 1 of the project are presented in Chapter 9.

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1 Introduction

In the Netherlands, annually about 185 cyclists are killed in road accidents. Half of this number results from a collision with a passenger car. The number of cyclist fatalities has remained constant in recent years, while the total number of fatalities shows a clear decreasing trend. Other European countries have even experienced an increase in the number of deaths and serious injuries among cyclists, as a result of the growing popularity of cycling as everyday transport.

In projects commissioned by the Dutch Cyclists' Union and the Dutch Ministry of Transport, TNO has investigated the specific properties of collisions between cars and cyclists. TNO has also examined (see report TNO-033-HM-200-00354) what measures can be incorporated in the car to increase the safety of cyclists and pedestrians (about 60 fatalities annually). For this, over 20,000 accidents were simulated. The most promising technological measures to improve the safety of vulnerable road users are:

- Systems for automatic braking or brake assistance
- An airbag that covers the car's windshield, to protect against harsh head impacts.

Some airbag manufacturers have developed prototypes of an airbag, to protect pedestrians. These cover only the bottom of the windscreen, and have a limited effect for cyclist protection. Adjusting the geometry of the airbag and the development of a detection system that can detect both pedestrians and cyclists are required to come to an airbag that protects all vulnerable road users, and can save significantly more lives than a pedestrian airbag. This VRU¹ airbag covers the entire windshield of a car.

This report describes phase 1 of a project, to come to an evaluated prototype of a VRU airbag, following the approach as given in TNO report *TNO-33-HM-2009-00741 An approach towards a dedicated windshield airbag; Improvement of the safety of vulnerable road users: Pedestrians and cyclists*. The current report describes the results of WP 1 *Specifications* and the results so far for WP 5 *Dissemination*.

Overall objective of the project is a prototype airbag system -evaluated according to the Beyond NCAP protocols of Euro NCAP- which is available in 2012. The introduction of the system in the vehicle fleet, depending on the interest from automotive manufacturers and consumers, is possible from 2015.

The main components of the project are:

- A study into the effectiveness of an airbag for all vulnerable road users, compared to other solutions, automatic braking and an airbag dedicated for pedestrians.
- Drawing up the specification of a VRU airbag, including the detection system.
- The development of an airbag and detection system prototype. The aim is to assess the feasibility and reliability of such an airbag.
- An important part of the detection system development consists of a sensor field test in a crowded urban environment. During this test, the decision algorithm for detecting pedestrians and cyclists can be optimized. The test will likely be conducted in Amsterdam, where many cyclists and pedestrians are. The planned start of this test is October 2010, the test lasts one year.
- The evaluation of the prototype airbag, according to the Euro NCAP test procedures.

¹ VRU = Vulnerable Road User; pedestrians and cyclists.

1.1 Project organisation and partners

Within the project, a core group is defined. Members are representatives of:

- the Dutch Ministry of Transport, constituent of the project;
- the Dutch Cyclists' Union, major interest group for cyclists, one of the initiators of the project;
- Autoliv Sweden, manufacturer of automotive safety equipment, including airbags and sensor systems;
- Centraal Beheer Achmea, major Dutch insurance company, also large fleet owner;
- TNO, R&D institute, performs within this project both R&D work and project management.

Furthermore, an advisory group is formed for controversial, high level decisions concerning the VRU airbag project, see also Figure 1. The Swedish Road Authority, SRA, is part of this group, too.

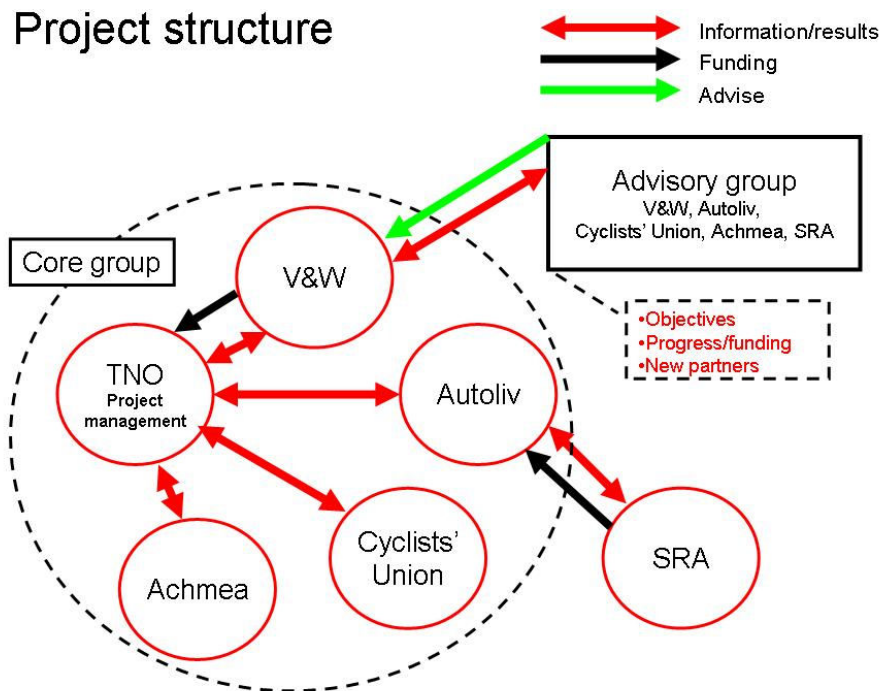


Figure 1: Project structure and partners

2 WP 1.1 Data analysis

2.1 Objective

The main objective of this task is to collect relevant accident data for cyclists' accidents. This data is required for the WP 1.2 "Effectiveness Study", WP 1.3 "Computer simulations" as well as WP 1.4 "Accident Reconstructions".

Equivalent data for pedestrians is available from other studies, such as the ESV 2009 paper *Priorities of pedestrian protection systems – a field data study of severe injuries and vehicle sources* by Rikard Fredriksson and Erik Rosén (Autoliv, Sweden) and the APROSYS project.

2.2 Activities

2.2.1 Introduction

The sensor system on the car classifies objects around the vehicle prior to an impact. To develop such a system, pre-crash information from real life accidents is very valuable. For the definition of the VRU airbag, information of the conditions during the crash, such as speed, impact locations and resulting injuries is required. TNO collected and analysed accident data as available at the accident database of Centraal Beheer Achmea. Autoliv has analysed likewise cyclist information from the GIDAS in-depth accident database and Swedish National statistical data.

To gain information for the specifications and needs of the pre-crash sensing system, for the accidents studied, it was tried to find the following accident information:

- Pedestrian / Cyclist: Age: 12+ / no skaters, lying bikes, mopeds, etc.
 - Position, if possible as function of time
 - Moving direction
 - Velocity, if possible as function of time
 - Injuries / MAIS 3+ / head and neck injuries only²
 - Head impact location
 - Location of first contact
 - Pre-crash actions: braking / steering / jumping / etc.

Aim: find out accident scenarios, including speed and actions of the pedestrian or cyclist, as well as resulting injury and injury mechanism. People too small to impact the windscreen are excluded, like people younger than 12 years.

- Vehicle
 - Passenger vehicles, mass < 3.5 ton
 - Speed: maximum 60 km/h
 - Pre-crash actions: braking / steering /

Aim: gaining insight in the accident scenarios from the vehicle side, including actions by the driver, influencing the impact speed or impact location on the vehicle. Only the interaction between the vehicle and the VRU is studied, not any potential interaction with infrastructure parts.

² Maximum Abbreviated Injury Score

- Road
 - Location: Urban, Rural
 - Situation: crossing, bicycle lane, etc.
 - Surface / friction /obstacles
 - Condition: wet / dry / day / night

Output: Specifications and supporting information for:

- Optimal sensor opening angle
- Detection distance
- Obstacle definitions
- Path prediction

2.2.2 *Achmea data*

Introduction

The archive of the Dutch insurance company Achmea is set up differently than an in depth database such as GIDAS. The Achmea archive includes all data Achmea needs to handle the claims of their clients. Per case the following information might be available:

- The European Accident Report (“Europees schadeformulier”) filled by all parties involved in the accident. This document is normally filled in on spot, hence this information is available for almost all cases.
- Police reports, available for most serious accidents.
- Medical reports for serious injured victims.
- Additional information of the involved parties such as lawyer reports and letters with a detailed description of the accident.

All this information³ is only available in an electronic system, based on scanned paper documents. Only a very limited query is possible to find specific cases.

TNO and Autoliv together developed a methodology to collect and analyse the data; both the Achmea data and the data from GIDAS and Swedish national data. A dedicated Excel sheet was developed.

Data collection

- **First option: Collect all data**

Initially it was the objective to investigate all cases available in the Achmea archive, following the following approach:

1. Selection of cases related to article 185 of the Dutch law. These are all cases which involve minimal one vulnerable road user: pedestrian or cyclist. This selection was carried out a by Achmea, resulting in a list with all related cases given to TNO for further investigation. About 1000 cases per year were found to fulfil this requirement.
2. From this list the cases with cyclists involved were selected by hand. It was not possible to filter out all cyclist cases based on an electronic filter mechanism.

³ Several practical requirements such as screening of the TNO staff as well as Achmea ICT preparations needed to be fulfilled before TNO staff had an efficient access to the Achmea archive. The requirements were bases on the stringent policy of Achmea to protect the privacy of their clients.

3. From all selected cases left, the main specifications (accident type, velocity, etc.) were recorded in the developed Excel sheet. For all cases as many parameters listed in paragraph 2.2.1. as available in the archive files were recorded.

The following remarks need to be made:

- As the total claim procedure can take more than 12 months, the collection has been initially limited to cases from 2008 and older, to be sure that the procedure has been finalized and all information is available in the archive.
- The marked share of Achmea in the Netherlands is about 25%, hence the Achmea archive can be regarded as representative for the Dutch traffic situation.
- Many visits to various Achmea locations in the Netherlands were needed to collect the required information.
- Interim analyses of the data, over 600 cases are analysed, show that only a very limited number of cases fulfil the general requirements of paragraph 2.2.1. and that of these cases only a very limited number had an injury level of MAIS 3+.

Based on this information it is concluded that likewise continuation of data collection is very inefficient and time consuming. Therefore, the option 2 approach is followed.

- **Option 2 Fatal and serious injured data**

- Achmea makes a selection of Article 185 cases with killed or seriously injured vulnerable road users.
- TNO investigates this set of selected cases using the developed methodology.

2.2.3 *GIDAS data*

The available data in the GIDAS database was collected and analysed by Autoliv, using the Excel sheets as developed in cooperation with TNO. The interim results as discussed with TNO during a telephone meeting on November 12th, 2009 are presented in Attachment A: “Cyclist real-life data – Germany and Sweden / Preliminary analysis”

2.3 Results

Interim results of the data collection activities were needed to define the baseline accident scenarios for task 1.3 “Computer simulations” and task 1.4 “Accident reconstructions”. As the most detailed information was available from the GIDAS database and the Swedish National statistics, the accident scenario’s for task 1.3 and task 1.4 are mainly based on this information. However the interim results of the Achmea data confirmed in general terms the information of GIDAS, especially regarding urban crossing situations. The high number of rear end impacts on rural roads however is not confirmed by the Dutch data. The Dutch situation with a lot of bicycle lanes separated from rural roads most probably results in a significantly lower number of this type of accidents.

Nevertheless, based on the European scope of the project, the rear end impacts are included in the scenario specifications of task 1.3 and task 1.4.

2.3.1 *GIDAS data*

Based on GIDAS information four baseline accident scenarios are proposed. The main characteristics of these scenarios are presented in

Figure 2. These four scenarios are representative for 75% to 90% of all serious cyclists' accidents with passenger vehicles in Sweden and Germany.

The four scenarios are used as input for task 1.3 and task 1.4, with the following remarks:

- For scenario 2 an angle of 30° instead of 20° between bicycle and vehicle is used to cover as many as possible relevant accident situations.
- All tests and simulations, for scenarios 1, 2 and 4 is carried with a ratio between bicycle and vehicle speed of 1:4.
- Two different cyclists are used: an average male, represented either by a 50th percentile Hybrid III dummy or a 50th percentile male human model and a 10 year old child represented either by a P10 dummy or 5th percentile female human model.

Proposed impact configurations

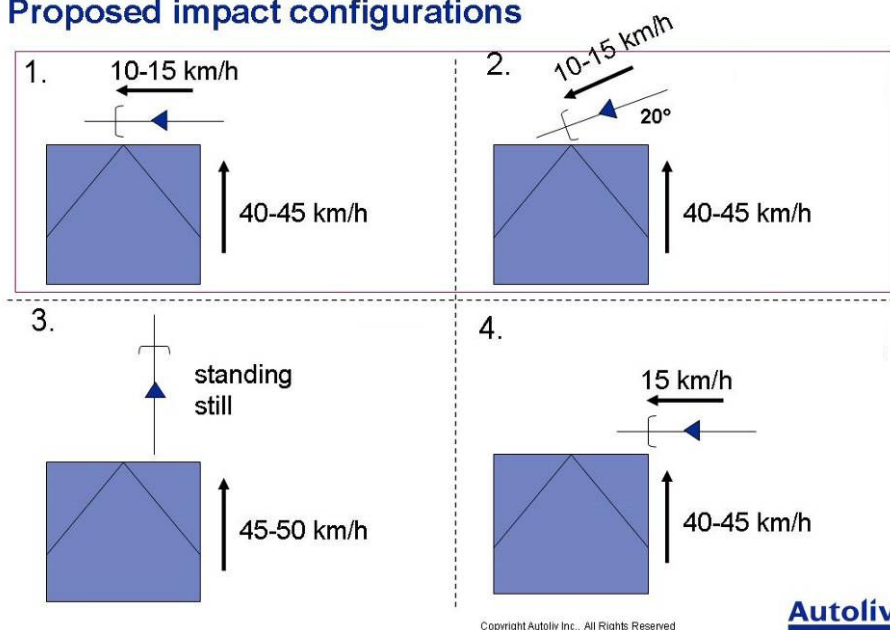


Figure 2: Baseline accident scenarios

3 WP 1.2 Effectiveness study

3.1 Objective

The objective of the effectiveness study is

a well thought-out estimation of the potential effectiveness and benefits of a VRU airbag in comparison to other solutions (automatic braking and a pedestrian airbag).

This effectiveness study compares:

- the number of fatalities and
- the number of severely injured Vulnerable Road Users (pedestrians and cyclists).

The effectiveness is regarded for the following scenarios:

- if no safety systems specific to VRU's are deployed (reference scenario),
- if automatic braking is deployed,
- if the pedestrian airbag (covering only the lower part of the windscreen) is deployed,
- if the VRU airbag (covering the full windscreen) is deployed.

This effectiveness study focuses on the situation in the Netherlands. The accident data used originated from two accident databases:

1. the Dutch database BRON (containing all police registration information),
2. the German in-depth database GIDAS, for in-depth accident information.

The first database is used as base, enriched with the second database.

3.2 Methodology

The effectiveness methodology is applied only to cases in a dedicated target group. This target group is obtained by a filtering procedure in which all cases in which the countermeasures would not have been effective are removed. For the filtering procedure see Figure 3.

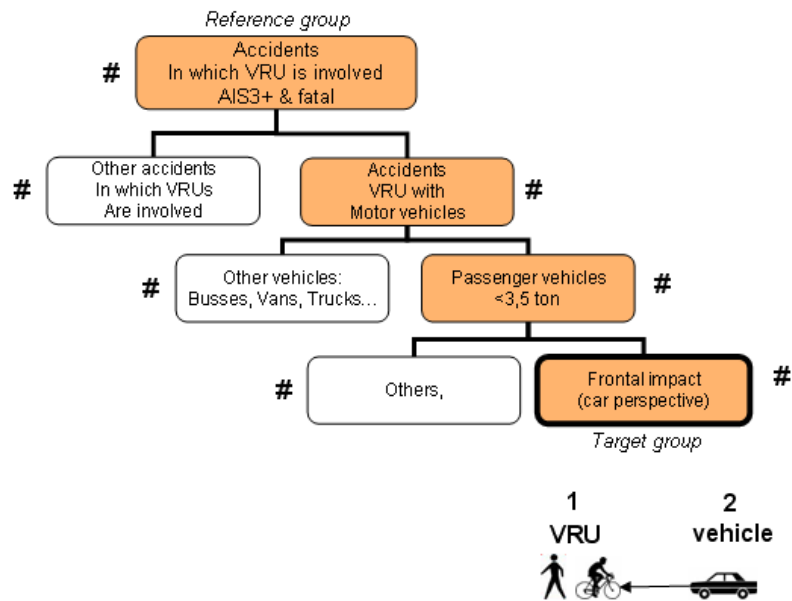


Figure 3: Tree structure for filtering out target group

The basis of the effectiveness methodology (also see Figure 4) is a tree structure in which all relevant accident conditions are captured.

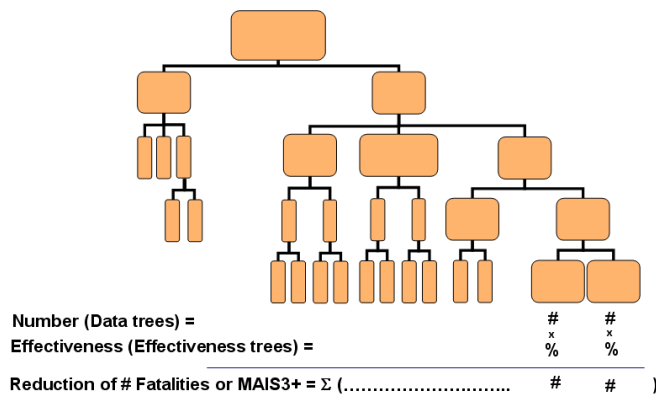


Figure 4: Schematic representation of the effectiveness approach

The effectiveness methodology procedure is as follows:

1. Firstly, the relevant conditions are placed in different levels of the tree. The levels of the tree correspond to the factors determining the effectiveness of the airbag (see Figure 5)
2. Secondly, information from databases (BRON & GIDAS) is used to fill the tree with casualty data. This shows under which condition the most injuries/fatalities are inflicted
3. Thirdly, the extent to which the countermeasure will be effective for VRU protection are estimated and put in the tree, where effectiveness is defined as the percentage of the VRU's who would NOT die or would NOT get severely injured as a result of the countermeasure

- By multiplying the numbers of the second step with the percentages of the third step (at each level) the reduction of the number of fatalities or severely injured people is estimated. This step assumes independence between levels in the tree.

Figure 5 shows the tree structure applied to both the data and effectiveness trees (as referred to in step 1, 2 and 3) with its categories and branches. Due to practical reasons the category of the branches are only specified once. Detailed information on the structure of this tree and the figures belonging to the data- and effectiveness trees can be found in TNO report TNO-033-HM-2010-00695/2.

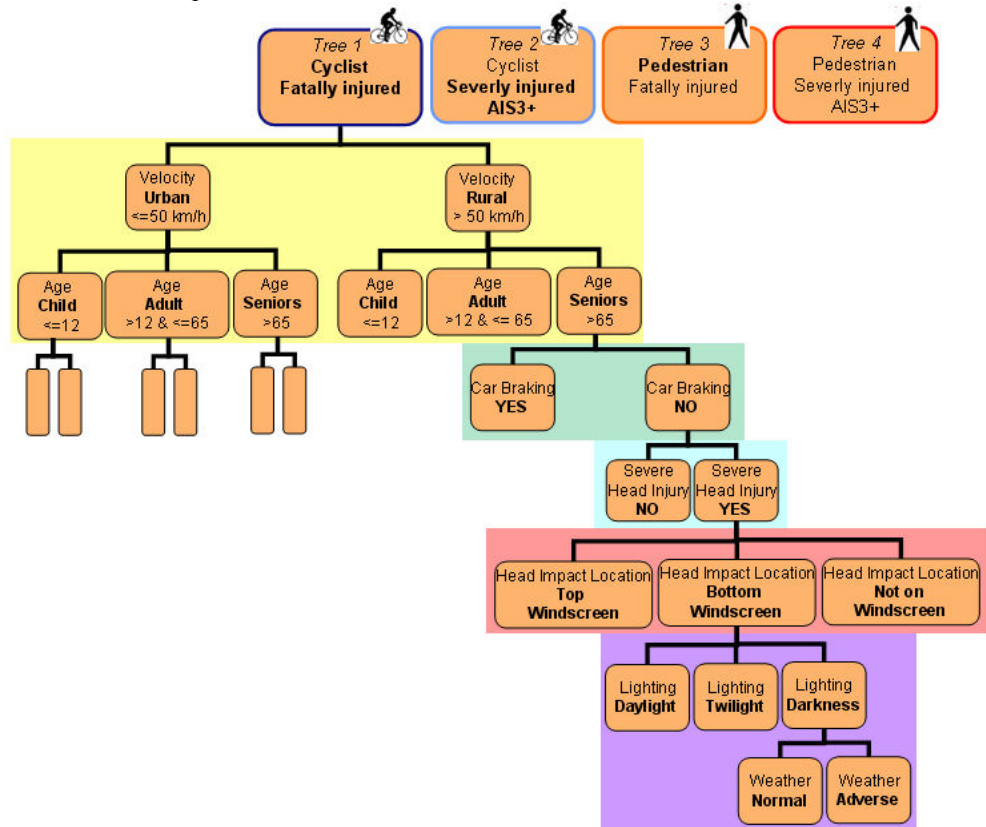


Figure 5: Specification of the branches and cells of the tree structure of the data and effectiveness trees

3.3 Results

In this study the potential effectiveness of 3 countermeasures (VRU airbag, pedestrian airbag and automatic braking) to improve VRU safety is investigated for two categories (severely injured and fatally injured VRU's). The effectiveness is expressed in the reduction of the number of fatally and severely injured VRU's. The numbers give an indication of the potential that can be reached in a future year, assumed to be 2025, see Figure 6 (Effects of e.g. penetration into the fleet will by than faded away).

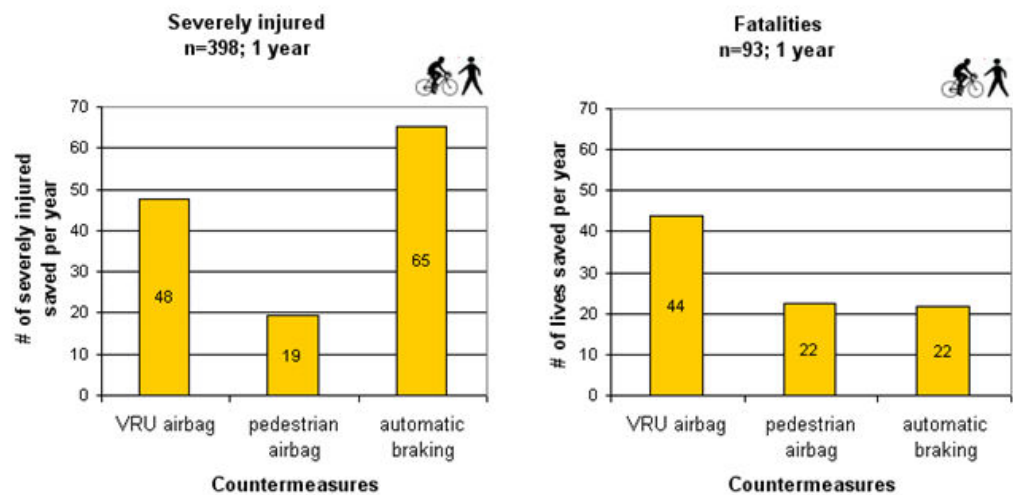


Figure 6: Number of severely injured (left) and fatalities (right) that can be saved by the three investigated countermeasures

Numbers and figures apply on the situation in the Netherlands over 1 year. The data is based on BRON data (2006-2008) and is enriched with detailed GIDAS data (1999-2008). The long period is used to increase the number of data for analysis. The results are presented as yearly figures based on multiple years of data. In TNO report TNO-033-HM-2010-00695/2 the target group is defined, containing 398 and 93 cases for severely injured and fatalities, respectively.

3.4 Conclusions

For the category **severely injured VRUs**, automatic braking is the most effective countermeasure.

Below, the countermeasures are ordered based on their effectiveness:

- automatic braking potentially reduces the number of severely injured annually in the Netherlands by 65 (16% of the target group)
- VRU airbag potentially reduces the number of severely injured annually in the Netherlands by 48 (12% of the target group)
- pedestrian airbag potentially reduces the number of severely injured annually in the Netherlands by 19 (5% of the target group.)

For the category **fatally injured VRU's**, the VRU airbag is the most effective countermeasure. Below the different countermeasures are ordered based on their effectiveness:

- VRU airbag potentially reduces the number of fatalities in the Netherlands by 44 (47% of the target group)
- pedestrian airbag potentially reduces the number of fatalities in the Netherlands by 22 (24% of the target group)
- automatic braking potentially reduces the number of fatalities in the Netherlands by 22 (23% of the target group)

All three countermeasures are roughly equally effective in reducing **pedestrian fatalities**. There are large differences among the countermeasures in reducing **cyclist fatalities**. The VRU airbag appears to be the most effective in reducing cyclist fatalities.

These conclusions are based on the following main assumptions:

- The focus is on head injuries as main cause of severe injuries and fatalities in the investigated type of accident.
- It is assumed that the injury level of fatalities and severe injuries will be reduced by the countermeasures to an injury level of maximum AIS2+. So by reducing the number of fatalities the number of severely injured is not increased.

TNO report TNO-033-HM-2010-00695/2 gives more insight in the background and the assumption made for the effectiveness calculations.

3.5 Recommendation

The potential of the three countermeasures examined in this study merits further investigation in the areas of system development of these and other countermeasures, as well as impact assessment on a European and world-wide scale.

4 WP 1.3 Computer simulations

In order to investigate the functional specifications of a windshield airbag more knowledge on path prediction is needed especially for the cyclist. In literature insufficient data can be found on parameters as maximal steering and the combination of steering and braking which are possible for a (normal) cyclist. Therefore an experiment is performed (see Figure 7) to get more insight in these aspects. The use of this experiment is to describe the possible bicycle path area of cyclists 2-3 seconds prior to possible impact with car heading straight forward.



Figure 7: Example of maximal steering.

4.1 Literature Study

The first step of the simulation study consists of a literature review on information on cyclists' kinematics and bicycle range of motion. Table 1 shows the relevant documents found in literature. The main key words used for the investigation are:

- Bicycle / Cycle / Bicycle dynamic,
- Bicycle / Cycle / Bicycle kinematic,
- Bicycle / Cycle / Bicycle simulations
- Fahrrad / Rad Kinematik,
- Fahrrad / Rad Bewegungsfreiheit,
- Bicycle / Cycle / Bicycle range of motion,
- Fietsgedrag.

Table 1: Relevant documents found in literature

APROSYS reports on cyclists and pedestrian safety: AP-SP311-001R-BASC
AP-SP311-002P-CHA: Presentation at APROSYS-SP3 WP3.1, The 3rd Technical Meeting in Brussels, Statistics Analysis of Pedestrian and Cyclist Accidents
AP-SP311-003P-DC: DC-Working Aprosys„Pedestrians“ Pedestrian Accident Analysis for Germany, Brussel, 14th September, 2004
AP-SP311-004P-INS: Presentation: National epidemiology analysis on pedestrian and pedal accidents (APROSYS)
Gösele-Koppeburg, A., Jenoure, P., Farkas, G. "Massenausdauersportarten Mountainbicycle – Verletzungen und Überlastungsschäden" SportOrthoTrauma 24, 143-148, 2008

Hendel, K., Asch, M., Parsche, U. „Dynamiksimulation eines Fahrradfahrer – Sturzes“, Technische Mechanik, Band 15, Heft 2, 119-128, 1995
Martens, K., “The bicycle as a feeding mode: experiences from three European countries”, Transportation Research Part D 9, 281-294, 2004
Martens, K., “Promoting bicycle-and-ride: The Dutch experience”, Transportation Research Part A 41, 326-338, 2007
Meijaard, J.P., Papadopoulos, J.M., Ruina, A. “Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review”, For Proc. R. Soc. A. 463, 2007
Schulzyk O., Bongartz, J. Bildhauer, T., “A Bicycle Simulator Based on a Motion Platform in a Virtual REality Environment – FIVIS Project”, Advances in Medical Engineering, 323-328, 2007
Shan, G., “Biomechanical evaluation of bicycle power saver”, Applied Ergonomics 39, 37-45, 2008
Stone, M., Broughton, J., “Getting off your bicycle: cycling accidents in Great Britain in 1990-1999”, Accident Analysis and Prevention 35, 549-556, 2003
Wesson, D., Spence, L., Hu, X., “Trends in Bicycling-Related Head Injuries in Children After Implementation of a Community-Based Bicycle Helmet Campaign”, Journal of Pediatric Surgery, Vol. 35, No 5, 688-689, 2000
Wood, J., Lacherez, P., Marszalek, R., “Drivers’ and cyclists’ experience of sharing the road: Incidents, attitudes and perception of visibility”, Accident Analysis and Prevention 41, 772-776, 2008
Zeegers, T. “Vrouwelijk ontwerpen”, Ketting 194, 2009

Though some information is found, the major outcome of this study is that hardly any suitable literature is available on this topic. Most documents listed above only contain very limited information suitable to carry forward for prediction of possible cyclist location and motion 2-3 seconds prior to a possible car-to-bicycle crash. Hence a volunteer experiment is conducted to obtain the boundary conditions for the bicycle path prediction described in the following section.

4.2 Bicycle path prediction; a MATLAB study

This section describes a brief volunteer study done to establish general bicycle range of motion for 3 different speeds, as well as a MATLAB simulation study to determine the area where a bicycle is able to be situated within 2-3 seconds before a possible impact when being ridden at these 3 different speeds. The last part of this section contains an additional task to the initial work plan: a brief investigation of crash possibilities for a car heading straight forward and a cyclist approaching this car perpendicular considering the previous determined path area for the cyclist.

4.2.1 Volunteer study (no impact)

4.2.1.1 Experimental setup

A normal bicycle (Gazelle) is used for this experiment. The road (normal asphalt) on which the experiment took place is estimated to have a friction coefficient between 0.5 and 0.8. Three volunteers of average posture (1 female, 2 male) perform five actions (with a short pause between each action):

1. Maximal steering to the left
2. Maximal steering to the right
3. Maximal braking
4. Maximal steering to the left and braking
5. Maximal steering to the right and braking

Each of these actions is performed at three velocities:

- 7.5 km/h,
- 12.5 km/h
- 17.5 km/h

This resulted in 45 tests. Each volunteer is asked to approach a line A. A perpendicular, visible, line B is followed by the volunteer, see Figure 8. The moment line A is reached with the front tire of the bicycle the specified action must be performed.

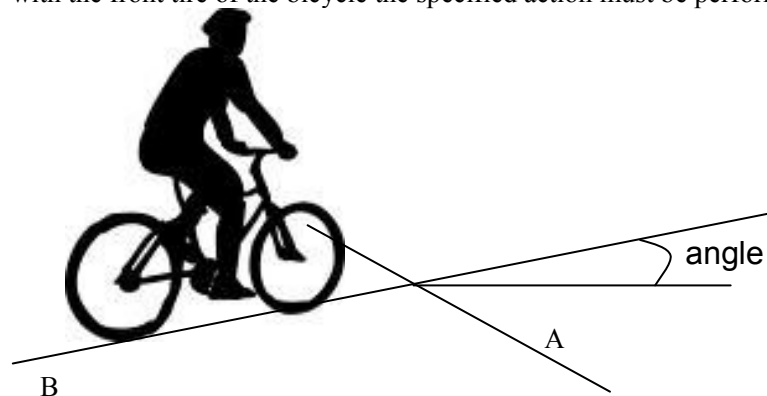


Figure 8: Line definitions and angle definition.

The angle is defined as the minimum between the line B and the tires of the bicycle. Lines on the asphalt representing several angles (in steps of 10 deg) are used to determine the angle by vision. These angles can be compared to sensor data afterwards. An X-sens sensor is attached to the exterior luggage rack. This sensor measures linear accelerations (in three directions), angular velocities as well as magnetic fields. The magnetic fields are used to determine Euler angles of the sensor (this is done with software provided with the sensor). Two camera's (frontal and lateral) are positioned as shown in Table 2.

Table 2: Camera position information.

	Frontal camera [cm] (from A in the direction of B)	Lateral camera [cm] (from B in the direction of A)
Left turn	912	1008
Right turn	580	970

4.2.1.2 Maximal steering – On-spot results

During the tests the angles which are reached (approximately) are noted. The average angles for each velocity are shown in Table 3. The measured angles and the total averages are shown in Figure 9.

Table 3: Average steering angles

Velocity (km/h)	Left steering angle (deg)	Right steering angle (deg)
7.5	42	52
12.5	32	37
17.5	25	27

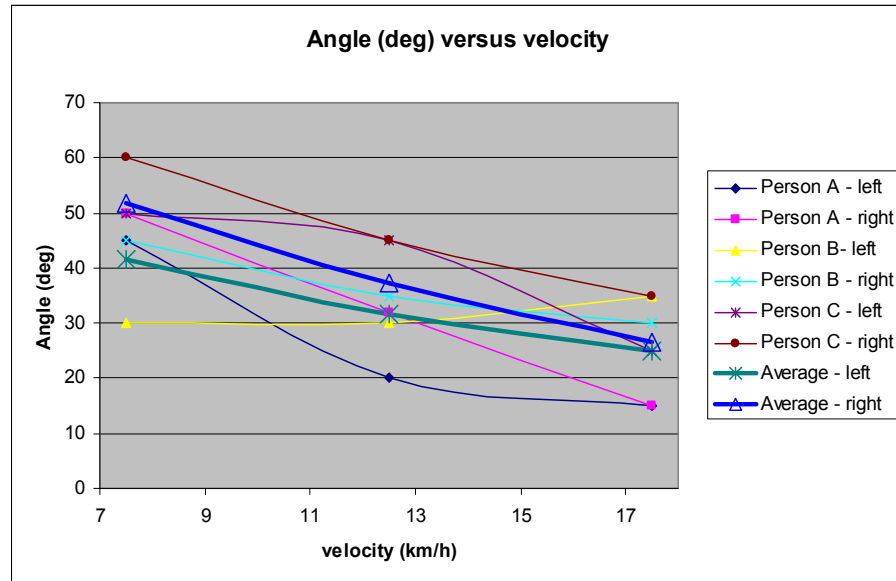


Figure 9: Angles versus velocity

4.2.1.3 Maximum steering - Measurement results

The measurements which are done with the X-sens are presented in this paragraph. The coordinate-system of the X-sens is defined as shown in Figure 10.

The angles for volunteer A, at a velocity of 7.5 km/h are shown in Figure . Note that the z-axis is not perpendicular to the asphalt, because the roll-angle (rotation about x-axis) does not equal 0. Therefore a coordinate translation might be needed. This translation is:

$$\alpha_z = \beta_z \cos(\beta_x) + \beta_y \sin(\beta_x)$$

in which α_z represents the angle mapped onto the asphalt and β represents the measured angles (x: roll, y: pitch, z: yaw). However, for a velocity of 7.5 km/h the roll angle is negligible. The same accounts for a velocity of 12.5 km/h.



Figure 10: Definition of the coordinate system of the X-sens.

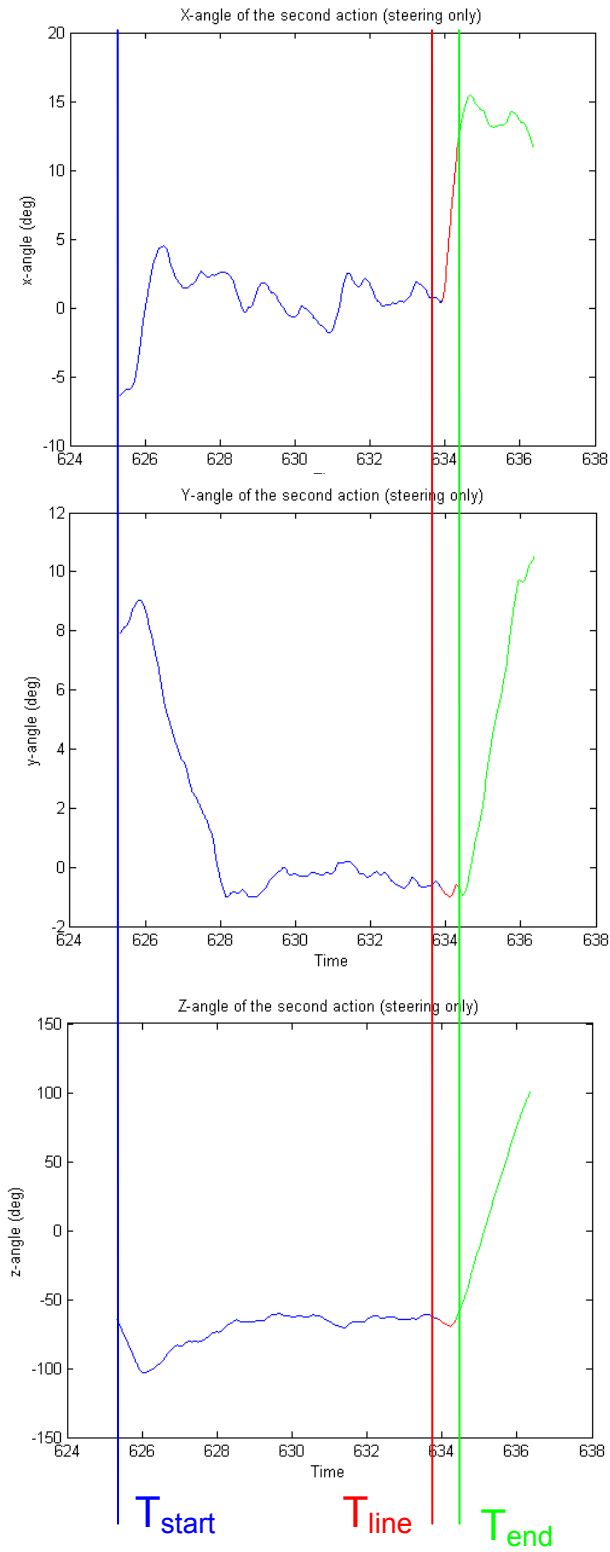


Figure 11: Angles during the traject for volunteer A, velocity 7.5km/h.

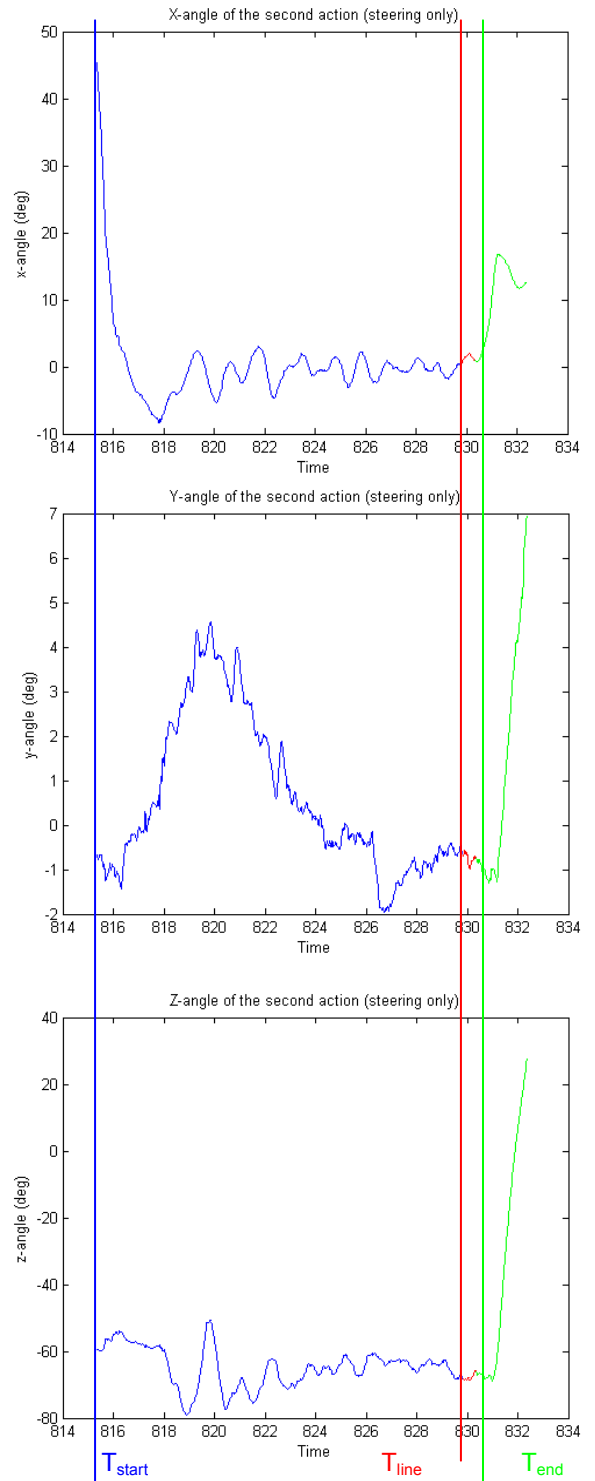


Figure 12: Angles during the traject of volunteer A at a velocity of 12.5 km/h.

The start time of the manoeuvre is very important but also very hard to define, due to the fact that also small movements of the bicycle are recorded. Therefore, the start of the manoeuvre can only be estimated by using the sensor data. The videos are used to clarify the timing, though the synchronization of the video towards the X-sens data is also challenging. Some examples of results are shown in Figure and Figure .

4.2.1.4 Maximal braking

The second action consisted only of maximum braking, while going straight. It should be noted that the braking path is in general dependent on the bicycle used. All tests are performed on the same bicycle, so the differences in obtained braking paths between the three volunteers are caused by the person only.

Table 4: Average braking paths.

Velocity (km/h)	Braking path (m)
7.5	0.61
12.5	1.31
17.5	2.85

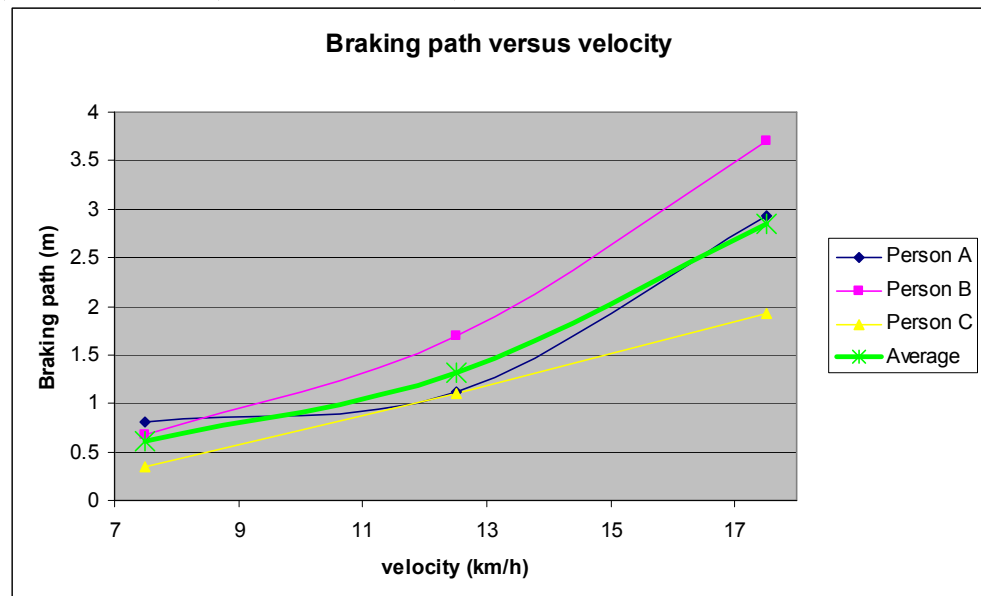


Figure 11: Braking paths versus velocity.

The average deceleration for each velocity is shown in Table 4. This deceleration is calculated by assuming it to be constant. In this way the time of the deceleration trajectory could be determined by:

$$t = d / (0.5 * v)$$

In which d represents the distance and v the velocity.

This time is needed to calculate the deceleration using

$$a = 2 * (x - vt) / t^2$$

in which a equals the deceleration, x the distance (between front wheel and line), v the velocity and t the time between crossing the line with the front wheel till standing still. Note that the velocity used for the calculation should be in m/s instead of km/h.

Table 5: Average deceleration.

Velocity (km/h)	Deceleration (m/s ²)
7.5	3.6
12.5	4.6
17.5	4.1

4.2.1.5 *Maximal steering and maximal braking*

Two measurements were performed while maximal steering and maximal braking: the angle and the braking path. The averages are shown in Table 6 and Table 7, respectively. The results are summarized in Figure 12 and Figure 13.

Table 6: Average steering angles while maximal braking.

Velocity (km/h)	Left steering angle (deg)	Right steering angle (deg)
7.5	47	47
12.5	38	40
17.5	34	36

Table 7: Average braking paths while maximal steering.

Velocity (km/h)	Braking path while left steering (m)	Braking path while right steering (m)
7.5	0.86	0.85
12.5	1.56	1.65
17.5	2.62	2.53

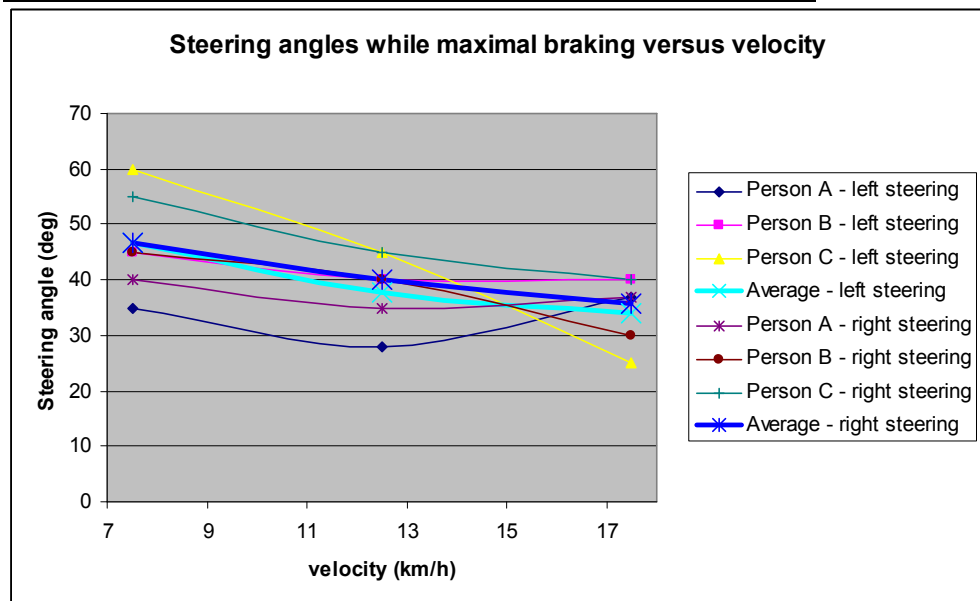


Figure 12: Steering angles while maximal braking.

The average deceleration is shown in Table 8.

Table 8: Average deceleration while steering.

Velocity (km/h)	Deceleration while steering to the left (m/s ²)	Deceleration while steering to the right (m/s ²)
7.5	2.5	2.6
12.5	3.9	3.7
17.5	4.5	4.7

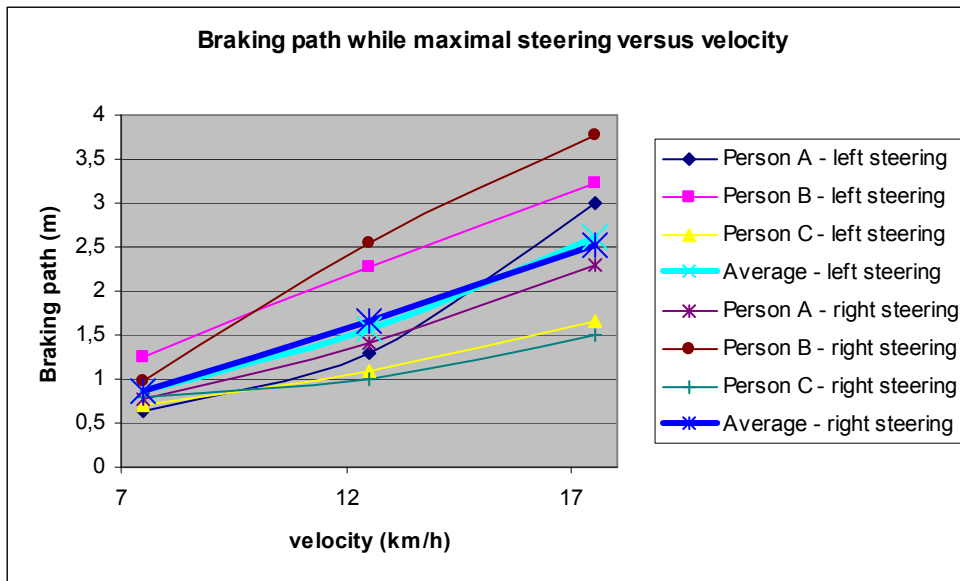


Figure 13: Braking path while maximal steering.

4.2.2 Discussion volunteer study

The limitations of this work are:

- The number of volunteers (3) is not representative for *all* cyclists. Nevertheless one volunteer was more experienced on the mountain-bicycle, thus leading to a better representation of the cyclist population.
- In case of a crash, steering and braking might be more extensive, however, this could not be verified due to the nature of the study.
- The velocity is determined based on a speedometer mounted on the bicycle which is considered to have limited accuracy only. However it can be assumed that each cyclist was between the intervals 5-10 km/h, 10-15 km/h and 15-20 km/h for the velocities 7.5 km/h, 12.5 km/h and 17.5 km/h, respectively.
- Each cyclist was asked to start the action in question when the front tire crosses the line on the asphalt. This timing might not be very accurate. Also the approach angle might not be exactly reached.
- The deceleration reached is also dependent on the bicycle, so some variation should be added in here as only one bicycle was used for the study.

The advantage is that this method is a quick way to obtain on-field-data which so far was not available in e.g. literature.

This experiment is considered to provide valid information on which areas can be reached by a cyclist, depending on the velocity.

4.2.3 Prediction of a bicyclist path

This section presents the results of an algorithm to predict the possible path area of a cyclist in a timeframe of 2 seconds prior to a possible impact with a car. The inputs presented in section 4.2.3.1 are based on the experimental results described in section 4.2.1. The algorithm itself is shortly explained in section 4.2.3.2. The results are shown in section 4.2.3.3.

4.2.3.1 Inputs

The fixed parameters which are needed for the algorithm are:

- the maximal steering angle
- the maximal deceleration.

The cyclist experiment is performed at three different velocities (7.5, 12.5 and 17.5 km/h). The results for the steering angle and deceleration are summarized in Table 9 and Table 10.

Table 9: Average results for steering angle (deg).

v (km/h)	Without braking		With braking	
	L	R	L	R
7.5	42	52	47	47
12.5	32	37	38	40
17.5	25	27	34	36

Table 10: Average results for deceleration (m/s²).

v (km/h)	Without steering	With steering	
		L	R
7.5	3.6	2.5	2.6
12.5	4.6	3.9	3.7
17.5	4.1	4.5	4.7

In order to predict the position where the bicyclist can be during 2 seconds before possible impact, it is chosen to use the maximal steering angles and the maximal decelerations (as marked in bolt) since these gives the largest area in which a bicyclist can be, so the reliability of the algorithm is maximal. For this same reason, the distinction between braking with steering and braking without steering is not made.

The maximal acceleration is given by the Dutch Cyclists' Union and equals 1 m/s². This value is used for all velocities.

The variable inputs for the algorithm are:

- the velocity in x-direction (vx) and the velocity in y-direction (vy),
- the x position and the y position.

The angle of the direction in which the cyclist is going to can be calculated as follows:

$$\alpha = \arctan(vy/vx)$$

4.2.3.2 Algorithm to predict path area

Path area is defined as the area in which a cyclist can be during 2 seconds

The following needs to be determined:

- The radius of the outer circle which a cyclist can reach when accelerating with 1 m/s².
- The radius of the inner circle which a cyclist can reach when maximal braking.
- The radius of the circles when turning left and right.
- The angle of lean, which is the angle between the vertical and the line between tire-contact position and centre of mass of cyclist and bike.
This will be explained further on.

A. Radius of outer circle when accelerating with 1 m/s²:

The path which can be achieved equals:

$$x_{acc} = x_0 + \cos(\alpha) * (v_0 + \Delta t * acc) * \Delta t$$

$$y_{acc} = y_0 + \sin(\alpha) * (v_0 + \Delta t * acc) * \Delta t$$

The radius thus equals:

$$r = \sqrt{(x_{acc} - x_0)^2 + (y_{acc} - y_0)^2}$$

B. Radius of inner circle when maximal deceleration:

The path which can be achieved equals:

$$x_{dec} = x_0 + \cos(\alpha) * (v_0 - \Delta t * dec) * \Delta t$$

$$y_{dec} = y_0 + \sin(\alpha) * (v_0 - \Delta t * dec) * \Delta t$$

The radius thus equals:

$$r = \sqrt{(x_{dec} - x_0)^2 + (y_{dec} - y_0)^2}$$

C. The radius of the circle when turning left and right:

The radius which describes the path to the left or right can be calculated from the measured angle as follows (see Figure 14):

$$r = BL * \cos(\alpha) / \sin(\alpha) = BL / \tan(\alpha)$$

in which BL equals the bicycle length (1.13m) and α the measured angle.

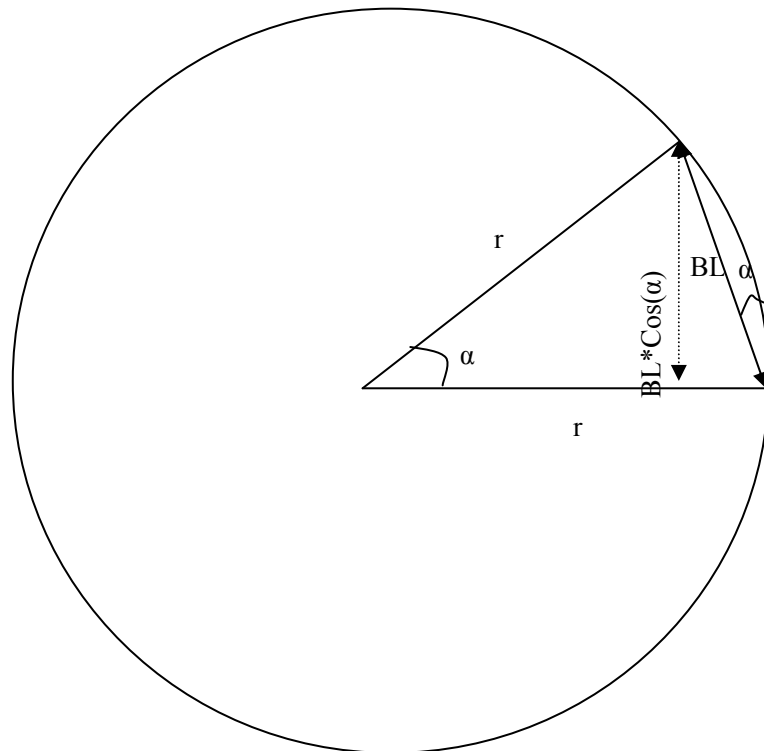


Figure 14: Calculation of radius based on angle

D. The angle of lean:

The angle of lean (θ) as shown in Figure 15 can be calculated as follows:

$$\theta = \arctan(mv^2 / mgr) = \arctan(v^2 / gr)$$

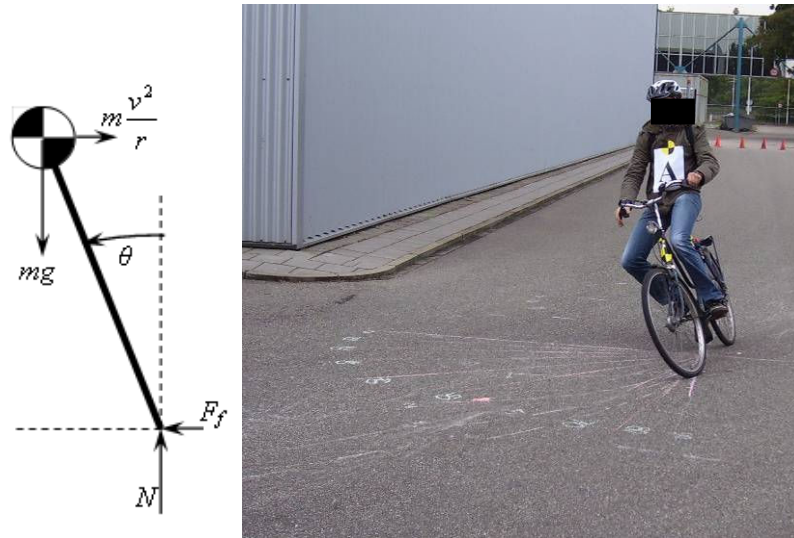


Figure 15: Definition of the angle of lean.

Since the maximal angles obtained often occurred during braking, the velocity during the steering is averaged.

4.2.3.3 Results

Figure 16 to Figure 18 show the possible path area for a timeframe of 2 seconds. The pink line represents the maximal circle which a cyclist is able to reach when accelerating 2 seconds with 1 m/s^2 , the green line predicts the circle at which a cyclist will be when his velocity is constant, the black line shows the circle where a cyclist will be when maximal braking occurs. The blue lines show the radius of maximal steering. Finally, the red line shows the path of a non braking non steering cyclist. Please note, that all circles are cut of at ± 90 degrees to increase readability of the figure.

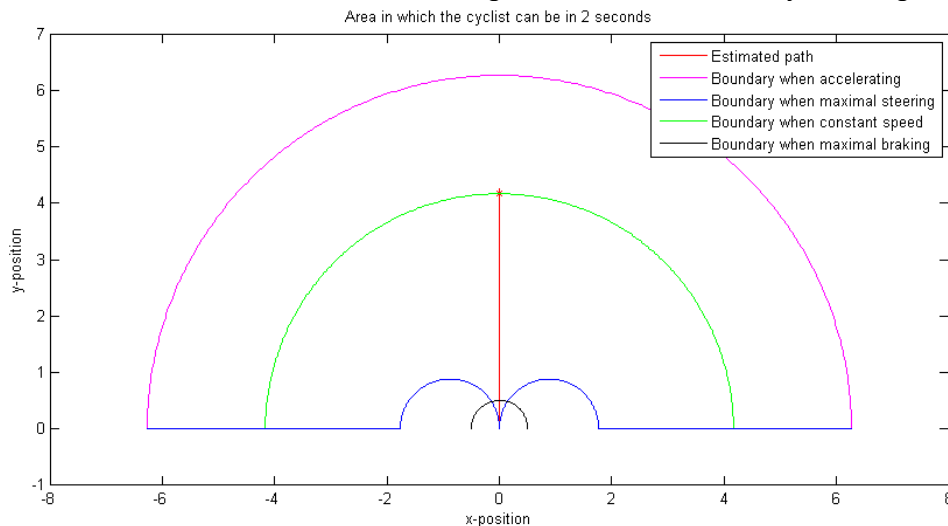


Figure 16: possible path area of a cyclist for a velocity of 7.5 km/h

The maximum angle of lean equals 18.9 deg.

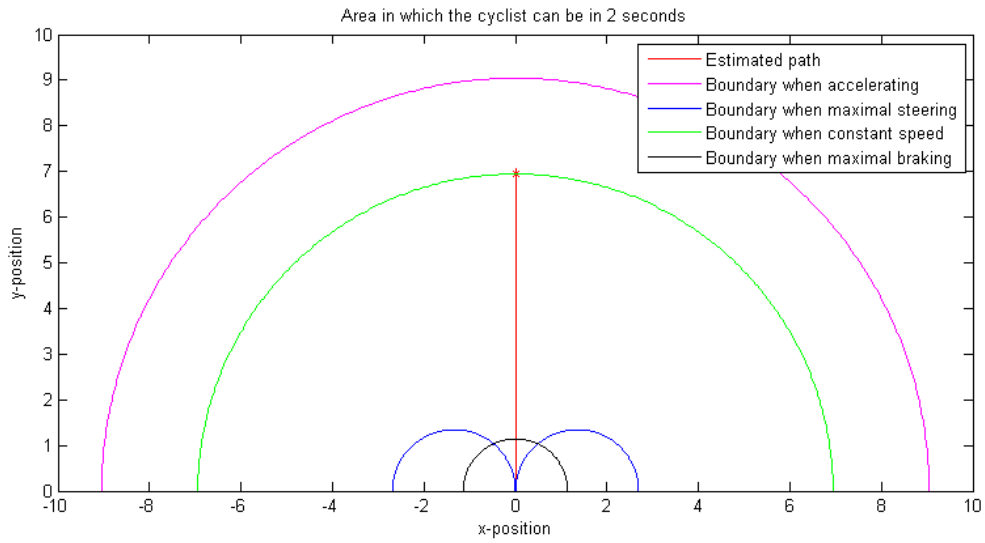


Figure 17: possible path area of a cyclist for a velocity of 12.5 km/h

The maximum angle of lean equals 18.3 deg.

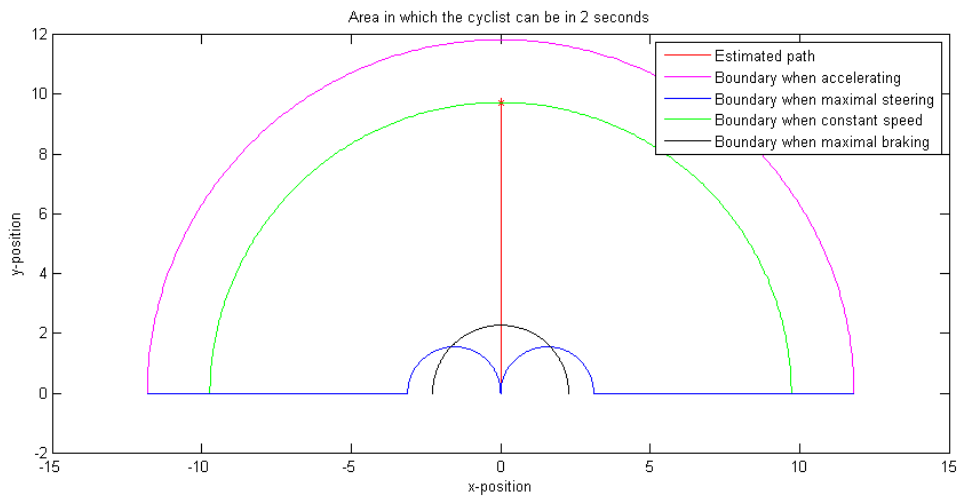


Figure 18: possible path area of a cyclist for a velocity of 17.5 km/h

The maximum angle of lean equals 38.0 deg.

In Table 11 the radii found in Figure 16 to Figure 18 are listed.

Table 11 radii found in Figure 16 to Figure 18

	7.5 km/h	12.5 km/h	17.5 km/h
Smallest turn	0.9 m	1.3 m	1.6 m
Breaking	0.5 m	1.1 m	2.3 m
Constant speed	4.2 m	6.9 m	9.7 m
Accelerating	6.3 m	9.0 m	11.8 m

4.2.4 Simplified determination of crash possibility between car and bicycle

An algorithm is developed to determine the collision probability between a car and a bicycle. The inputs are the velocity (x and y) and position (x and y) of bicycle and car. The output is the collision probability at time T for positions at which the collision probability >0.

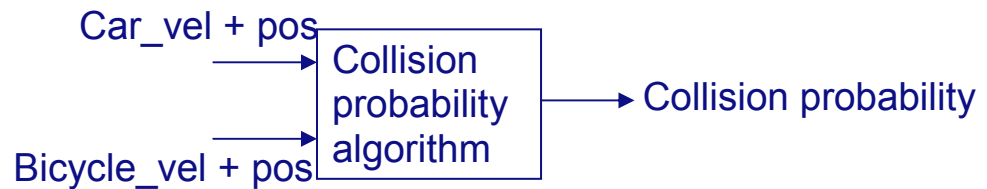


Figure 19: Schematic view of collision probability algorithm.

The algorithm assumes that the technical inputs on the behaviour of a cyclist and car are known (max angle/dec/acc). For the cyclist the data obtained from the experiment is used. An example of the inputs and outputs of the algorithm is shown below, based on a time interval of 2s. For the car the boundary for maximal braking is assumed to be 8m. The boundary for maximal acceleration is assumed to be 20m. The inputs for the cyclist are:

- positions $(x,y)=(8,-20)$
- velocity $(v_x,v_y)=(2,5)$

An example of the scenario of this algorithm is shown in **Error! Reference source not found.** The outcome of this algorithm is shown in Figure 21. The interpretation of this figure is as follows: the location (x,y) is shown on the x and y axis. The collision probability at those positions is shown on the z-axis. The maximum collision probability equals $2.0798e-005$ and occurs at position $(11.4;-10.1)$. Note that this probability is still very low, which is due to the fact that the car and cyclist can both still reach a large area in 2 seconds time.

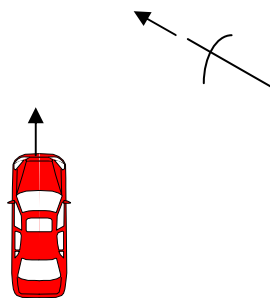


Figure 20: Example input scenario

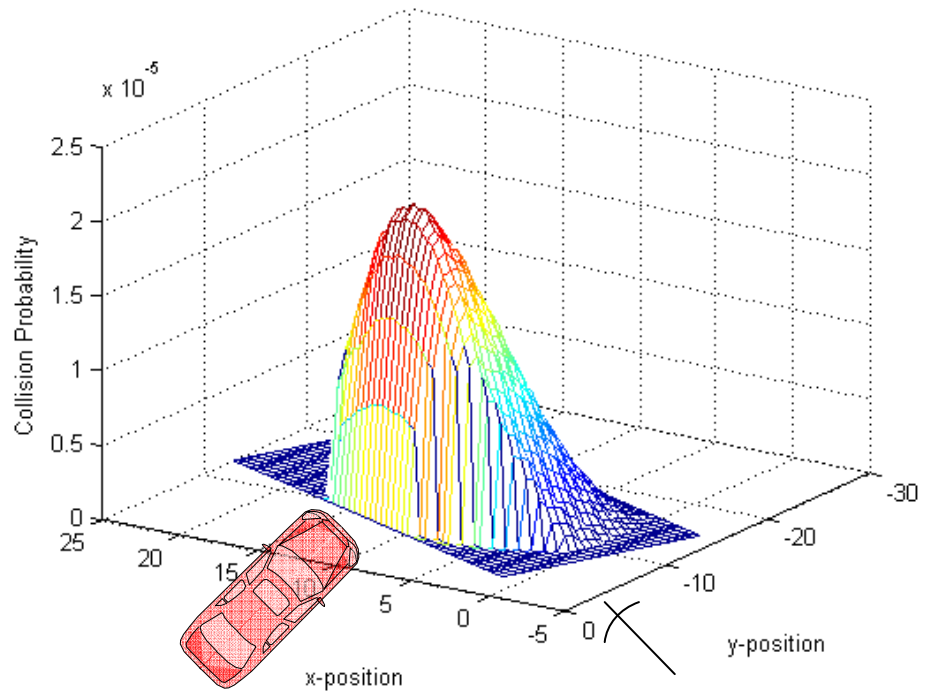


Figure 21: Collision probability between bike and car in specific scenario.

4.3 PreScan simulation study

In a last step, the simulation software PreScan⁴ is used to obtain movies of selected pre-crash scenarios. As base for the scenario selection, the preliminary test-matrix from WP 1.4 as presented in Table 12 is used.

Table 12 Preliminary test – matrix for the accident reconstruction performed in WP1.4

Test number	Configuration	Vehicle speed	Bike speed	Angle	Bike	pedal position	Impact point	Dummy
x11	1	45	11.25	90	man	vertical	central	HIII
x12	1	45	11.25	90	man	horizontal	central	HIII
x13	1	60	15	90	man	vertical	central	HIII
x14	1	45	11.25	90	female	vertical	central	P10
x21	2	45	11.25	120	man	vertical	central	HIII
x22	2	45	11.25	120	man	horizontal	central	HIII
x23	2	60	15	120	man	vertical	central	HIII
x24	2	45	11.25	120	female	vertical	central	P10
x31	3	50	0	0	man	vertical	central	HIII
x32	3	60	0	0	man	vertical	central	HIII
x41	4	45	11.25	90	man	vertical	-1000 mm	HIII
x42	4	60	15	90	man	vertical	-1000 mm	HIII

⁴ PreScan is a desktop simulation software tool that supports in developing intelligent vehicle systems. It runs on a normal Windows PC and it has strong interface with the “industrial standard” Matlab/Simulink

As so far no sensor is specified to detect a cyclist on the road, for this study no sensor is implemented into the PreScan set-ups. Instead, a human view looking straight forward is implemented for both, car driver and cyclist. However, with given specifications a sensor could still be implemented into the simulations at a later stage to investigate its performance in the chosen scenarios.

For each of the crash scenarios in Table 12, 4 pre-crash scenarios are evaluated:

- 1 No reaction of the cyclist
- 2 Cyclist heading straight forward braking
- 3 Cyclist turning at minimum angle to the left (no braking)
- 4 Cyclist turning at minimum angle to the right (no braking)

The following assumptions are made:

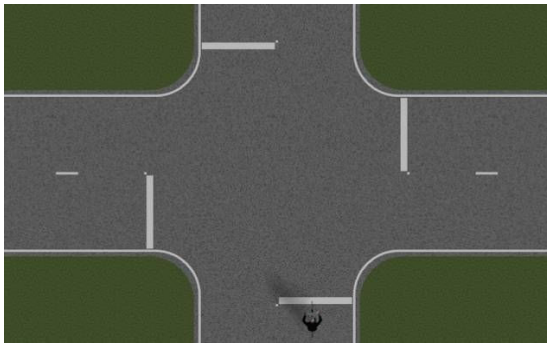
- No pre-crash action of the car (no braking / accelerating / steering)
- Only simulation of the pre-crash behaviour.
- The accident happens at a plain crossing. No environment (buildings, traffic signs, trees, other cars or pedestrians) is visible
- Scenario 1 forms the base scenario for Scenario 2 to 4. This means that all 4 simulations would end in the same accident configuration as determined in Table 12 in case no pre-crash action would be undertaken by the cyclist.
- Within PreScan only one cyclist and one bicycle is available. Therefore test x14 as well as x24 is neglected.
- Within PreScan the cyclist is pedaling and the pedaling can not be tuned towards a vertical or horizontal pedal position for the impact. Hence, test x12 as well as x22 is neglected.
- For test x31 as well as x32 no pre-crash action can be simulated as the bicycle speed is set to 0. In order to obtain a suitable test scenario anyway, scenario 1 is simulated with an initial bicycle speed similar to test x12 and x14. No other pre-crash scenario is considered as the cyclist can be considered unaware of a possible accident.
- When this study was carried out, no final specifications were so far determined for the offset tests x41 and x42. Therefore these are neglected for this analysis.
- For all braking scenarios the maximum deceleration are kept at 3.6 m/s^2
- For all turning scenarios the smallest turn radius is kept at 1.3 m ($\cong 12.5 \text{ km/h}$ bicycle velocity results)

These assumptions and boundary conditions lead to the following simulation matrix:

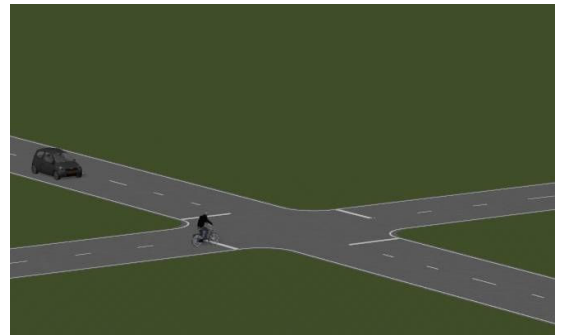
Table 13 Simulation matrix for PreScan

Test number	Pre-crash action	Vehicle speed	Bike speed	Angle	Bike	Impact point	No. simulations
x11	none, braking, left turn, right turn	45	11.25	90	man	central	4
x13	none, braking, left turn, right turn	60	15	90	man	central	4
x21	none, braking, left turn, right turn	45	11.25	120	man	central	4
x23	none, braking, left turn, right turn	60	15	120	man	central	4
x31	none	45	11.25	0	man	central	1
x32	none	60	15	0	man	central	1
Total							18

For each simulation 4 videos are recorded:



View 1: Top view



View 2 Isometric view



View 3: Driver view



View 4: Cyclist view

4.3.1 Results

In each of the four situations where the cyclist can be aware of the oncoming car (x11, x13, x21 and x23) the cyclist is able to avoid the accident still 2 seconds prior to the expected impact. Both, emergency braking as well as emergency steering of the cyclist lead to an avoided accident when initiated early enough even though the car driver is not acting. It is shown that in the chosen experiments the cyclist was even able to avoid the accident with the car front up to a TTC (Time To Collision) of 0.55 seconds in the best case (Scenario x13) and get parallel to the side of the car. It should however be noted that in this situation though the primary accident is avoided the car is still likely to get in contact with bicycle at least causing the cyclist to fall.

5 WP 1.4: Accident reconstruction

5.1 Objective

This section describes the accident reconstruction activities and results. The accidents that are reconstructed resolve most often in fatal or severe injuries for cyclists across Europe. It is chosen to reconstruct the accidents for two reasons:

1. Since the accidents are reconstructed in a controlled environment a lot of knowledge is gained how an accident actually develops.
2. In accident reconstructions it is possible to determine what the sensors in the fascia of the test vehicle measure during the accident.

The main goal of the accident reconstruction is to generate data necessary for the development of the VRU airbag specifications.

5.2 Test setup

The accident reconstruction is performed at TÜV Rheinland TNO Automotive International B.V. (TTAI). For all tests, the test vehicle is a Volvo V70. After each test the bumper, with accelerometers, is replaced. If necessary the hood, energy absorber, windscreen, head lights and/or metal structure behind the bumper are also replaced. The bumper and energy absorber are instrumented with 13 and 3 unidirectional accelerometers, respectively. On the right side of the bumper 4 accelerometers are placed in the lateral direction of the vehicle, determining the lateral accelerations of the impact between cyclist and vehicle.

For each tests a new bicycle is used. All bicycles are made and delivered by Batavus. The cyclist is represented by a Hybrid III, the 50th percentile male dummy. The dummy is 175 cm tall and has a mass of 78.15 kg. The Hybrid III dummy is equipped with a standing pelvis, which ensures that the dummy is able to sit on a bicycle. Numerous spare parts are used to replace dummy parts that are damaged during the accident. The moments and accelerations of the neck and the accelerations of the head of the dummy are measured. Numerous parts of the dummy and bicycle are painted in order to determine the initial impact point of those parts after each test. The pedal axis of the bicycle is painted yellow, the left foot, left ankle and head of the dummy are painted red, blue and green, respectively. The accidents are recorded with three high speed cameras; one top view, one view perpendicular to the bicycle and one view perpendicular to the vehicle. The cameras record with 1000 frames per second. The test setup is schematically shown in Figure 22.

The vehicle and the construction that is around the bicycle are accelerated with a pulley. A gear ratio of 1 or $\frac{1}{4}$ is used between the vehicle and the construction around the bicycle to ensure different speeds. The construction pushes the bicycle forward. Two meter in front of the sled track, which pulls the vehicle forward, the construction that is around the bicycle is decelerated to stand still with the use of crumble tubes, and the bicycle, with dummy, is driving the final meters completely alone. About one second after the vehicle and bicycle collide the Volvo V70 is decelerated by wirelessly activating the brake pedal.

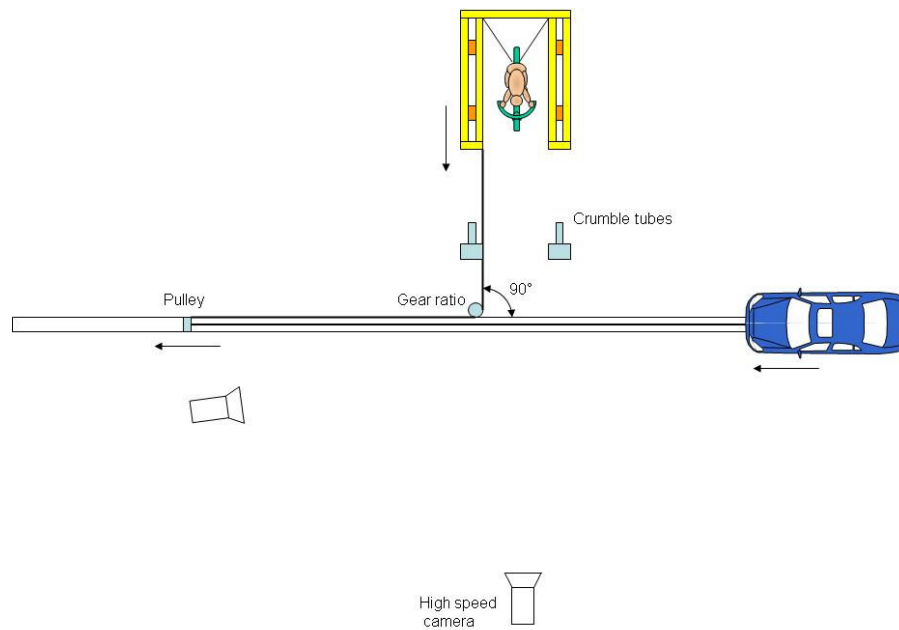


Figure 22: Test setup of the accident reconstruction for the 90° angle accidents

5.3 Test description

In total 12 accidents are reconstructed. In Table 14 all tests are specified.

Table 14: Desired test description of the accident reconstruction

Test	Vehicle speed [km/h]	Bike speed [km/h]	Angle [°]	Biker	Impact point
1	20	0	90	Male	Centre of vehicle – centre of bicycle
2	20	0	90	Male	Pedal at impact side is 500mm left of centre
3	20	20	90	Male	Front wheel of bicycle hits between sensor +440mm and +660mm
4	45	11.25	90	Male	Centre of vehicle – centre of bicycle
5	45	11.25	90	Female	Centre of vehicle – centre of bicycle
6	45	11.25	90	Male	Pedal at impact side is 700mm left of centre
7	45	0	0	Male	Rear tire of bicycle is 350mm right of centre of vehicle
8	50	0	0	Male	Rear tire of bicycle is 350mm left of centre of vehicle
9	45	11.25	120	Male	Centre of vehicle – front wheel bicycle
10	55	13.75	90	Male	Centre of vehicle – centre of bicycle
11	20	0	120	Male	Pedal at impact side is 500mm left of centre
12	55	0	0	Male	Rear tire of bicycle is 350mm right of centre vehicle

5.4 Results

In this section the results of the tests are analyzed. In general the difference between the desired impact point and the actual impact point is within 20 mm. Only the impact point of test 6 is less accurate, compared to the other tests. In test 6 the impact point is 430 mm off. This test is not re-done, since it gives relevant information what the sensors measure when the first impact point is between the sensors that are 220mm and 440mm out of the centre of the vehicle. The difference between the desired velocity and the actual velocity of both vehicle and bicycle is within 1 km/h for all tests. In Table 15 all actual measured speeds and impact points are shown. The wrap around distance of the impact point of the head of the Hybrid III dummy is measured as well. The wrap around distance is the distance from the ground over the hood of the car to the impact point of the head of the dummy.

Table 15: Actual test description of the accident reconstruction

Test	Actual vehicle speed [km/h]	Actual bike speed [km/h]	Wrap around X/Y [mm]	Actual impact point [mm]
1	20.05	0	--/--	Pedal impacts 115 mm left of centre
2	19.84	0	1800/560	Pedal impacts 486 mm left of centre
3	19.87	20.98	2000/560	Front wheel impacts 535 mm left of centre
4	44.33	11.09	2120/-200	Pedal impacts 150 mm left of centre
5	44.33	10.95	2200/-200	Pedal impact 100 mm left of centre
6	44.32	10.94	2400/-520	Pedal impacts 270 mm left of centre
7	45.16	0	2310/-275	Rear wheel impacts 365 mm right of centre
8	49.98	0	2480/390	Rear wheel impacts 365 mm left of centre
9	44.20	10.91	2500/670	Front wheel impacts 35 mm left of centre
10	54.62	13.61	2000/0	Pedal impacts 115 mm left of centre
11	20.01	0	1920/640	Pedal impacts 490 mm left of centre
12	54.96	0	2480/410	Rear wheel impacts 365 mm left of centre

As an example, in Figure 23 the impact location of test 4 is illustrated, both on the vehicle and cyclist.

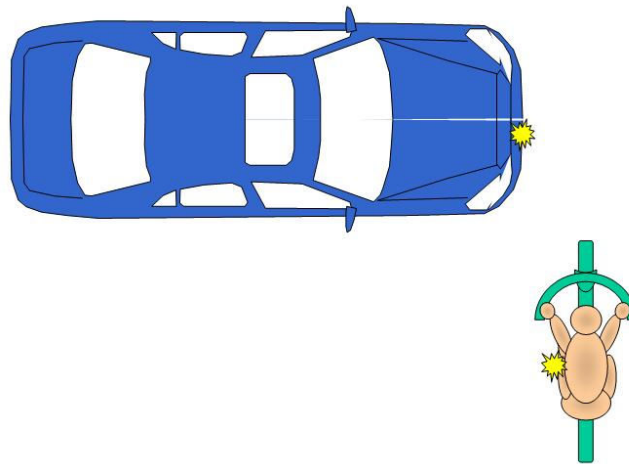


Figure 23: Impact point of test 4

The first point of impact of the cyclist is at the pedal. In Figure 24 an overview is shown of the collision between cyclist and vehicle from the high speed camera that is perpendicular to the vehicle. A time span of 240 ms is shown, which is the most important part of the impact. During this time the head of the dummy impacts with the windscreen of the vehicle.

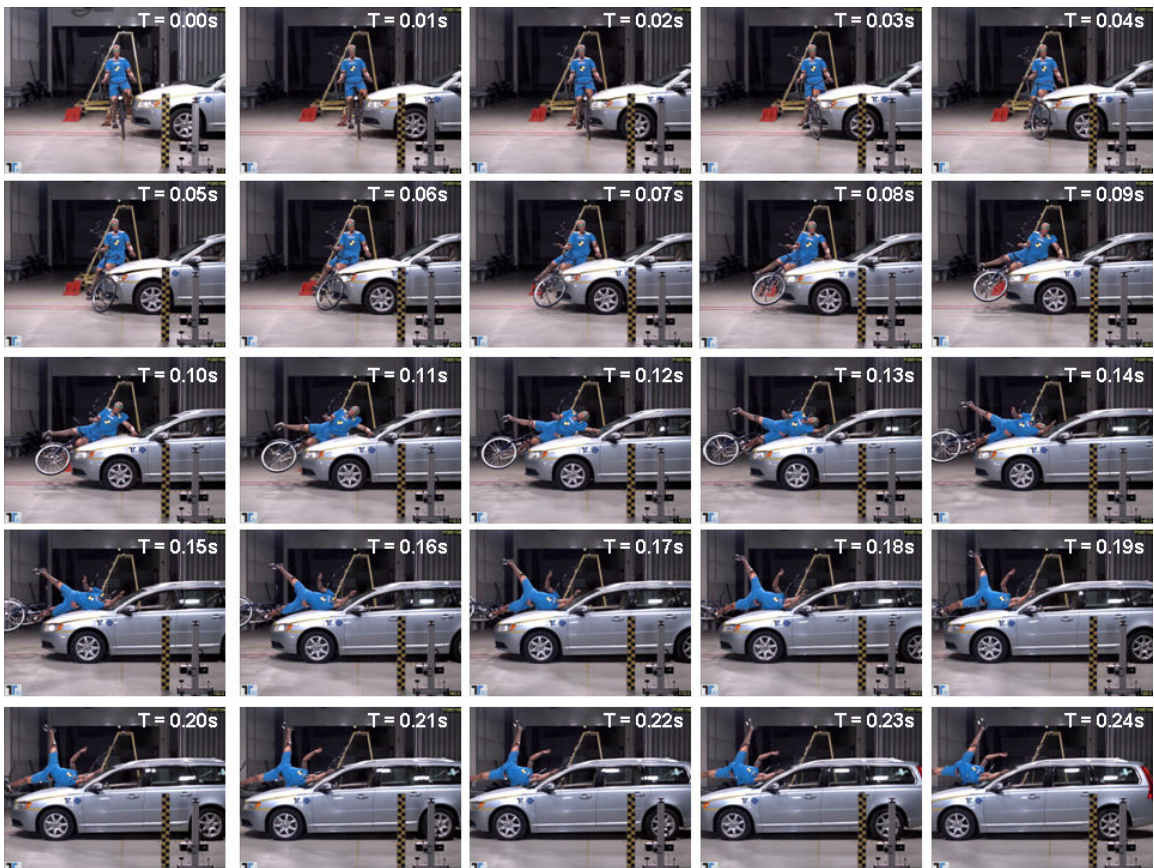


Figure 24: An overview of the collision for the duration of 240 ms

In Figure 25 the color markings of the bicycle and dummy are shown.



Figure 25: The color markings for the initial impact point of the bicycle and dummy

In the left part of Figure 25 the yellow, red and blue markings of respectively the pedal axis, foot and ankle are shown. In the right figure the impact location of the head on the windscreen is shown. Since the green marking is difficult visible, a white circle is added to illustrate the initial impact point of the head. In Figure 25 is also shown how the measurements of Table 15, e.g. impact point and wrap around distance in X- and Y-direction, take place. In Figure 26 the signals of the accelerometers in the bumper are shown.

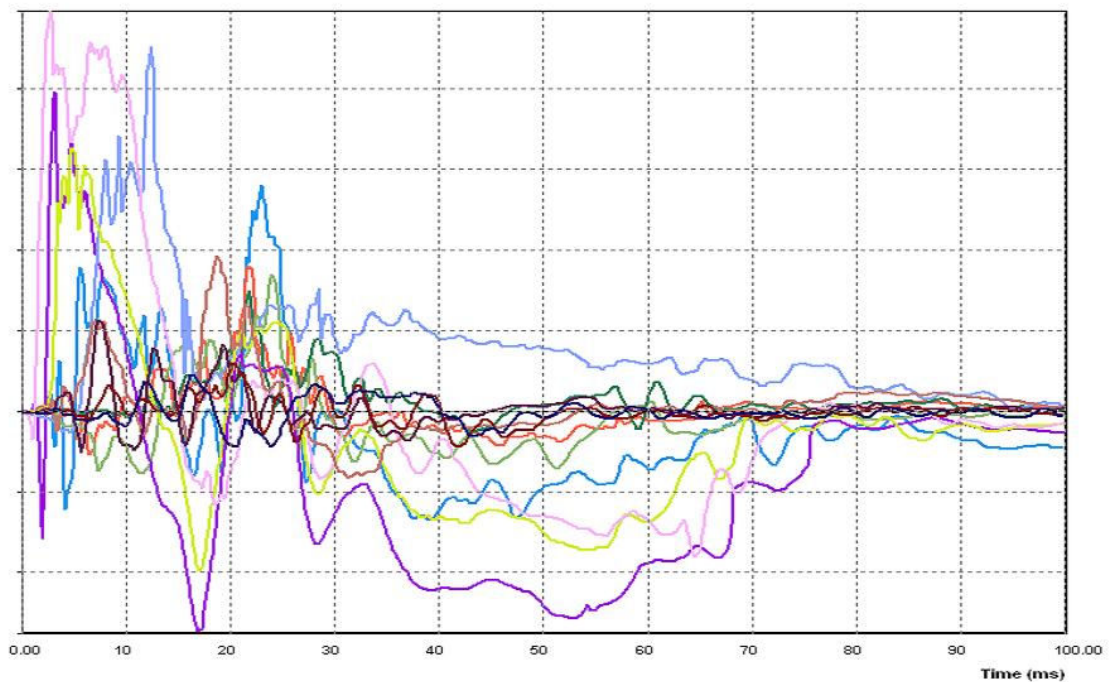


Figure 26: The signals of the 12 accelerometers of test 4

Accelerometers at and near the middle of the bumper measure the first large accelerations, since the first impact between vehicle and cyclist is between those two sensors. After roughly 12ms another large acceleration is measured. The time delay of 12ms is due two reasons; the curvature of the bumper and the impact point is no longer the pedal, but the bicycle frame and rear wheel.

The test results described in this chapter are compared to test results of reconstructed accidents between pedestrians and vehicles at Autoliv. The results show that the acceleration signals of both pedestrians and cyclists are very similar. As such, it should be possible to detect both pedestrians and cyclists with the same sensors. Though,

detecting impact with a cyclist is more complicated than detecting impact with a pedestrian. The first contact with a pedestrian is practically always the leg, while the first contact with a cyclist can be the pedal, wheel, frame or leg. To verify the influence of different impact locations more testing will be necessary in the future, which ensures that a robust algorithm is designed for detecting both pedestrians and cyclists. The future testing is divided into two parts of the next phase of the project:

1. the sensors, which are being developed by Autoliv, will be tested in VeHIL. VeHIL is a laboratory that is able to test vehicle hardware at a safe, efficient and accurate way;
2. crash testing with a POLAR dummy at TTAI, with sensor-and-airbag system implemented in the test vehicle. A polar dummy is used for a better resemblance of an actual kinematics of a cyclist. It normally is used in pedestrian testing.

Additional testing will take place in-house at Autoliv with dummy and bicycle, which is similar of set up to the tests performed at TTAI. Specific component impacts, e.g. a leg and parts of the bicycle, will be tested as well.

6 WP 1.5 Functional system requirements

6.1 Sensor specifications

To trigger to airbag the vehicle has to be equipped with two sensor systems; a pre-crash sensor for the detection and classification of vulnerable road users and an in-crash contact sensor (accelerometers) for the actual firing of the airbag system.

6.1.1 Pre-crash sensor

Based on the results of the WP 1.1 *Data analysis* and in cooperation with Autoliv experts the draft specifications for the pre-crash sensor are:

Sensor type	Stereo vision camera <ul style="list-style-type: none"> • Provides 3D image information <ul style="list-style-type: none"> ○ More cues/possibilities for object detection than single camera systems • Provides ranging measurements <ul style="list-style-type: none"> ○ Less dependent than a single camera system on the pre-defined object attributes such as width and height • Two cameras are able to validate each other. • Robust solution
Opening angle	40°
Detection range	30 meter
Mounting	Behind rear view mirror, fixed on the windscreen
Remarks	<ul style="list-style-type: none"> • The number of visible pedestrians as function of detection range and opening angle at 1 second before a potential impact are presented in Table 16. Source: GIDAS database analyzed by Autoliv. • The number of visible cyclists, based MAIS3+ cases. Source: GIDAS database analyzed by Autoliv. • Based on the current available technology these specifications are the best option for this combined long-range and short range application. • During the SFT specifications may be updated based on the recorded results

Pedestrian coming from the left or right side		$\beta = 20^\circ$		$\beta = 40^\circ$		$\beta = 60^\circ$	
		N	% (N=174)	N	% (N=174)	N	% (N=174)
Detection Range	15 m	55	31,6%	104	59,8%	111	63,8%
	30 m	91	52,3%	152	87,4%	159	91,4%
	45 m	95	54,6%	156	89,7%	163	93,7%

*Total opening angle

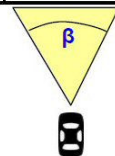


Table 16 Total opening angle with fully visible pedestrians coming from the left or the right side.

6.1.2 *In-crash sensor (accelerometers)*

During WP 1.4 *Accident reconstruction* an array of accelerometers was installed in the bumper of the test vehicle to detect the impact between vehicle and cyclists in various crash conditions, such as speed, impact angle and impact location. For more detailed information about the tests see chapter 5.

Analysis by Autoliv shows that their decision algorithm was able to detect the cyclist, based on the recorded accelerometer signals, in all tests. However, the locations of the accelerometers and the decision algorithm are dependent of the vehicle type and bumper specifications. For the vehicle type selected as demonstrator for the airbag project, the accelerometer locations should be defined and an number of accident reconstruction tests should be repeated to tune the decision algorithm, based on the knowledge resulting from WP 1.4.

6.2 Airbag specifications

Based on the results of WPs 1.1 and 1.2 the VRU airbag should cover the complete windscreen during an impact with a pedestrian or cyclist.

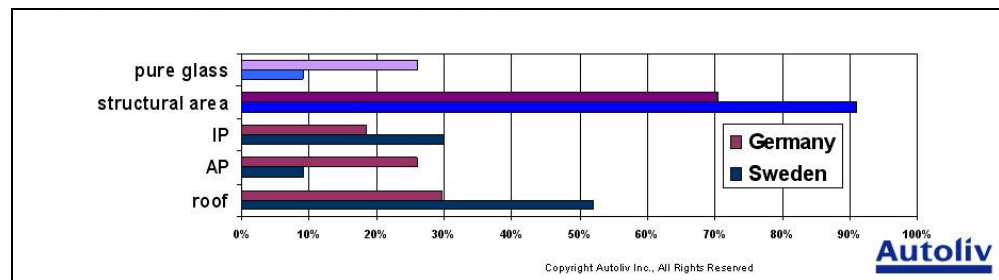


Figure 27: Head impact locations

The head impact locations of fatal and serious cyclist's accidents are presented in Figure 27. Based on this information the airbag design should focus on covering the structural parts and the glass area directly in contact with these structures.

Based on WP 1.4 *Accident reconstruction* the airbag should be fully deployed at about 100 ms after impact and stay stable for minimal 500 ms. All impact during the test series were between 120 and 350 ms. However this timing is highly related to the vehicle front geometry and should be specified for the demonstrator test vehicle when it is made available.

7 WP1.6 Specification of the Sensor Field Test

7.1 Objectives

The main objective of the Sensor Field Test (SFT) is to establish and minimized the number of “false positives” (FP) of a pre-crash VRU sensor system. A “false positive” is a situation that the sensor system predicts incorrectly a potential impact with a pedestrian or cyclist.

The pre-crash sensor system can be used:

- In combination with a in-crash sensor (bumper contact) to trigger the deployment of a windshield airbag
- As stand alone system to trigger pre-crash automatic braking systems.

Based on the recorded results, the sensor decision algorithm can be updated every three months during the SFT, to reduce the risk on FP's. Autoliv's target for risk on FPs follows industry practice.

7.2 Test set up

The SFT will be carried out with 5 test vehicles during a 12 month test period, covering all seasons and weather conditions. The test vehicles will be used mainly in an area with much mixed traffic: passenger cars, cyclists and pedestrians. The driven kilometres will be translated to “average” Dutch driving kilometres, using statistical information and recorded GPS data, to establish the FP-rate based on standard travel situations.

To trigger airbag and automatic braking systems, future vehicles will be equipped with a pre-crash sensing system for the classifications of objects and to predict potential impacts situations. In case of an airbag system an additional actuator in the bumper will be installed for the actual triggering of the airbag deployment.

During the SFT only a pre-crash sensor system, a stereo vision system, will be installed in the test vehicles. The required crash sensor will be developed using laboratory tests.

During the SFT the decision algorithm will detect potential FP situations and most probably no or only a very limited number of potential impacts (“true positive” TP situations). The data of the vision system from 7 to 8 second before a FP situation and 4 to 5 seconds after this situation will be recorded onboard for further analysis by TNO and Autoliv.

7.2.1 Test vehicles

The test vehicles for the SFT will be made available by KPN, a big Dutch telephone and internet provider. The vehicles of five service engineers, operating in city centres, will be used. The service vehicles have a good technical infrastructure; enough space for logging equipment, power supply and drivers with a technical background.

The KPN services vehicles drive about 40.000 km/year, so the SFT will record data of about 200.000 km travelling, in an environment with a high level of mixed traffic.

The vehicle type will be a Volkswagen Caddy; the front structure of this vehicle type is identical to the Volkswagen Golf.

Arrangements will be made with the fleet owner about:

- installation of the test equipment, in close cooperation with TNO and Autoliv
- financing of the required down time of the vehicles during installation and update and repair

- data handling during the SFT, including update and repair actions
- driver instructions
- legal affairs.

7.2.2 *Vehicle instrumentation*

During the SFT the test vehicles will be equipped with:

- A stereo vision camera mounted on the windscreen behind the rear view mirror. The opening angle of this camera will be 40°, the range about 30 meters, as specified in paragraph 6.1.1. Autoliv will prepare and calibrate the cameras to be used in a Volkswagen Caddy
- PC based logging equipment, including power supply and hard disc storage capacity. In addition to the camera data the following data will be recorded, using CAN data and/or a reference GPS sensors:
 - vehicle velocity and acceleration
 - steering wheel angle
 - vehicle location (traffic situation / road conditions / weather conditions)
 - date and time of the recorded events, including day/night conditions.

7.2.3 *Test preparation and execution*

During the preparation of SFT the following activities will be carried out:

- writing a test protocol, including
 - test organisation, including responsibilities, legal affairs and privacy rules
 - test activities, daily, weekly, monthly
 - driver instructions (equipment handling / disk interchange if needed),
 - maintenance and repair instructions
- designing the recording and logging equipment, including an interface with the CAN-bus data and reference sensors.
- installation of the first test vehicle by Autoliv, installation of the other four test vehicles by TNO
- installation of a dedicated computer server at TNO, with about 10 TB data storage, accessible by TNO and Autoliv.

During the execution of the SFT test the following activities will be carried out:

- transfer of the recorded data from test vehicles to TNO, using WIFI and/or exchanging hard-disks.
 - at the start of the testing the transfer will be on a daily basis, as soon as the system has proved that it is reliable, the transfer will be weekly or monthly.
 - about 500 MB/event will be recorded
- TNO will store the recorded data on the dedicated computer service and will check and analyse the data quality.
- Autoliv can update the decision algorithm every three months, to improve the FP rate of the system under tests
- TNO will daily check the status of the test activities, equipment, number of kilometres, recorded intervals.
- TNO will report periodically the status of the test to the Dutch Ministry of Transport and the project partners
- TNO will carry out required maintenance and repair actions.
 - if needed Autoliv will support TNO during this activity

8 WP 1.7 Final system evaluation – specification

In the final stage of the project, the sensor and airbag system as developed in WP2 will be evaluated to confirm the “Proof of Concept” of this safety application. One complete prototype system, installed in a demonstrator vehicle, will be evaluated. The results of the WP1 activities, accident analysis, effectiveness study, computer simulations and the accident reconstruction tests, will be used for this system evaluation too, as well as the results of the WP4 Sensor Field Test and additional field tests carried out by Autoliv.

8.1 Beyond NCAP test protocol

The prototype system will be evaluated according to the Beyond NCAP protocol as developed by Euro NCAP; this protocol is public available on www.euroncap.com. The objective of the evaluation of the “Proof of concept VRU airbag” is a potential positive result according to the Beyond NCAP protocol. An official assessment by Euro NCAP is not possible as the protocol is only valid for on the market vehicles and safety applications.

The Beyond NCAP assessment protocol, based on amongst others the APROSYS SP3 activities, assesses new safety features on the following topics; per topic is described which methods and sources this project will be used for the evaluation:

- 1 Innovation
 - This part of the assessment addresses the technical description of the innovation, its originality and usability.
 - A detailed description of the system will be prepared to fulfil the requirements of this topic.
- 2 Safety issue
 - This topic scrutinises the extent of the safety problem that exists. The manufacturer should make the case that there is a safety issue which need to be addressed.
 - The results of WP 1.1 *Accident analysis* and WP 1.2 *Effectiveness study* will be used to quantify the safety issue. If possible the potential effect, for pedestrians and cyclists, for the EU27 should be estimated to fulfil the Euro NCAP requirements.
- 3 Accident Mechanism and Injury Causation
 - The evaluation report should demonstrate a clear understanding of the mechanisms which lead to accidents and injuries.
 - The results of the TNO simulation study in combination with the results of WP 1.1 *Accident analysis* and WP 1.2 *Effectiveness study* will be used to describe the accident mechanism.
- 4 Target requirements
 - This part of the assessment focuses on the safety benefit, in terms of accidents, fatalities or injuries reduced, that the airbag is targeting on a European scale.
 - The results of WP 1.1 *Accident analysis* and WP 1.2 *Effectiveness study* will be used to quantify the safety issue. If possible the potential effect, for pedestrians and cyclists’, for the EU27 should be estimated to fulfil the Euro NCAP requirements.
- 5 Test procedures and criteria
 - This topic addresses the test procedures, criteria and limits by which the performance of the airbag system was verified.

- The results of WP 1.4 *Accident reconstruction* and from WP4 *Sensor Field Test* will be used for this item.
 - Additional laboratory tests, as specified in paragraph 8.2, will be carried out to prove the overall performance of the airbag system.
- 6 Expected Benefit / Side effects
- The report should clearly quantify the expected benefit that the airbag is finally capable to deliver on a European scale.
 - Most of the required information reflects to on the market safety system. This information is not available yet for the prototype airbag system.
 - The results of WP 1.2 *Effectiveness study* will be used for an estimation of the expected benefit. If possible the effect for pedestrians and cyclists, for the EU27 should be estimated to fulfil the Euro NCAP requirements.
 - The results of WP4 *Sensor Field Test* and additional field test carried out by Autoliv will be used to describe potential side effects.
- 7 Real World Evaluation
- If available, the report should summarize the findings from real-world or simulated real-world evaluations.
 - Most of the required information reflects to safety systems available. This information is not available yet for the prototype airbag system.

The official Beyond Euro NCAP assessment is based on the scores of independent experts, the so-called assessment group, on the above mentioned topics using dedicated assessment forms.

Within the project, experts active within the project team as well as an expert not related to one of the project partners will score the available information.

8.2 Laboratory tests

The following tests with sensor and airbag system will be carried out to prove the overall performance of the airbag system.

8.2.1 *Sensor Field Test*

The results of the WP4 “Sensor Field test”, especially the results of the last 4 months of the test when the latest version of the decision algorithm has been installed in the test vehicles, will be analysed to estimate the risks of “False Positive” results.

The project target is a FP rate of $FP < 1/100.000$ km travelling in standard traffic.

The results of an additional Field test to be carried out by Autoliv, will be used to estimate the risk on “False Negative” (FN) results.

8.2.2 *Sensor tests*

The performance of the pre-crash sensor (stereo camera) and the in-crash sensor (accelerometer) will be checked with a number of laboratory tests. The final tests specifications will be based on the accident scenarios as specified in WP 1.1 *Accident analysis* which are already used for WP 1.4 *Accident reconstructions*.

Two types of tests will be used to evaluate the pre-crash sensor system:

- tests using the Autoliv test location “Carson City” in Vårgårda, Sweden. “Carson City” has been specially developed for tests with pre-crash safety systems. A number of tests with a moving vehicle against a moving and stationary pedestrian dummy will be carried out.

- tests using the TNO VeHIL laboratory in Helmond, the Netherlands. In the vehicle laboratory tests simulating pedestrian's and cyclist's accidents will be carried out.

To evaluate the crash sensor and the accelerometers mounted in the vehicle bumper, a number of accident reconstruction tests, as carried out in task 1.4 will be repeated with a demonstrator vehicle.

The results of identical development tests, carried out by Autoliv as part of the system development, will be used for the system evaluation.

8.2.3 *Airbag system tests*

Two series of tests will be carried out to evaluate the performance of the airbag systems:

- a series of head impacts tests, according to the Euro NCAP protocol, will be carried out with a deployed windscreen airbag system and, if relevant, an activated pop-up bonnet. The test results will be compared with the test results of the vehicle without airbag system.
- the four most relevant accident reconstruction tests of WP1.4 will be repeated with the demonstrator vehicle with airbag and sensor system.
The test specifications will be identical to the specifications of the previous tests but instead of a Hybrid III dummy a POLAR dummy can be used. This POLAR dummy has been specially designed for full scale tests with VRU protection systems.
These full scale tests will show the overall performance of the complete protection system.

9 Conclusions

The effectiveness study shows that

- For the category **fatally injured VRU's**, the VRU airbag is the most effective countermeasure.
Below the different countermeasures are ordered based on their effectiveness for fatally injured VRU's:
 - VRU airbag potentially reduces the number of fatalities annually in the Netherlands by 44 (47% of the target group)
 - pedestrian airbag potentially reduces the number of fatalities annually in the Netherlands by 22 (24% of the target group)
 - automatic braking potentially reduces the number of fatalities annually in the Netherlands by 22 (23% of the target group)
- For the category **severely injured VRU's**, automatic braking is the most effective countermeasure.
Below the countermeasures are ordered based on their effectiveness for severely injured VRU's:
 - automatic braking potentially reduces the number of severely injured annually in the Netherlands by 65 (16% of the target group)
 - VRU airbag potentially reduces the number of severely injured annually in the Netherlands by 48 (12% of the target group)
 - pedestrian airbag potentially reduces the number of severely injured annually in the Netherlands by 19 (5% of the target group.)
- All three countermeasures are roughly equally effective in reducing pedestrian fatalities.
- The VRU airbag appears to be the most effective in reducing **cyclist** fatalities.

The scientific background information, created by the computer simulations and accident reconstruction tests are sufficient to set up specifications for airbag and sensor system and to start the actual pre-development of such a system. The detailed output of these activities will be used during the development phase; project phase 2.

A Sensor Field Test is an essential activity during the development of the pre-crash sensor system, to be used for both a VRU airbag and automatic braking systems. The main objective of this test is to establish and minimize the number of false triggers.

Main stakeholders and national international organisations show a lot of attention for the project. The dissemination activities should be continued during phase 2 of the project, in which a demonstrator vehicle with active airbag will become available.

10 Signature

Helmond, 8 September 2010

TNO Science and Industry

A handwritten signature in blue ink, appearing to read 'V.G.M. Hendrickx', written in a cursive style.

V.G.M. Hendrickx
Head of department

A handwritten signature in blue ink, appearing to read 'M. van Schijndel-de Nooij', written in a cursive style.

M. van Schijndel- de Nooij
Author