AUTONOMOUS EMERGENCY BRAKING TEST RESULTS

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ABSTRACT

Autonomous Emergency Braking (AEB) systems are becoming increasingly available on new vehicles as either standard fit or as an optional extra. AEB systems use sensors around the vehicle to detect potential collisions and warn or even intervene on behalf of the driver to prevent or mitigate the collision. A group of Insurance funded Research Centres, the AEB Group, authored a series of test procedures based on real world scenarios with the aim of introducing performance tests of these new technologies. Test procedures measure and rate system performance relevant to real world accidents and drive development of AEB systems. 11 different passenger car models from 2012 equipped with second generation AEB systems were tested to the AEB procedures. System performance is rated based on the quantitative response to incrementally more demanding scenarios and differences have been found in the efficacy of systems both in terms or sensor type and implementation. Assessment of system performance provides consumer groups and insurers with a clear indication of which systems may provide the greatest real world benefits.

INTRODUCTION

Various AEB systems have been on the market for a number of years, though mainly on high end luxury models as optional equipment. These AEB systems use RADAR, LIDAR and camera sensors either standalone or in combination to establish the range and movement of potential hazardous car and pedestrian targets. If a potential collision is identified, they provide a warning and/or braking response to help prevent the collision or reduce its severity.

In 2008 Volvo introduced a low cost standard fit laser based system that offered auto-braking (but no warning) at low speed up to 30km/h. The Insurance Institute for Highway Safety (IIHS) analysed insurance claims data to compare the Volvo XC60, which is fitted as standard with a low speed LIDAR system called City Safety, against other similar 4x4 models and other Volvos [1]. The study compared 22 mid-size 4x4s and showed that the XC60 had lower overall claim frequencies in all crash types; 27% reduction in third party damage claims, 22% in first party claims, and 51% reduction in personal injury claims. There are also two studies from AXA Winterthur [2] and Tristar [3] that showed rear-end crash reductions of 31% and 28% respectively.

A further study from IIHS [4] has shown the effectiveness of optional RADAR systems that also reduce crash rates by up to 14%; largely due to lower relevant crash population at higher speeds. These systems also offer a warning and can operate at higher speeds. When comparing the studies a range of effectiveness is found, but the overall trend is for reduced crashes involving vehicles with AEB systems.

Test procedures have been developed that aim to assess the performance of AEB systems in order to drive real world reductions in collision frequency and severity. The aim was to create a standardised set of conditions that would enable the objective, repeatable and reproducible assessment of AEB systems that would allow their performance to be reliably quantified in such a way that would reward more effective systems. This paper summarises the development of those test procedures from accidentology studies. As part of the development and validation of those test procedures, a range of vehicles have been tested. This paper also aims to give an insight into the range of performance identified in this testing.

REAL WORLD ACCIDENTOLOGY

Analysis of real world crash events enabled the AEB group to study the most common crash types to ensure the test procedure addressed a target population relevant to these technologies. The development of these procedures is described in more detail by [5] [6] [7] but is summarised here.

In order to define test scenarios that are representative of real-world collisions, an accidentology study was completed on behalf of the AEB Group by Loughborough University [5]; this report formed the basis of the analysis. It used two major sources of information describing crashes in Britain: the national accident database

STATS 19 [8] and the in-depth On-the-Spot study (OTS) [9].

The exact methodology used to derive the clusters can be reviewed in the report from Loughborough University [5] or in [6]. In summary, the accidents were identified as being a Car-to-Car Rear (CCR) accident and then a cluster analysis was performed to group them mathematically according to common features. The datasets used for the cluster analyses of STATS 19 were derived directly from the source files by programmed computer logic; whereas the summary datasets used for OTS were compiled by analysts who completed a full accident reconstruction and based their assessment on the full range of materials contained in the OTS case files. In order to help define the most important features of that cluster so that they could be used to generate test scenarios a Chi-squared test was used to identify the features of the scenarios that were statistically over-represented.

The cluster analysis of STATS 19 was taken as a nationally representative result for the UK, and the OTS clusters also showed a similar trend. More importantly the additional case reconstruction evidence from OTS was used to provide additional detail about the UK accidents that could not be provided by the STATS 19 database. This additional detail from the OTS case reconstructions includes braking responses, overlaps between vehicles, and analysis of the travel and impacts speeds and headway conditions.

The next stage in defining the test scenarios was to move from a range of accident clusters to an initial definition of test scenarios. The STATS 19 clusters indicated too many CCR accident scenarios to be practically feasible for completion in one test day, which is the preferred time for practical requirements of a consumer/insurer test program. Therefore some clusters were either amalgamated or discounted as testing scenarios for two reasons; low frequency of occurrence or practical difficulties in test implementation. The test scenarios that were selected cover 73% of real world CCR collisions, and are summarised as a Car-to-Car Rear collision against a stationary target, angled stationary target (for future development), moving target and braking target.

OTS was then used to verify this selection of test scenarios, and to add further detail such as speeds and headways. For example, cluster 1 of the OTS CCR cases shows a mean approach speed of 41km/h toward a stationary target. However the sensor technology developments mean that avoidance up to 50km/h is feasible, so 50km/h was selected as the upper speed for the CCR stationary (CCRs) test, so called the ‘CITY’ test.

The CCRs was given an additional speed range for approaches at 50-80km/h, and called the ‘INTER-URBAN stationary high speed’ test. The terms ‘City’ and ‘Inter-urban’ are used to help aid consumer understanding of the type of collisions that the systems are addressing, and the speed ranges and conditions of the test.

The ‘INTER-URBAN moving’ (CCRm) test scenario for a moving target was defined as a target moving at 20km/h, with approach speeds 50 to 80km/h, and these speeds were similarly drawn from the accidentology study.

The ‘INTER-URBAN braking’ (CCRb) test represents a braking (decelerating) target car. Both test and target vehicles are moving at 50km/h based on the OTS data. A matrix of four tests was devised to represent a two headway conditions: a long headway of 40m, and a short headway of 12m typical of the following distance in busy traffic; and two braking conditions: $2m/s^2$ to represent the levels of braking in normal driving, and $6m/s^2$ to represent emergency braking.

The next stage in the selection of test scenarios was to carry out some international comparison to ensure that the scenarios selected for the UK are also relevant to other nationalities. UDV reported on their analysis of insurance claims from Germany, and an accidentology workshop by the vFSS reported on analysis of GIDAS (an accident investigation and reconstruction database); this data was used in comparison against the UK data. The frequencies for the different test scenarios were accepted as reasonably comparable, and more importantly there have been many stakeholder meetings regarding the selection of test scenarios since this area of work began in 2009, and these test scenarios are now widely accepted in the industry.

The final stage in definition of the test scenarios was to consider whether just a single point test was required, e.g. CCRs CITY at the highest speed 50km/h, or whether a range of speeds was required. Whilst safety testing of vehicles in consumer assessment programs has typically been limited to a single test speed; with AEB testing there is opportunity to run repeated tests over a speed range. The advantage of testing over a speed range is that the range of system performance can be assessed. In particular testing over a speed range can better represent the speed range of collisions occurring in the real world, and can be used to identify any subtle performance differences between systems. There are also practical reasons for running tests over a range of speeds: firstly for the safety of the test driver since it is safer to start with tests at a low speed and gradually increase the speed; and secondly since additional runs at different speeds are not a large time burden in comparison with changing test scenarios. Therefore it was decided to include a range of speeds were possible for the stationary and moving target tests.

The test scenarios have been widely accepted in the industry, and although there have been some variations in the exact speed ranges selected since [7], the overall test scenarios remain the same. This paper describes the latest status of the test procedures.

TEST SCENARIOS

Analysis of the real world accident data has helped to generate four accident scenarios that were used as the basis of the AEB tests:

Table 1. AEB Test Scenarios

Test type		**Illustration**	**Test description**
CCRs CITY Stationary low speed	Car drives into stationary vehicle (low speed)		Approaching a stopped vehicle at test speeds from 10 to 50km/h in 5km/h increments.
CCRs INTER-URBAN Stationary high speed	Car drives into stationary vehicle (high speed)		Approaching a stopped vehicle at test speeds of 30 to 80km/h in 5km/h increments.
CCR INTER-URBAN Slower moving	Car drives into slower moving vehicle		Approaching a moving target at 20km/h. Test vehicle speed 50km/h up to 70km/h in 5km/h increments.
CCR INTER-URBAN Braking	Car drives into braking vehicle		Approaching a decelerating target, both vehicles initially moving at 50km/h. Target car has two headway conditions (short 12m and long 40m) and two braking levels (normal $2m/s^2$ and emergency $6m/s^2$).

The test scenarios in this procedure are applicable to passenger cars with an Autonomous Emergency Braking (AEB) system or Forward Collision Warning (FCW) system. They are valid only for vehicles where the detection system responds to the visual, RADAR or reflective (LIDAR) signature of the rear of a passenger car.

TEST TARGET

The ability of the test target to accurately represent the characteristics of a real vehicle in the eyes of a variety of different sensor types was quickly recognised to be a critical part of a realistic, technology neutral test to drive real world safety improvements. The AEB group used information from a vehicle with sensor fusion (RADAR and camera) and took outputs from the vehicle CAN bus to identify the confidence with which the AEB sensors recognised a variety of different vehicle test targets proposed by a variety of organisations and compare them with real vehicles. The results are summarised in *Figure 1* below. The test illustrated shows the output from the sensors, where the outputs are green high confidence in the target threat is shown. When coloured red there is a low confidence, and where no colour is shown neither RADAR nor camera registered a threat.

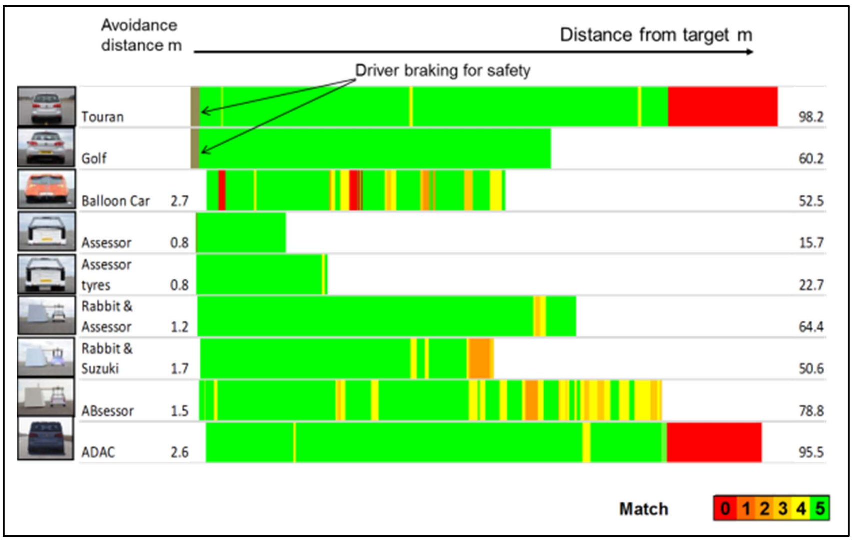

Figure 1: Confidence with which a radar camera AEB system detected a range of vehicles and test targets.

It can be seen that the device with the closest match to a real vehicle was that termed the ADAC target. This target was developed by Continental and was improved by ADAC for use in AEB testing. This was further developed by Thatcham to include the correct visual characteristics to accommodate camera based systems. This target was subsequently adopted by the AEB and Euro NCAP group as a suitable AEB evaluation target. Its development is covered in a separate paper.

TEST PROCEDURE

Having defined the scenarios that needed to be assessed in order to reflect real world accident situations and identified a realistic and practical test target, the next step was to define the detail of the test procedure itself. The aim was to provide accurate and repeatable results while minimising the test burden. As such, the procedure starts with the lowest test speed specified for the particular scenario. Test speed was then increased in 10km/h increments until a test speed is reached where the AEB system no longer avoids the collision and an impact occurs between the test vehicle and car target. At this stage, the test is repeated at a speed 5km/h lower than that in which the impact occurs. AEB performance is measured in all test scenarios. For Inter-Urban test scenarios CCRs, CCRm and CCRb, an additional assessment of the vehicle FCW system (if present) was also undertaken. The process for determining the tests to be undertaken is shown in *Figure 2*.

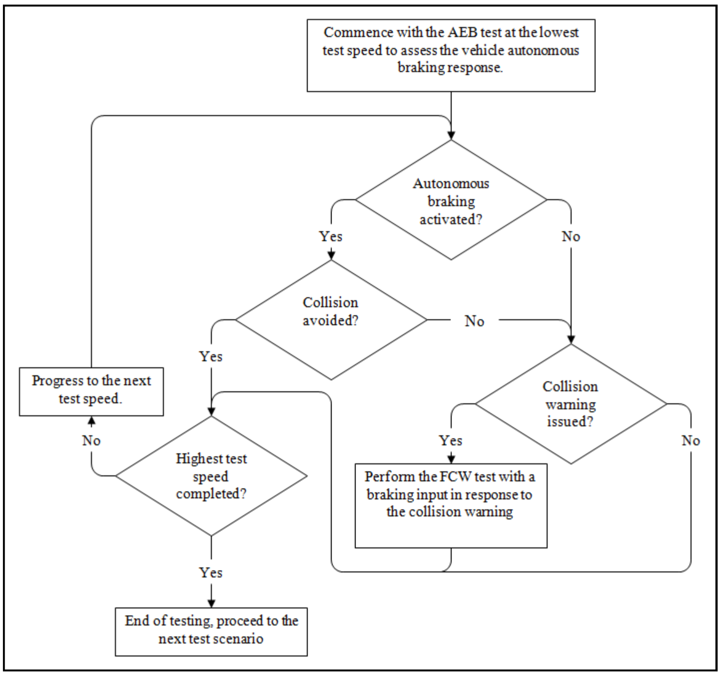

Figure 2. Flow diagram for AEB testing.

The aim of the test is to replicate an inattentive driver. For this reason, it is important to have constant inputs immediately before the test because it was considered possible that some AEB systems may take variation in driver inputs as evidence that they were alert and this information may be used to influence the reaction of the driver assistance. The tests are also relatively complex, particularly in the inter-urban scenario requiring the speed and alignment of two vehicles to be tightly controlled relative both to absolute requirements and to each other as well as requiring defined braking inputs from both the target vehicle and the test vehicle (response to FCW). Each of these variables was found to have the potential to influence the results from the system and as such some very restrictive tolerances were targeted, for example:

- Target consistency limits (CCR lead vehicle stopped and CCR lead vehicle decelerating)
  - Speed +1.0km/h
  - Lateral position ±0.10m
  - Yaw rate ±1.0º/s
  - Deceleration ±[0.5]m /s^2
- Test vehicle approach consistency limits
  - Nominal test speed +1.0km/h
  - Steering wheel velocity ±10 º/s
  - Accelerator pedal position ±5%
  - Lateral position ±0.10m
  - Yaw rate ±1.0º/s
  - Headway +1.0m

It was found that it was not feasible to reliably meet this type of test tolerance, and thus ensure accuracy and repeatability, with human drivers and thus robotic control of steering, accelerator and brake was required. Thatcham has used path following steering and combined brake and accelerator robot from Anthony Best Dynamics as shown in Figure 3.

Figure 3. Combined Brake and Accelerator robot (CBAR) and steering robot used to control the test vehicle.

RATING SYSTEM

The final part of the development of the AEB procedures was defining a scheme for scoring the performance of different vehicles. This development has been described in more detail by Schram *et al* [10].

EVALUATION VEHICLES

Eleven vehicles have been assessed either as part of final validation of the test procedure, as part of the UK insurers Group Rating programme, or for Euro NCAP Advanced awards. The vehicles and the technologies they use are defined below:

- Ford Focus: LIDAR sensor
- Mazda CX-5: LIDAR sensor
- FIAT Panda: LIDAR sensor
- Mazda 6: LIDAR sensor
- FIAT 500L: LIDAR sensor
- VW UP!: LIDAR sensor
- Volvo XC60: LIDAR sensor
- Mitsubishi Outlander: RADAR sensor
- Volvo V40: LIDAR sensor (standard fit)
- Volvo V40: LIDAR, RADAR and Camera sensor fusion (optional fit)
- Subaru Outback: Stereo camera fusion

RESULTS

Most of the vehicles tested so far have been equipped with low speed systems and as such the results presented here have been restricted to those from the City test. Performance is characterised by the initial test speed and the actual impact speed, effectively the speed reduction. An example of this is shown in Figure 4 below.

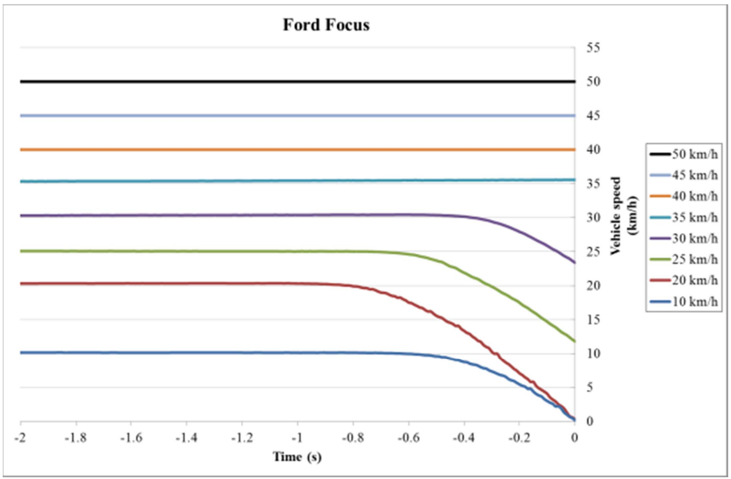

Figure 4. Example of results presentation.

The graph is a time history of individual test runs and T_0 is the time at which either an impact occurs with the target or the vehicle comes to rest. Thus, the example above shows that the Ford Focus system avoided a collision entirely from initial speeds of 10km/h and 20km/h, mitigated the collision from initial speeds of 25km/h and 30 km/h and had no effect at speeds of 35km/h and above.

These results have been calculated for each vehicle and then grouped by the sensor technology used.

LIDAR

Analysis of the results from the 8 LIDAR only systems (see Figure 5 to Figure 12 below) showed several distinct groups.

The Mazda 6, the Fiat 500L and the VW Up! were all found to have systems that had no effect at speeds of 30km/h or above. The 500L and the Up! fully avoided collisions at all speeds less than this, whereas the Mazda 6 just failed to avoid the collision at 25km/h.

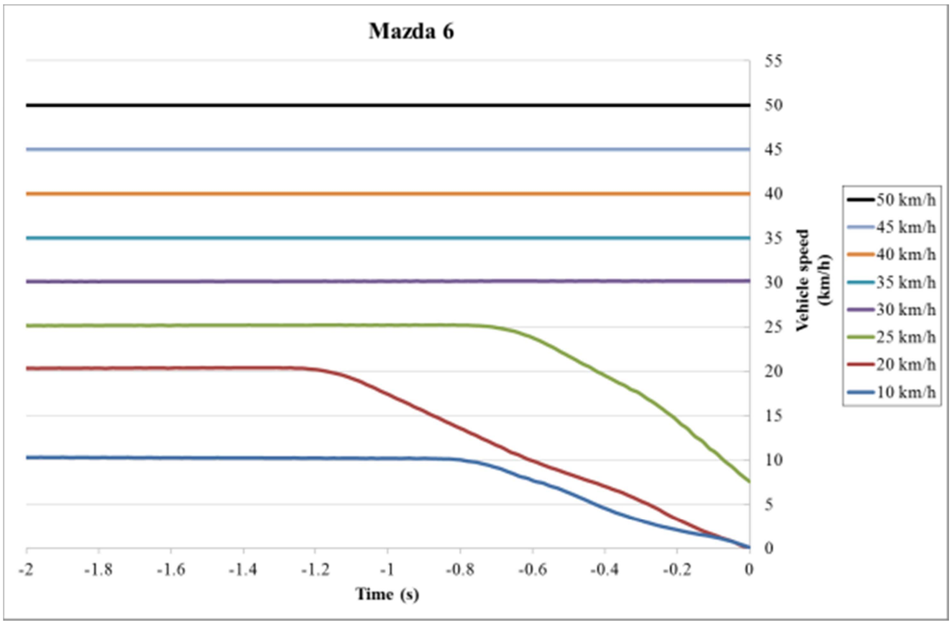

Figure 5. Time history for Mazda 6 tests at each test speed.

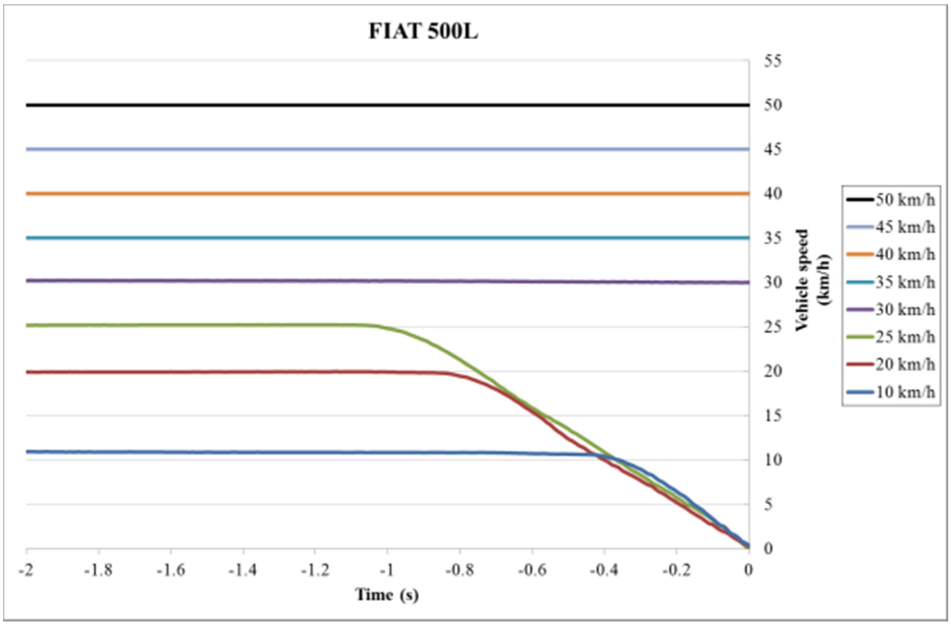

Figure 6. Time history for Fiat 500L tests at each test speed.

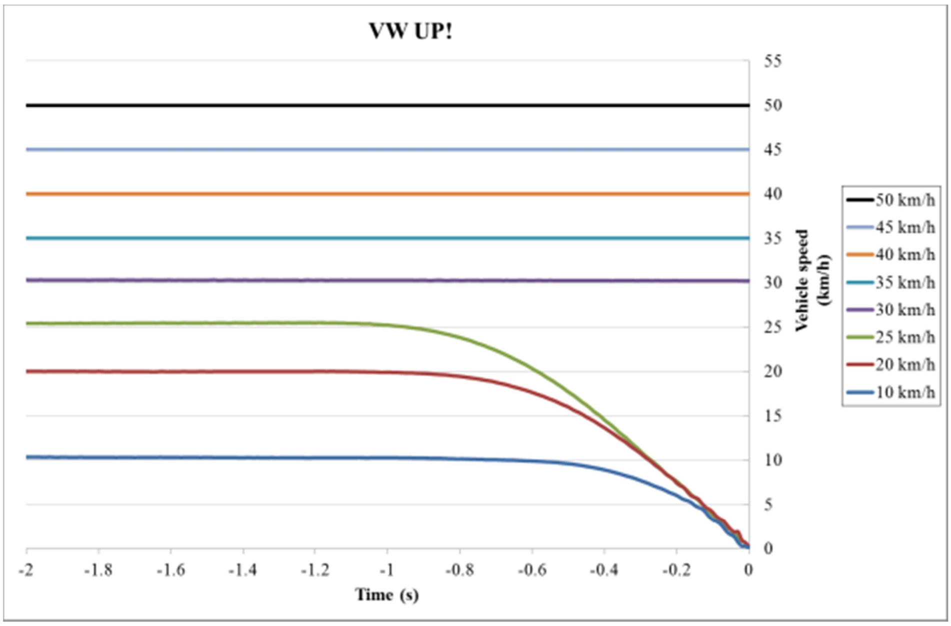

Figure 7. Time history for VW Up! tests at each test speed.

The next performance group was formed by the Mazda CX-5, the Ford Focus and the Fiat Panda. For each of these vehicles the systems had a mitigation effect at 30km/h (one test speed increment higher than the first group). However, despite the extra effects at 30km/h, the CX-5 and the Focus only mitigate the collision at 25km/h whereas the Up! and the 500L fully avoid at that speed.

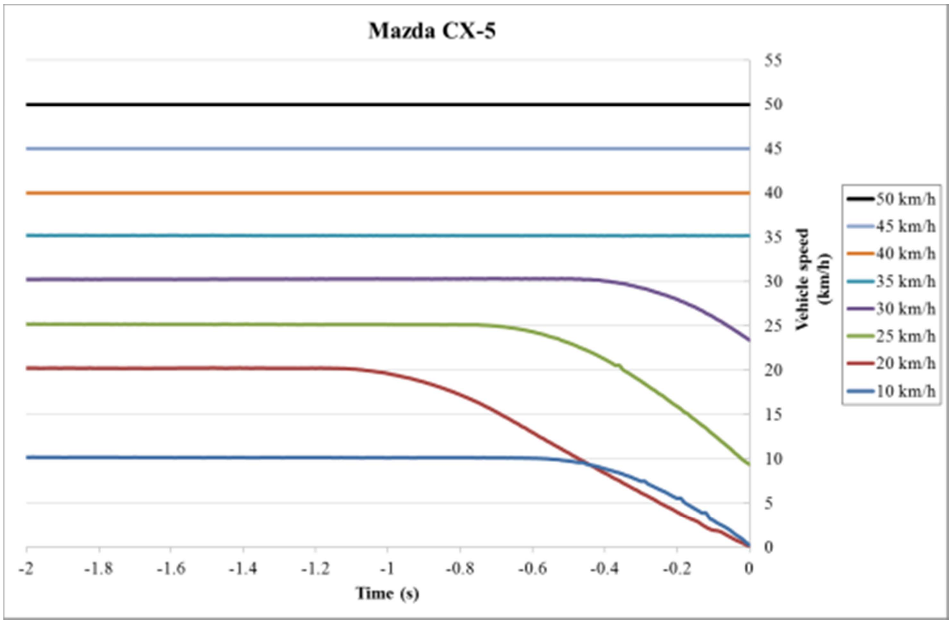

Figure 8. Time history for Mazda CX-5 tests at each test speed.

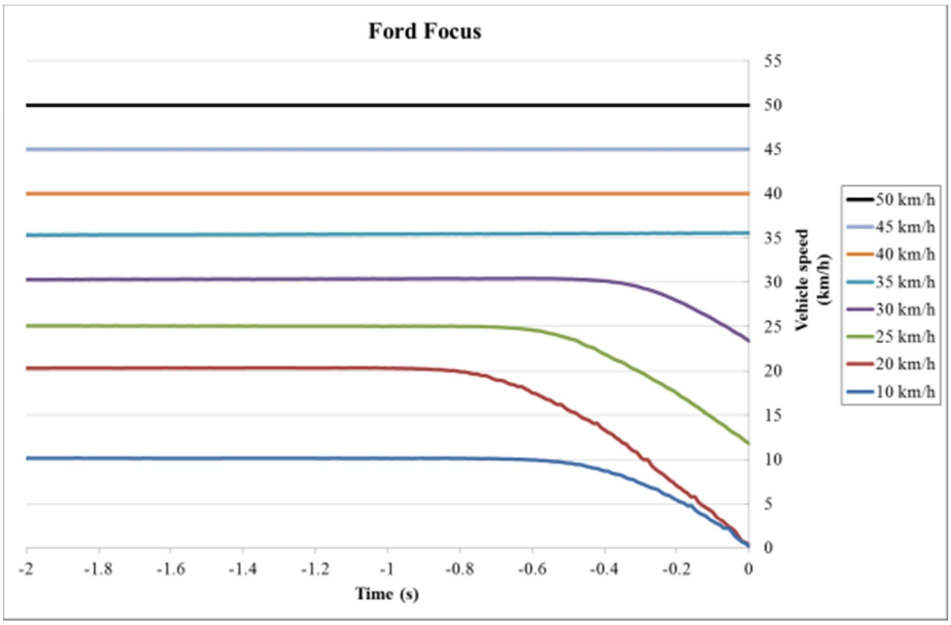

Figure 9. Time history for Ford Focus tests at each test speed (same as *Figure 4*).

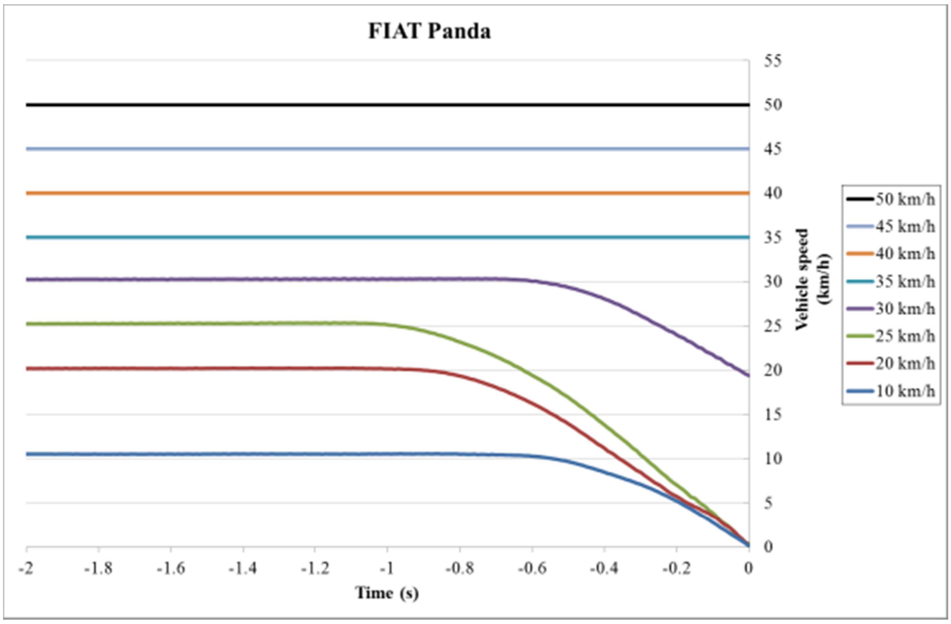

Figure 10. Time history for Fiat Panda tests at each test speed.

The final group of vehicles, both Volvo's, offer some function at test speeds right up to 45km/h, though the speed reductions involved are very small at test speeds of 35km/h and above. Again, these systems will avoid only up to 20km/h.

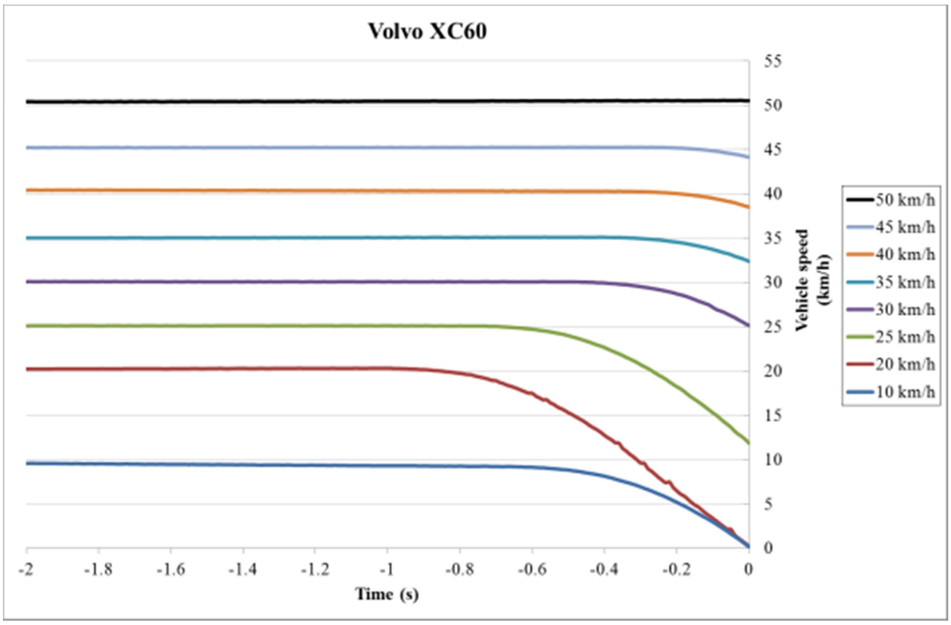

Figure 11. Time history for Volvo XC60 tests at each test speed

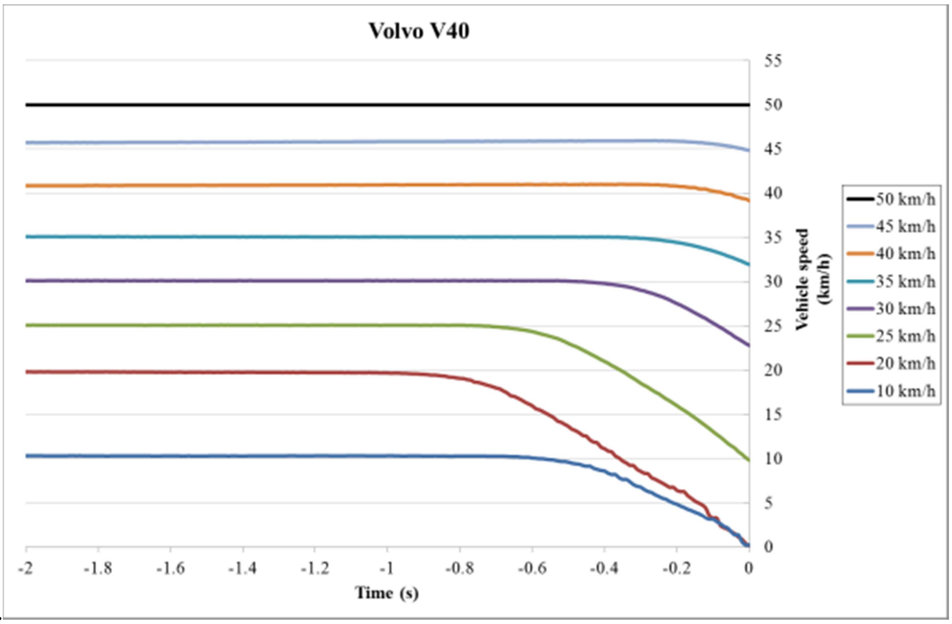

Figure 12. Time history for Volvo V40 (standard fit) tests at each test speed.

The results suggest significant variation in the implementation of the system even within the same sensor technology. The limited comparisons available also suggest that this variation is not brand specific with Fiat and Mazda both having different levels within their range.

The main difference between the groups appears to be the time at which the sensor reacts. For all those systems that avoid at 25km/h, it can clearly be seen that speed reduction commences progressively earlier as test speed increases from 10km/h to 20km/h and then 25km/h. At a test speed of 25km/h, braking commences approximately 1 second before the vehicle comes to rest.

For the vehicles that fail to avoid at 25km/h, it can be seen that speed reduction only commences at a time closer to the point of collision, typically around about 0.6 seconds before impact. The same systems react earlier at 20km/h. This suggests that the reason for the difference is some function of sensor range and the time required to process data and to initiate braking.

RADAR

The Mitsubishi Outlander is the only vehicle in the sample using a RADAR only system to achieve AEB functions in the City test. It can be seen that this system falls into the category of system that either avoids fully or has no effect. However, this RADAR system offers full avoidance from 30km/h, 5km/h greater than any of the LIDAR systems could offer.

It can also be seen that this is achieved by early reaction. At 25km/h the reaction time is similar to the LIDAR systems that avoided at the same speed (approximately 1 second). At 30km/h, braking commences at around 1.5 seconds before the impact point.

A further notable difference with the Mitsubishi implementation is that there is a noticeable two-phase deceleration profile; moderate deceleration in the first phase of braking followed by a step increase as the target approaches. This can be seen as the change in the slope of the time history and may possibly be seen as mitigating any risks of unintended consequences arising from the earlier intervention strategy.

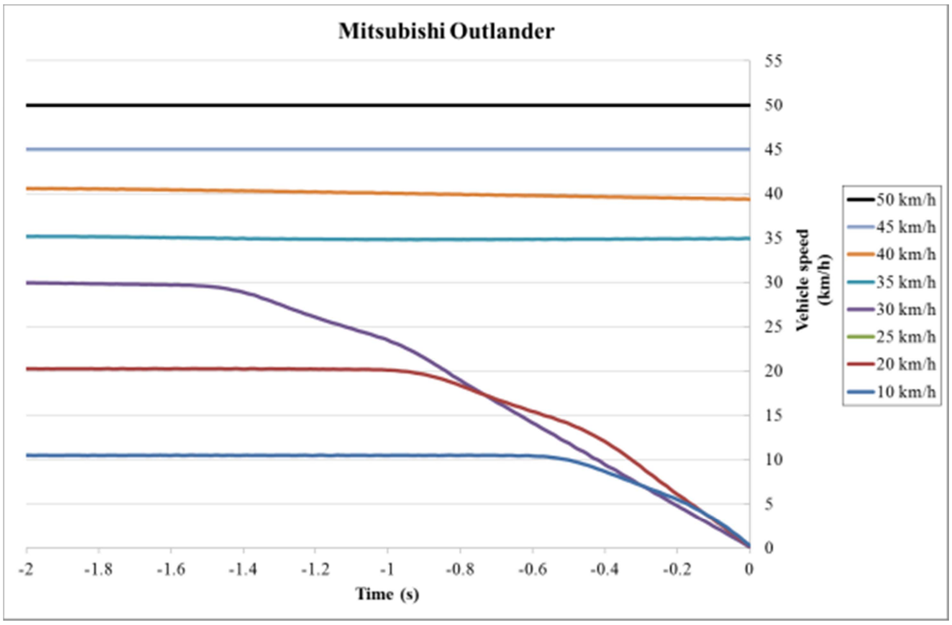

Figure 13. Time history for Mitsubishi Outlander tests at each test speed.

LIDAR/RADAR/camera fusion

The Volvo V40 has a LIDAR system as standard fit and a test of this system was reported in the LIDAR section. It is also possible to optionally add a RADAR and a camera to the LIDAR system to create a 3-way sensor fusion system, known as CADS III+. This system is also capable of pedestrian AEB, though this functionality is not assessed in this paper.

The sensor fusion system on the V40 offers full avoidance from speeds of up to 35km/h and strong mitigation from speeds right up to 50km/h. Again, the time at which the brake system reacts is a significant factor with braking commencing at approximately 1.2 seconds before impact at both 30km/h and 35km/h. This also shows deceleration is a factor; the system reacts later than the Mitsubishi but still avoids at a higher speed.

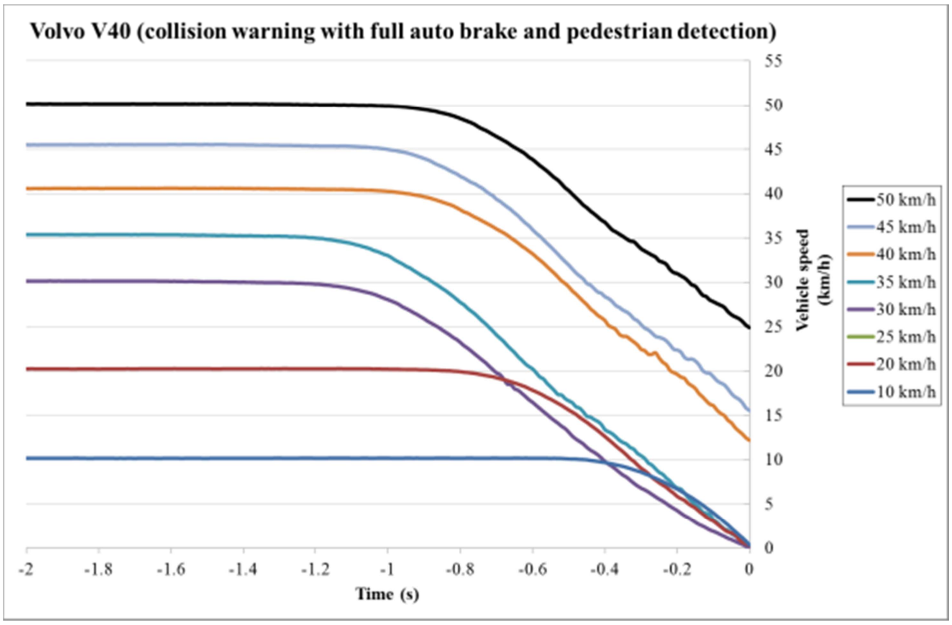

Figure 14. Time history for Volvo V40 (Optional fit CADS III+) tests at each test speed.

Stereo Camera

The Subaru Outback is the only vehicle in the sample equipped with a Stereo Camera system and it should be noted that the example tested was an imported Japanese specification not available in the UK. The stereo camera system is also capable of pedestrian AEB. This vehicle achieved the highest performance level from the sample tested, with full avoidance achieved at 50km/h. The system shared the two phase deceleration strategy with the Mitsubishi Outlander but reacted even earlier and decelerated harder at the higher speeds.

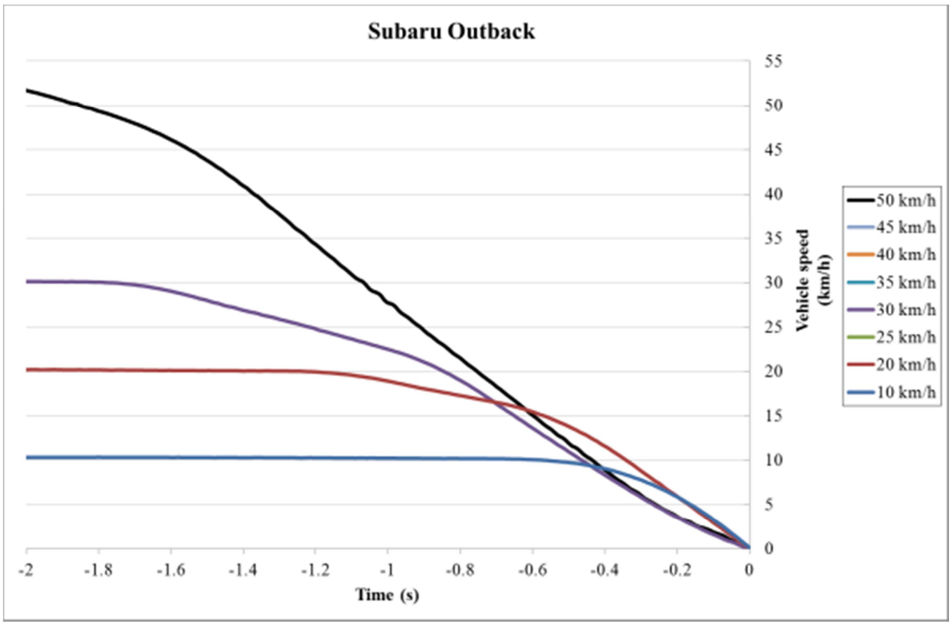

Figure 15. Time history for Subaru Outback tests at each test speed.

DISCUSSION

Test procedures have been rigorously developed based on real world accident scenarios and these have been shown to be capable of accurately and repeatably assessing the effectiveness of AEB and FCW systems in both low and high speed traffic situations. Tests undertaken according to the newly developed protocol have shown that there is quite a wide variation in the performance of current production AEB systems. This variation is related to the technology employed but variation in the implementation strategies is also apparent even within individual technology groups. This has been summarised in *Figure 16* below, which shows the time histories for the highest test speeds at which full avoidance was achieved by each vehicle in the City test.

It can be seen that the more sophisticated multiple sensor systems capable of pedestrian detection also offer the best performance in the Car to Car Rear test (city).

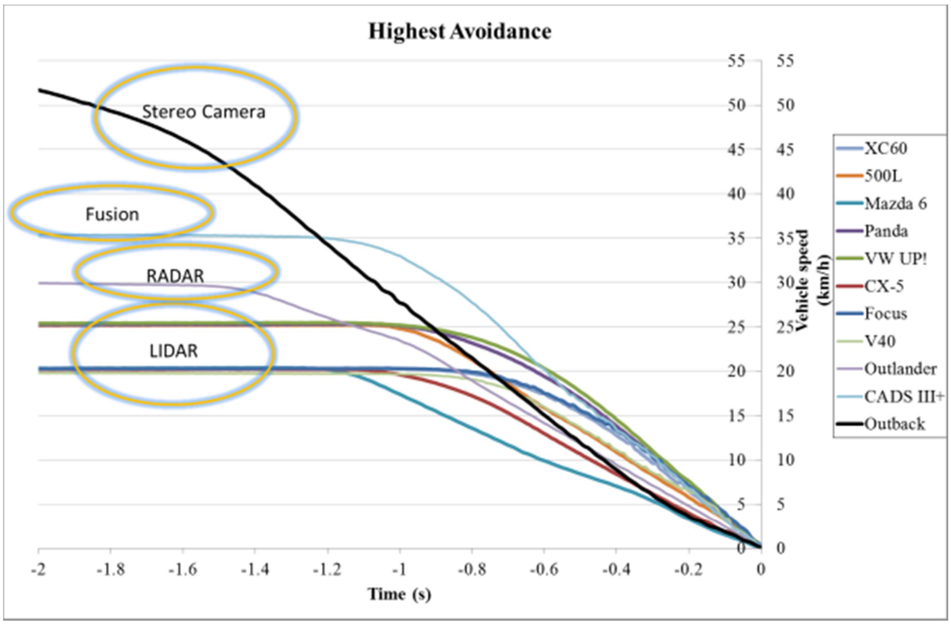

Figure 16. Time history for the highest avoidance speed for each vehicle.

There are some limitations of this study. The vehicles tested in this paper are representative of the current AEB systems fitted and available from major manufacturers and across vehicle segments, but they may not reflect the performance of all different types of systems implemented on models on the current market. Also, since the assessment is based on comparative testing within the scope of the test scenarios no comment can be made on the how system performance would differ outside of these scenarios; however the AEB test procedures are highly relevant being based on statistically significant scenarios from accident data [5] [6] [7].

CONCLUSIONS

AEB systems are becoming more popular and have a positive effect on real world crash rates. There is a need to provide information to consumers on the effectiveness of these systems. Test procedures have been developed to reflect the most important accident configurations for Car-to-Car Rear. These tests can be used to assess the performance of both AEB and FCW systems and are expected to be a strong driver of improved safety in the real world.

Eleven vehicles have been assessed in the city tests and variations have been found in performance both between different technology solutions, but also in the way a particular technology is implemented.

LIDAR systems can be broadly categorised in three groups; those that avoid up to 25km/h and have no effect at 30 km/h or above; those that avoid up to 20km/h, mitigate to 30km/h and have no effect at 35km/h or above; and those that avoid up to 20km/h and mitigate at least small amounts from speeds of up to 50km/h.

One RADAR-only system has been tested and was found to offer higher speed avoidance (up to 30km/h) than any of the LIDAR systems but this had no mitigation effect at higher speeds. Two multiple sensor systems were tested and both offered greater performance than either LIDAR or RADAR alone. The stereo camera system was most effective, with full avoidance from test speeds of up to 50km/h.

The way in which the speed reduction is achieved by vehicles also varies significantly. The time to collision at which the vehicle begins to brake varies most significantly but the level of deceleration also differs.

The AEB test procedures referred to in this paper have been adopted by Euro NCAP (European New Car Assessment Programme) to form the basis of their AEB assessment from 2014 [10]. The UK insurance Group Rating Panel has also adopted the ‘City’ test (CCR test towards a stationary target at low speed) from 2012. Assessment of system performance provides stakeholders with a clear indication of which systems provide the greatest real world and cost benefit.

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