AN INTEGRATED ADAS SOLUTION FOR PEDESTRIAN COLLISION AVOIDANCE

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ABSTRACT

Accident statistics indicate that pedestrians constitute a large share of vehicle-related fatalities worldwide. Due to continuing trends towards urbanization, this proportion can be expected to further increase. Advances in passive safety have already proven their effectiveness, but since injuries cannot be completely avoided at higher collision speeds a preferred solution is the complete avoidance of collisions.

In this paper, we introduce an active safety approach for preventing collisions with pedestrians that integrates advanced perception systems and executes emergency braking and steering maneuvers. The functional concept and system architecture are introduced, followed by the design of the actuation setup. Finally, the results of extensive driving tests are given for validation.

As part of the validation strategy, a testing facility has been constructed that comprises a horizontal truss with a pedestrian dummy suspended beneath it. This pedestrian dummy can be moved laterally to simulate pedestrian motion.

The presented system architecture includes abstract levels for sensorics, perception refinement, situation analysis and actuation. The functionality is realized using a stereo camera and radar, both of which are high-performance, state-of-the-art automotive sensors currently in series production. The stereo camera integrates a pedestrian classification algorithm, and together the sensors provide extensive knowledge about the available maneuvering space. The sensor data are combined into a hybrid environment representation with two separate entities for moving objects and static structures. This representation can be used as a basis for the situation analysis logic, determining if an emergency braking or steering maneuver is necessary. Two actuators are used to facilitate maneuver execution: an electric power steering (EPS) system and an innovative brake system specifically designed for a fast and precise electronic actuation.

One algorithm implemented for handling pedestrian scenarios is the pedestrian motion prediction. In these cases, commonly-used models for vehicle motion are no longer valid, so a motion prediction algorithm has been developed that specifically considers pedestrian behavior. The result, as demonstrated in relevant scenarios, is a significant decrease in false-positive system reactions.

In this paper, possibilities for how an emergency situation can evolve with respect to available maneuvering space and last point to brake or steer are extensively discussed and examined through driving tests.

An additional challenge is the handling of scenarios where a pedestrian assumes a more generic appearance, such as a person using a wheelchair or pushing a stroller.

A holistic system for avoiding pedestrian accidents has been designed, implemented and extensively tested. The results quantitatively show the benefits in terms of the detection performance of the environmental sensors and the sophisticated environment model, including information about the available maneuvering space. Classification and prediction algorithms have been implemented that take into account the characteristics of pedestrian behavior to determine the desired system reactions. Since all sensors and actuators

are currently in or near series production, the presented approach demonstrates how pedestrian safety can be greatly enhanced in the near future.

MOTIVATION

Accident statistics

The worldwide traffic volume has markedly increased within the last 10 to 15 years, but in the EU, the improvement in both driving and transport safety has led to a significant reduction in traffic fatalities. In addition to traffic-focused educational and political efforts, major improvements in active and passive vehicle safety systems have proven their effectiveness.

Due to this development and the trend toward increased urbanization, which leads to increased potential for urban accident scenarios, the proportion of pedestrian fatalities naturally emerges as a focus of discussions. According to the most recent statistics, around 8,000 pedestrians and cyclists are killed, and a further 300,000 injured, each year in road accidents in the EU. Therefore, it is expected that systems to protect vulnerable road users, especially pedestrians in urban areas, will receive increased attention in the assessment of vehicle safety systems in Europe, see for example according activities at EuroNCAP [1].

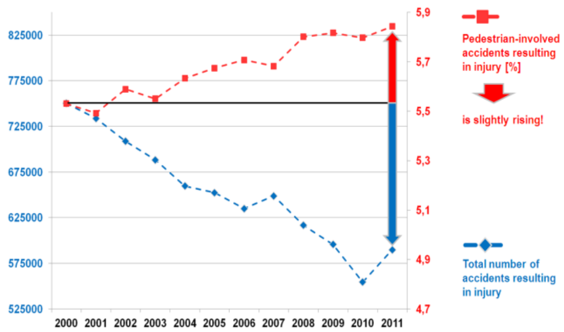

Figure 1. The overall number of fatal accidents is decreasing, but the corresponding share of pedestrian fatalities is not [2].

According to the German Federal Statistical Office (Statistisches Bundesamt), the overall number of accidents with injuries has been reduced year-over-year throughout the last decade. The percentage of pedestrian-involved accidents has increased slightly. One reason could be the focused development on occupant safety, with many active and passive safety systems reducing this corresponding share of accidents.

Better protection of pedestrians and other vulnerable road users, especially in urban areas, would clearly reduce fatalities and severe injuries.

Research by the German UDV shows that the most effective countermeasure in the event of a crash is the reduction of vehicle speed prior to impact [3]. If an emergency braking system, capable of recognizing pedestrians, could reduce the crash velocity from 40 kph to 30 kph, many types of vehicles with differing front shapes would be sufficient to achieve the minimum desirable rating. Further reduction of the speed of impact to 20 kph would result in a “very good” rating. This could also be considered as a logical next step, given the existing foundation of passive safety measures, including outside airbags and active hoods.

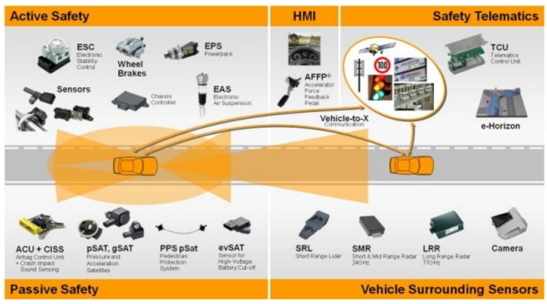

Figure 2. ContiGuard® spectrum of components for effective active and passive safety systems.

ContiGuard® - Safety in all domains

Continental has demonstrated with ContiGuard® that further development in traffic safety, in both the active or passive domains, must include the complete network and integration of vehicle surrounding information as well as a human-machine interface (HMI). ContiGuard® covers all safety functions through the integration of active safety, passive safety, vehicle surrounding sensors, HMI and safety telematics, as well as driver assistance. Instead of “comfort ADAS”, which concerns enhanced driving comfort, this paper considers “safety ADAS”, i.e. challenging driving situations where the safety of the occupants and other road users is at risk.

CONTINENTAL'S DESIGN APPROACH FOR FUTURE PEDESTRIAN PROTECTION SYSTEMS

The ContiGuard® function of an active pedestrian protection system consists of sensors, algorithms and actuators. A prototype vehicle for system development and functional evaluation was built with available components. A stereo camera is used as the primary environmental sensor, while a software framework runs the core functional algorithms for situation interpretation, decision making and actuator control. Brake and steering system were adapted in software to be able to cover the control requests.

General system architecture

To maintain system extensibility and functionality outside of pedestrian protection, a general approach was chosen for the system architecture. This has been developed by Continental's Advanced Engineering Department (Chassis & Safety Division) to address a wide spectrum of ADAS applications. See [4] and [5] for examples. It is built upon four functional levels that represent the generic components of any ADAS system (Figure 3).

First, there is the *sensor level*, where all of the environment sensing elements are located, together with all sensor-specific algorithms (e.g., object detection algorithms operating on a digital image).

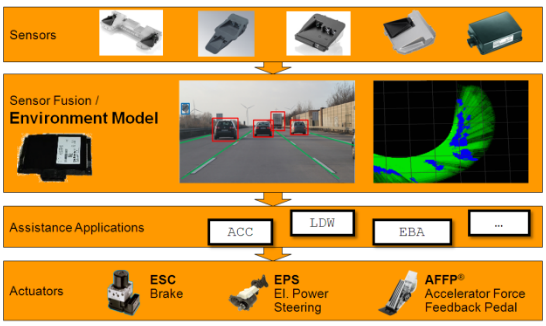

Figure 3. The generic ADAS architecture from Continental's Advanced Engineering Department.

The second level, *hybrid environment representation,* forms an environmental model independent from the features of a specific sensor, allowing a flexible interchange of the sensors deployed in the architecture level above. As a special property, this level is split into two separate entities. One forms an object abstract environmental representation in the appearance of an object list for moving objects like vehicles or pedestrians, with object attributes assigned to it. The other one contains dense information about static restrictions in the ego vehicle's surroundings, providing precise information about usable maneuvering space required for planning and execution of automated evasion maneuvers.

On the *application* level, all ADAS function-specific algorithms can be found. These functions are meant primarily for analyzing the situation using the state of the environment model and for deriving a decision, if there is an active intervention required in the present situation.

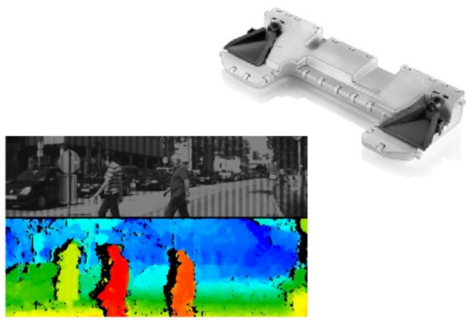

Figure 4. Automotive stereo camera, combining the ability to classify pedestrians with direct measurement of distances to objects.

If the decision-making algorithm comes to the conclusion that an active intervention is necessary, then this can be performed using the lowest-level *motion control & actuation.* Here, all of the requests from the ADAS applications are collected and arbitrated together with driver inputs, according to a predefined guideline that considers the presumed importance of the request. Subsequently, the requests are transformed into actuation commands for the available actuators in the vehicle. For instance, a deceleration request is turned into a brake pressure request with respect to the specific brake actuation characteristic of the existing brake system.

The following subsection considers the elements used in the proposed pedestrian protection system, mapped to the architectural levels described above.

Sensorics

The basis of an effective system for active safety is the utilization of a subsystem for environmental sensing that fulfills the requirements of the scenarios addressed. In order to apply pedestrian-specific algorithms, it is important to identify objects in the vehicle's vicinity as persons in the road. Visual sensors, like automotive cameras, are the most promising choice in this respect. Furthermore, since accidents with pedestrians happen within the limits of the vehicle path, a frontal sensor was chosen, covering this area (Figure 4). For the system considered in this paper, a stereo camera was used, since it has an important advantage in addition to the capability to execute pedestrian classification: It has the ability to measure the distance to objects using the disparity between the two captured images.

These properties allow us to use this device as a standalone sensor for ADAS applications, without the sensor fusion required with other sensor types. However, in the present concept vehicle, a radar sensor was also incorporated for object fusion in order to assess the impact on system performance when the radar sensor is switched on or off.

Environment representation

Any ADAS function uses an internal representation of the vehicles surrounding as a basis. Since the function shown here handles scenarios with pedestrian classification in a first approach, here mostly relevant is the EGO-vehicle movement together with the actual or predicted movement of the person on the road. Therefore it is primarily sufficient to focus on the object abstract part of the environmental model. In the future, when decisions are made to utilize free space for an emergency steering maneuver, the dense information from the environment model must also be used. This could be a tessellated area in the vehicles field of view, for example in the appearance of a so-called Occupancy Grid, giving data about the occupancy state of each according area in the real world. Hence, the installed environment representation is well-prepared for this evolution.

Application

The application-specific algorithms for analyzing the situation and making decisions are located in this level. Together, they assess whether or not the situation is evolving into a potential driving intervention. Typical functions realized within this level could comprise emergency braking, emergency steering through to functions towards automation of specific driving tasks.

Motion control and actuation

Besides several HMI-related actuation elements like visual, auditory and haptic warnings, there are two main elements available for executing driving interventions. One is a brake system allowing the electronic requests of vehicle deceleration without the brake being applied by the driver. It is a system currently in series production, normally providing stability functions like ABS or ESC and performing brake actuations for adaptive cruise control (ACC). Our system was equipped with enhanced firmware to enable arbitrary requests from additional sources. The other actuation element is electric power steering (EPS), which is increasingly available for cars in series production. Again, by using modified firmware in the ECU, it is possible to apply steering torque independent from the inputs the driver provides, enabling active interventions in any driving situation. The motion control layer, between the application, driver and actuators, coordinates the requested vehicle path in a safe and efficient manner by allocating requests to the different actuator subsystems, which also include the engine, gearbox and electric drivetrain components. The braking and drivetrain components were more significant for this application.

Demonstration vehicle

The system described has been integrated into a test and demonstration vehicle based on a Volkswagen Passat B7 (Figure 5). This vehicle is

Figure 5. Demonstration vehicle equipped with environmental sensors and actuators for driving interventions.

equipped with all required sensors and actuators mentioned above. Furthermore, a rapid prototyping middleware concept is used, which allows for flexible and fast implementation and verification of software algorithms.

GENERAL FUNCTIONAL CONCEPT

Emergency braking

To better explain the system's functional concept, consider the simple example of a vehicle approaching a stationary pedestrian in the road. This is considered a kind of baseline function, and illustrates the basic functionality of the system.

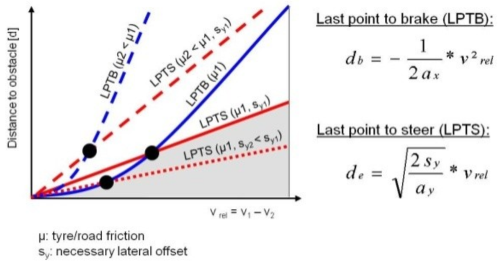

Figure 6. Necessary distances to avoid a collision by braking or steering

First, the vehicle drives along a straight road until it encounters a person (in this case, the soft dummy) not leaving the vehicle's path. As soon as the object is determined to be a potential collision target, pedestrian classification is initiated as part of the environmental perception function, and identifies whether or not the detected object is a pedestrian. This is possible through the use of features characteristic of a person in the road, such as a specific height-to-width ratio or the existence of a head or extremities. If the classification algorithm detects a pedestrian, the situation analysis algorithm assesses the risk of a collision, using the assumption that the movement of the ego vehicle remains constant. The required deceleration to avoid the collision is calculated considering also known delays from sensors and actuators, and if a certain threshold value is exceeded, an automated braking maneuver is executed to avoid the collision with the pedestrian.

Emergency steering

If emergency steering around the obstacle would be optimal, there is another threshold chosen. Here, permanently a path for the evasive maneuver is calculated, together with the hypothetic maximum lateral acceleration to be expected while following this path. If this value exceeds a certain value, this is used as the trigger for the automated evasion.

For executing evasive steering, there is a crucial requirement: It must be positively determined that the required maneuvering space is free, i.e., there is no object or other impediment in the path that the evasive maneuver will follow. Despite the corresponding free space analysis implemented in the system, it remains a challenging task for the future to achieve the very high reliability needed for triggering an automated steering maneuver as described, this together with a limitation of the necessary path width to a value representing the distance to the white centerline. An example where evasive steering could be more effective than emergency braking is formed by the combination of some boundary conditions: If the speed of the vehicle is quite fast and the lateral offset required for the evasion is quite small, the collision might only be avoidable with evasive steering if the braking distance is too great. In those cases, e. g. a small obstacle width affects the range of speed, where evading is more effective.

Static pedestrian

This scenario has already been described at the beginning of this section, but this is not purely an academic example. It could occur in reality when a person in the road does not take notice of an oncoming vehicle operated by a distracted driver, who would otherwise fail to prevent the collision.

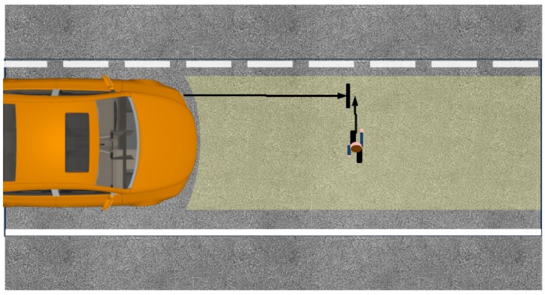

Figure 7. Laterally moving pedestrian shown at the point in time, when the required deceleration is reached

Moving pedestrian

Situations with moving persons in the road could be considered much more common. Figure 7 shows a scenario with a laterally-moving pedestrian at the point at which emergency braking is triggered.

In this case, the pedestrian is located directly in the path of the vehicle, which makes early detection more likely. Emergency braking can then be executed so that the collision is avoided.

In Figure 8 the situation is slightly different, even though the speed of the vehicle and speed of the pedestrian are the same. In this case, a second pedestrian begins crossing the road at a later point in time. This leads to a situation where the collision is no longer preventable using emergency braking for pedestrians in the vehicle's path.

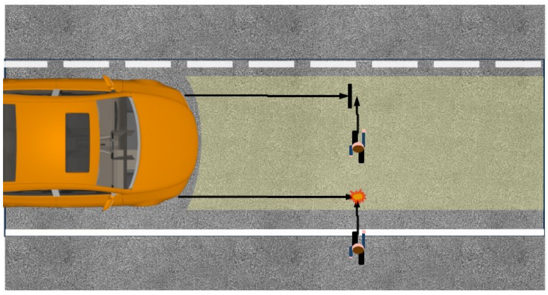

Figure 9. Laterally-moving pedestrians shown at the point in time when the required deceleration is at a value of 8.5 m/s². The lower pedestrian enters the path of the vehicle too late for the collision to be avoided.

Pedestrian movement prediction

The solution to this situation is the inclusion of a pedestrian motion prediction algorithm. This enables the prediction of when a person might enter the vehicle's path in the future, so that emergency braking could be initiated in time. A drawback of this solution is that the risk of false positives is greatly increased. This is obvious, because if a pedestrian is detected and its movement calculated some time into the future, the predictions would become invalid if the pedestrian were to stop. So, the technique of using pedestrian movement prediction must to be implemented with care.

Pedestrian target device (PTD)

Because of the inherent danger associated with persons in the road, it is a challenge to perform verification tests with these algorithms. It is necessary to represent the tested scenarios in a realistic fashion to keep the result representative of real situations with pedestrians in normal traffic.

Figure 6. Continental's pedestrian target device. The soft dummy can be moved laterally, and is set in motion by an oncoming vehicle passing through a light-barrier.

Additionally, it is necessary to ensure safety for the occupants of the demonstration vehicle during the algorithm development process. To meet these requirements, Continental has introduced a customized tool, the pedestrian target device (PTD), shown in Figure 6. This device consists of a horizontal truss spanning the entire width of a simulated road laid out on a test track. On the bottom of the truss, there is a rail with a soft pedestrian dummy attached to it. The dummy is made of a special material that allows for collisions of up to 70 kph without any damage to the vehicle or the dummy. For executing tests with a pedestrian crossing the road laterally, the dummy can be moved arbitrarily using a motor-driven pulley system, and the specific movement sequence can be predefined with a computer. The pedestrian motion can be initiated when the vehicle passes through a light barrier set up in front of the arrangement.

Test scenarios on the proving ground

To assess the effectiveness of the algorithms and system concepts described above, a rigorous testing procedure was followed. Due to the fact that the emergency braking capability is more likely than emergency steering to be integrated into a series system, it was chosen for evaluation in relevant scenarios. Furthermore, there are many parameter variations which can affect the performance of the system.

Following are the parameters that were varied:

- **Vehicle approaching speed**
  This is the velocity at which the ego vehicle approached the dummy attached to the PTD. By using an appropriate vehicle speed controller, it was ensured that the velocity was held constant once the maneuver began, i.e., the first time the obstacle was detected. In the test setup, three velocities were chosen: 30, 40 and 50 kph.
- **Variation of collision point**
  As previously mentioned, the entry point for a laterally-moving pedestrian is an important consideration. This determines where on the front of the vehicle the collision point will be located. In the test spectrum, three different collision points were considered: the left, right and center of the vehicle´s front.
- **Pedestrian speed**
  Since scenarios with stationary pedestrians were also considered, the speed was varied from 0 to 6 kph.

- **Prediction horizon**
  Since this is a crucial determining factor for the effectiveness of the system, it was varied over a relatively-fine resolution: 0, 0.5, 1, 1.5, 2, 2.5 and 3 s.

The tests were performed at Continental's proving ground in Frankfurt, Germany, with the PTD and test vehicle described earlier.

RESULTS

Proving ground evaluation with variation of the prediction horizon

As a metric for the evaluation of the effectiveness of the introduced system, Figure 10 shows in black the achieved speed reduction with respect to the prediction time system parameter.

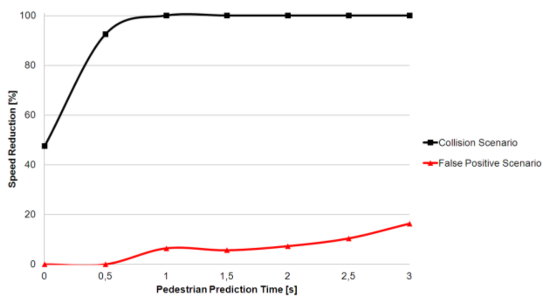

Figure 10. Achievable reduction in collision speed and number of false-positive system reactions with respect to the prediction horizon.

Altogether, 135 situations were tested throughout the procedure. The speed reduction measurements were collected from across all test runs conducted, and can be interpreted as the expected system performance for a given prediction time. It is clear that the system effectiveness reaches 100 % by choosing a prediction horizon of about 1 s. This means that for such a system, all collisions with the pedestrian could be avoided without any intervention from the driver. This is a significant result, and demonstrates the performance of the system across a wide range of pedestrian-related scenarios, proving its potential for active pedestrian protection.

It can also be seen from the red plot that the number of false-positive system reactions increases with the prediction time horizon. These results indicate the need for a system configuration that is customized for the individual requirements of the customer.

A prediction time horizon of 1 s appears to reach a good balance for the two plots shown.

System potential with powerful brake systems

Another crucial factor for system effectiveness is the brake system used. Figure 11 shows a comparison of achieved speed reductions for real brake systems. The change in the vehicle's velocity after an emergency braking actuation is shown with respect to time.

Different colors differentiate between different brake control systems. Light blue represents a system with today's standard performance (Continental MK 100 2PP), green represents a premium system (Continental MK 100 6PP) and red represents the MK C1 system, which is optimized for space efficiency and extremely fast system reactions for automated maneuvers. Other performance related components of the brake system like calipers are unchanged in this potential evaluation for competitive reasons, but could also be optimized. For the scenario shown in the figure, the MK C1 is able to completely avoid contact with the person in the road. On the other hand, the premium system collides with a speed of 15 kph, while the standard system collides with a speed of 24 kph.

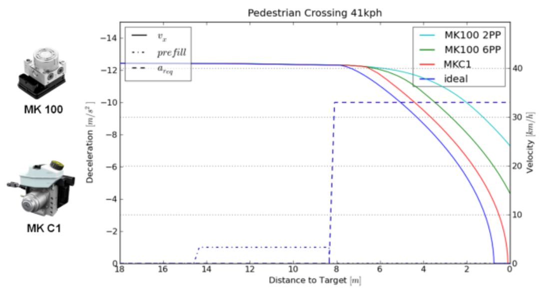

Figure 11. Effect of different braking systems on overall system effectiveness for the active pedestrian protection concept.

These numbers make clear that a highly-effective brake system is essential for active pedestrian braking.

CONCLUSION

In this paper, a prototype active pedestrian protection system has been introduced. By using environmental sensors like an automotive stereo camera, it is possible to detect dangerous situations with pedestrians and to execute active driving interventions braking the vehicle so that the collision with persons in the road can be avoided.

The system has been thoroughly tested and evaluated in 135 situations, which were designed according to typical pedestrian accidents. To achieve a realistic setup and gain a good representation of real situations, a customized pedestrian target device (PTD) has been used.

The results show that, with relevant system parameterization, all of the defined dangerous scenarios could be handled safely without any intervention from the driver.

In conclusion, the system effectively demonstrates its potential to meet all requirements for following the path to zero fatal accidents in the future, as well as to meet the increasingly demanding legislation worldwide concerning pedestrian safety.

OUTLOOK

A major challenge for the future is the handling of complex scenarios where available maneuvering space can be determined and reliable decisions about the execution of an automated evasion maneuver are possible. The foundation has already been laid with the generic environment model of Continental's Advanced Engineering.

Furthermore, future work will address scenarios that contain pedestrians or vulnerable traffic participants with a more generic appearance in traffic. Examples include people in wheelchairs and those pushing carts or strollers.

REFERENCES

[1] Euro NCAP: Rating Review - Report from the Ratings Group, V2.1, www.euroncap.com, Juni, 2012

[2] German Federal Statistical Office / Statistisches Bundesamt: Zeitreihen 2011, Wiesbaden, 2012

[3] Press release GDV, Unfallforschung der Versicherer (UDV) fordert Notbremssysteme für besseren Fußgängerschutz (Insurance accident research claims emergency brake systems for improved pedestrian safety)

[4] A. Hohm, R. Grewe, S. Lüke: Environment modelling for future ADAS functions, *ITS World Congress, Austria, Vienna, 22-26 October 2012*

[5] A. Hohm, R. Grewe, S. Lüke: Hybrid Approach of a Future Environmental Representation for Advanced Driver Assistance Systems, *SAE World Congress, USA, Michigan, Detroit, 16-18 April 2013*