DEVELOPMENT OF A TARGET PROPULSION SYSTEM FOR ASSESS

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ABSTRACT

The ASSESS project is a collaborative project that develops test procedures for pre-crash safety systems like Automatic Emergency Braking (AEB). One key criterion for the effectiveness of e.g. AEB is reduction in collision speed compared to baseline scenarios without AEB. The speed reduction for a given system can only be determined in real world tests that will end with a collision. Soft targets that are crashable up to velocities of 80 km/h are state of the art for these assessments, but ordinary balloon cars are usually stationary targets. The ASSESS project goes one step further and defines scenarios with moving targets. These scenarios define vehicle speeds of up to 100 km/h, different collision scenarios and relative collision speeds of up to 80 km/h. This paper describes the development of a propulsion system for a soft target that aims to be used with these demanding scenario specifications.
The Federal Highway Research Institute's (BASt's) approach to move the target is a self-driving small cart. The cart is controlled either by a driver (open-loop control via remote-control) or by a computer (closed-loop control). Its weight is limited to achieve a good crashability without damages to the test vehicle. To the extent of our knowledge BASt's approach is unique in this field (other carts cannot move at such high velocities or are not crashable).
This paper describes in detail the challenges and solutions that were found both for the mechanical construction and the implementation of the control and safety system. One example for the mechanical challenges is e.g. the position of the vehicle's center of gravity (CG). An optimum compromise had to be found between a low CG oriented to the front of the vehicle (good for driveability) and a high CG oriented to the rear of the vehicle (good for crashability).
The soft target itself which is also developed within the ASSESS project will not be covered in detail as this is work of a project partner. Publications on this will follow.
The paper also shows first test results, describes current limitations and gives an outlook. It is expected that the presented test tools for AEB and other pre-crash safety systems is introduced in the future into consumer testing (NCAP) as well as regulatory testing.

INTRODUCTION

Advanced driver assistance systems, collision mitigation systems and anti-collision systems have been part of the research community since the beginning of the last decade (see e.g. [1] p.541). They promise a sustainable decrease of road traffic fatalities all over the world. Today's production systems will apply full brake deceleration up to a few 0.1 seconds before an unevitable accident in the full speed range (see [2]), some production systems are already able to completely avoid an accident in the speed range of up to 30 km/h [3].
No manufacturer would only start selling a system before its functionaly has been validated, so all systems will have passed extensive testing with proprietary dummy targets during the development phase (see e.g. [1] p. 43). These dummy targets will have been adjusted to the sensor technology used by the specific system (see e.g. [4]).
However, there is no harmonized and universal test procedure (based on a common agreement of all stakeholders) available neither for regulatory testing (e.g. for the verification whether a system conforms to future UN ECE regulations) nor for consumer testing (e.g. Euro NCAP test procedures beyond the generic "Beyond NCAP"-procedure).
Without this, it will not be possible to compare different system designs in their functionality and liability.
This is where the EC-funded framework project "ASSESS – Assessment of Integrated Vehicle Safety Systems for improved vehicle safety" comes in (see [5]). This project, in cooperation with other initiatives, develops an integrated test methodology for advanced safety systems. Accident research leads to the definition of relevant test scenarios, test tools for the scenarios are being developed and validated, recommended adaptions for current crash test procedures are investigated, and a way to estimate the socio-economic benefit of each tested Advanced Driver Assistance System (ADAS) is proposed.
The methodology will be applicable for all kinds of systems. That means that not only will the test tools have to be compatible for different sensor technologies, but also the driver behaviour needs to be taken into accout.

This paper describes the development process for one part of the ASSESS project – one of three target propulsion systems.
The target in that context can in general be some random mock-up appearing to ADAS as a relevant vehicle. There is only one (soft-crash) target developed within the ASSESS project. The three test labs TNO, BASt and IDIADA are responsible to provide for the propulsion of that target, capable of dealing with the test scenarios defined within the project.
After a survey of available systems, BASt decided to develop a relatively simple system almost from scratch.

Development processes are usually structured according to the V-model for product development, and so is this paper. The start of all development is the definition of the requirements (what should the product do?) and validation test criteria (does it do what it should?). The next step is the definition of specifications (how will the product do that?) and verification criteria. The link between definition phase and testing phase is the implementation phase.

The development process is still ongoing by the time of paper preparation (March 2011), so no final validation can be presented.
This paper will present the requirements and specifications, briefly describe how the system is implemented, show verification results and give an outlook on validation tests. Since the topic is relatively broad, the paper will focus on the development process of a system for rear-end collisions.

REQUIREMENTS

The target propulsion system to be used within the ASSESS project needs to be able to perform the test scenarios defined within the project, as well as other scenarios that might become standard test scenarios for Autonomous Emergency Braking systems in the future. The main purpose is the evaluation of ADAS from a regulatory point of view and it is not designed for development purposes.
In particular, the system is not intended to be a multi-purpose propulsion system for complex situations with various vehicles, and it is also not intended to be operable in a fully automated test setup. Other approaches fulfil these requirements very well but are relatively complex and expensive to use for possible test labs or are not able to achieve the necessary decelerations and driving dynamics (see e.g. [6]).

Requirements are derived top-down from the scenario definitions from the ASSESS project. Key domains in the propulsion system development process are the crash performance, the driving dynamics and the reproducibility. These three domains (and also other important domains) will be traced during the development phases.

Scenario definitions

This paper focuses on rear-end collisions, relevant scenario definitions are given in Table 1. A full set of the scenario definitions is available in [7], available for download on the ASSESS website. Almost all of the scenario definitions will be tested with fast, slow or no driver reaction. Experiments with no driver reaction and with failing autonomous brake systems will certainly be the worst case for the target propulsion system development, so the requirements will point towards these scenarios. Scenarios with a stationary target do not require the propulsion system and therefore do not affect the system's requirements.

Table 1.
Relevant rear-end scenario definitions (see [7])

Ego Vehicle Behaviour	Target Behaviour	Comments
Constant velocity, 50 km/h	Constant velocity, 10 km/h	Initial TTC > 3 s, no and 50% lateral offset
Constant velocity, 100 km/h	Constant velocity, 20 km/h	Initial TTC > 3 s
Constant velocity, 50 km/h	Braking 4 and 7 m/s² from 50 km/h	Initial distance 14 m
Constant velocity, 80 km/h	Braking 4 and 7 m/s² from 80 km/h	Initial distance 45 m

A test run can only be valid if specific accuracy requirements are met. These requirements are summarized in Table 2. The requirements affect not only the measurement equipment used for both vehicles, but also the design of the kart (e.g. chassis stability, steering actuators) and control systems as well as the whole experiment setup.

Table 2.
Preliminary accuracy requirements (see [7]).

Parameter	Controllability	Repeatability	Measurement Accuracy
Test Velocity	± 1.0 km/h	± 0.5 km/h	± 0.1 km/h
Distance (longitudinal)	± 0.50 m	± 0.20 m	± 0.03 m
Distance (lateral)	± 0.20 m	± 0.20 m	± 0.03 m
Acceleration / Deceleration	± 0.5 m/s^2	± 0.2 m/s^2	± 0.1 m/s^2

Crash performance

Vehicle tests will need to cover the full timespan from first detection of a target to the collision. Neither vehicle under test nor the soft-crash target system should suffer significant damage during the tests.
Therefore the most demanding requirement for the combination of target system and soft-crash target is the maximum impact velocity to be endured. An impact velocity of 40 km/h is required to perform most of the scenarios.
Probably the most important contributing factor to crash performance is the design of the soft-crash target. The ASSESSOR soft-crash target will be designed within the ASSESS project as a universal target for all test scenarios. The development is done by a project partner and will not be described in detail, however the basic principle and the implications for the propulsion system need to be discussed.
During a collision of two vehicles, energy needs to be transferred between the faster vehicle under test and the slower soft-crash target system. The vehicle under test would then be decelerated and the target system accelerated. The distribution of the accelerations and decelerations between the two vehicles depends on stiffness and masses.
An ideal soft soft-crash target system or a soft-crash target system with no mass would be accelerated to the test speed with no significant speed reduction for the vehicle under test – in this case the forces acting on the vehicle would not be significant, it would suffer no significant damage.
The whole soft-crash target system therefore needs a relatively low stiffness and low mass – stiffness is a parameter of the soft-crash target, while the mass is mainly a parameter of the propulsion system.

Driving dynamics

Also quite demanding are the driving dynamics requirements: the whole system needs to be able to reach a maximum speed of 80 km/h and a maximum deceleration of 7 m/s^2.
Lane-change manoeuvres and oncoming collisions will also need to be performed but are not subject of this paper.

Sensor visibility

The test procedures developed in the ASSESS project aim at consumer and regulatory testing where no modifications to the vehicle under test are allowed, and where the vehicle under test should have no chance to detect an ongoing test. That means that any combination of propulsion system and soft-crash target needs to appear like a car – to all kinds of autonomous emergency brake sensor systems. Sensors available on the market today are e.g. RADAR, LIDAR, video and fusion approaches involving these technologies.

SPECIFICATIONS

Concepts

Several methods for moving the soft-crash target are already being used for development purposes. The methods can be divided into three groups: self-propelled soft-crash targets, soft-crash targets fixed to a crane that is carried by a vehicle driving parallel to the soft-crash target, and methods where the vehicle under test is running on a test-bed with objects moving in front of the vehicle. The target supporting structure for crane-fixed soft-crash target can be very light, but they require a vehicle driving in a parallel lane. This vehicle will need to be masked in order to not confuse the ego vehicle's systems.
The mass of self-propelled target systems will very likely be significantly higher compared to the other methods, but they do not need a vehicle driving in a parallel lane. Any other vehicles need to be masked to all sensor technologies that could possibly be used. Vehicles running on a test-bed could have a chance to detect an ongoing test by evaluating the satellite navigation signals.
A crane-supported target will also be used within ASSESS and is described in [7], and also test-bed experiment setups will be carried out.
Different approaches either do not deliver the necessary crash performance [8] or are not able to drive at a constant speed [4].
The BASTKART propulsion system belongs to the group of self-propelled systems. It is based on a standard race kart driven by a 125 cc two-stroke engine and equipped with a supporting rear frame and carrier plate to carry the soft-crash target.

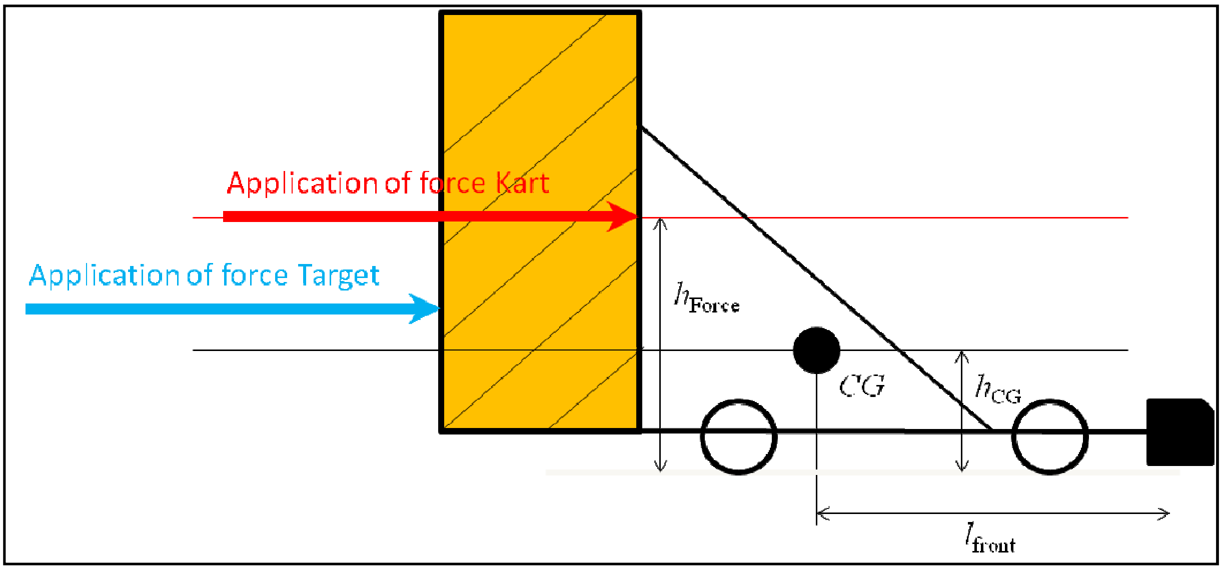

Figure 1. Forces acting on the kart during impact of the vehicle under test.

Future versions will very likely be able to withstand oncoming collisions, however this is not the focus of this paper.

Crash performance

A maximum impact velocity of 50 km/h will be required for the ASSESS test scenarios. Requirements and development of a similar soft-crash target itself have already been published by [6]. The paper primarily addresses the development of the propulsion system, however the propulsion system does significantly contribute to the achievement of a sufficient crash performance.
Basically the soft-crash target is a pneumatic spring-damper. The intruding vehicle deforms the soft-crash target and thus builds up air pressure in the moment of the impact. Venting holes in the target introduce a damping effect. Finally, the air pressure inside the target generates a force on the carrying plate. This force's point of attack is assumed to be the centre point of the plate. Other forces acting on the kart are the inertia force (opposite to the direction of acceleration) and gravitation force. The situation is shown in Figure 1.
The equations of motion (neglecting pitching motion) are

$$m \cdot \ddot{x} = F_{Target} \qquad (1).$$

$$F_{Target} \cdot h_{Force} - m \cdot \ddot{x} \cdot h_{CG} - m \cdot g \cdot l_{Front} \overset{!}{=} 0 \qquad (2).$$

Any arm between the propulsion system's centre of gravity and this force would generate a pitching moment, finally a pitching motion, a lift-off of the whole kart – which would then be uncontrollable. Hence, pitching motions definitely need to be avoided. The maximum acceleration limit that would not result in pitching motions is given by

$$\ddot{x}_{max} = g \cdot \frac{l_{Front}}{h_{Force} - h_{CG}} \qquad (3).$$

There would be no limit if the height of the target force matches the kart's centre of gravity.
The centre of gravity of the BASTKART propulsion system would need to be in the height of the supporting plate centre point in order to let the BASTKART withstand high impact velocities without pitching movements. However, the high masses are the kart's chassis and engine, almost at road level.

Driving dynamics

Accident scenarios demand a relatively high deceleration of up to 7 m/s² and driving speeds of up to 80 km/h. The achievable deceleration does not depend on the vehicle's centre of gravity, as long as both axles are braked and the brake force distribution is adjustable.
The maximum velocity is limited by the air drag resistance of the vehicle. An approximation of the power needed for a specific velocity is

$$P = c_w \cdot A_{Front} \cdot \frac{\rho}{2} \cdot v_{rel}^3 \qquad (4).$$

with the air drag coefficient c_w, the front surface A_{Front}, air density ρ and relative velocity v_{rel}. With the assumption for the product of air drag and front surface (worst case: 2 m²) the power necessary for a velocity of 80 km/h (= 22 m/s) is 13 kW.
The scenarios do not demand a specific maximum lateral acceleration of the kart, however manoeuvrability and lateral stability are important for safe testing. For sufficient manoeuvrability, the

wheel load on the front axle is important – this contradicts the crashability requirement to have the center of gravity relatively near to the rear axle.

Measurement accuracy and reproducibility

Inertial measurement units (IMUs) supported by Differential GPS are state of the art in vehicle dynamics testing. They deliver accuracies well below 10 cm, they are lightweight and relatively easy to use. IMUs will be used in the propulsion system as well as in the vehicle under test.
The final test results will very likely be sensible to variations in the propulsion system's velocity and deceleration. A closed-loop control would be needed to achieve a relatively high reproducibility.
The main requirement for lateral stability is to stay in a corridor with a width of 40 cm throughout a test run. It will certainly be possible to maintain this requirement with manual steering control of the kart. The kart should always be under command of the kart operator, so manual control is also a good choice from the safety perspective.

IMPLEMENTATION

Vehicle Concept

This first implementation of the BASTKART propulsion system focuses on rear end collisions only but will be adopted to other accident scenarios in the future. It is based upon a FIA-approved race kart of the class KF3 (125 cm³, up to 30 hp) and can be equipped with either a 21 kW or a 15 kW two-stroke engine, both of which deliver enough power to reach a velocity of more than 80 km/h. Two brake circuits brake either the front or the rear axle with adjustable brake force distribution. Steering and braking system are actuated by powerful (but rather slow) servo motors, the engine's throttle is actuated a light servo motor.

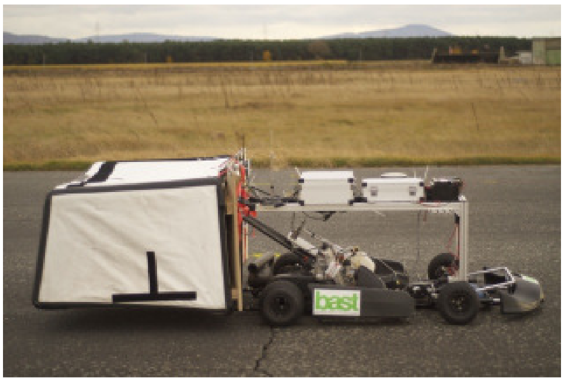

Figure 2. Overview over the BASTKART propulsion system, including the rear of the soft-crash target.

An additional structure to carry the soft-crash target is made from steel pipes and rectangular steel profiles. This structure has been designed to endure a maximum target force of up to 50 kN without significant distortion. Taking into account a mass of around 200 kg, this would result in a possible acceleration of up to 25 g, which is roughly the acceleration that occurs for a crash velocity difference of 50 km/h (see [6]).
The supporting structure and the engine accumulate to a relatively low center of gravity. All additional equipment is mounted as high as possible in order to move the system's center of gravity as high as possible. An additional 'equipment frame' is introduced for this purpose.
Position and movement of the BASTKART as well as of the vehicle under test is measured by means of two GeneSys ADMA inertia & DGPS platforms which also have trigger inputs (e.g. for the touch sensor on the soft-crash target, for the warning sound detection on board of the vehicle under test etc.). All measurements are synchronized via the GPS satellite time signal. A CAN-WiFi-bridge transmits all measured data from the propulsion system to the vehicle under test for recording and display.
The kart is mainly controlled by a human operator. The operator will be assisted by deceleration and cruise control for the actual manoeuvres, however lateral control will always be done manually, and the operator can always override the controller settings. The advantage of this concept is to have all relevant persons on board of the vehicle under test. Test results can be evaluated immediately after each test run, and it is not necessary to implement desired trajectories for the BASTKART system for quick tests.
Manual control is done via a RC Control regularly used for model planes. In addition, a second remote control can independently start or stop the kart's engine and actuate an emergency brake. Both remote control devices use different radio channels and operate independently. The steering remote control's transmission distance is greater than 1000 m.
The gross mass of the final propulsion system (excluding the soft-crash target) is 224 kg, with 43% on the front / 57% on the rear axle (this will be shifted to the rear axle when the soft-crash target is mounted).
The BASTKART propulsion system with soft target attached is shown in Figure 2.

VERIFICATION

Crash Performance

Theoretical considerations have led to the definition of the system's maximum acceleration without pitching movement. If these considerations are true,

it would be possible to calculate the maximum acceleration for different configurations.
Two different system setups with different positions of the center of gravity have been tested in BASt's crash facility. Kart and soft-crash target were equipped with crash acceleration sensors, especially in longitudinal and vertical directions. The intruding vehicle was a regular passenger car, its velocity was measured with a light switch. Time of impact was sensed with a touch sensor attached to the kart. The experiment setup is shown in Figure 3, a typical graph is shown in Figure 4.

Figure 3. Test setup for crashability verification, early configuration.

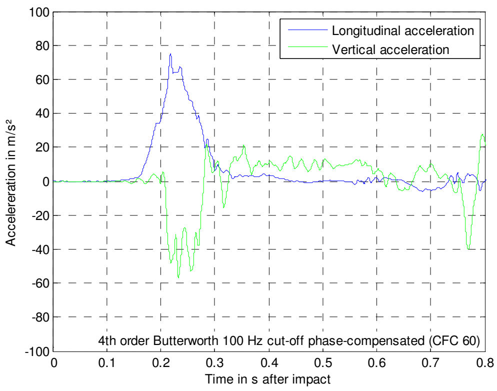

Figure 4. Typical plot of an impact test. Note longitudinal acceleration rises some 150 ms after the time of impact, the vertical acceleration (pitching movement) does increase only after the longitudinal acceleration has reached the threshold given by eq. (3).

The longitudinal acceleration threshold after which pitching occurs has been calculated according to eq. (3) for two different configurations. Calculated values lie well within the spread that was observed in each series of tests. Results therefore do not lead to a falsification and the theory can be used for further optimization of the kart system.
The actual kart configuration has been tested up to impact velocities of up to 40 km/h without major pitching movement.

Driving dynamics

Manoeuvrability is sufficient, the turning radius of approximately 10 m is also sufficient for practical considerations.
As of February 2011, a velocity (cruise) controller and a brake deceleration controller will need to be implemented. They will probably be available for the final validation testing (which will be finished by the time this paper is published). System identification data has been collected.
These tests show a maximum deceleration of 7 m/s² (see Figure 5 for plots of a deceleration step from 0% to 100% brake actuation) which satisfies the specifications derived from the ASSESS scenario definitions.
The maximum velocity is far beyond 80 km/h, however lateral stability on uneven roads is still a problem to be solved, and the brake swell time will need to be improved.

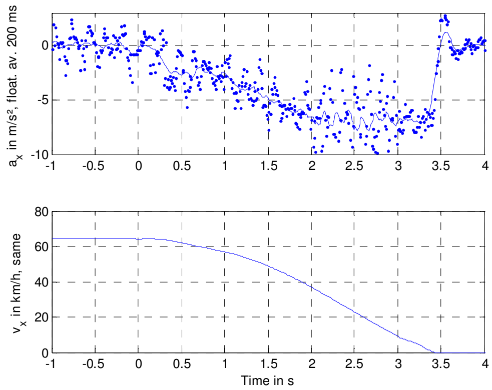

Figure 5. Deceleration (upper plot) and velocity (lower plot) during a braking manoeuvre.

Reproducibility

While velocity and deceleration of the BASTKART will be controlled, the lateral control will – mainly for safety reasons - stay within the hands of the kart operator.
During pre-tests, 22 test runs on a relatively uneven road have been investigated for corridor widths and relative deviations during full test runs. Figure 6 shows a summary of the results.

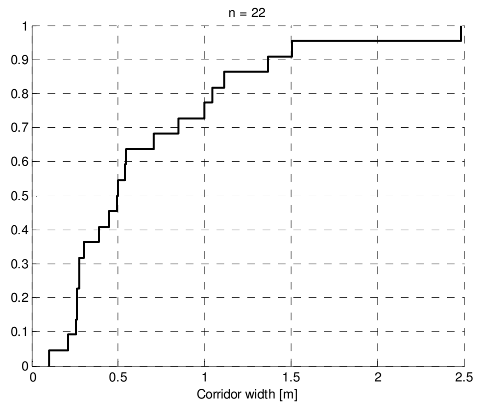

Figure 6. Cumulated maximum corridor width for 22 pre-test runs. 40% of all test runs are within the limit of 40 cm defined within ASSESS.

For the investigation, a virtual center line of the test run is defined by averaging the kart and vehicle positions for the last three seconds before impact (individually per test run). The absolute corridor width then is the addition of the maximum lateral deviations of each vehicle during that last three seconds.

The absolute corridor width (black plot in Figure 6) lies within 40 cm (borders according to reproducibility requirements for ASSESS test scenarios, see [7]) in 40% of all test runs.
This means that – right before vehicle stability improvements that will also contribute to a better reproducibility) at least 40% of all test runs would have been valid test runs.

FIRST VALIDATION RESULTS

The validation process ensures that the system fulfils the requirements: it can be used to test advanced driver assistance systems according to the test procedure defined within the ASSESS project. The propulsion system and the soft-crash target itself are still under development. A full validation has not yet been carried out, but a few tests have already shown the potential of the test method.
Figure 7 shows a full test run performed according to ASSESS test scenario A1A (first row of Table 1).

A slower lead vehicle travels at a velocity of 10 km/h and is being approached by the vehicle under test with 50 km/h. The fictive Time-To-Collision is a common measure for distinct points

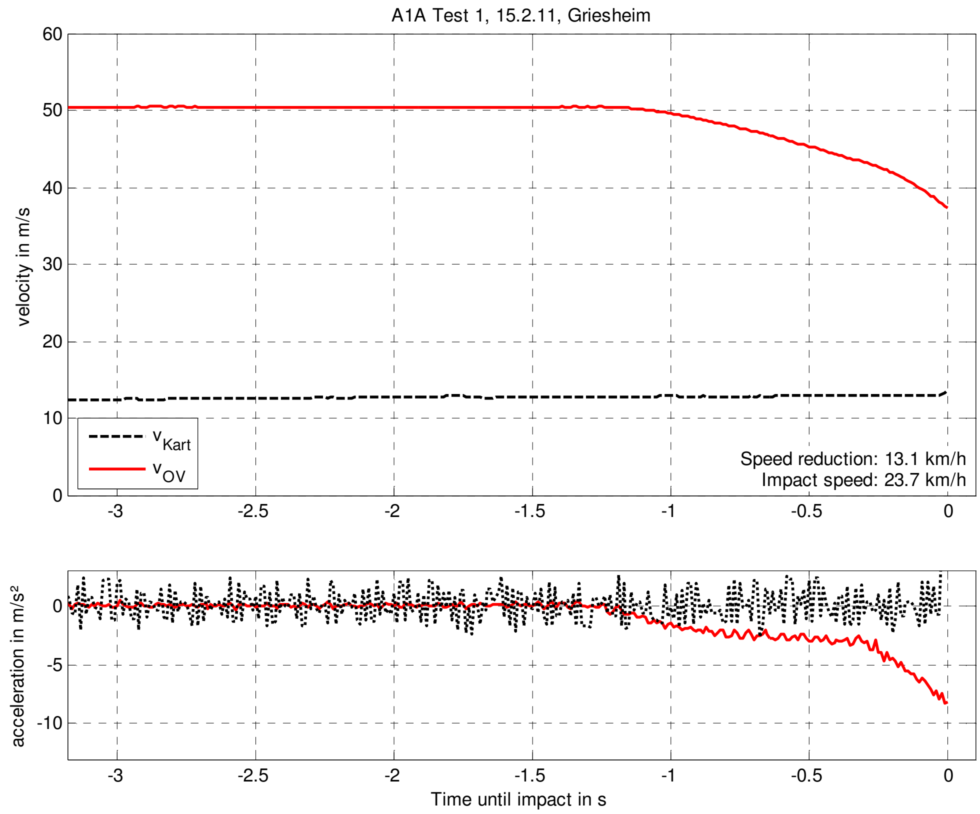

Figure 7. Plot of velocity (upper) and acceleration (lower) of a typical vehicle under test, ASSESS scenario A1A. No manual brake actuation during the experiment. Note that the parameter time refers to real time, not to time-to-collision.

in time. It is given by

$$TTC = \frac{x_2 - x_1}{\dot{x}_2 - \dot{x}_1} \qquad (5).$$

with the longitudinal distances and velocities of both vehicles.
The initial TTC is greater than 2.6 s. The vehicle under test is equipped with an autonomous emergency brake system that starts to brake around a TTC of 1 second (if both vehicles maintain a constant velocity, the collision would occur in 1 second). The BASTKART was controlled manually and maintains a constant velocity slightly higher than 10 km/h, the vehicle under test maintains a constant velocity of 50 km/h due to the use of an active speed limiting device.
It can be observed that autonomous braking occurs around a TTC of 1 s, with a peak deceleration of 4 m/s². In total, a speed reduction of 10.9 km/h has been achieved purely with autonomous braking, and the impact velocity of 27.4 km/h did not cause any damage to the BASTKART and soft-crash target combination.

SUMMARY

A method to test autonomous brake systems has been developed. This method uses a modified kart that carries a soft-crash target. The development process has been presented in detail. The method is a simple but yet efficient way of testing AEB systems.
First tests show the potential of the method. Further research in the soft-crash target characteristics is needed, and also improvements for the reproducibility of velocities and decelerations need to be achieved.

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