PEER REVIEW PAPER

This paper has been peer-reviewed and published in a special edition of Traffic Injury Prevention 24(S1), by Taylor & Francis Group. The complete paper will be available on the Traffic Injury Prevention website soon. To access ESV Peer-reviewed papers click the link below
https://www.tandfonline.com/toc/gcpi20/24/sup1?nav=tocList

PEER REVIEW PAPER

This paper has been peer-reviewed and published in a special edition of Traffic Injury Prevention 24(S1), by Taylor & Francis Group. The complete paper will be available on the Traffic Injury Prevention website soon. To access ESV Peer-reviewed papers click the link below
https://www.tandfonline.com/toc/gcpi20/24/sup1?nav=tocList

**DEVELOPMENT OF REAR-SEAT OCCUPANT SAFETY METRICS FOR THE MODERATE OVERLAP FRONTAL EVALUATION TEST**

**Marcy A. Edwards**
**Sushant R. Jagtap**
**Jessica S. Jermakian**
Insurance Institute for Highway Safety
United States of America

Paper Number 23-0173

## ABSTRACT

Rear seat safety advancements have lagged those in the front. To address this gap, this research aimed to develop assessment metrics to evaluate the relative protection provided by rear seat restraint systems across a series of vehicle crash tests.

Thirty-two full-scale vehicle crash tests were conducted with a Hybrid III 5th percentile female dummy seated in the left rear seating position in a 64.4 km/h, 40% offset deformable barrier test. Vehicles varied in size, class, and presence of belt pretensioners and load limiters. Dummy injury metrics for the head, neck, thorax, and femur were evaluated along with occupant kinematic metrics including head excursion and submarining. Of the 32 tests, 18 also included a pressure sensor on the rear occupant's thorax to locate the dynamic shoulder belt position.

Shoulder belt tensions ranged from 3.4 to 8.3 kN, and higher shoulder belt tensions were generally associated with higher head and neck injury values, but sternum deflection did not show a similar relationship. High (> 40 mm) and low (~20 mm) sternum deflections were observed for vehicles with and without pretensioners and load limiters and for a wide range of belt tensions. Higher dynamic belt positions were correlated with lower chest deflections and compensating for the effect of belt position aligned sternum deflections with expectations based on shoulder belt tensions. Head contact only occurred in one vehicle, but head excursion boundaries in the absence of impact remain important to ensure that restraint systems limit excursion and the risk of head injury for higher severities or larger occupants. The dummy showed propensity for submarining, an important risk factor for abdominal injuries. Femur axial forces were low for all vehicles, even in cases where the knees contacted the front seatback.

Assessment metrics were developed to evaluate the relative protection of rear occupants across a range of vehicles. A novel dummy-based metric, called the Chest Index, was developed that allows the comparison of chest protection across vehicles with a range of dynamic belt fit.

## BACKGROUND

In 1995, when the Insurance Institute for Highway Safety (IIHS) began assessing occupant safety for drivers in moderate overlap frontal crashes, only 16% of the vehicles rated received a good overall rating. By 2008, all new U.S. cars were equipped with pretensioners and load limiters for front-seat occupants and by 2013, all vehicles rated received a good overall rating in this test. The benefits of better performance in the moderate overlap crash test are evident in field data, where drivers of vehicles rated good in this test are 46% less likely to die in a frontal crash than drivers of poor-rated vehicles [1]. Similarly, an analysis of U.S. New Car Assessment Program (U.S. NCAP) frontal test scores found a correlation between composite scores and fatality rates for belted drivers in collisions during 1979–1991 [2]. Frontal crash test programs have historically prioritized reducing injuries for drivers due to their higher occupancy rates, which has led to a lag in rear-seat occupant safety to the point that the rear seat is now considered less safe than the front, especially for older adults [3]. In 2015, the European New Car Assessment Programme (Euro NCAP) introduced occupant safety ratings for rear-seat occupants in frontal crashes, which resulted in almost all European vehicles being equipped with pretensioners and load limiters by 2020, but until recently, U.S. crash tests conducted under Federal Motor Vehicle Safety Standards (FMVSSs), the U.S. NCAP, and IIHS have not evaluated occupant safety for rear-seated occupants in frontal crashes [4].

Rear-seat injuries differ from front-seat injuries due to the wide range of occupant sizes and restraint environments (e.g., no airbags or knee bolsters and belt-anchorage variability). In 2003, Parenteau and Viano found that primary Abbreviated Injury Scale (AIS) 3+ injuries for restrained rear-seated adults and teens in frontal crashes were to the thorax (78%), head (9%), lower extremities (8%), and abdomen (5%) [5]. Primary AIS 3+ injuries for children ages 4–12 years old were to the head (30%), upper and lower extremities (33% and 20%), and abdomen (10%) [6]. In 2019, Jermakian et al. studied rear-occupant injuries and causation scenarios in frontal crashes in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) and from police –reported crash records in the Fatality Analysis Reporting System (FARS). This study documented the chest, head, and abdomen as the most common injuries in both datasets and documented shoulder belt loading, head impacts with the interior, and lap belt submarining as the most common injury causation scenarios for these injuries, respectively [7].

To address the gap in protection for rear-seat occupants, IIHS has examined whether to include a rear-seated dummy in its frontal crashworthiness evaluations. Initial research studied various crash modes, human surrogates, and occupant positions and found that the 40% offset deformable frontal crash test (64.4 km/h) with an H3-5F dummy seated in the left second-row seating position provided the best opportunity to represent the rear-occupant injuries observed in field data [8]. However, dummy limitations affect the alignment between crash test results and real-world outcomes. Kuppa et al. studied rear-seat occupant injuries from both field studies and anthropomorphic test devices (ATDs) and found that while real-world occupant injuries indicated the thorax as the most frequently injured body region, the ATDs reported the head and neck as the most seriously injured body region [9]. Other researchers have observed issues specifically with the sternum deflection metric on the Hybrid III 5th percentile female (H3-5F) dummy, indicating a sensitivity to belt position that could affect dummy outcomes [10,11,12]. Edwards et al. confirmed this sensitivity and quantified its relationship with belt position for the H3-5F with sled testing [13]. Assessing the safety performance of vehicle restraint systems with metrics that can both faithfully represent the injuries observed in real-world crashes and reliably differentiate performance is important to encourage meaningful improvements in rear-seat occupant safety in frontal crashes. This research aimed to address the known shortcomings with ATDs and develop reliable assessment metrics to evaluate the protection from head, neck, chest, abdomen, and lower extremity injury provided by rear-seat restraint systems in 64 km/h, 40% offset deformable barrier (ODB) vehicle crash tests.

## METHODS

Thirty-two full-scale frontal vehicle crash tests were conducted with a H3-5F seated in the second-row left-seating position and a 50$^{th}$ percentile male dummy (THOR-50M or H3-50M) in the driver seat in the IIHS moderate overlap test condition, where 40% of the width of the vehicle impacts a deformable, aluminum honeycomb barrier at 64.4 km/h. Vehicles tested varied in class and rear seat-belt restraint technology. A complete test matrix is shown in Table 1.

The IIHS *Dummy Seating Procedure for Rear Outboard Positions, Version II* [14] was used to position a H3-5F dummy in the left second-row seating position. The IIHS procedure described in *Guidelines for Using the UMTRI ATD Positioning Procedure for ATD and Seat Positioning, Version V* [15], was used to position both the THOR-50M and H3-50M dummies in the driver seat. After the seat was set using the H3-50M dummy, the seat was not moved in the process of positioning THOR-50M. Thus, the seat position was the same for all the tests, regardless of which dummy was in the front seat.

The H3-5F dummy metrics included triaxial head accelerations and angular rates; thorax triaxial accelerations, y-axis angular rate, and sternum potentiometer deflection; pelvis x- and z-axis accelerations and y-axis angular rate; upper neck, lower neck, thoracic spine, and lumbar spine x- and z-axis forces and y-axis moments; left and right anterior superior iliac spine (ASIS) x-axis forces and y-axis moments; and femur axial forces. Instrumentation also included shoulder and outboard lap-belt load cells. All dummy and vehicle sensor data were collected at a sampling rate of 10,000 Hz in accordance with the SAEJ211 coordinate system [16].

To gather additional information on shoulder belt position and loading on the thorax, a thin high-frequency, high-resolution pressure mat (XSensor, Calgary, Canada) was also included in 18 tests to provide contact locations and pressures between the shoulder belt and thorax. The pressure sensor mat provided time-dependent, two-dimensional mapping of the pressures between the seat belt and thorax at a frequency of 3900 Hz and a resolution of 5 mm x 15 mm for the belt-shaped sensor (XSensor belt, HX210:30.40.05-15M HSS) (Figure 1a) and 3300 Hz and a resolution of 5 mm x 5 mm for the vest-shaped sensor (XSensor vest, XSensor HX210:36.48.05M-HSS) (Figure 1b). Three of the 18 tests employed the belt-shaped sensor, and the remainder used a vest-shaped sensor fitted to the anterior chest of the H3-5F. The pressure mat was secured using adhesive tape on all sides to prevent migration of the sensor relative to the flesh. The location of the pressure mat was quantified relative to ATD landmarks with a 3D coordinate measurement machine (CMM) in a dummy-based coordinate system prior to the test according to the IIHS *Moderate Overlap Frontal Crashworthiness Evaluation 2.0 Crash Test Protocol (Version I)* [17], so that belt placement could be related to the sternum potentiometer location. For this measurement, individual sensor rows and columns were mapped prior to testing using a CMM, so row and column positions at the belt centerline could be mapped to the dummy-based coordinate system. The vertical distance from the centerline of the belt path relative to the sternum potentiometer was then calculated using a linear equation representing the belt path and sternum potentiometer coordinates according to the IIHS *Moderate Overlap Crashworthiness Evaluation 2.0 Rating Guidelines (Version I)* [18].

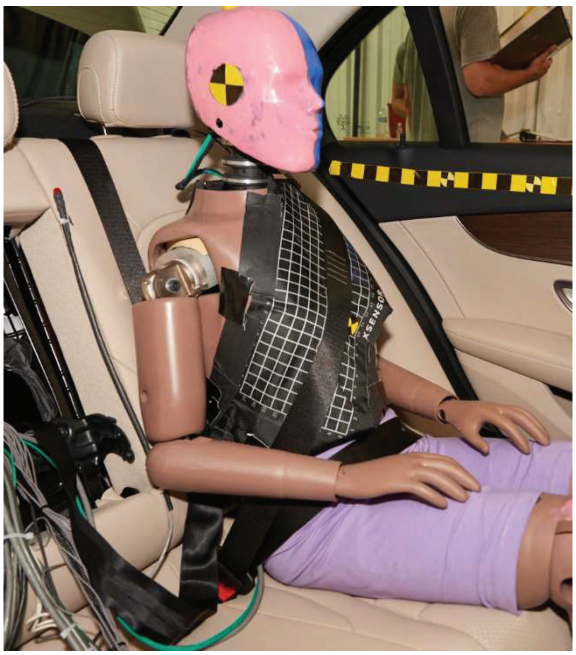


***Figure 1a. Belt sensor***

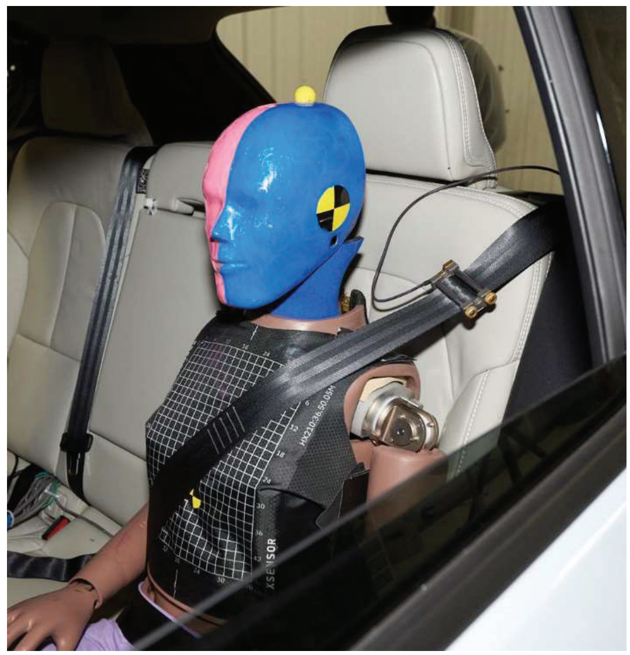


***Figure 1b. Vest sensor***

Head excursion for the rear occupant was measured via video analyses. Vertical tapelines were applied on the left rear door at locations corresponding to the pre-impact position of the rearmost point on the front seatback in test position and 50 mm rearward of the front seatback. Head excursion was measured in four segments: (1) rearward of the 50-mm line, (2) between the 50-mm line and the front seatback, (3) beyond the front seatback line, and (4) contact with the front seatback.

In this research series, submarining was evaluated primarily with video analysis of the belt position. However, the H3-5F is also equipped with ASIS load cells that measure both load on the ASIS and moment about the lateral axis at the center of the ASIS, which provides information on whether the belt is loading the top or bottom of the ASIS. These sensors, along with lap belt load, were used to confirm findings observed in the video analysis.

*Table 1.*
*Test matrix of full-scale vehicle crash tests conducted at 64.4 km/h into a deformable barrier at a 40% overlap*

| Rear occupant seat belt design | Vehicle tested | Vehicle class | Test ID | Belt position measurement |
|---|---|---|---|---|
| Standard belt | 2021 Chevrolet Equinox | Small SUV | CEF2116 | XSensor vest |
| | 2021 Hyundai Tucson | Small SUV | CEF2104 | XSensor vest |
| | 2021 Jeep Compass | Small SUV | CEF2117 | XSensor vest |
| | 2022 Mitsubishi Eclipse Cross | Small SUV | CEF2107 | XSensor vest |
| | 2020 Hyundai Santa Fe | Midsize SUV | CF19031 | None |
| | 2018 Mazda 6 | Midsize car | CF19026 | None |
| | 2019 Chevrolet Equinox | Small SUV | CF19027 | None |
| | 2021 Jeep Renegade | Small SUV | CEF2118 | XSensor vest |
| | 2021 Buick Encore | Small SUV | CEF2103 | XSensor vest |
| | 2021 Honda CR-V | Small SUV | CEF2115 | XSensor vest |
| | 2021 Honda HR-V | Small SUV | CEF2111 | XSensor vest |
| | 2020 Kia Rio | Minicar | CF21010 | XSensor belt |
| | 2020 Toyota Yaris | Minicar | CF21006 | None |
| | 2017 Honda Civic | Small car | CF19028 | None |
| | 2017 Chrysler Pacifica | Minivan | CF19029 | None |
| | 2020 Chevrolet Colorado | Small pickup | CF21011 | None |
| | 2021 Mazda CX-5 | Small SUV | CEF2109 | XSensor vest |
| Load limiter belt | 2018 Volkswagen Atlas | Midsize SUV | CF19024 | None |
| Pretensioner and load limiter belt | 2021 Volvo XC40 | Small SUV | CEF2108 | XSensor vest |
| | 2021 Nissan Rogue | Small SUV | CEF2112 | XSensor vest |
| | 2020 Nissan Sentra | Small car | CF21007 | None |
| | 2020 Mercedes-Benz C 300 | Midsize luxury car | CF21008 | XSensor belt |
| | 2019 Volvo XC60 | Midsize luxury SUV | CF19023 | None |
| | 2019 Nissan Altima | Midsize car | CF19025 | None |
| | 2021 Toyota RAV4 | Small SUV | CEF2110 | XSensor vest |
| | 2021 Ford Escape | Small SUV | CEF2114 | XSensor vest |
| | 2021 Audi Q3 | Small SUV | CEF2105 | XSensor vest |
| | 2019 Volvo XC60 (Dual LL) | Midsize luxury SUV | CF19032 | None |
| | 2020 BMW 3 series | Midsize luxury car | CF21009 | Xsensor belt |
| | 2020 Ford Escape | Small SUV | CF19033 | None |
| | 2021 Subaru Forester | Small SUV | CEF2113 | XSensor vest |
| | 2020 Subaru Forester | Small SUV | CF19030 | None |

This paper discusses results for shoulder belt tension, head injury criterion, resultant head acceleration, head excursion, upper neck tension, upper neck compression, Nij, sternum deflection, the influence of belt position on sternum deflection, submarining (migration of the lap belt into the abdomen) and femur axial compression. However, more dummy metrics were evaluated than will be discussed in this paper. In addition to upper neck tension, upper neck compression, and Nij, upper neck flexion and extension moments were also evaluated. Peak moment values, particularly extension moment, often were recorded after the forward loading phase of the event. Since the biofidelity of the dummy kinematics for the H3-5F for rebound are uncertain, these values are a lower priority than those measured during the loading phase. Resultant thoracic acceleration was also considered for evaluation but excluded because it “sums the effects of force inputs from the ribcage, shoulder and arms, abdomen, neck and lumbar spine,” which does not necessarily represent the rib cage compression injuries that cause rib fracture and organ injury [19]. Sternum deflection rate and viscous criterion were also evaluated, but closely followed the trends of sternum deflection so were not considered further.

Metrics were evaluated for both their prediction of injury compared to field observations and their correlations with expected beneficial technology, like shoulder belt tension, and with potential confounding factors like belt position (Table A2, Appendix).

## RESULTS

### Seat belt technology in the rear seat

Of the 32 vehicles tested, 17 had standard belts, 1 had only load limiters, and 14 had both pretensioners and load limiters. Shoulder belt tensions for standard belts ranged from 6.0 to 8.3 kN and ranged from 3.4 to 5.5 kN for the pretensioning and load-limiting belts (Table A1, Appendix). The one belt with only a load limiter had a shoulder belt tension of 6.4 kN. All belts with pretensioners and load limiters had shoulder belt tensions under 6.0 kN, and all standard belts had shoulder belt tensions of 6.0 kN or higher. Rear-seat pretensioning and load limiting for all vehicles equipped were exclusively in the shoulder belt retractor.

### Head Injury

Two injury metrics, head injury criterion calculated over a 15-ms interval (HIC 15) and peak resultant head acceleration, were used to assess risk of head injury for the rear occupants. HIC criterion and peak resultant head acceleration are both meant to assess the risk of skull fracture from hard contacts. In this test series, the dummy contacted the interior structure (front seatback) in only one test; the extended cab CF21011 Colorado, which had the smallest rear-occupant space of all the vehicles tested. Though no head contact with the seatback occurred in any of the other vehicles, in some cases, the front seatback pivoted away from the rear occupant in phase with the excursion of the rear-seat occupant’s head. In Figure 2a, the pre-impact, rearmost point of the front seatback is marked on the left rear door by the leading edge of the most forward vertical tape line. In Figure 2b, the same vehicle is shown 110 ms after impact. At this time, the front seatback has moved forward from the original position and, though the head crosses the boundary for the original position of the seatback, it still does not contact the front seatback.

***Figure 2a. Pre-impact photo showing the front edge of the vertical tapeline positioned at the rearmost point of the front seatback***

***Figure 2b. Photo at 110 ms showing the front seatback moving in phase with the rear-seat occupant’s excursion***

To evaluate the risk of head impacts in the absence of contact with the front seatback, measurements were taken of the head relative to the pretest position of the seatback. Figure 3 shows the rear-seat occupant’s head excursion for each vehicle relative to the front seatback. The head impacted the seatback in 1 vehicle, crossed the pre-impact seatback line in 3 vehicles, came within 50 mm of the pre-impact seatback line in 13 vehicles, and remained farther than 50 mm from the pre-impact seatback line in 15 vehicles. The 4 vehicles where the head either contacted the seatback or crossed the seatback line all had standard rear-occupant belts and of these, 2 were small SUVs, 1 was small pickup with an extended cab, and 1 was a minicar.

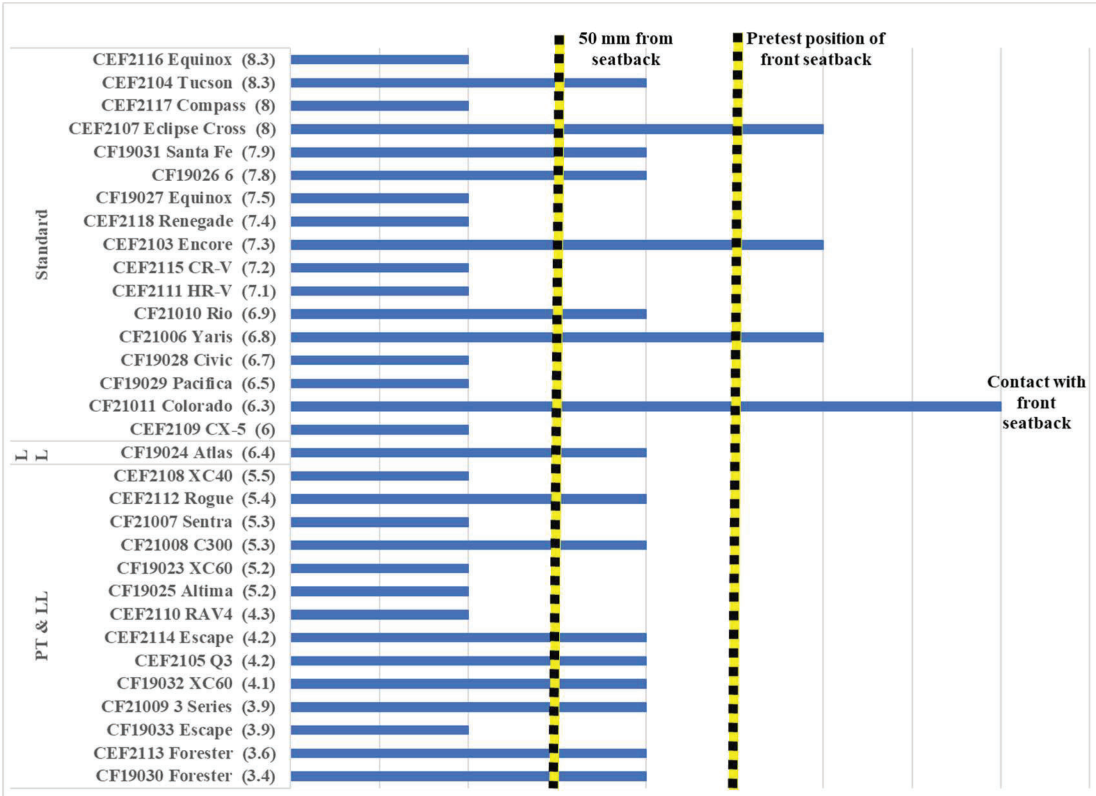



***Figure 3. Rear-occupant head excursion categories (relative to the front seatback). Vehicle tests are organized by rear seat-belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT & LL]) and ordered by shoulder belt tension (kN).***

Figure 4 shows both normalized HIC 15 and peak resultant head acceleration. Peak resultant acceleration values ranged from 66 to 106 g for standard belts and 49 to 74 g for belts with pretensioners and load limiters. Peak resultant head acceleration reported its highest value (106 g) in the one vehicle where the occupant's head impacted the vehicle interior. HIC 15 values ranged from 433 to 1393 for standard belts and 222 to 598 for belts with pretensioners and load limiters. HIC 15 reported its highest value (1393) in the vehicle with the highest shoulder belt tension. Both HIC 15 and peak resultant head acceleration had positive correlations (r = .85 and 0.81, respectively) with shoulder belt tension.

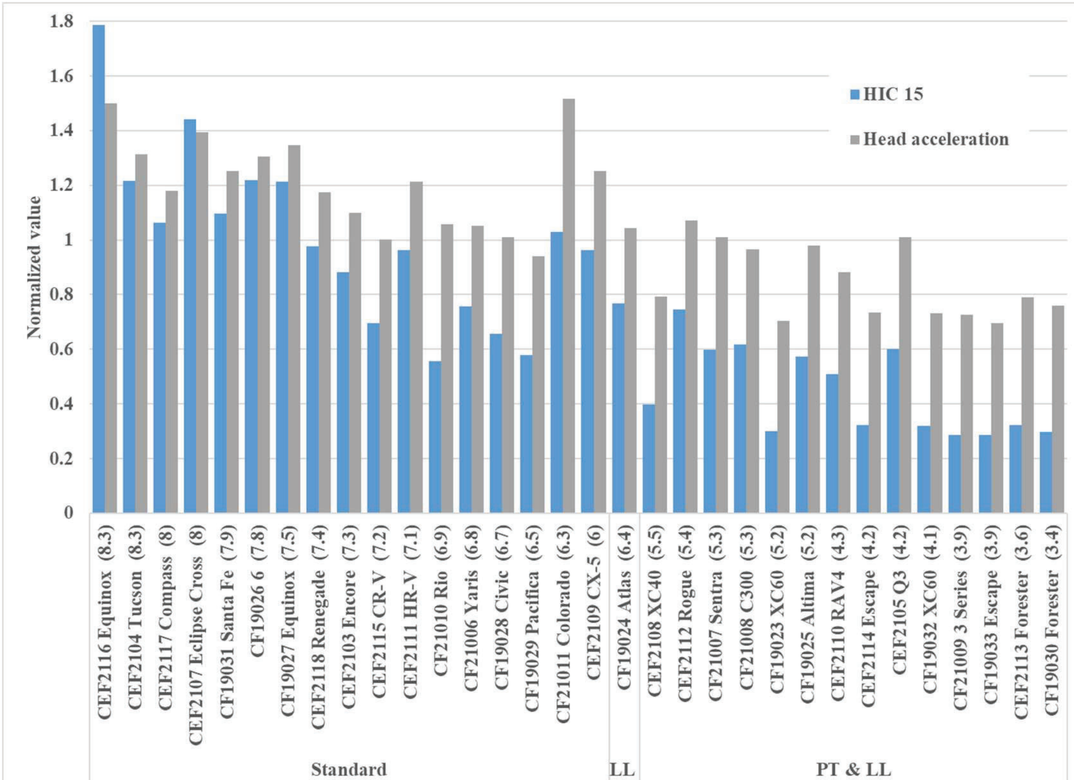



***Figure 4. HIC 15 and resultant head acceleration normalized by the reference values 779 and 70 g, respectively. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).***

**Neck Injury**

Three injury metrics were evaluated for assessing the risk of neck injury for rear occupants: upper neck tension, upper neck compression, and maximum Nij (Figure 5). Peak neck tensions and maximum Nij values occurred primarily during the loading phase of the crash, while peak compression values occurred primarily during rebound. Peak neck-tension values ranged from 1.6 to 4.3 kN for standard belts and 1.6 to 3.2 kN for belts with pretensioners and load limiters. Fourteen of the 32 tests had neck tensions that exceeded the Injury Assessment Reference Value (IARV) of 2.6 kN for in-position occupants [20]. Peak neck compression values ranged from 0 to 0.7 kN for standard belts and 0 to 0.6 kN for belts with pretensioners and load limiters. None of the peak compression values exceeded the 2.5 kN IARV (Mertz, 2016). Peak Nij values ranged from 0.7 to 1.3 for standard belts and 0.5 to 0.9 for belts with pretensioners and load limiters, all of which were recorded during the loading phase and included the tension component.

Both neck tension and maximum Nij had positive correlations (r = .76 and .74, respectively) with shoulder belt tension, indicating that the restraint system affects neck forces during loading. Neck compression, however, had no correlation with shoulder belt tension (r =.1). Further, correlations between neck tension and HIC 15 were high (r = .88) for noncontact cases, indicating that both metrics are similarly reporting the effect of the restraint system forces on the occupant.

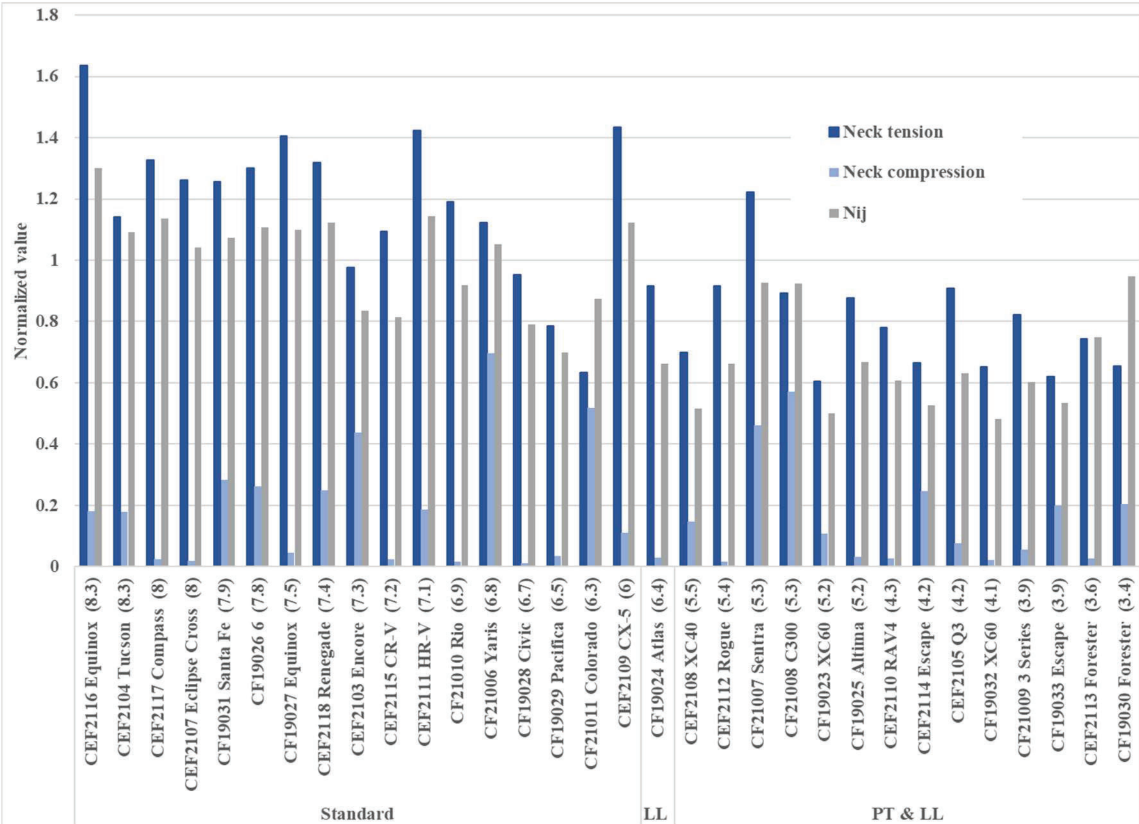



***Figure 5. Neck tension, neck compression and Nij values normalized by 2.1 kN, 2.5 kN and 1.0, respectively. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).***

Figure 6 shows the correlation between neck tension and maximum Nij plotted with their respective IARVs. Because of the mostly linear nature of the relationship between these two metrics, there are no tests where maximum Nij exceeds the IARV, but neck tension does not. However, there are two tests where max Nij does not align with the linear relationship with neck tension and maximum Nij reports a higher normalized value than neck tension, the CF19030 Forester and CF21011 Colorado. In these two tests, Nij tension-extension, rather than tension-flexion, reported the highest value during the loading phase of the event. The CF21011 Colorado was the one vehicle where the head impacted the front seatback, which reduced neck tension but increased extension moment (Figure 7). The CF19030 Forester had the lowest shoulder belt tension in the test series, which also reduced neck tensions but resulted in alternate head-neck kinematics that increased neck extension during the loading phase of the event.

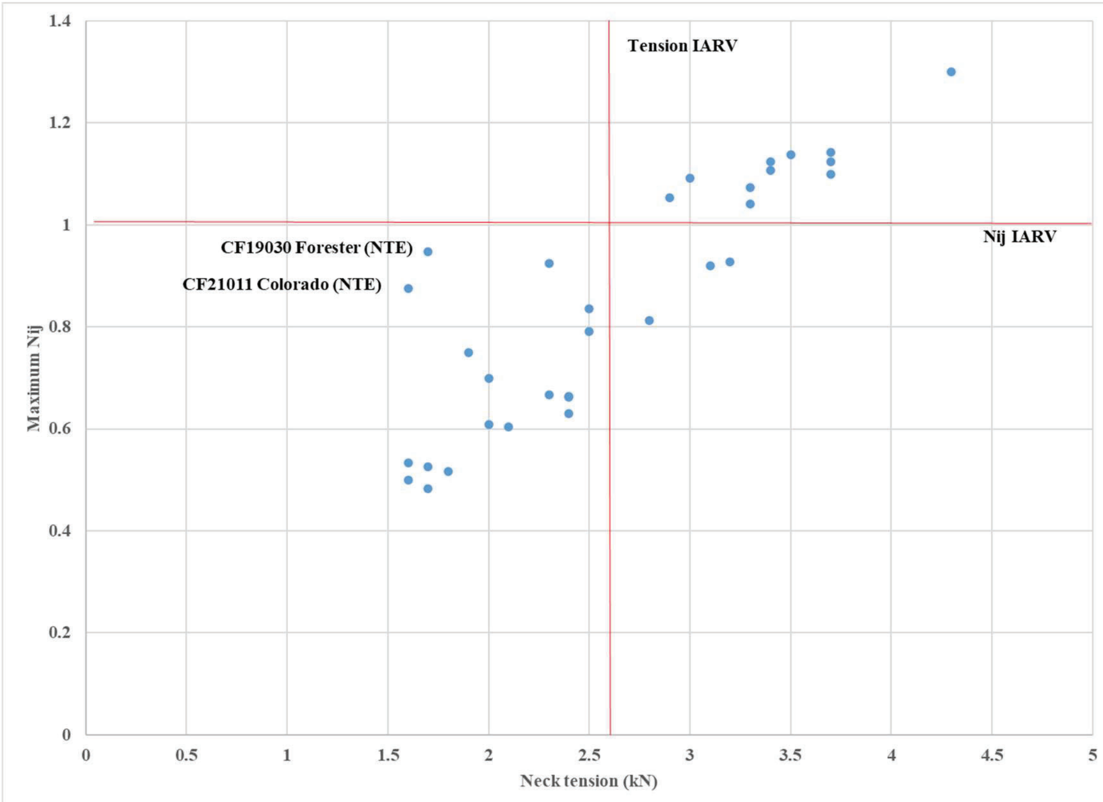



*Figure 6. Correlation of neck tension to maximum Nij plotted with IARVs*

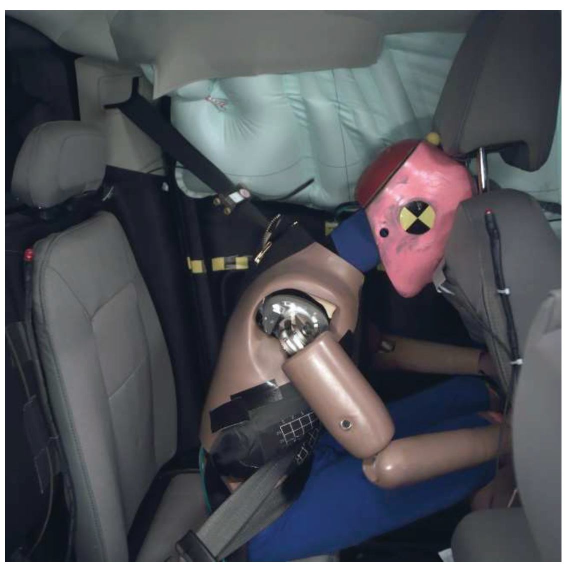


*Figure 7. CF21011 Colorado at 100 ms*

**Chest Injury**

Sternum deflection was the only metric evaluated for assessing the risk of chest injury for rear occupants. Sternum deflection provides information about the loads sustained directly to the rib cage, which are the source of many life-threatening organ injuries. Figure 8 shows peak sternum deflection values. Peak sternum deflection values ranged from -43 to -20 mm for standard belts and -41 to -20 mm for belts with pretensioners and load limiters. Only three of the tests had sternum deflections that exceeded the IARV of -41 mm (Mertz, 2016).

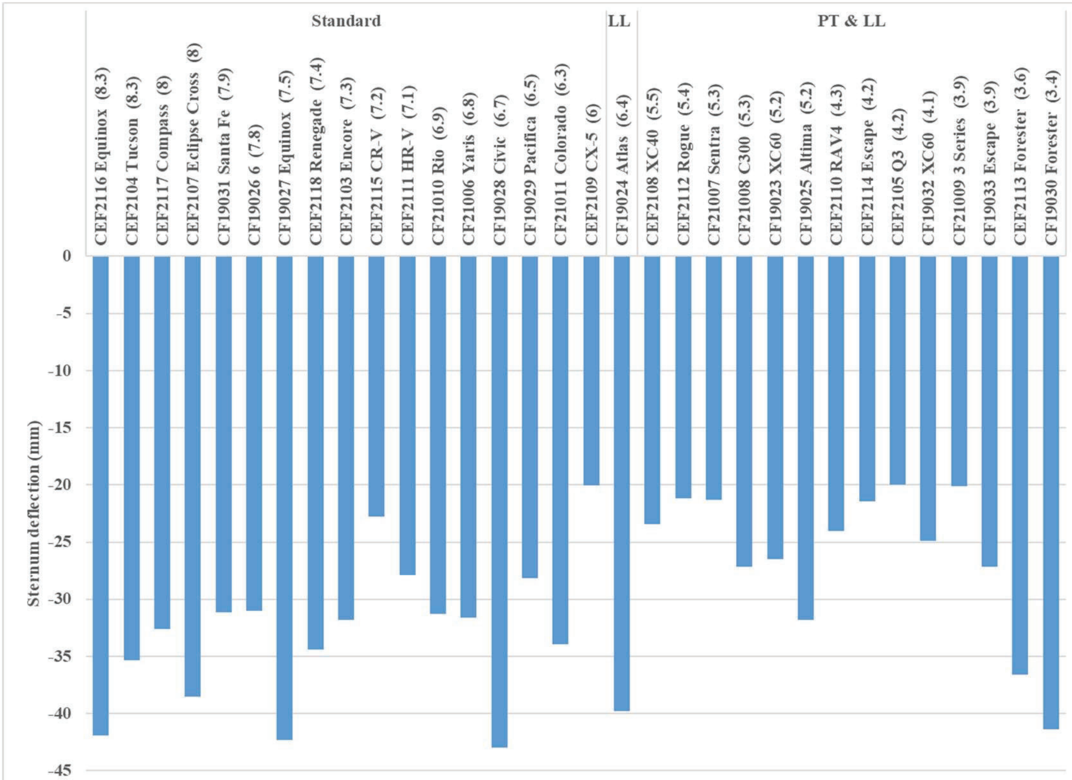



***Figure 8. Peak sternum deflection values. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).***

Video analysis of the first 14 tests in this data series showed a wide range of pretest belt positions and factors like belt pretensioning and the lap belt migrating over the ASIS into the abdomen sometimes caused greater shoulder belt movement on the chest (Figure 9). Figure 10 shows the relationship between and variation in pretest static belt positions and dynamic belt positions at the time of maximum sternum deflection for the 18 tests with a pressure mat. Static belt positions ranged from 40 to 80 mm above the sternum potentiometer, a range of 40 mm. Dynamic belt position ranged from 48 to 129 mm above the sternum potentiometer, a range of 81 mm. Static belt positions show some relationship with dynamic belt positions ($r = 0.68$), but the wide range of dynamic results for a given static position show that static position is not a good predictor of dynamic position. Figure 11 shows the examples of the lowest and highest dynamic belt positions. Belt positions above 110 mm mostly loaded the neck rather than the shoulder.

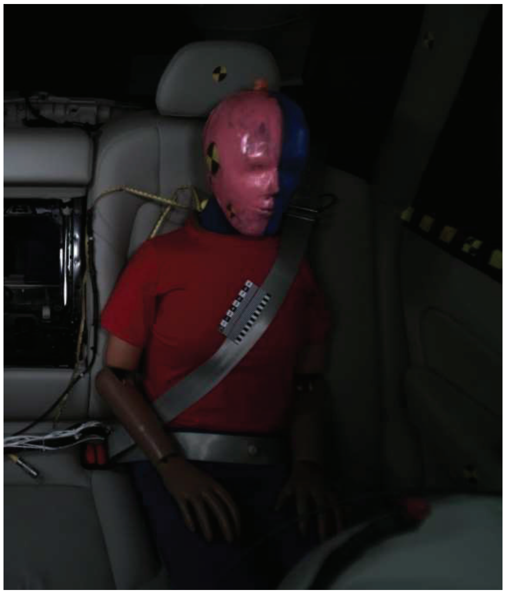


***Figure 9a. CF19023 (XC60) Pre-impact belt position***

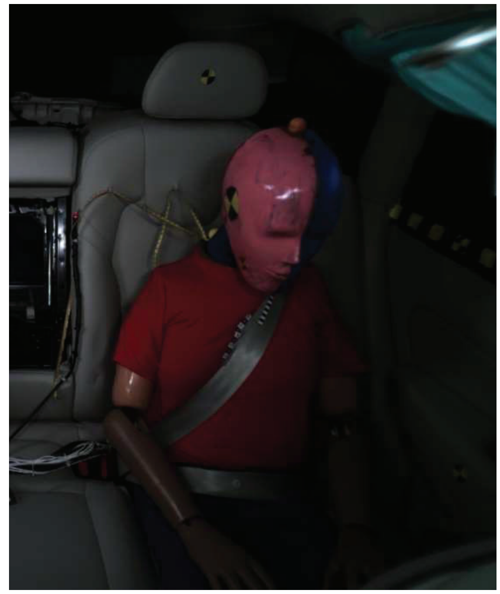


***Figure 9b. CF19023 (XC60) belt position after pretensioning***

***Figure 9c. CEF2109 (6) Pre-impact belt position***

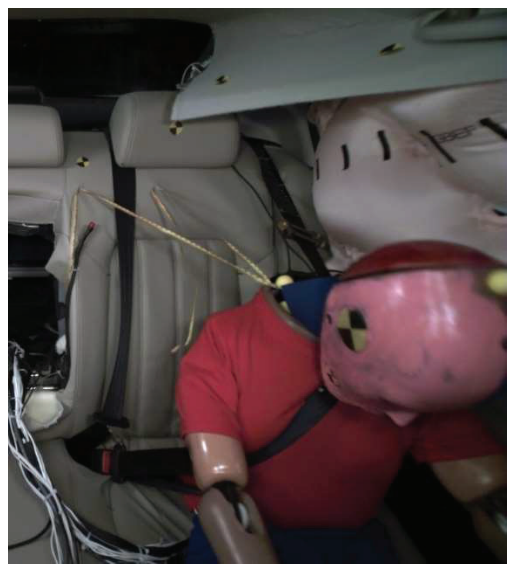


***Figure 9d. CEF2109 (6) belt position @ maximum excursion***

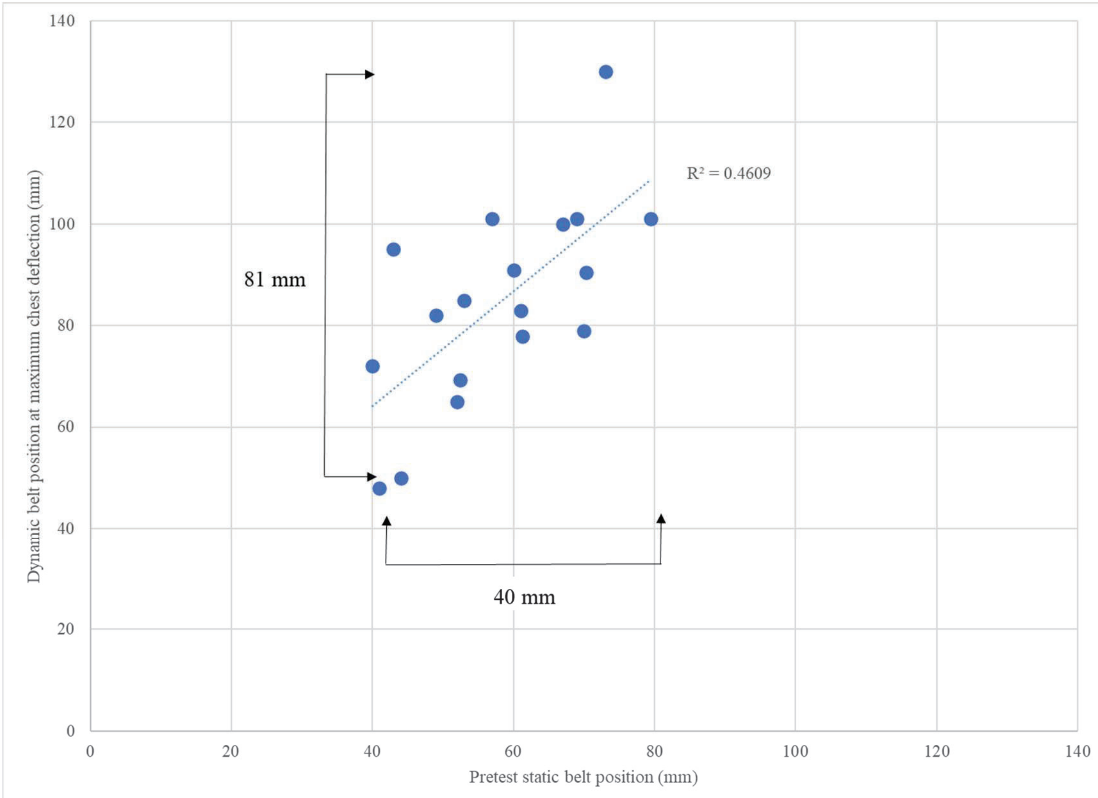



***Figure 10. Belt positions relative to sternum potentiometer at pretest and maximum chest deflection.***

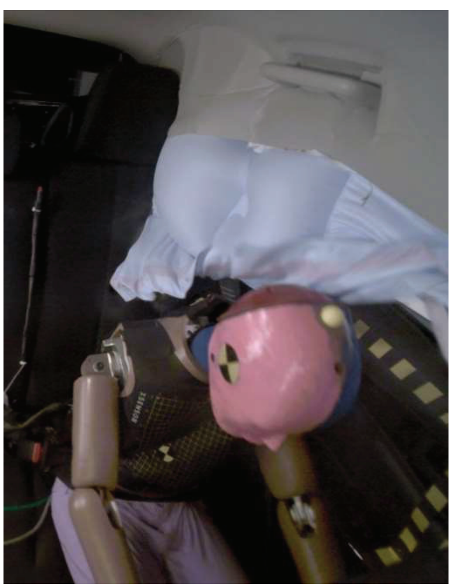


***Figure 11a. Lowest dynamic belt position (104 ms); CEF2107 (Eclipse Cross)***

***Figure 11b. Highest dynamic belt position (120 ms); CEF2115 (CR-V)***

Figure 12 shows the relationship between sternum deflection and both shoulder belt tension and dynamic belt position for the 18 tests where belt position could be measured. In the complete 32 test dataset, shoulder belt tension explained only 19% (r = .44) of the variance in sternum deflection values. The correlation between sternum deflection and shoulder belt tension was slightly higher in the smaller (18 test) dataset (r =.62) where belt position could be measured. Conversely, the correlation between sternum deflection and dynamic belt position was high (r = .75), indicating that dynamic belt position influenced sternum deflection more than belt tension. Shoulder belt tension and dynamic shoulder belt position were not highly correlated (r = .13), so their effect on sternum deflection was largely independent.

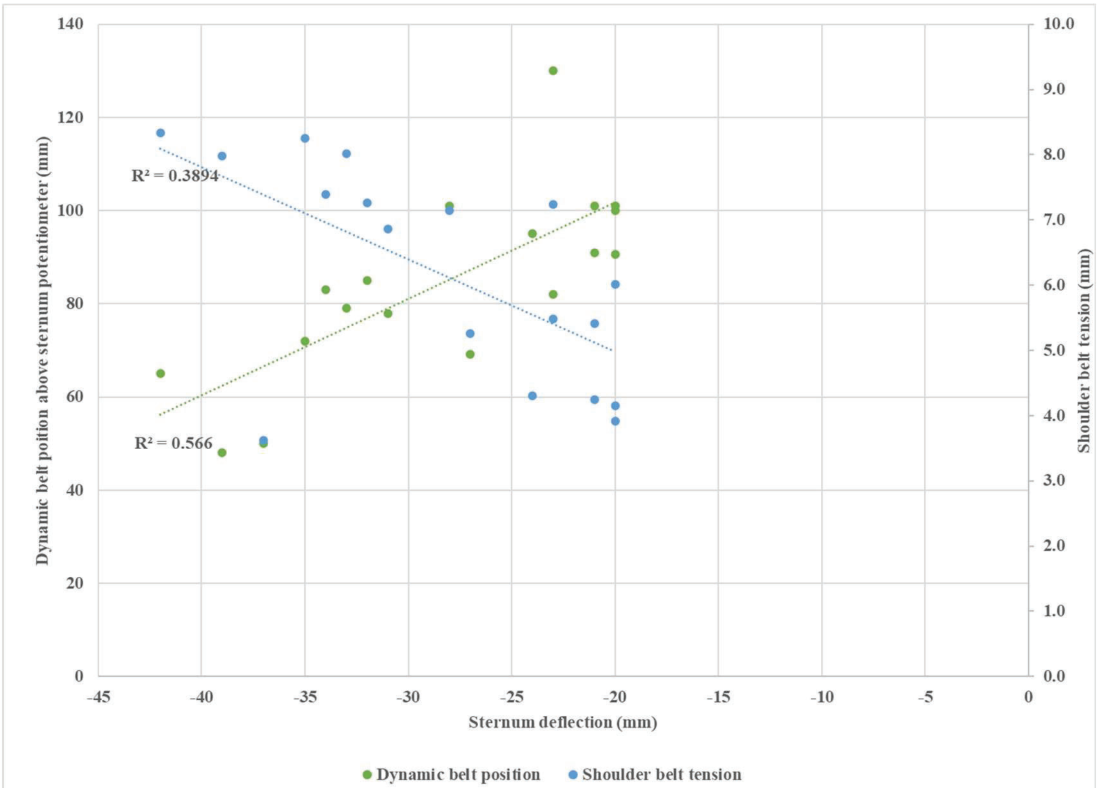



*Figure 12. Correlation of sternum deflection to belt position and shoulder belt tension*

Edwards et. al studied the sensitivity of the H3-5F sternum deflection measurement to belt position in the rear-seat environment and found the linear relationship of a 0.5% reduction in sternum deflection per millimeter of vertical distance from the sternum potentiometer [13]. In the current study, this sensitivity was used to compensate the sternum deflection outputs in each test for the effect of belt position. This calculation, called Chest Index (Equations 1 and 2), predicts what the sternum deflection would have been for a given vehicle and restraint environment without the influence of shoulder belt position. The calculation predicts the sternum deflection with a belt located on the third rib, which is 17 mm above the sternum potentiometer ball location on the uncompressed thorax. Chest Index is meant to provide a fair comparison between restraint systems regardless of the belt position on the chest, but because it is a departure from the sternum deflection output of the sensor, it does not relate to injury risk curves that have been established for sternum deflection for the H3-5F dummy.

**Chest Index Calculation**

$$Predicted\ percent\ change\ in\ sternum\ deflection\ (Pchange) = 0.5\% \times (dynamic\ belt\ position - 17)$$ **Equation (1)**

$$Chest\ Index = \frac{|Measured\ sternum\ deflection|}{\left(1 - \left(\frac{Pchange}{100}\right)\right)}$$ **Equation (2)**

| Constant | Definition |
|---|---|
| 0.5% | Reduction in sternum deflection per 1-mm increase in belt position (Edwards et al., 2022). |
| 17 mm | Position of rib 3 relative to the sternum pot ball on the H3-5F dummy's uncompressed thorax. |
| Dynamic belt position | Vertical distance from the sternum pot ball on the H3-5F dummy's uncompressed thorax to the centerline of the shoulder belt at the time of maximum sternum deflection. |
| Measured sternum deflection | Maximum value measured by the sternum potentiometer on H3-5F dummy. |

Figure 13 shows the results for the Chest Index calculation for each vehicle where the dynamic belt position could be measured along with the original sternum deflection values. Since all the shoulder belt positions were higher than 17 mm (the Chest Index belt-reference point), the Chest Index value increased compared with the sternum deflection value. Unlike sternum deflection that had almost an identical range of results for belts with and without pretensioning and load-limiting technology, Chest Index ranged from 34 to 56 for shoulder belts without this technology and from 32 to 44 for belts with this technology, and, with the exception of one vehicle, all values for standard belts were higher than all values for belts with this technology. Further analysis of the correlation between Chest Index and both shoulder belt tension and dynamic belt position (Figure 14) shows that Chest Index has a higher correlation (r = .8) with shoulder belt tension than sternum deflection (r = .62). In addition, whereas sternum deflection had some relationship with dynamic belt position (r = .75), Chest Index shows no relationship with dynamic belt position (r = 0.46) (Figure 14).

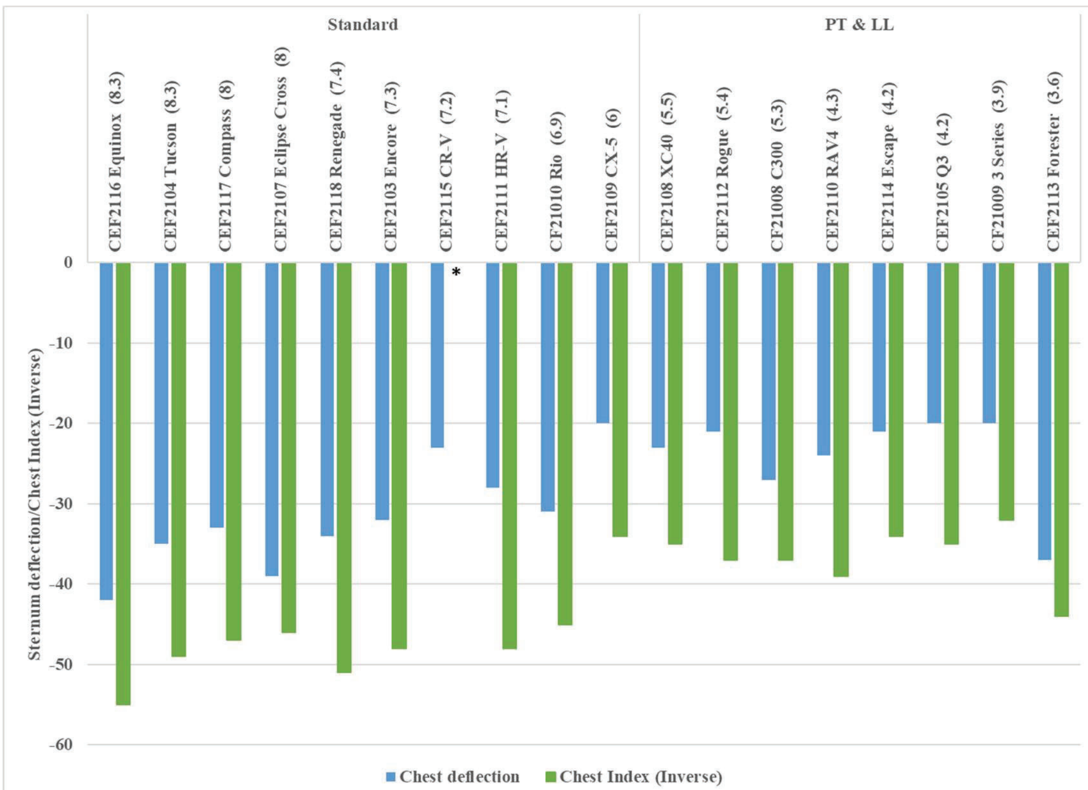



***Figure 13. Chest Index (inverted for plot) and sternum deflection values. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT & LL]) and ordered by shoulder belt tension (kN). *Indicates test where belt position was too high to calculate Chest Index***

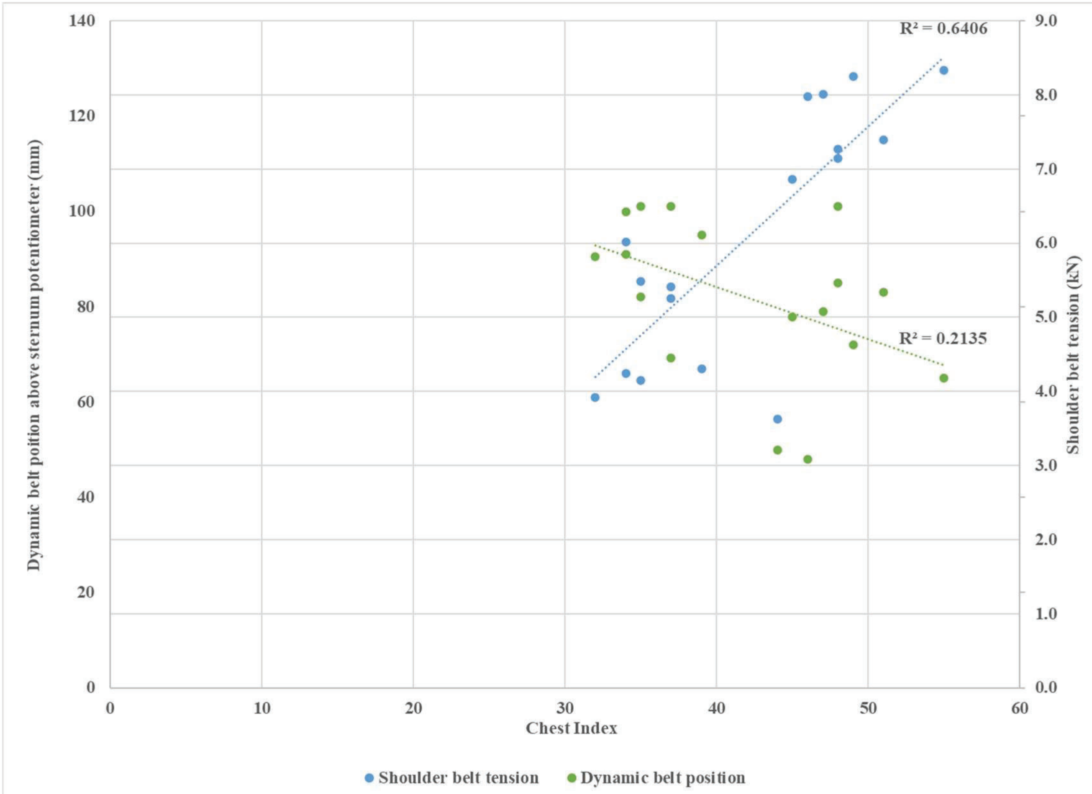



*Figure 14. Correlation of Chest Index to belt position and shoulder belt tension*

**Abdominal Injury**

The primary source of abdominal injuries is loading from the lap belt after it migrates over the ASIS and into the abdomen, called submarining. The H3-5F dummy does not have sensors to directly assess the risk of injury due to this type of loading to the abdomen, so the increased risk due to this belt behavior was assessed by observing whether the behavior is present. In this research series, submarining was evaluated primarily with video analysis of the belt position and confirmed with ASIS and lap-belt load cells. Figure 15 shows examples of stable belt position (Figure 15a), the lap belt migrating over only the right ASIS (15b), and the lap migrating over both the left and right ASIS (15c). Table A1 (Appendix) shows a summary of submarining behavior for all tests. Lap belt migration over one or both ASISs were both considered submarining. Submarining was observed in 6 of the 17 vehicles with standard belts and 6 of the 15 vehicles with pretensioners and load limiters. Overall, submarining was observed in 38% percent of the tests.

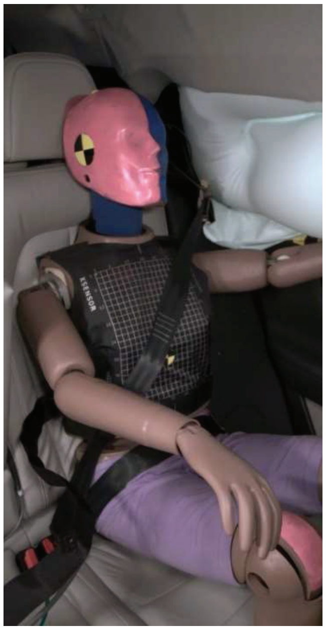


*Figure 15a. Stable belt position*

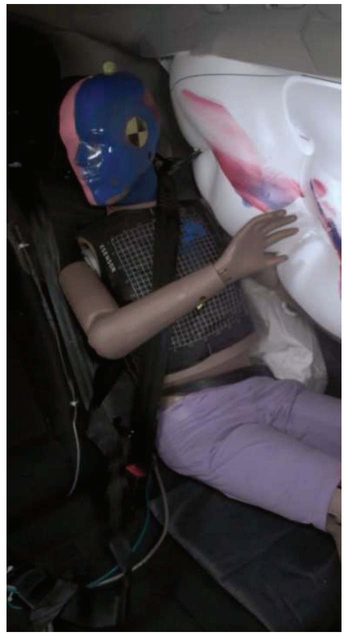


*Figure 15b. Belt migration over the right ASIS*

*Figure 15c. Belt migration over both the left and right ASIS*

**Femur injury**

To assess the risk of lower extremity injuries in the rear seat, this study looked at femur axial compression in the left and right femur. Results for femur compression are shown in Figure 16. The knees contacted the front seat in only 6 of the 32 vehicles, several of which had the smallest rear-occupant space: the CF21006 Yaris, CF21007 Sentra, CF21010 Rio, CF21011 Colorado, CEF2109 CX-5 and CEF2103 Encore. Contacts are shown in red in Figure 16. Femur compression values ranged from 0.1 to 1.3 kN, which are well below the IARV of 6.2 kN. The highest femur compression value reported was from a case where the knees contacted the front seatback.

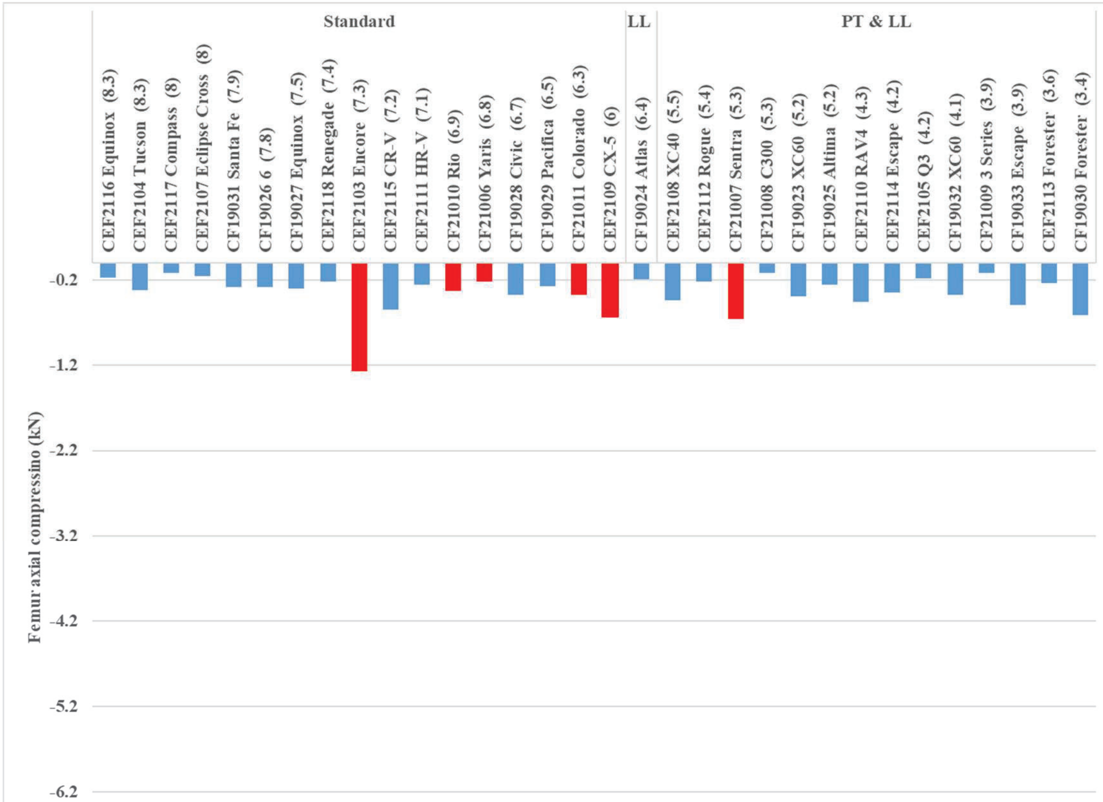



***Figure 16. Peak femur axial compression values with contacts shown in red. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).***

## DISCUSSION

Advancements in rear seat-belt technology are important countermeasures for improving safety for rear-seat occupants. However, the presence of force-limiting and pretensioning belts in these tests did not guarantee better overall performance.

### Head Injury

The two primary sources for head injuries in the rear seat are impacts with the vehicle interior and inertial loading [7]. Injury metrics, HIC 15 and peak resultant head acceleration, are both meant to reflect injury due to contacts. In this dataset, both peak resultant head accelerations and HIC 15 showed elevated values for the one test where the rear-seat occupant's head impacted the seatback. HIC 15 values, however, also predicted risk of skull fracture as high as 40% for non-contacts, which are unlikely in the absence of hard contacts. HIC 15 had a strong relationship with belt tension (r = .85), which can relate to inertial injuries, but, according to Prasad and Mertz, neck forces and not HIC 15 should be used to assess restraint performance [21].

Since head contacts were rare, these two injury metrics alone do not provide a robust evaluation of how well the head is protected from injury in the rear seat. One potential trade off with the introduction of force limiting in the rear seat is increased head excursion. In this dataset, the head only contacted the front seatback in the vehicle with the smallest occupant space. The absence of head contacts for the rear occupant was unexpected, since head injuries comprise 9% of serious injuries for belted adults and teens and 30% of serious injuries for belted children in the rear seat, and over half of these injuries for children are with the front seatback [5, 6]. In three vehicles, the front seatback pivoting forward prevented a head contact. In an additional 13 vehicles, the head came within 50 mm of the pretest position of the front seatback. Changes in occupant stature, mass, or crash severity could influence head-impact results for real-world occupants, so it is important to encourage automakers to design restraints that maintain a larger buffer of space between the occupant's head and the front seatback than is required for the H3-5F in this test condition.

**Neck Injury**

Parenteau and Viano did not observe any AIS 3+ neck injuries in their 2003 study of NASS-CDS belted rear-seat occupants in frontal crashes [5]. Jermakian et al. found the same results for cases in the NASS-CDS dataset in their 2019 study but found very serious neck injuries in the FARS cases [7]. In the FARS cases, neck injuries were documented as atlantooccipital dislocation/disarticulation, cervical spine fractures and "massive neck trauma" or "neck instability." Some of these cases reported no head contacts, but serious thorax injuries from belt loading, indicating that these neck injuries may be due to high inertial loads. Upper neck tension in the current dataset had a positive correlation with shoulder belt tension ($r = .76$), indicating that technology that limits belt forces can also reduce forces in the neck. Though there is an absence of neck injuries in the NASS-CDS dataset, it is important to set thresholds for performance to pragmatic values that will encourage safety technology that limits the neck tensions that lead to very serious neck injuries in higher severity crashes.

Maximum Nij values are dominated by neck tension values; however, as shown in Figure 7, there are loading scenarios like head contact with the front seatback where neck tension alone does not capture how these forces affect the neck. In these cases, Nij reflects the elevated extension moments.

Neck compression values for the rear-seat occupants were well below IARVs, however, innovative restraints in the rear seat may change patterns in occupant loading, so monitoring compression values remains important.

**Chest Injury**

Several researchers have documented the thorax as the most frequently injured body region for belted adults in the rear seat, yet Kuppa et al. observed that dummy head and neck injury metrics predict a higher risk of injury in the rear seat [5, 7, 9]. Similar results were observed in the current study where HIC 15 and upper neck tension exceeded the IARV in 25% and 44% of the vehicles, respectively, but sternum deflection only exceeded the IARV in 9% of the vehicles. In these tests, shoulder belt tension explained only 19% ($r = .44$) of the variance in sternum deflection values, despite previous research suggesting that shoulder belt tension should explain nearly all of the variance in this outcome in a consistent vehicle environment (98%; $r = .99$) [13]. Reducing shoulder belt tension with force-limiting technology is a primary strategy for reducing chest injuries, but these results showed that sternum deflection did not reflect the benefit of this technology [22, 23].

In this dataset, belt positions varied as much as 82 mm of vertical distance on the centerline of the thorax due to belt-anchorage location variability, belt technology, and dummy kinematics. Edwards et al., observed an inverse linear sensitivity between shoulder belt position relative to the sternum potentiometer and the sternum deflection measurement, which confirmed observations from other researchers that the H3-5F has a sensitivity to belt position [10-13]. However, this sensitivity does not have an established relationship with human sensitivity to belt position. Vehicle test results also show a relationship between the measured dynamic belt position and sternum deflection ($r = .62$), which obscures the benefit of added belt technology and provides a challenge for consumer information organizations in trying compare the effectiveness of restraint designs.

The sensitivity from Edwards et al. [13], the measured dynamic belt position, and sternum deflection were used to calculate the expected sternum deflection, called Chest Index, for a given vehicle and restraint system if the belt had been placed 17 mm above the sternum potentiometer. Results for Chest Index show an improvement over sternum deflection in reflecting the benefits of added belt technology. While pretensioner and load limiter belts and standard belts had similar ranges of values for sternum deflection, all Chest Index values for standard belts, with one exception, were higher than all the values for pretensioner and load limiter belts. In contrast with sternum deflection, Chest Index also shows little correlation with dynamic belt position ($r = .14$) and an improved relationship with shoulder belt tension ($r=0.79$) compared with sternum deflection ($r = .62$). These results indicate that the Chest Index value can differentiate between restraint designs without results being confounded by the dummy's sensitivity to belt position. However, caution must be used with applying this metric to prediction of human injury. Because it is a departure from the sensor output for which injury risk curves were developed, the values reported should not be used to predict thoracic injury risk.

Additionally, Edwards et al. established the sensitivity of sternum deflection to belt position for belt positions that ranged from 25 to 81 mm above the sternum potentiometer [13]. These values were chosen, on the low end, because it was the lowest position where the shoulder belt would stay on the shoulder during the event and, on the high end, because it was the highest position achievable without moving beyond the molded flesh at the dummy's neck. However, in some vehicles in the current dataset, belt positions were measured as high as 131 mm above the chest potentiometer. Photographic review determined that belt positions higher than 110 mm compromise the effectiveness of the restraint system because the shoulder belt is actually loading the neck (Figure 11) instead of the thorax. Further, since the belt is no longer loading the thorax in these positions, extrapolating the linear relationship found in Edwards et al. [13] beyond 110 mm is not appropriate.

**Abdominal Injury**

Abdominal injuries account for 5% and 10% of all AIS 3+ injuries for adults and children wearing seat belts in the rear seat, respectively [5,6]. Jermakian et al. observed that the majority of abdominal injuries were the result of lap belt load and saw evidence of submarining in three quarters of the abdominal injury cases [7]. Because the H3-5F lacks sensors to assess risk for abdominal injury, increased risk of abdominal injury can only be assessed by observing whether submarining behavior is present. Submarining behavior was observed in 38% of this test group, evenly distributed between vehicles with and without pretensioners and load limiters. Though it is unknown if this frequency represents the incidence of submarining in the field because submarining can occur in the absence of injury, it does indicate that the H3-5F positioned according to IIHS's rear-occupant seating procedure [14] can highlight issues with belt migration over the ASIS.

**Pelvis/femur injury**

Lower extremity injuries account for 8% of all AIS 3+ injuries for belted rear-seat adults [5]. The dummy's knees contacted the seatback in 6 of the 32 vehicles tested, but none of these impacts resulted in loads that indicate a high risk of injury. Though the H3-5F dummy represents the stature of the majority of rear-seat occupants, its stature may be a shortcoming when trying to represent risk of femur injuries. Further, though the H3-5F does reflect the risk of submarining, the occupant kinematics after the lap belt leaves the pelvis may not be biofidelic, and real-world occupants may move further forward than the dummy, putting the femur at risk of fracture. Though current injury values do not indicate a significant risk of injury, it is important to monitor femur axial force because it is a potential load path for occupant restraint.

## CONCLUSION

Dummy head injury metrics, HIC 15, and head resultant acceleration reflected the risk of head injury due to impacts with the vehicle interior. However, these tests did not show the field-relevant problem of head contacts with the vehicle interior, which necessitates an excursion evaluation that rewards leaving a large buffer of space between the occupant's head and the seatback to account for occupants of larger stature. Dummy neck tension correlated with shoulder belt tension, indicating that neck tension reflects the high inertial loads that can cause fatal inertial head-neck junction injuries. Nij reflects the elevated moments associated with head impacts. Sternum deflection underestimated the frequency of chest injury observed in field data relative to neck injuries, in part due to variance in belt position. Adjusting the sternum deflection to compensate for the belt position, called Chest Index, provided a metric that better reflected the expected benefit of force limiting and pretensioning. The H3-5F dummy showed a propensity for submarining, an important risk factor for abdominal injuries. Femur axial forces for the H3-5F, however, showed no indication of injury. The alignment of crash test results with real-world outcomes is affected by using one stature of ATD (H3-5F) to represent the broad range of occupants in the rear seat and by the limitations of the H3-5F dummy. Adding head excursion limits to prevent head impacts, compensating for the effect of belt position on chest deflection and setting neck-tension performance boundaries to encourage safety technology that reduces neck tensions all help address the known ATD shortcomings in order to develop reliable assessment metrics. However, other shortcomings in representing field injuries, like lower extremity injuries, may not be assessed in a way that will affect design changes but will only ensure that countermeasures do not increase values to injurious levels.

## REFERENCES


[1] Insurance Institute for Highway Safety. (2006). Major change in frontal crashworthiness evaluations. *Status Report, 41*(3), 1–7.

[2] Kahane, C. J. (1994). *Correlation of NCAP performance with fatality risk in actual head-on* collisions (DOT HS 808 061). National Highway Traffic Safety Administration.

[3] Durbin, D. R., Jermakian, J. S., Kallan, M. J., McCartt, A. T., Arbogast, K. B., Zonfrillo, M. R., & Myers, R. K. (2015). Rear seat safety: Variation in protection by occupant, crash and vehicle characteristics. *Accident Analysis & Prevention, 80*, 185–192. https://doi.org/10.1016/j.aap.2015.04.006

[4] Barry, K. (2020, September 3). Making back seats safer: When it comes to safety advances, the back seat hasn't kept pace with the front—But that could be about to change. *Consumer Reports*. https://www.consumerreports.org/car-safety/making-car-back-seats-safer/

[5] Parenteau, C., & Viano, D. C. (2003). *Field data analysis of rear occupant injuries, Part I: Adults and teenagers* (2003-01-0153). SAE International. https://www.sae.org/publications/technical-papers/content/2003-01-0153/

[6] Parenteau, C., & Viano, D. C. (2003). *Field data analysis of rear occupant injuries, Part II: Children, toddlers and infants* (2003-01-0154). SAE International. https://www.sae.org/publications/technical-papers/content/2003-01-0154/

[7] Jermakian, J., Edwards, M., Fein, S., & Maltese, M. R. (2019). Factors contributing to serious and fatal injuries in belted rear seat occupants in frontal crashes. *Traffic Injury Prevention, 20*(sup1), S84–S91. https://doi.org/10.1080/15389588.2019.1601182

[8] Jagtap, S. R., Edwards, M. A., & Jermakian, J. S. (2023). Development of a consumer information crash test program to evaluate the safety of rear seat occupants. *Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles* (ESV), Yokohama, Japan.

[9] Kuppa, S., Saunders, J., & Fessahaie, O. (2005). Rear seat occupant protection in frontal crashes. *Proceedings of the19th International Technical Conference on the Enhanced Safety of Vehicles* (ESV), Washington, DC.

[10] Beck, B., Brown, J., & Bilston, L. E. (2014). Assessment of vehicle and restraint design changes for mitigating rear seat occupant injuries. *Traffic Injury Prevention, 15*(7), 711–719. https://doi.org/10.1080/15389588.2013.867433

[11] Tylko, S., Higuchi, K., Lawrence, S. S., Bussières, A., & Fiore, J. M. (2006). A comparison of Hybrid III 5th female dummy chest responses in controlled sled trials. *SAE Transactions*, 283–290. https://doi.org/10.4271/2006-01-0455

[12] Yamasaki, T., & Uesaka, K. (2011). Rear occupant protection JNCAP test—Test results and findings. *Proceedings of the 22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Washington, DC.

[13] Edwards, M. A., Jagtap, S. R., Jermakian, J. S. (2022). Sensitivity of established and alternative rear occupant thoracic injury metrics to seat belt design variables in frontal impacts. *Proceedings of the International Research Council on the Biomechanics on Injury*, Porto, Portugal.

[14] Insurance Institute for Highway Safety. (2022, December). *Dummy seating procedure for rear outboard positions (Version II)*. https://www.iihs.org/media/ea4bf33b-074b-49c9-915e-adb6c48efe19/_GodSA/Ratings/Protocols/current/Dummy%20Seating%20Procedure%20for%20Rear%20Outboard%20Positions_December%202022_FINAL.pdf

[15] Insurance Institute for Highway Safety. (2004). *Guidelines for using the UMTRI ATD positioning procedure for ATD and seat positioning (Version V)*. https://www.iihs.org/media/91f36dba-f599-4353-9963-cde5749aaeba/G6ZfeQ/Ratings/Protocols/current/ATD_positioning_procedure.pdf

[16] SAE International. (1995). *Instrumentation for impact test – Part 1 – Electronic instrumentation* (Surface Vehicle Recommended Practice J211). https://www.sae.org/standards/content/j211/1_199503/

[17] Insurance Institute for Highway Safety. (2022). *Moderate overlap frontal crashworthiness evaluation 2.0 crash test protocol (Version I)*. https://www.iihs.org/media/df1fdcc9-8335-4c79-a6e7-c2eca304a8c4/Xow7XA/Ratings/Protocols/current/Moderate%202.0%20Test%20protocol_December%202022_FINAL.pdf

[18] Insurance Institute for Highway Safety. (2022). *Moderate overlap crashworthiness evaluation 2.0 rating guidelines (Version I)*. https://www.iihs.org/media/804980e6-18f0-4590-b0f7-44483b1ce419/WAND-Q/Ratings/Protocols/current/Moderate%202.0%20Rating%20guidelines%20Version%20I_FINAL.pdf

[19] Horsch, J. D., Melvin, J. W., Viano, D. C., & Mertz, H. J. (1991). Thoracic injury assessment of belt restraint systems based on Hybrid III chest compression. *SAE Transactions, 100*, 1875–1898.
[20] Mertz, H. J., Irwin, A. L., & Prasad, P. (2016). Biomechanical and scaling basis for frontal and side impact injury assessment reference values. *Stapp Car Crash Journal*, *60*. 625–657. https://doi.org/10.4271/2003-22-0009
[21] Prasad, P., & Mertz, H. J. (1985). The position of the United States delegation to the ISO Working Group 6 on the use of HIC in the automotive environment. *SAE Transactions, 94*, 106–116.
[22] Foret-Bruno, J. Y., Trosseille, X., Le Coz, J. Y., Bendjellal, F., Steyer, C., Phalempin, T., Villeforceix, D., Dandres, P., Got, C. (1998). Thoracic injury risk in frontal car crashes with occupant restrained with belt load limiter. *Proceedings of the 42nd Annual Stapp Car Crash Conference*, Tempe AZ. https://doi.org/10.4271/983166
[23] Kahane, C. J. (2013). *Effectiveness of pretensioner and load limiters for enhancing fatality reduction by seat belts* (DOT HS 811 835). National Highway Traffic Safety Administration.

## APPENDIX

***Table A1.***
***Occupant injury metrics and test metrics***

| Belt technology | Test ID | Shoulder belt tension | HIC 15 | Peak acc | Head contact | Upper neck Tension | Upper neck Compression | Maximum Nij | Nij mode | Chest deflection | Dynamic belt position (maximum) | Dynamic belt position at max chest | Chest Index | Left femur | Right femur | Submarining | Cross excursion line |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **IARV** | | | **779** | | | **2.6** | **2.5** | **1.00** | | **-41** | | | | **-6.2** | **-6.2** | | |
| **Units** | | **kN** | | **g** | | **kN** | **kN** | | | **mm** | **mm** | **mm** | | **kN** | **kN** | | |
| **Standard** | **CEF2116** | 8.3 | 1393 | 105 | No | 4.3 | 0.5 | 1.30 | NTF | -42 | 65 | 65 | 55 | -0.2 | -0.2 | No | 0 |
| | **CEF2104** | 8.3 | 947 | 92 | No | 3.0 | 0.4 | 1.09 | NTF | -35 | 74 | 72 | 49 | -0.3 | -0.2 | No | 1 |
| | **CEF2117** | 8 | 827 | 83 | No | 3.5 | 0.1 | 1.14 | NTF | -33 | 100 | 79 | 47 | -0.1 | -0.1 | No | 0 |
| | **CEF2107** | 8 | 1124 | 98 | No | 3.3 | 0.0 | 1.04 | NTE | -39 | 48 | 48 | 46 | -0.1 | -0.1 | No | 2 |
| | **CF19031** | 7.9 | 853 | 88 | No | 3.3 | 0.7 | 1.07 | NTE | -31 | | | | -0.3 | -0.1 | No | 1 |
| | **CF19026** | 7.8 | 951 | 91 | No | 3.4 | 0.7 | 1.11 | NTF | -31 | | | | -0.3 | -0.1 | Yes | 1 |
| | **CF19027** | 7.5 | 945 | 94 | No | 3.7 | 0.1 | 1.10 | NTF | -42 | | | | -0.3 | -0.2 | Yes | 0 |
| | **CEF2118** | 7.4 | 760 | 82 | No | 3.4 | 0.6 | 1.12 | NTF | -34 | 107 | 83 | 51 | -0.2 | -0.1 | No | 0 |
| | **CEF2103** | 7.3 | 687 | 77 | No | 2.5 | 1.1 | 0.84 | NTF | -32 | 85 | 85 | 48 | -0.4 | -1.3 | No | 2 |
| | **CEF2115** | 7.2 | 541 | 70 | No | 2.8 | 0.1 | 0.81 | NTF | -23 | 130 | 130 | - | -0.5 | -0.5 | No | 0 |
| | **CEF2111** | 7.1 | 750 | 85 | No | 3.7 | 0.5 | 1.14 | NTF | -28 | 101 | 101 | 48 | -0.3 | -0.2 | Yes | 0 |
| | **CF21010** | 6.9 | 433 | 74 | No | 3.1 | 0.0 | 0.92 | NTF | -31 | 78 | 78 | 45 | -0.3 | -0.1 | Yes | 1 |
| | **CF21006** | 6.8 | 589 | 74 | No | 2.9 | 1.7 | 1.05 | NTF | -32 | | | | -0.2 | -0.2 | No | 2 |
| | **CF19028** | 6.7 | 512 | 71 | No | 2.5 | 0.0 | 0.79 | NTF | -43 | | | | -0.3 | -0.4 | Yes | 0 |
| | **CF19029** | 6.5 | 451 | 66 | No | 2.0 | 0.1 | 0.70 | NTF | -28 | | | | -0.2 | -0.3 | No | 0 |
| | **CF21011** | 6.3 | 802 | 106 | Yes | 1.6 | 1.3 | 0.88 | NTE | -34 | | | | -0.3 | -0.4 | No | 2 |
| | **CEF2109** | 6 | 750 | 88 | No | 3.7 | 0.3 | 1.12 | NTF | -20 | 123 | 100 | 34 | -0.6 | -0.4 | Yes | 0 |
| **LL** | **CF19024** | 6.4 | 598 | 73 | No | 2.4 | 0.1 | 0.66 | NTF | -40 | | | | -0.1 | -0.2 | No | 1 |

| Belt technology | Test ID | Shoulder belt tension | HIC 15 | Peak acceleration | Head contact | Upper neck Tension | Upper neck compression | Maximum Nij | Nij mode | Chest deflection | Dynamic belt position (maximum) | Dynamic belt position at max chest | Chest Index | Left femur | Right femur | Submarining | Cross excursion line |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PT & LL | CEF2108 | 5.5 | 309 | 55 | No | 1.8 | 0.4 | 0.52 | NTF | -23 | 82 | 82 | 35 | -0.3 | -0.4 | No | 0 |
| | CEF2112 | 5.4 | 581 | 75 | No | 2.4 | 0.0 | 0.66 | NTF | -21 | 110 | 101 | 37 | -0.2 | -0.1 | Yes | 1 |
| | CF21007 | 5.3 | 465 | 71 | No | 3.2 | 1.2 | 0.93 | NTF | -21 | | | | -0.7 | -0.3 | Yes | 0 |
| | CF21008 | 5.3 | 482 | 68 | No | 2.3 | 1.4 | 0.92 | NTE | -27 | 69 | 69 | 37 | -0.1 | 0.0 | No | 1 |
| | CF19023 | 5.2 | 234 | 49 | No | 1.6 | 0.3 | 0.50 | NTF | -26 | | | | -0.4 | NA | No | 0 |
| | CF19025 | 5.2 | 445 | 69 | No | 2.3 | 0.1 | 0.67 | NTF | -32 | | | | -0.2 | -0.3 | Yes | 0 |
| | CEF2110 | 4.3 | 396 | 62 | No | 2.0 | 0.1 | 0.61 | NTF | -24 | 95 | 95 | 39 | -0.5 | -0.3 | Yes | 0 |
| | CEF2114 | 4.2 | 251 | 51 | No | 1.7 | 0.6 | 0.53 | NTF | -21 | 92 | 91 | 34 | -0.3 | -0.1 | Yes | 1 |
| | CEF2105 | 4.2 | 468 | 71 | No | 2.4 | 0.2 | 0.63 | NTF | -20 | 101 | 101 | 35 | -0.1 | -0.2 | Yes | 1 |
| | CF19032 | 4.1 | 250 | 51 | No | 1.7 | 0.1 | 0.48 | NTF | -25 | | | | -0.3 | -0.4 | No | 1 |
| | CF21009 | 3.9 | 224 | 51 | No | 2.1 | 0.1 | 0.60 | NTE | -20 | 91 | 91 | 32 | -0.1 | -0.1 | No | 1 |
| | CF19033 | 3.9 | 222 | 49 | No | 1.6 | 0.5 | 0.53 | NTE | -27 | | | | -0.5 | -0.2 | No | 0 |
| | CEF2113 | 3.6 | 251 | 55 | No | 1.9 | 0.1 | 0.75 | NTE | -37 | 50 | 50 | 44 | -0.2 | -0.2 | No | 1 |
| | CF19030 | 3.4 | 232 | 53 | No | 1.7 | 0.5 | 0.95 | NTE | -41 | | | | -0.6 | -0.1 | No | 1 |

***Table A2.***
***Correlation coefficients and coefficients of determination for select metrics***

| | **$R^2$** | | **r** | |
|---|---|---|---|---|
| | **Shoulder belt tension** | **Shoulder belt position** | **Shoulder belt tension** | **Shoulder belt position** |
| **HIC15** | 0.73 | NA | 0.85 | NA |
| **Peak acc** | 0.66 | NA | 0.81 | NA |
| **Neck tension** | 0.58 | NA | 0.76 | NA |
| **Neck compression** | 0.01 | NA | 0.10 | NA |
| **Maximum Nij** | 0.54 | NA | 0.74 | NA |
| **Chest deflection (32 tests)** | 0.19 | NA | 0.44 | NA |
| **Chest deflection (18 tests)** | 0.39 | 0.57 | 0.62 | 0.75 |
| **Chest Index** | 0.64 | 0.21 | 0.80 | 0.46 |
| **Shoulder belt tension** | NA | 0.02 | NA | 0.13 |

# THE EFFECTIVENESS OF SEAT BELT REMINDER(SBR)S BY ANALYZING THE RESULT OF THE PILOT PROJECT OF AN INTERURBAN BUS WITH SBR

**Jinseop Park**
**Seung Hoon Lee**
**Joon-Ho Jun**
Korea Automobile Testing & Research Institute (KATRI)
Republic of Korea

Paper Number 23-0190

## ABSTRACT

It is a widely accepted fact that seat belts have been saving numerous lives in traffic crashes. However, if the effectual means are not used, discussing the effects is meaningless. This is why many countries make seat belt reminders (hereafter SBR) mandatory or introduce SBR assessment in their New Car Assessment Programs (hereafter NCAP). Although a SBR is a good solution for raising the seat belt wearing rate, the opinion on how many seat-belt non-users can be restrained by SBRs is arguable. This paper discussed the effect of SBR systems through the pilot project of an SBR-equipped interurban bus.

Korea Automobile Testing and Research Institute (hereafter KATRI) developed the customized SBR system for an interurban bus, which is actually being operated between two cities in Korea. The system consisted of a visual warning device, an occupancy detection sensor, and a buckle-up detection sensor (buckle-switch) on each passenger seat. There was a monitoring display system on the bus driver seat, so which seats are unfastened can be monitored and recorded. In order to figure out how many passengers wore seat belts, both the observational investigation and recorded data analysis were conducted. The results were compared with the one of buses without the SBR system.

According to the observed result, the wearing rate of seat belts in a bus without the SBR was 9.6% and the rate in a bus with SBR was 59.0%. To figure out how effective the SBR system is, the recorded log data was also analyzed. The overall average seat belt use rate of the SBR-installed bus was calculated to be approximately 55.82%.

There was a difference between both results of the observational investigation and log data analysis, but it is clear that the SBR system noticeably increased seat belt wearing rate. The SBR system applied to this pilot project did not include an audible warning. This means that the system reminded passengers of not wearing seat belts only by a warning light when they did not buckle up. Therefore, the effectiveness of SBR in this paper is only limited to the type of SBR with a visual warning.

SBR systems do influence the seat belt use rate. This paper showed that the SBR with occupant detection and visual warning could increase the rate by about 40 to 50%, compared to the case without the SBR. The current regulation does not require mandatory SBR for all seats and most NCAPs do not equally assess SBR in front and rear seats. Mandatory SBRs in the rear seats of M2 and M3 and the introduction of more advanced SBR assessment for NCAPs need to be studied and discussed.

## INTRODUCTION

It is a widely accepted fact that seat belts have been saving numerous lives in traffic crashes. According to the result comparison of crash tests conducted by Korea Automobile Testing and Research Institute, the possibility of serious injury of restrained occupants by seat belts is approximately 6 times higher than the unstrained [1]. However, if the effectual means are not used, discussing the effects would be meaningless.

Unfortunately, there are many countries struggling with the low seat belt wearing rate of occupants in vehicles. Korea is one of them. Especially, the wearing rate in rear seats of passenger cars is extremely low, compared to the one in front seats. On the other hand, northern or western European countries show comparatively high seat belt wearing rate in the rear seats, which is often almost similar to the rate in front seats. Figure 1 shows the seat belt wearing rate of each country in around 2013 [2].

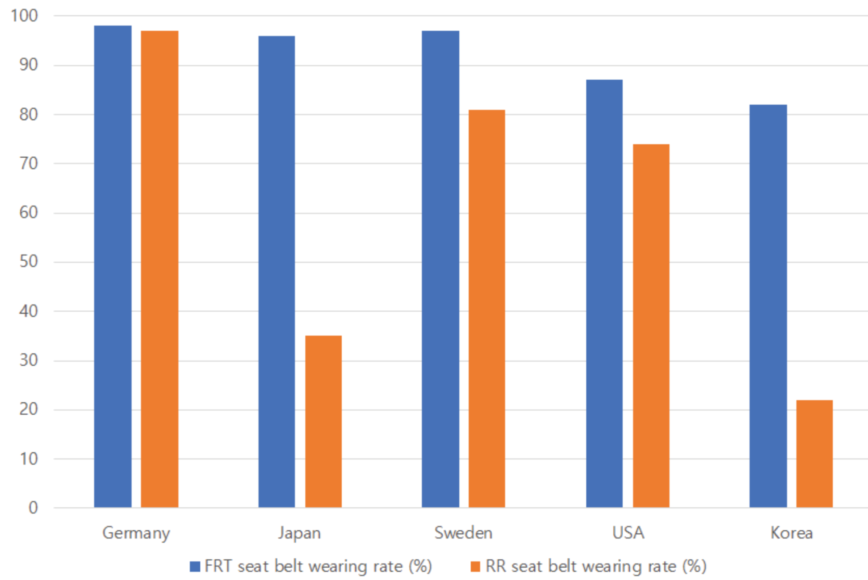



***Figure 1. Seat belt wearing rates of front and rear seats by countries (2015 IRTAD report).***

Because of this issue, Korean government has made nationwide efforts for the several years at the seat belt usage increase since 2010s. Continuous campaigns have been conducted and educational programs have been widely provided. On top of that, the Seat Belt Reminder (hereafter SBR) assessment has been introduced in Korean New Car Assessment Program (hereafter KNCAP) since 2013 [3]. Slight increases in the wearing rate appeared, but the rate has remained at about 40 to 60 % [4]. The seat belt usage rate of passengers in buses was nothing better than that, either.

Korea suggested the amendment of UN Regulation to mandate SBRs not only in a driver seat of M1 vehicles but also in other seats in 2014 and has been actively involved in the development of the amendment to UN Regulation 16 with European Commission and Japan. In 2016, the amendment extending the scope from M1 to other categories was finally approved with a few seat exemptions in UNECE WP.29 session [5].

Although there is no doubt a seat belt reminder is a good solution for raising this seat belt wearing rate, the opinion on how many seat-belt non-users can be restrained by it or how much effective it has been contributing to the seat belt use is various and arguable. Therefore, this paper studied the effects of SBRs in raising the seat belt usage rate through the monitoring process of an SBR-installed bus, which was actually being operated between two cities in Korea. Furthermore, how the more advanced SBR assessment can be introduced in KNCAP and regulations was discussed.

## METHODS

Korea Automobile Testing & Research Institute (hereafter KATRI) conducted a pilot project to study the effectiveness or influence of a SBR system on increasing a seat belt wearing rate. The project purpose was to compare the seat belt use rate of a bus with a SBR system to the rate of a bus without the SBR system. So, the effectiveness of SBRs in raising the seat belt wearing rates of passenger seating positions can be figured. Before the project, Korea Transportation Safety Authority (hereafter KOTSA), the mother organization of KATRI, has investigated the wearing rate of passengers in buses and reported that the interurban buses showed about 15% of seat belt wearing rate.

### Pilot project using an interurban bus with SBR

The customized SBR system was installed in an inter-urban bus, which is actually being operated between two cities, Seoul and Suwon in Korea. KD transit group operated the SBR bus. The information on the route or specification of the bus is as follows (See Table 1).

***Table 1. Information on pilot project of an interurban bus with SBR.***

| Bus Number | 5500-2 | | |
|---|---|---|---|
| Departure | Suwon | Destination (Turn-around) | Seoul |
| Overall route distance (km) | 40 | Route map | |
| Highway route distance (km) | 24 |  | |
| Number of stops | 25 | | |
| Passenger seating capacity (Number of persons) | 45 | | |
| Belt type | 2-point belt | | |
| Project term | July 11, 2015 ~ September 6, 2015 | | |



**Bus SBR system**

KATRI developed the SBR systems for the project with Controller Area Network (CAN) experts and installed the system to the interurban bus provided by the bus operator. All components including control circuits were newly designed, but the occupancy detection sensors and buckle-up detection sensors were used and modified from the parts of existing passenger cars. Each passenger seat had a visual warning indicator, an occupancy detection sensor, a buckle-up detection sensor (buckle-switch), a control unit. There was a monitoring display system and main controller on the bus driver seat, so which seats were not fastened was able to be monitored and recorded. The configuration is described in Figure 2.

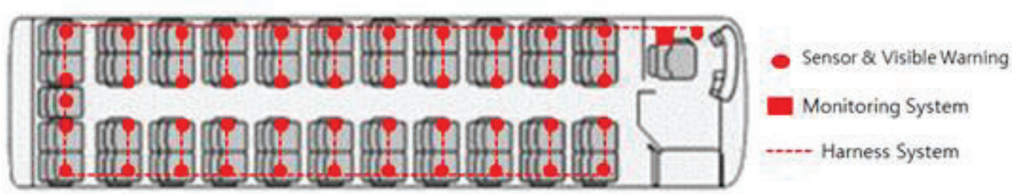



***Figure 2. Configuration of SBR system in the bus (top view).***

Basically, the system was designed to give a passenger a visual warning when the passenger did not wear the seat belt. Because KATRI was concerned that audible warnings could negatively affect the driver's safe driving and comfortable travel of many passengers, the simple reminding method was applied. In addition, the failure possibility of the SBR system with audible warning function was also considered.

In this system, when a passenger did not wear the seat belt after being seated, the visual warning light from the indicator on the back side of the seat in front of the passenger comes on with the symbol in table of UN regulation No.121, and the unrestrained seats appears on the monitoring display. This process is operated by controllers mounted beneath seat cushions and the program in the monitoring display system. How the system gives the warning and what are relevant parts in the system are shown in the Figure 3 below.

The program in the monitoring system also had a function to record data regarding occupancy and buckle status of each passenger seat. In every 5 seconds, it recorded the number of taken seats in the bus, the number of buckle-up seats in the buses, and the number of abnormal seats, etc. Here, the abnormal seats mean seats with worn seat belts when no one is seated, or seats with abnormal signals detected.

The monitoring system was made using a tablet and mobile application. Thus, the bus operator was able to easily download data and send those to the research team. Additionally, it was helpful for the research team to communicate with the application developer and bus operator because revising, updating, and upgrading the application program could be done easily.

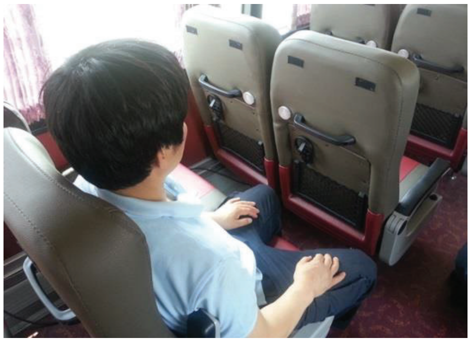
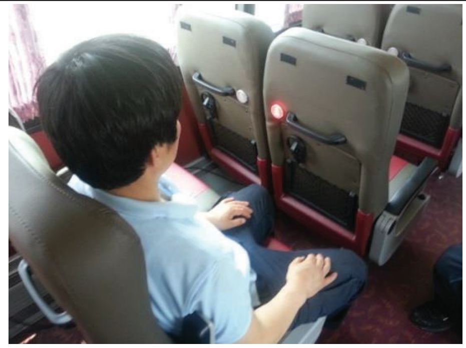
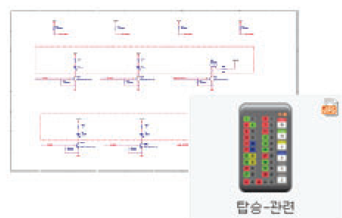
| | |
|---|---|
|  |  |
| Fastened (warning light off) | Un-fastened (warning light on) |
|  |  |
| Occupancy detection sensor and controller | Monitoring display system |

***Figure 3. Visual warning indicator and components of SBR system***

**Investigation into seat belt wearing rate**

**<u>Observational investigation</u>**

KOTSA carried out the investigation on the seat belt wearing rate of the public bus with the SBR system and buses not equipped with the SBR system. Here, the buses without the SBR system included not only the bus running on the same route but also interurban buses running on 6 other routes between Seoul and satellite cities. Investigators were on board and observed the wearing rate after the bus entered to the highway. After the observation, an interview regarding the effectiveness of the SBR system was conducted on the passengers wearing seat belts. To find out the pure SBR effect on the increase in seat belt use rate, bus drivers were asked not to encourage passengers to wear seat belts

**<u>Data analysis of SBR system</u>**

As it was mentioned earlier, the system was designed to record the number of taken seats in the bus, the number of buckle-up seats in the buses, and the number of abnormal seats every 5 seconds. The team analyzed the seat belt wearing rate everyday using two methods. For the first method, the wearing rate was calculated by the summation of the number of taken seats, the summation of the number of seats with seat belt fastened, and the summation of the number of abnormal seats. Equation (1) described how the rate was calculated. The second method is to average the seat belt wearing rates of all data sets for the day. At each data set, the wearing rate was calculated using the number of taken seats, the number of seats with seat belt fastened, and the number of abnormal seats. Equation (2) explained that in mathematical form. In both methods, for a more accurate and conservative calculation, the numbers of abnormal seats were subtracted from the number of restrained seats because it could be the case where seat belt was worn behind the back when the passenger was seated or the seat belt was fastened before the passenger took the seat.

$$seat\ belt\ wearing\ rate\ A = \frac{(\sum_{i=1}^{n} fs - \sum_{i=1}^{n} as)}{\sum_{i=1}^{n} os} \quad equation\ (1)$$

$$seat\ belt\ wearing\ rate\ B = \frac{\left(\sum_{i=1}^{n} \frac{fs - as}{os}\right)}{n} \quad equation\ (2)$$

*where,*

$os$: *number of taken seats at data set (occupancy)*

$fs$: *number of seats with seat belts fastened at data set*

$as$: *number of abnormal seats at data set*

$n$: *number of data sets every 5 seconds during an analysis duration*

## RESULTS

### Seat belt wearing rate from observational investigation

166 passengers of the buses with and without the SBR system on the project route were observed by KOTSA, and 526 passengers of interurban buses with 6 other routes were observed. The wearing rate of the bus with the SBR system was 59.0%. This was 49.4% higher than the rate of the bus without the SBR system. In case of 6 other interurban bus routes, only 15.2% of passengers used seat belt. Figure 4 summarizes the result.

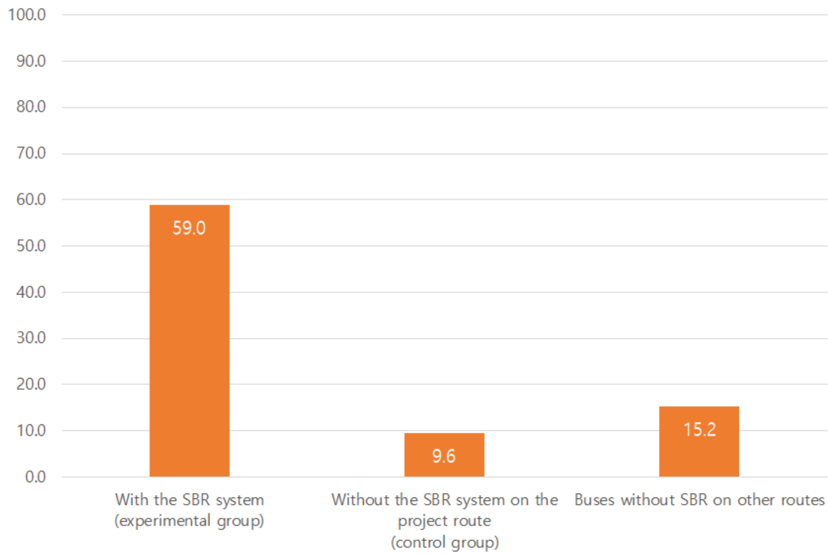



***Figure 4. Seat belt wearing rate (%) depending on applying the SBR system***

After the observation, investigators interviewed some passengers who buckled up in the bus. In the interview with 40 passengers, 19 passengers answered that the SBR system affected them to wear seat belts. This means 47.5% of passengers directly agreed on the effectiveness or influence of the SBR system with a visible warning on the increase in seat belt usage rate.

### Seat belt wearing rate from SBR system data analysis

There was 49-day data obtained from the system. Since some data were incorrectly saved or even not saved on certain days, those were excluded. Finally, the data for consecutive 40 days from July 27th to September 4th was selected and analyzed. As a result of analyzing all data sets of 40 days, the seat belt wearing rate A by equation (1) showed 55.82%, and the seat belt wearing rate B by equation (2) was 52.08%. The both results were slightly lower than the one by observational investigation, but about 42 to 46% higher than the wearing rate of buses without the SBR system. Therefore, whether the used method was by an observational investigation or by SBR data analysis, the project result clearly showed the SBR system is very effective for increasing the seat belt wearing rate. One thing noticeable was the difference between the result by equation (1) and equation (2). Because while equation (1) calculated the rate using the whole number of taken seats and seat-belt-fastened seats during a day, equation (2) averaged the every-5-second wearing rates of the day, if there were not many passengers in the bus and some passengers did not wear seat belts for a long time, then the individual rate values from the data sets with small number of passengers might have dominated the overall wearing rate calculated by equation (2). Due to this reason and a lot of data sets, the seat belt wearing rate from the data analysis result based on equation (1) was referenced for further discussion on this paper. Unlike the observational investigation, the data analysis method was able to analyze how long the SBR effect could last. The team looked at the change by computing the seat belt wearing rates on a weekly basis. Figure 5 displayed the trend of seat belt wear rate during the project term.

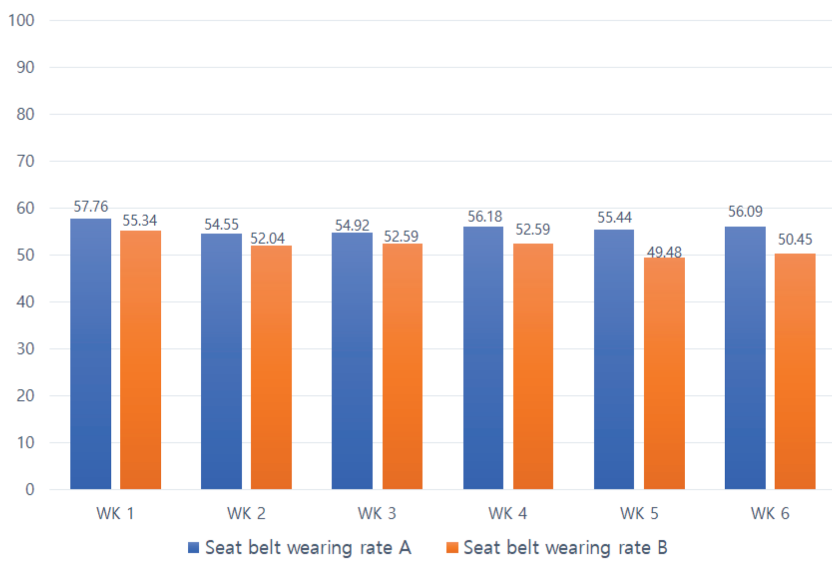



***Figure 5. Change of the seat belt use rate (%) of the SBR bus during the project period***

## DISCUSSION AND LIMITATIONS

### Literature reviews

There were several studies and papers on the effect of SBRs on seat belt wearing rate out there. According to an extensive study by Sweden, 85.8% belt wearing rate in driver seat positions without SBRs and 97.5% with Euro NCAP compliant SBRs were observed. The paper also reported about 80% of drivers not wearing seat belts without SBRs wore seat belts in vehicles equipped with an SBR with a light signal and a sound signal [6].
In order to figure out the effectiveness of Ford SBR system, Insurance Institute for Highway Safety (IIHS) and Ford motors made observations of driver belt use at 12 Ford owned dealers in 2001. The author estimated the overall use rate at 71% for drivers of vehicles without SBRs and 76% for drivers of vehicles with SBRs. The author concluded the difference of 5% points was statistically significant ($p<0.01$) [7].
In 2015, Mousel et al summarized results of a laboratory study conducted by Japan in relation to effect of SBRs on belt use of both driver and rear seat passengers. In this study, the initial belt wearing rate without a SBR warning was 38%. When both driver and rear seat passengers were presented with a visual warning, the usage rose to 72%. When an audiovisual warning was applied, the rate rose to 97% [8].

### Effectiveness of SBRs on increasing a seat belt wearing rate

Through this pilot project, it was confirmed that the effectiveness of the SBR with even only a visual warning on increasing seat belt wearing rate could be more than 40%. The wearing rate increased by approximately 50% according to the result from the observational investigation, and the rate increased by about 45% based on the result of SBR data analysis, compared to the rate in a bus without the SBR system. The result from the interview with 40 restrained passengers also stated that SBR visual warnings given directly to passengers could increase seat belt use rate by about 48%. The issue also has been discussed that the SBR effectiveness might be diminished as passengers adapt to the SBR system. Because this SBR system was installed in one particular bus and same people usually use the bus, some may be concerned about the reduction in the SBR effectiveness by familiarity resulting from prolonged exposure to the SBR. However, no strong correlation between the duration to use the SBR and the effectiveness of the SBR on the increase in seat belt usage rate was observed in the result of data analysis, which has been done through the procedures to compare the seat belt usage rate of each week.

## KNCAP and SBR

KNCAP introduced the SBR assessment in 2013. The maximum 0.3 additional points had applied to KNCAP overall rating until 2016 as an incentive. In 2017, KNCAP included the SBR rating in the overall rating scheme with maximum 1 point. After UN regulation No.16 extended the SBR scope from M1 driver seat to other vehicle categories, the new SBR test protocol and rating scheme were included in KNCAP as an incentive again.
Indeed, the program was successful. The installation rate of SBRs in the test vehicle models has increased rapidly since 2013. For domestic vehicles in Korea, the SBR already became a standard device in both front and rear seats in 2019 before the implementation date of the mandatory regulation (See Figure 6).

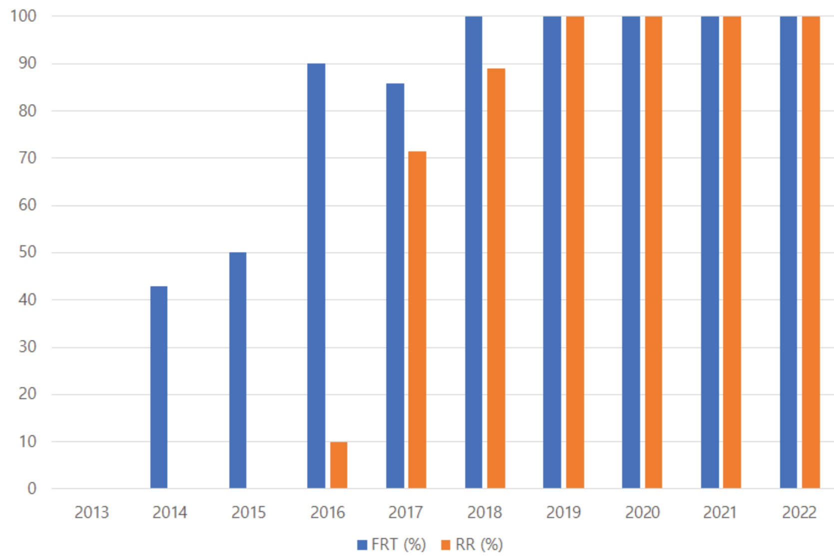



***Figure 6. Annual SBR installation rates of assessed passenger car models(≤ 10 passengers) in KNCAP***

Even though SBR systems have been installed in all seats of passenger cars as a standard, the seat belt wearing rate of rear passenger seats are still much lower than the rate of front passenger seats in Korea. As Figure 7 shows, the rate change of rear seats is standstill recently. This is why KNCAP needs to pay attention to and come up with idea to raise the seat belt wearing rate in rear seats to the level of the seat belt wearing rate in front seats.

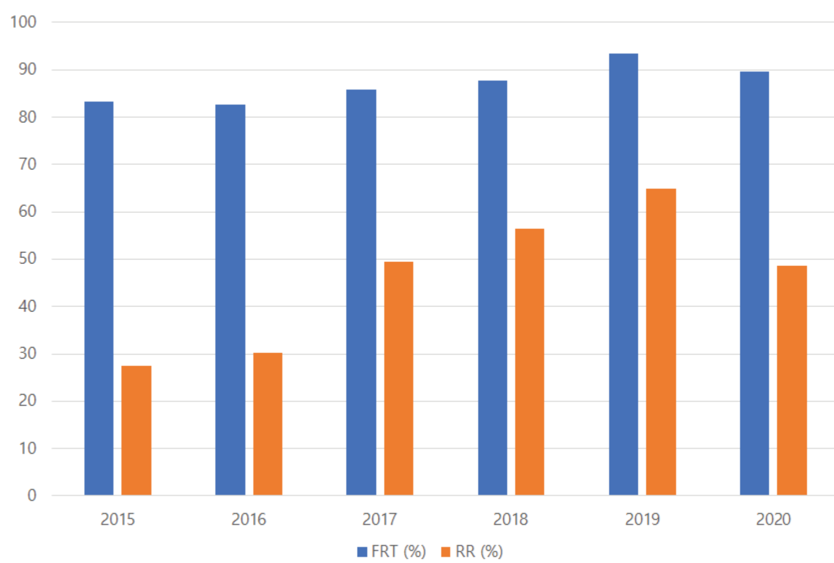



***Figure 7. Trend of seat belt wearing rates of FRT & RR seats***

This study gives some clues to it. The SBR system of this project directly warned each passenger with an occupancy detection sensor and a constant warning light unlike the current typical SBR system of passenger cars. First of all, the application scope of detection sensors should be reviewed. Currently, an additional score is given to a car applying occupancy detection sensors to rear seats in KNCAP. There are already many vehicle models with detection sensors in the rear seats. The technology is sufficiently available and mature in the market, and various occupancy detection sensing systems are under research and development. Therefore, including the assessment of a seating detection function as a standard in the program is highly recommended. This may also be an effective way to facilitate all passenger seats of various vehicle models to be equipped with appropriate SBRs. Secondly, KNCAP needs to encourage all cars to warn all passengers in cars when they are not retrained by seat belts, so they can recognize that they have to wear seat belts. Because the current protocol requires SBRs to remind only a driver of the unrestrained seating positions, there is an issue that the SBR effectiveness relies on the driver's second reminding and responsibility. The issue is soluble. Future cars will include various interior displays. It means many potential measures to remind all passengers of their restraint status will be available. On the other hand, the issue must be solved. The future cars will provide driverless ride environment in the age of autonomous vehicles sooner and later. Equal reminding is inevitable. This study obviously showed direct warnings to passengers worked. Almost half of passengers who fastened their seat belts in this project responded that they buckled up by the warning light in front of them. KNCAP should consider the introduction of new technologies and assessment protocols in relation to direct warnings to all passengers.

In line with this, there was research on different seat belt assurance systems, which are, so called, seat belt interlock (hereafter SBI). Two concepts, vehicles with speed limiter and with transmission interlock were suggested. Unlike SBR, SBI is a more active system to render passengers restrained with seat belts. [9]

Since KNCAP is about to establish the next KNCAP roadmap, KNCAP and stakeholders need to discuss and consider new measures to increase the seat belt wearing rate as the previous KNCAP protocol made contribution to the increase in the seat belt wearing rate. It is time to change and take a second leap forward in SBR assessment.

### Regulation and SBR

The current Korean Motor Vehicle Safety Standard (KMVSS) and UN regulation mandate SBRs for all vehicle categories, but have several exceptions, which exempt folding seats and passenger seats in the rear of buses. Excluding passenger seats in buses and coaches is debatable because applying SBRs to driver seating positions in those vehicles is mandatory. It is not fair that passengers in the same car are provided with different levels of safety performance. This study presented a solution to apply SBRs to passenger seats in buses and demonstrated its possibility. Discussion on mandating SBRs in all passenger seating positions is highly recommended with the follow-up benefit-cost analysis.

### Limitations

The SBR system developed and applied in this pilot project included only a visual warning, which was a constant light signal when the passenger did not wear a seat belt. Therefore, the effectiveness of the SBR system is limited to only a visual warning function, not a flashing optical warning function, an audible warning function or an audiovisual warning function in this study.

The research team found that seat belts on the bus were sometimes fastened without seated passengers while the bus was in service. This might have led to incorrect data analysis if passengers had been seated on the seats. In addition, hardcore seat belt non-users might have affected the overall wearing rate calculation depending on a situation as it was mentioned earlier.

## CONCLUSIONS

For decades, seat belts have played an important role in car safety. Even in the era of autonomous vehicles, they will remain effective for a considerable period of time. According to the survey conducted by KATRI, consumers still wanted to have injury mitigation systems in their autonomous vehicles and preferred seat belts the most among currently existing restraint devices [10]. Hence, SBR systems is also important. This paper demonstrated the SBR with only a visual warning to each passenger influenced the increase in the seat belt use rate by more than 40%.

To keep passengers in cars safer, manufacturers have to develop more advanced SBR technologies and try to introduce those for future vehicles. It could be the extension of passengers in cars who benefit from SBRs, direct warnings not only to a driver but also to individual passengers using new interior displays or indicators, or mild interlock function. In line with the new technologies, the government and society also need to improve the safety assessment system to raise the wearing rate of seat belts.

## REFERENCES


[1] Korea Transportation Safety Authority. 2017. "If you don't fasten your seat belt properly, the possibility of serious injury is up to 99.9%." [press release]. https://www.kotsa.or.kr/portal/bbs/report_view.do?bbscCode=report&cateCode=&bbscSeqn=10327&pageNumb=1&sechCdtn=1&sechKywd=%EC%95%88%EC%A0%84%EB%9D%A0&menuCode=05010200.

[2] International Transport Forum. 2015. "Road Safety Annual Report 2015." OECD publishing. Paris, https://www.itf-oecd.org/road-safety-annual-report-2015.

[3] Ministry of Land, Infrastructure, and Transport (Republic of Korea). 2013. "Rules on the safety assessment test, etc. of vehicles (KNCAP)." Ministry of Land, Infrastructure, and Transport notification 2013-286.

[4] Korea Transportation Safety Authority (KOTSA). 2016~2021. "Report on Transport Culture Index of Korea." KOTSA publishing. Gimcheon, Korea, 2016~2021.

[5] United Nations Economic Commission for Europe (UNECE). 2016. "Reports of the World Forum for Harmonization of Vehicle Regulations on its 170th session, Administrative Committee of the 1958 Agreement on its sixty-fourth session, Executive Committee of the 1998 Agreement on its forty-eighth session, Administrative Committee of the 1997 Agreement on its ninth session." ECE/TRANS/WP.29/1126 of 170th WP29 session. Geneva, Switzerland, 2016

[6] Lie, A., Krafft, M., Kullgren, A., Tingvall, C. 2008. "Intelligent seat belt reminders-do they change driver seat belt use in Europe?." Traffic injury prevention, 9(5), 446–449. https://doi.org/10.1080/15389580802149690

[7] Williams AF, Wells JK, Farmer CM. 2002. "Effectiveness of Ford's belt reminder system in increasing seat belt use." Injury Prevention 2002;8:293-296.

[8] Mousel T., Ueda K., Takahashi M. 2015. "Advanced seat belt reminder system for rear seat passengers." Paper no. 15-0018 of 24th ESV conference proceedings. Gothenburg, Sweden, 2015.

[9] National Highway Traffic Highway Administration. 2018. "NHTSA's research on seat belt interlocks." SAE government-industry meeting. Washington D.C, USA, 2018.

[10] Korea Automobile Testing & Research Institute (Republic of Korea). 2021. "Crash safety of autonomous vehicles based on a survey result." Informal document GRSP-70-15e of 70th GRSP session, Geneva, Switzerland, 2021

**Virtual Simulation Based Assessment of ADAS in Consumer Tests by openPASS**

**Felix Fahrenkrog**
**Manel Hammouda**
**Florian Fischer**
BMW AG
Germany

**Ludwig Maier**
Hochschule München University of Applied Sciences
Germany

Paper Number 23-0191

## ABSTRACT

Test of consumer protection organizations like the New Car Assessment Programmes (NCAPs) play an important role in the overall safety of modern vehicles. Being focused on passive safety over the past decades, the importance of active safety systems has grown in recent times more and more. To assess the performance of active safety systems, standardized test scenarios which are supposed to represent real world accidents are used today. The constantly increasing requirements and the goal of ensuring the robustness of those active safety systems lead to a vast amount of test scenarios. This trend is accompanied with the aim of testing more complex scenarios. In the future, it will hardly be possible to cover this amount of test by track tests alone. Therefore, new virtual methods to support the assessments are required. This paper aims to discuss the question: What are the requirements for these virtual methods to be implemented on manufacture and consumer rating organization side? To discuss the posed question, a two-stage process is foreseen. In the first step, an exemplary virtual assessment of safety oriented ADAS is conducted. For this purpose, consumer rating test scenarios are set-up within the simulation software openPASS. After the implementation, an assessment for one vehicle and one active safety function is conducted in this virtual environment. Finally, the difference between simulation and real vehicle tests is analyzed. In the second step, the learnings and findings from this study will be used to discuss the requirements for future virtual assessments. The demonstration study in openPASS will cover only an exemplary set of test scenarios. Furthermore, the study will only be conducted for one vehicle. The generalization of the study's findings needs to be investigated further.

## INTRODUCTION

Today's vehicles are equipped with different Advanced driver assistance systems (ADAS), ranging from short-intervening autonomous braking systems (AEB) to continuously operating systems like Adaptive Cruise Control (ACC) or Lane Centering Assist (LCA). ADAS play a major role in the overall vehicle safety. To be able to compare different vehicles regarding their overall safety and to push the overall development of those systems, customer protection organizations like the European New Car Assessment Program (EuroNCAP) were established [1].

To be able to compare the different systems, it is necessary to use standardized test methods and scenarios. These test scenarios are developed by the individual customer protection organizations, mainly by looking into recent accident statistics. To assess the performance of the ADAS, real vehicle tests are conducted on test tracks with the help of surrogate collision targets like pedestrian, cyclist or vehicle dummies. Although it is tried to design the tests as realistic as possible, the tests cannot replicate the much more complex reality on public roads to the full extent.

In contrast to passive safety, the fast development of ADAS technology leads to regular updates for the testing procedure. This resulted in an increase of the number of test scenarios as well as of the requirements (see ***Figure 1***). Furthermore, customer protection organizations are becoming more and more focused on the topic of robustness [1], which lead to additional test scenarios where parameters like number of objects, collision point, and daytime are varied to evaluate the systems real world performance. This development further increases the number of tests as well. This triggers the question, whether traditional track testing will be sufficient in the future. In 2015 BMW already proposed a virtual testing approach combing different test tools for comprehensive real-world assessment of ADAS [2].

Euro NCAP initiated a working group to investigate the future test [3]. One promising testing approach is to apply virtual simulation to complete the picture of real-world tests. Virtual test can be applied easily in complex scenario and allow for testing much quicker than on a test track (Reference). On the hand there is always the question about validity of virtual simulation [5].

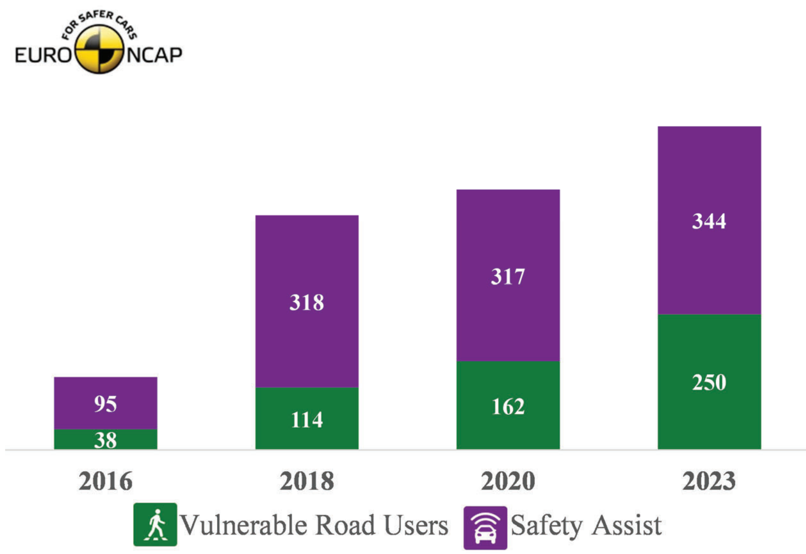



***Figure 1. Increase of Euro NCAP test in the last years (based on [5]-[12])***

This paper aims contribute to the general discussion about virtual testing of ADAS by addressing the following questions: What are the requirements for these virtual methods to be implemented on manufacture and consumer rating organization side? To approach this question first it is shown, how Euro NCAP scenarios for an effective virtual assessment can be implemented in the open-source simulation tool openPASS [13]. Afterwards, it is reported on the study that compared virtual tests with outcome of the test track test for one AEB function. This exemplary study is the initial point to discuss the future requirements for virtual testing. In the last part requirement for the virtual testing are discussed.

## SIMULATION TOOL OPENPASS

### Background

OpenPASS is an open-source software [13], which is being continuously developed by the Eclipse openPASS Working Group (WG). The openPASS WG manages the sim@openpass project under the roof of the Eclipse Foundation. It is the driving force behind related development of the simulation platform and its modules. The goal is to ensure a transparent and publicly available simulation framework for the assessment of safety systems. The idea of openPASS started with P.E.A.R.S. [14] in 2014. Back then inquiries within the P.E.A.R.S. group showed that many partners used own developed tools and that there was no specialist tool for the assessment of the safety performance of ADAS. Some partners – namely BMW, Mercedes and Volkswagen – want to address this lack of a common appropriated simulation by initiating an own software tool, which should cover the different baseline approaches of P.E.A.R.S. and which should allow also for a transparent virtual assessment. This led to the founding of the openPASS project in 2016.
openPASS covers two main use-cases, namely the PCM (PreCrash Matrix) crash re-simulation and scenario-based simulations. The PCM crash database is a subset of the GIDAS (German In-Depth Accident Study), in which real world crashes are reconstruct through on-site measurement and evidence. The PCM crash cases describe the trajectory of the traffic participants, and the road setting seconds before the crash. openPASS allows the re-

simulation of these crashes under the consideration of cars equipped with ADAS. In this simulation use case it is assessed whether the tested technology would avoid the crash in question.
The traffic/scenario-based simulation is indeed the most common use-case of openPASS since it offers more opportunities to investigate a larger scenario space and much more scenarios than the crashes re-simulation. This approach includes the stochastic variation of those scenarios, surrounding traffic as well as the intervention through detection of events and triggered actions and much more. Typically, this approach relies on comparison of the results in the baseline (situation without the technology in question) and the treatment condition (situation with the technology). For the comparison first a basic conflict scenario is described. This is done by means of defining the starting conditions of the ego-vehicle (e.g., velocity position), the potential conflicting partner (e.g., velocity, relative distance to the ego-vehicle, and trajectory of the maneuver to be executed). The surrounding traffic is stochastically varied in its position, driver characteristics and speed by openPASS. Then the scenario is run multiple times under variation of the starting conditions and the maneuver of the conflicting partner until a solid statement regarding the influence of the technology on the safety performance can be derived.
Thus, openPASS is capable to covering all by P.E.A.R.S. [14] and in the ISO21934 [15] named baseline approach for the prospective safety performance assessment by virtual simulation. However, openPASS can also be applied in other use cases. One example is the comparison of different technology-wise solutions in the early development stage. If it is applied in other use case adaptation of the used models might be necessary.
One of the most important characteristics of openPASS is the flexibility that it offers through the modular architecture. In fact, the simulation platform allows the connection of models as well as scenarios and maps to the simulation by the means of standardized interfaces and standards, as depicted in **Figure 2**.

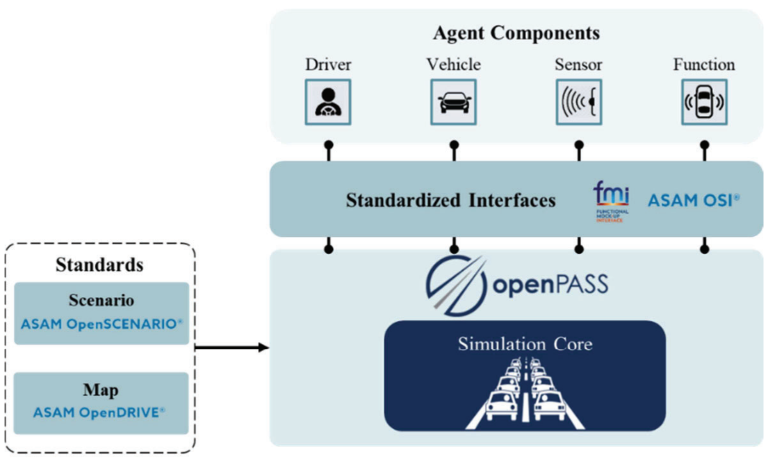



***Figure 2: A set of supported standards and standardized interfaces in openPASS***

The supported standards OpenSCENARIO [18] and OpenDRIVE [19] allow the description of the scenario setting and the road infrastructure with the possibility to trigger events at certain conditions. Furthermore, the supported standardized Interfaces like OSI (Open Simulation Interface, [16]) and FMI (Functional Mock-up Interface, [17]) enable the coupling of external models. FMI represents a crucial interface in this work. It is indeed an open format specification for exporting and importing simulation models. For instance, a Simulink model can be built as an FMU (Functional Mock-up Unit), which is a packaging format defined by FMI. It basically encapsulates a compiled code (as *.dll or *.so, depending on the platform) and an xml-file that is describes the inputs and outputs of the FMU (modelDescription.xml). This model can be coupled to openPASS using the FMU Wrapper Interface.

**Input to openPASS simulation**
The simulation tool requires different input files that are described in the following.

- **Scenario** (*.xosc): This file describes the overall situation in terms of the ASAM OpenSCENARIO 1.0 standard [18]. It includes an Init-Tag, which describes the initial setting in the simulation, such as the positions and the velocities of the traffic agents. Additionally, the scenario file contains a Story-Tag, that allows the triggering of certain events at certain conditions e.g., the ego vehicle performs a lane change to the right when the simulation time reaches 10 s. The end simulation time itself, i.e., how long should the simulation run, is also part of the scenario configuration. Furthermore, the scenario contains references to additionally needed files, like the scenery configuration and other relevant catalogs explained in the following.

- **Scenery** (*.xodr): The scenery file describes the road infrastructure following the ASAM OpenDRIVE 1.6 standard [19]. As such, it contains the description of the road network and its geometries e.g., the numbers of the lanes, the curvature of the road and the lane markings. Moreover, the scenery defines the traffic signs and traffic lights as well as any static object or obstacles that may occupy the road.
- **ProfilesCatalog** (*.xml): This catalog is the probabilistic heart of the simulation as it describes the composition of various simulation components and entities, using both, deterministic and stochastic definitions. It defines the composition of the traffic agents that may be vehicles (from the VehicleModelCatalog.xosc) or pedestrians (from the PedestrianModelCatalog.xosc) and their underlying components like sensors, driver assistance systems or driver models. The name ProfilesCatalog comes from the profiles idea that lies behind this file. A profile is indeed a template that defines how an agent is configured in terms of driver models, sensors, and assistance systems, each provided with a certain occurrence probability. As OpenSCENARIO does not support this level of probabilistic variations probabilities (yet), this file is not compliant to the standard.
- **VehicleCatalog** and **PedestrianCatalog**: (*.xosc): These catalogs follow the OpenSCENARIO standard and describe the physical parameters of available vehicles or pedestrians, respectively.
- **SimulationConfig** (simulationConfig.xml): This is the entry point for the simulation, containing the setup of the core, such as active observers, reference to the scenario, the initial random seed, and the number of invocations. Furthermore, the used spawner libraries are referenced in this file. The spawner is one the main core module in openPASS, that allows the spawning of traffic agents during pre-runtime and runtime following certain parameters distributions, such as velocities and time gaps. These parameters are defined in the ProfilesCatalog, explained above.
- **SystemConfigBlueprint** (systemConfigBlueprint.xml): This file consists of a superset of all possible components and their valid connections. Such components can be lateral and longitudinal controllers, assistance systems, prioritizes, driver models, and so on. Depending on the configured profiles and their probabilities, the core picks a subset of components to create one complete system. This file should only be edited by experienced users with a deep understanding of the framework architecture.

**Output of openPASS simulation**

Outputs are generated by individual observers, configured in the SimulationConfig, and collected within the folder results. This section describes the output files by the Observation_Log, as configured by the provided example configurations.

- **Simulation Output** (simulationOutput.xml): This file acts as a central entry point for further evaluations, such as the visualization. It contains central information about all executed invocations within an experiment, such as the executed scenario and the run results, which can be seen as current values from the random sampling of the given probabilities. As such, each run result contains, a list of participating moving entities (also referred to as agents), events related to the entities, such as collisions or activation of ADAS's, and a reference to the cyclics file. This file does not contain information about the actual position and movements of the different agents.
- **Cyclic Output** (Cyclics_Run_###.csv): This file contains the ground truth information for each agent at each time step. For each invocation, a new file is generated (starting with Cyclics_Run_000.csv) and referenced in the according run results in the simulationOutput.xml.

Next to the output files provided for each simulation runs, there is the option to visualize the output in a separate application, namely the opVisualizer.exe. It represents a 3D visualization of the simulations results, as shown in **Figure 5**; and allows an offline navigation throughout the simulation time and space. Additional to a 3D animation of the simulation results, the opVisualizer offers the representation of occurring events, such as collisions or ADAS warnings or interventions, and displays the sensor ranges.

## TOOLCHAIN FOR VIRUTAL TESTING OF EUROPE NCAP SCENARIOS IN OPENPASS

**Task of the toolchain**

The general aim of the ENCAP-openPASS-Toolchain is to support the concept evaluation of scenarios from the Euro NCAP in the part of the active safety functions for AEB (Automated Emergency Braking)- and LSS (Lateral Support System). The toolchain aims to assess the system performance in the concept phase of function – a particular focus is on assessing the vehicle's sensor setup. For this purpose, an idealized sensor model is used. The tool verifies whether an existing sensor setup can cover the Euro NCAP scenarios [5][9]. In addition, by means of the tool also the functions logic can be assessed to provide a first prediction about its potential performance. The ENCAP-openPASS-Tool uses openPASS software. In this sense the tool is an addon tool to openPASS. The main task of this tool is to generate and define trajectories from the published protocols of Euro NCAP which leads to the defined collision point between the ego-vehicle and the target object as specified in the protocol [Quelle]. The tool also generates all the other required input files for the openPASS simulation. Finally, the tool, which is implemented in Python [Quelle], can trigger openPASS simulation and evaluate the outcome of the openPASS simulation.

**Definition of scenario simulation parameters**

To create and simulate the AEB or LSS-scenarios it is necessary to set the parameters for the simulation. There are different scenario specific parameters like the curvature of the trajectory, velocities or collision points at the front of the ego. All these parameters are defined in testing protocols of the Euro NCAP. Another scenario parameter that needs to be defined individually is to create a specific ego profile with its corresponding sensor setup. The ego vehicle is considered as a 2D-boudingbox which is created by the tool. The input values for that are the length, width, the position of the axes and the position of the center position. These dimensions are required for the simulation with openPASS.

To ensure the right collision point when defining the trajectory, the ego-vehicle's width has been divided in constant segments (e.g., every 5% of the vehicle's width) with potential collision points. The user can set the collision point as a percentage value. However, the default setting with a step-size of 5% allows the calculation of all Euro NCAP scenarios without any loss of accuracy. The sensor setup of the ego is idealized like it is shown in the introduction of openPASS. One sensor is described by the x- and y-position, its heading angle, the field of view (FOV) and the detection range. These parameters must be given in the ego-vehicle's coordinate system. For every simulation a specific ego profile can be implemented with one or more sensors. The targets are given as a catalog since they have fix dimensions according to the Euro NCAP protocols.

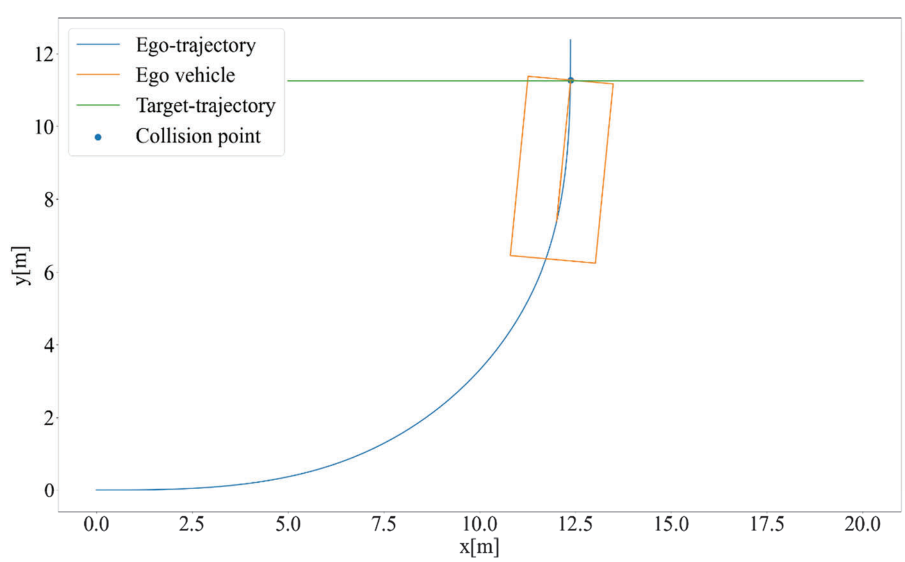



***Figure 3: Visualization of collision point calculation for scenario CPTA (Car-to-Pedestrian Turning Adult).***

**Collision point calculation**

To get a defined collision point between the ego and the target, it is important to know the collision point at the front of the ego. This value is given by the protocols or can be adjusted by the user. The second step is to create the ego trajectories according to the specifications of the Euro NCAP protocols. For instance, in case of a turning scenario, it is necessary to know the curvature in advance. These trajectories are created dependent on the velocity of the agents. The explanations from the protocols were deployed in the ENCAP-openPASS-tool for an automated creation. After the calculation of the ego trajectory the ego profile is positioned at all points of the trajectory stepwise. This procedure is repeated as often as the collision point at the front of the ego profile reaches a specific distance according to the given protocol. This is shown in the **Figure 3**. If the specific distance is reached, the target trajectory can be created in a reverse calculation starting from the end point. The length of the target trajectory depends on the simulation time.

**Sequences in the simulation tool**

The first step is to create the input files where the calculated trajectories are also implemented. This has been described above. In the next step, the openPASS is started. The simulation is triggered for all defined scenarios. The execution of the simulation of the different simulation runs automatically. Before the execution, the user can decide whether to include an already implemented active safety function as a FMU or not. The user can change the settings of the scenario in a GUI (Graphical User Interface), which is depicted in **Figure 4**.

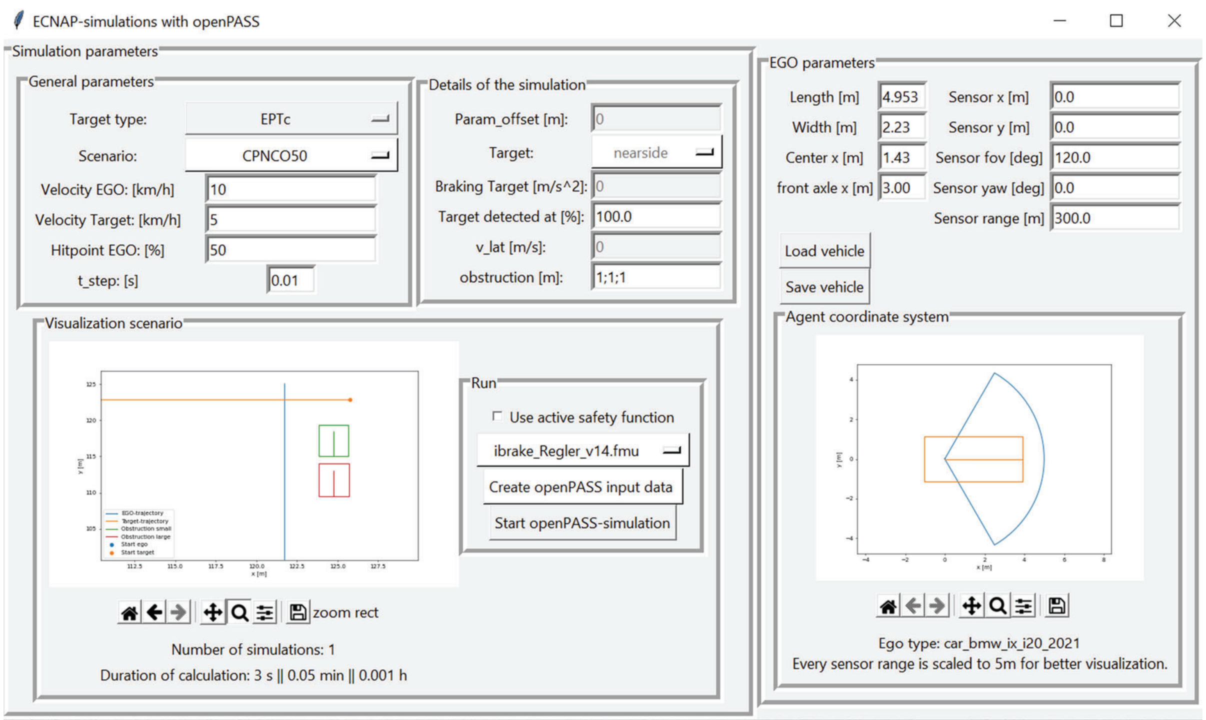



***Figure 4: NCAP tool GUI interface for openPASS simulation**.*

The figure shows all the different changeable boundary conditions of one specific scenario on the left-hand side. The right-hand side encapsulates all the parameters which can be configured for the ego vehicle. For better explanation, the GUI visualizes the planned scenario and the ego vehicle as a plot in the bottom left part of the tool.

**Evaluation**

For each time step, several output variables can be analyzed, such as the velocity, the acceleration, the position of the agents and the visible and detected objects by the implemented sensor setup. The simulation verifies an agent as visible, if one point of the 2D-boundingbox lies within the field of view of the idealized 2D sensor setup. If an agent is detected, it is necessary that at least a minimum percentage of visible area is in the field of view of the sensor. This value can be setup by the user in the configuration files. The sensor model needs a minimum visible area of an object to correctly classify it, e.g., as a bicyclist. Indeed, this information can be found in the results files of openPASS. These trace files can be visualized in a 3D-visualization toll, namely the opVizualizer. An example of a visualized Euro NCAP scenario is shown in **Figure 5**. The red ego vehicle (0) and the bicyclist (1) are the relevant collision agents. Their trajectories are synchronized to meet at the calculated collision point at the front of the ego by the absence of an active safety function. The agents (2) and (3) simulate the necessary obstructions of the scenario. This timestep shows the moment when the bicyclist is detected from one example sensor setup.

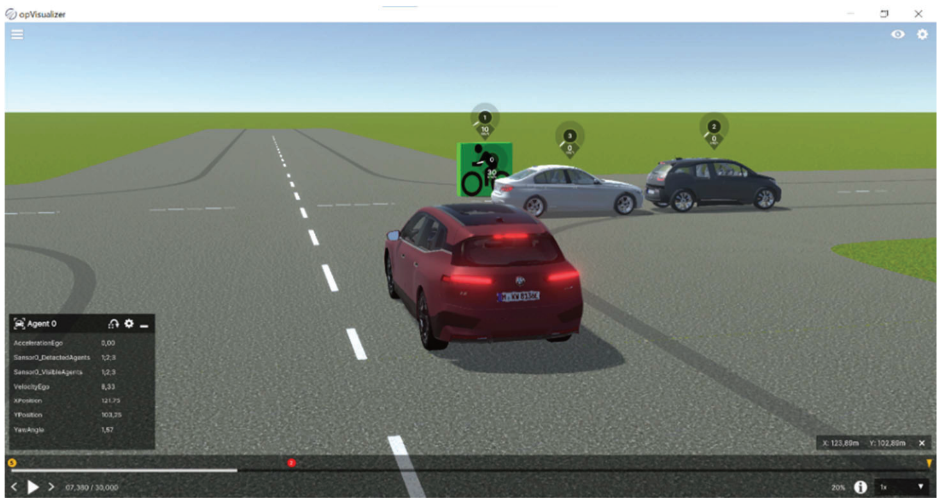



***Figure 5: 3D visualization of openPASS simulation in the CBNAO (Car-to-Bicyclists Near Side Adult Obstructed) crossing scenario (ego vehicle: red vehicle).***

## COMPARISON VIRTUAL TEST AND TEST TRACK

The major purpose of this paper is to raise awareness about the urgent need to define the requirements of virtual testing for consumer ratings. To approach this question, an exemplary comparison of simulation results and real test tracks using some KPIs (Key Performance Indicators) are presented in this section. Therefore, rear-end Euro NCAP conflict scenarios are simulated in openPASS. The method and tools presented in the sections “Simulation tool openPASS” and “Toolchain for Virutal testing of europe NCAP Scenarios in openPASS” are applied to evaluate a concept model of an AEB (Automated Emergency Braking) function. It is important to note that the model that is deployed in this study does not fully represent the real function and may include some differences for the sake of simplification. The AEB model is implemented as a Simulink model, which is later built as a FMU following the FMI Standard. This kind of standardized encapsulation of models allows their co-simulation in different platforms that support FMI. In this case, the AEB FMU is connected to openPASS through an FMU-Wrapper. For the end-user, the FMU connection in openPASS consists of an xml-configuration of the inputs and outputs.
In this study, a total of 22 scenarios are implemented. These scenarios can be divided in 3 categories:

- CCRb (Car to Car Rear braking): These scenarios involve an Ego and a Target vehicle with a rear-end conflict, where the target travels with the same velocity as the Ego vehicle and then carries out a braking maneuver. The deceleration varies between -2 m/s$^2$ and -6 m/s$^2$. Here only a 100% overlapping is considered. The velocities of the two cars lay by 50 km/h and the distance between the vehicles is 12 m or 40 m. This leads to exactly 4 combinations.
- CCRm (Car to Car Rear moving): These scenarios involve an Ego and a Target vehicle with a rear-end conflict, where the target travels with the constant velocity of 20 km/h. The Ego velocity covers the interval [30,70] km/h with a 5 km/h step. With only 100% overlapping, a total of 9 scenarios is obtained.
- CCRs (Car to Car Rear standing) scenarios: These scenarios involve an Ego and a Target vehicle with a rear-end conflict, where the target is standing. The ego velocity varies between 10 km/h and 50 km/h with a 5 km/h step. This results as well in exactly 9 scenarios.

The above Euro NCAP scenarios are carried out during test tracks, where a real AEB function is tested. Indeed, the results of two real test runs following the same settings are available. To have a basis for a comparison between the test tracks results and the obtained simulation traces, multiple KPIs are computed. These KPIs include continuous variables courses over time, e.g., acceleration, distances, velocities, as well as discrete indicators, such as the trigger TTC (Time To Collision), the final minimal distance of Ego and the collision result. The TTC is the remaining time before a collision occurs between ego-vehicle and target object if none of the vehicles performs an evasive action. Therefore, it is the time needed to travel the net gap distance with the relative speed between the leading and the following agent. In this context, the trigger TTC represents the TTC where the AEB function starts the braking maneuver. It is indeed an indicator about the reaction rapidity of the function.

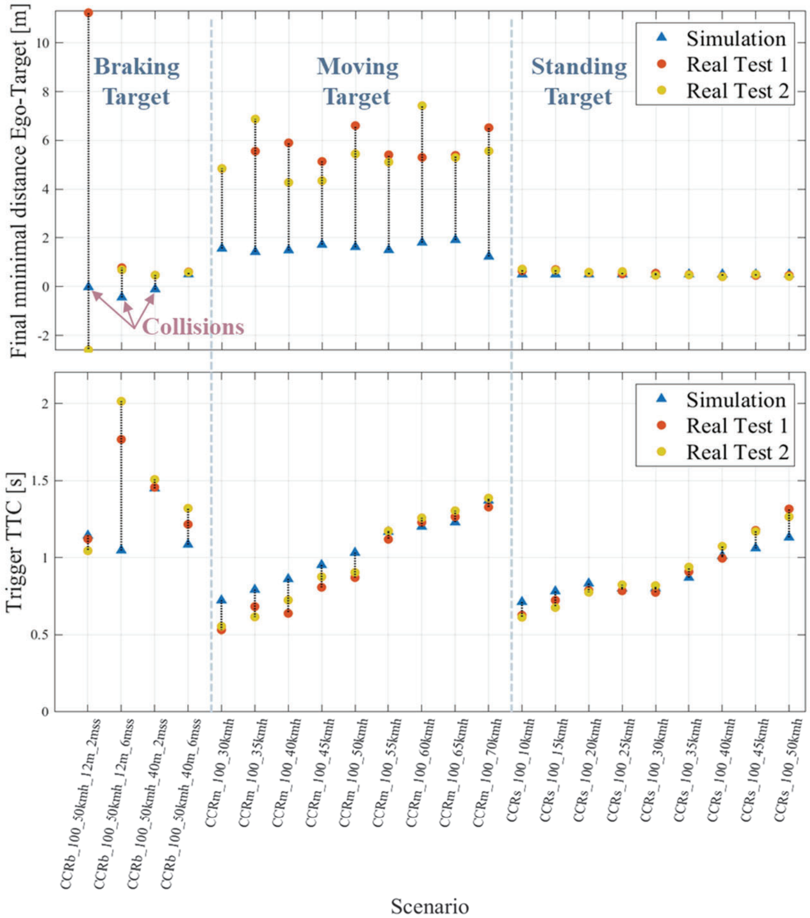



***Figure 6: Comparison of the trigger TTC and the final minimal distance btw. Ego and Target in openPASS and in two test tracks.***

**Figure 6** presents the overall results of the comparison between the simulations and the two test tracks in terms of trigger TTC and the final minimal position of the Ego vehicle, i.e., the minimal net distance that separate the ego-vehicle from the target vehicle. A key indicator for evaluation is indeed the collision status. This is shown in the figure implicitly. A negative net distance between the two vehicles indicates the occurrence of a collision. As clearly depicted in **Figure 6**, three simulation runs involving a braking target scenario resulted in a collision. These include critical settings with an initial gap distance between the vehicles that is equal to 12 m additional to one scenario with 40 m gap distance. On the one hand, this may be explained by the relatively late TTC trigger in the simulation, especially for the second CCRb scenario, where the trigger TTC lies by 1 s in the simulation in contrast to both test tracks that lie around 1.8 s and 2 s (see **Figure 6**). Although the trigger TTC does not show a considerable difference compared to the other test tracks, the deceleration development over time may be the main reason for the collisions in the simulation. For the real test tracks, only the second recording marked in yellow of the first CCRb scenario resulted in a collision. All other cases, the real AEB function managed to avoid the crash. For the moving target scenarios (CCRm), the results in the simulation and in the real world align in terms of crash occurrence. Whereas the final net gap distance between Ego and Target lies around 2m in the simulation, the test recording show a certain scattering of the values 8 and 4 m. Clearly, even the real tests show variations themselves and do not completely overlap on many levels. The trigger TTC shows relatively similar values in both cases. Finally, the runs including a standing target (CCRs) demonstrate harmonized values in the final standing position around 0.5 m. The trigger TTC shows an increasing trend with the increase of the ego-vehicle's velocity similar to the moving target scenarios, however with lower values due to the larger difference velocities that would consequently lead to a faster reaction.
**Figure *7*** and ***Figure 8*** presents the time courses of two important signals, namely the ego-vehicle's acceleration and the net distance between ego-vehicle and the target-vehicle. Here, two exemplary scenarios are presented. The upper

one shows the CCRs scenario with an ego-vehicles velocity of 25 km/h, whereas the lower plots represent the results of a CCRb scenario with a net initial distance of 40 m and a target deceleration of -6 $m/s^2$. Both cases the system reacted to the given thread and avoided a collision (positive net distance in the end). The net distance signals show in this case a good alignment between the simulation and the real test tracks results. The acceleration courses in the CCRs scenario triggers approximately at the same time as in the real tests, whereas the CCRb scenario shows a slightly delayed reaction that does not affect the overall result. Nevertheless, the simulation results evolve in a rather discrete and smooth manner compared to the real test results, which show a more continuous evolution over time as well as some oscillations due to the real vehicle dynamics.

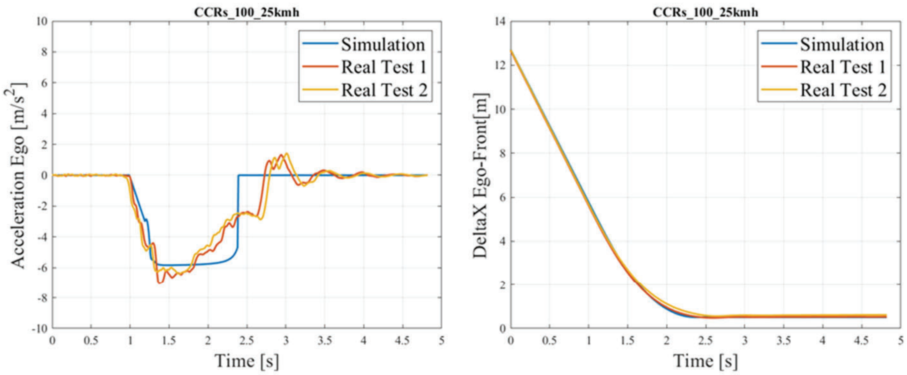



**Figure 7: Comparison between simulation (openPASS) and two test tracks tests for acceleration and delta positions in CCRb.**

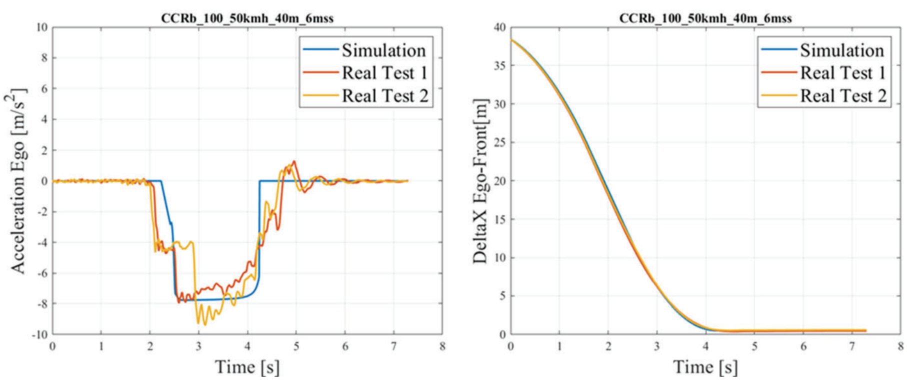



**Figure 8: Comparison between simulation (openPASS) and two test tracks tests for acceleration and delta positions in CCRs.**

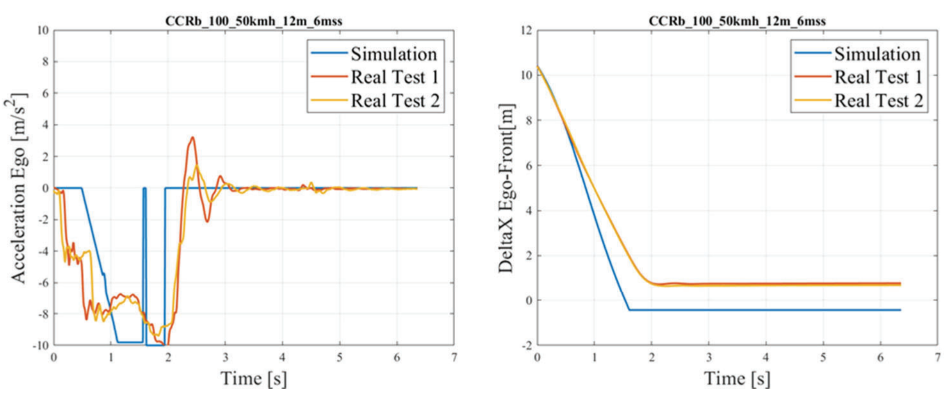



**Figure 9: Comparison between simulation (openPASS) and two test tracks tests for acceleration and delta positions in CCRb.**

***Figure 9*** corresponds to the CCRb scenario with a net initial distance of 12 m and a target deceleration of -6 $m/s^2$. This case includes a collision, as mentioned before. The longitudinal acceleration signal shows indeed a delayed activation of the braking maneuver as well as a slower development of the deceleration over time. This leads to a crash in the simulation, while in the test track test the collision was avoided. Further investigation in the reasons for the different behavior are planned. However, the example should indicate that different scenario poses different challenges for the simulation.

To conclude, this exemplary study showed that the simulation results for most of the scenarios align with the test track results. The deviations observed in the challenging CCRb scenarios may be explained by the simplified AEB function model in the simulation combined with the idealized object-based sensor models deployed in the simulation. Nevertheless, this study represents an adequate discussion basis for the needed requirements towards a widely accepted virtual testing approach for consumer ratings.

## FUTURE REQUIREMENTS FOR VIRUTAL TESTING

The exemplary studies in the previous section give an indication what can be achieved by simulation and where challenges start to arise. It is obvious that there is potential to optimize the results further. Nevertheless, the learnings from this study should be used to approach the initial questions: What are the requirements for these virtual methods to be implemented on manufacture and consumer rating organization side?

The first aspect is to clarify the scope of the assessment. There are multiple approaches and tools to simulate the performance of ADAS and ADS to assess their safety performance. This paper provides only an example implementation. It is also clear that the different tools have different advantages and disadvantages. Certainly, there is not one simulation solution that fits all problems respectively. And even if such a solution would exist, it would come with compromises in terms of performance. Therefore, the first step before defining any requirements is to clearly identify the purpose and scope of the virtual assessment. Once this is clarified, the requirements and the simulation solution can be chosen.

1. **What do I want to assess exactly with the simulation?**
   This is the key question to be answered. This question should not be answered by a general statement, like e.g. I want to assess an AEB virtually. It is rather about the details, like do I want to focus on the perception, logic or actuator? What are the scenarios I am interested in, and which metrics do I intend to use? Do I need a quick answer or a very detailed answer? The answers to these questions will already point to the required solution for the virtual assessment. Depending on the considered use case, the solutions may differ. One example for defining the evaluation scope is given be by the P.E.A.R.S. initiative. It defined five aspects (metric to be used, technology, scenario, region for prediction) to be covered by each research question in the domain of prospective safety performance assessment (see [20]). These aspects will not hold true for each evaluation use case if the scope of the evaluation varies. But they provide hints about what should be specified before defining the further virtual assessment.
2. **Which accuracy of the simulation is required for the intended results?**
   The second question is equally important for defining the virtual assessment approach as the first one. Even if the virtual assessment use case is clearly described there are often multiple technical solution in terms of fidelity of models and simulation execution (e.g., simulation step size). It often requires a trade-off between accuracy and simulation effort. In general, it can be assumed that models with a higher fidelity will require also more computation time. Therefore, it is crucial to decide on the required accuracy. If the user is just interested in knowing whether a collision is avoided, potentially less detailed and faster models can be applied compared to question to determine the stopping distance in cm (e.g., vehicle model could be represented by a point mass model and not multi-body-system model). In the context, it must be understood that best model is not necessarily the most detailed one, but rather the fastest model that delivers the results in the asked accuracy.
3. **How can I generate trust and acceptance for my simulation result?**
   The biggest question of virtual assessment is always: does the simulation represent the real world? First, it needs to be recognized that a simulation is not the real world. Thus, there will be always a difference. The same would apply for a test on a test track. In this case the environment and surrounding traffic is represented by physical models (e.g., balloon dummy cars such as [21], artificial building such as described in [22]). However, these tests are widely accepted as representative for the real world. It is rather the question how large / how small this difference is and whether the difference in the evaluation use case is

acceptable. The answers to these questions are not straightforward. Therefore, it should be considered from the beginning what can be done to generate trust and acceptance for the simulation results. There are indeed different options. Examples are using transparent open-source approach (see openPASS above), a comprehensive V&V process for the virtual assessment tools, documentation, and publications. Whether these steps or the combination of these steps are sufficient will also depend on the stakeholder of the results.

4. **Which existing standards can be applied?**
   This question addresses again the simulation approach. The use of existing standards whenever applicable is recommended for different reasons. It will help to generate trust for the simulation results. It makes it easier to cooperated with third parties. Furthermore, it allows the exchange and usage of different models. In this context, the ASAM standards OpenSCENARIO [18] and OpenDRIVE [19] already represent a solid start basis. They allow to have a common definition of the executed scenario and the simulated road. Clearly, standards are only useful if they are applied by several different organizations. Thus, not only the organization applying the standards benefits from them, but also the standards themselves.
5. **Which aspects need to be harmonized respectively which not?**
   The last question addresses post assessment phase. It deals with the learnings of the study and how future assessment can benefit from theses learnings. It is quite likely that issues that one person encountered in his/her work might also be relevant for other. And as stated earlier standard help to generate trust for virtual assessment. At this stage more exchange between the different stakeholders is required. The German founded research project "Set Level [23] is here a good example for such activities leading to new standards (see OSI activities in Set Level [24]).

The final simulation result is an interplay between the simulation tool, the applied model – in particular vehicle, sensor and technology model – as well as the parametrization of these models. Different solutions and simulation approaches might lead depending on the simulation scope to sufficient accurate results. From a development perspective of a simulation tool, it is effort- and efficiency-wise reasonable to accept minor deviation in case the result is still accurate enough for the simulation use case. At this point it must be considered that the also real-world tests differ slight in their outcome. Therefore, it would be questionable to require from one tool a 100% precise answer while today test tools can also not provide a 100% precise answer.
Therefore, it is in the authors opinion not reasonable to set requirements for above mention simulation models (vehicle, sensors, and technology model) or tools. In the authors opinion, the definition of requirements should focus instead rather of the following aspects

- **Scenario format:** A clear description of the scenario to be tested is essential if standardized tests should be executed in a simulation. This description shall be delivered in standardized format to guarantee a consistent scenario interpretation as well exchangeability between different tools.
- **Interface of the simulation**: Standardized interface enable the possibility to exchange models between simulation tools. This becomes highly relevant if certain standardized models (e.g., environmental model) should be used during an assessment.
- **Models not related to the technology or vehicle**: This aspect is closely linked to the previous one. Today in test track test standardized objects are used to ensure similar conditions for everyone. The pendant to this in the virtual assessment are standardized models. However, to gain the maximum use out of the virtual environment larger variation can be considered. Thus, it is necessary to not only discuss the models but also the variation of these models.
- **Definition of metrics**: This aspect sounds obvious. However, the work of P.E.A.R.S. has showed that there could be easily different interpretation of one metric [25]. Therefore, a clear description of the evaluation criteria is required to ensure to ensure a consistent and harmonized calculation throughout different evaluations.
- **Required accuracy of simulation**: This is the core aspect of virtual assessment and should be one of the first aspects to be discussed for the virtual assessment, since it implicitly sets the requirements for the technical solution of the virtual assessment. Therefore, the discussion among the stakeholders shall focus on this aspect also to avoid misunderstandings.
- **Documentation and expected validation & verification activities**: Another vital part of the discussion between the different stakeholders is the documentation of the virtual assessment's results and the expected V&V activities to be reported. The documentation has certainly a close link to the assessment metric. A standardization of the documentation format will help in the comparison of different results. The same

applies to the V&V process, which is of importance to demonstrate the correctness of the virtual results and to increase their acceptance.

## CONCLUSIONS

Consumer ratings are an important tool to communicate and promote the value of safety oriented ADAS. They also allow to compare the performance of different safety systems from individual manufacturers. In the past this has been done by means of test track test. However, the increasing number of systems as well as the extension of the test spaces also requires the consideration of other test tools. Thus, virtual assessment approaches will play a major role in this area in the future. This paper will contribute to this topic in different ways. Starting with the simulation tool openPASS, the ENCAP toolchain have been implemented that allows to set up and asses a system in virtual Euro NCAP tests. The toolchain has been used to run a comparison between real-world test on a test track and simulation for one implementation. The assessed exemplary system was an AEB. For some scenarios the results of both environments are in good accordance, while the scenarios with higher dynamics showed some differences. It needs to be noted here that the function model and the vehicle model were not optimized for this assessment. Thus, it can be expected that improves even with the same simulation setup could be achieved.
This exemplary study allowed to investigate the difference between both test environment deeper. This led to the definition of relevant question to be answered in case a virtual assessment should be set up. Furthermore, six important aspects are described which should be focused on in the discussion consumer ratings, namely scenario format, interfaces for the simulation, non-technology models, metric, required accuracy and documentation including validation and verification of the simulation. To find appropriated solution the discussion should involve all relevant stakeholders.

## REFERENCES


[1] Euro NCAP. 2022. “Euro NCAP Vision 2030 - a safer future for mobility.” Euro NCAP road map.
[2] Helmer, T. 2016. Safety Performance Assessment of Assisted and automated driving. Presentation at SAE Government Industry meeting 2016, Washington D.C.
[3] Euro NCAP 2017. “Euro NCAP 2025 Roadmap – in pursuit of vision zero”. Euro NCAP road map.
[4] Vergnaud, J., Piperno, A., Herveleu, F. 2020. „Validation Method: Virtual Testing”, Virtual Testing AEBS, UNECE AEBS Meeting, https://wiki.unece.org/download/attachments/101554586/AEBS-12-07%20%28UTAC%29%20Virtual%20testing%20AEBS.pdf?api=v2
[5] Euro NCAP. 2019. “Test Protocol – AEB Car-to-Car systems”, Test protocol Version 3.0.2.
[6] Euro NCAP. 2017. “Assessment Protocol – Safety assist”, Test protocol Version 8.0.2.
[7] Euro NCAP. 2015. “Assessment Protocol – Safety assist”, Test protocol Version 6.1.
[8] Euro NCAP. 2022. “Vulnerable Road User Testing Protocol”, Test protocol Version 9.0.1.
[9] Euro NCAP. 2020. “Test Protocol – AEB VRU systems”, Test protocol Version 3.0.3.
[10] Euro NCAP. 2019. “Test Protocol – AEB VRU systems”, Test protocol Version 2.0.4.
[11] Euro NCAP. 2017. “Test Protocol – AEB VRU systems”, Test protocol Version 2.0.2.
[12] Euro NCAP. 2015. “Test Protocol – AEB VRU systems”, Test protocol Version 1.0.1.
[13] openPASS. 2022. “openPASS Working Group” website: https://openpass.eclipse.org/, accessed 18th November 2022.
[14] P.E.A.R.S. 2021. “Prospective effectiveness Assessment for road safety”. Presentation at 12th UNECE VMAD Sub Group 2 Virtual Testing meeting, https://wiki.unece.org/display/trans/VMAD-12th+SG2+session
[15] ISO. 2021."Road vehicles — Prospective safety performance assessment of pre-crash technology by virtual simulation — Part 1: State-of-the-art and general method overview", ISO Standard 21934-1, https://www.iso.org/standard/76497.html
[16] ASAM. 2022. “OSI - Open Simulation Interface”, https://www.asam.net/standards/detail/osi/, accessed 4th November 2022
[17] Modelica Association Project. 2014. “Functional Mock-up Interface for Model Exchange and Co-Simulation“, https://fmi-standard.org/assets/releases/FMI_for_ModelExchange_and_CoSimulation_v2.0.pdf , July 25, 2014
[18] ASAM. 2022. “OpenSCENARIO”. V1.2.0. https://www.asam.net/standards/detail/openscenario/, accessed 4th November 2022

[19] ASAM. 2020 "ASAM OpenDRIVE V1.6.0 User Guide". V1.6.0 https://www.asam.net/index.php-?eID=dumpFile&t=f&f=3495&token=56b15ffd9dfe23ad8f759523c806fc1f1a90a0e8, accessed 4th November 2022

[20] Page et al. 2015. "A comprehensive and harmonized method for assessing the effectiveness of advanced driver assistance systems by virtual simulation: the P.E.A.R.S. initiative". 24th ESV Conference. Gothenburg, Sweden

[21] Euro NCAP. 2018. "Global Vehicle Target Specification". Technical Bulletin, Volume 1.0, https://cdn.euroncap.com/media/39159/tb-025-global-vehicle-target-specification-for-euro-ncap-v10.pdf

[22] Sayer, J.R. 2018. "Connected/Automated Vehicle and Infrastructure Research". Final Report- SPR 1695, Research Project No. OR14- 053, University of Michigan Transportation Research Institute, Ann Arbor, https://www.michigan.gov/MDOT/-/media/Project/Websites/MDOT/Programs/Research-Administration/Final-Reports/SPR-1695-Report.pdf

[23] Köster, F. and Rude, S. 2021. "SET Level Mid-term Event Introduction and Challenges". Presentation at Set level mid-term event. https://setlevel.de/assets/mid-term-presentation/Introduction.pdf

[24] Mai, P. R., Aue, R., Friedmann, L., Habedank, C., Rosenberger, P., Sachsenweger H. 2022. "Industrial Standards for Development of Automated Driving" Presentation at Set level final event. https://setlevel.de/assets/s2v2-industrial-standards.pdf

[25] Wimmer, P.; Düring, M.; Chajmowicz, H.; Granum, F.; King, J.; Kolk, H.; Op den Camp, O.; Scognamiglio, P.; Wagner, M. 2019. "Toward harmonizing prospective effectiveness assessment for road safety: Comparing tools in standard test case simulations", Traffic Injury Prevention, Volume 20 p. 139-145, https://doi.org/10.1080-/15389588.2019.1616086

# USER-CENTERED COMMUNICATION OF AUTOMATED DRIVING TO PROMOTE ROAD SAFETY

**Elisabeth Shi**
Federal Highway Research Institute (BASt),
Germany

Paper Number 23-0208

## ABSTRACT

Both research literature and fatal accidents on roads worldwide question whether users and manufacturers of a driver assistance system indeed share the same understanding of the intended system use, and the extent of assistance provided. Traditionally and until today, irrespective of whether assistance systems (SAE Level 1 and 2) are active or not (SAE Level 0), the person on the driver's seat is in charge of the driving task, and any driver assistance systems only support the driver, but do not relieve him or her. In the near future, further driving automation systems of SAE Levels 3 will become available. A first Level 3 function on a series production vehicle has been granted type approval in Germany in December 2021. With increasing driving automation, the driving-related role changes for the person seated on the driver's seat. For instance, when Level 3 driving automation is active, the role changes from the "driver" to the "fallback-ready user" with fundamentally different responsibilities. Considering that misconceptions about the driver role already exist today, it is to be expected that with increasing diversity of the role, misconceptions will likewise grow.

Researchers point out non-expert users' difficulties in understanding the provided extent of assistance or automation, and highlight negative examples of misleading communication. Raising awareness to these problems may constitute a first step towards finding a solution. Social psychological research on social influence, however, shows that social norms strongly influence our behavior. Considering these findings on the influence of social norms, this article reminds how a focus on (a) some drivers' system misuse and (b) negative examples of some automakers' misleading communication may just promote these among the respective target groups ((a)system users, (b) automakers). Instead, this article provides a concept for user-centered communication that focusses on how to use respective systems, rather than on what not to do.

In this context, the user-centered communication concept by the German Federal Highway Research Institute (BASt) is presented. The communication concept provides the central information that users of different driving automation systems need to know. The target group of such communication are non-expert users and the communication's aim is to convey the relevant information about their responsibilities when using different driving automation systems. The communication concept can serve as a basis to develop specific communication campaigns or strategies in different contexts, such as driver education and training, tutoring, or marketing. The concept has been adopted by the Round Table for Automated Driving of the German Federal Ministry for Digital and Transport, and is currently applied in the context of consumer protection by EuroNCAP and other national consumer protection associations.

## INTRODUCTION

Driving automation systems are expected to increase both drivers' comfort and road safety. For their positive effect on road safety to unfold, the respective systems need to be used as originally intended by the manufacturer. While there has been a strong focus on the technical aspects of driving automation, the eventual use of the driving automation system has been neglected in comparison. This relative neglect might also mirror the implicit notion that a well-researched and developed driving automation system can only be used as intended by the manufacturer. However, already today, accidents involving driver assistance systems raise the question if drivers and manufacturers indeed share the same understanding. In addition, research suggests that non-experts' understanding of system capabilities and their own role indeed differs from the actual. In this context, this article focuses on how to communicate the in-vehicle human's responsibilities in the interaction with different systems that provide sustained driving automation.

### Need for clear communication of driving automation

Research and practice highlight the need for clear communication of driving automation:

For example, in 2016, the driver of a Tesla Model S died in a crash with a semitrailer on a US highway [1]. The semitrailer was turning left, when the Tesla struck the right side of the semitrailer, went underneath the semitrailer tearing off the Tesla's roof. The US National Transportation Safety Board (NTSB) initiated an investigation on the use of the Autopilot system in the Tesla. As one of the probable causes for this crash the report states "*the car driver's inattention due to overreliance on vehicle automation, which resulted in the car driver's lack of reaction to the presence of the truck*." [1, p. vi]. In 2020, the same automaker was convicted for unfair business practices related to the advertisement of its Autopilot system in Germany. The choice of words and phrases were judged to convey an image that does not correspond with actual system capabilities [2].

Misunderstandings of the own responsibilities when using a driver assistance system may be one contributing factor to fatal accidents as described above [1]. More so, today the person in the driver's seat always acts as the driver of the vehicle, irrespective of any activated assistance systems (such as Tesla Autopilot). With increasing driving automation new roles for the person in the driver's seat emerge [3]. The new diversity of roles adds a further source for misconceptions (e.g. mode confusion) and raises the importance of clear communication of system users' responsibilities. Considering that first series production vehicles equipped with a SAE Level 3 received type approval in Germany recently [4], such communication gains importance.

Research on the perceived extent of provided driving automation or driver assistance indicates that "the terms used to name and label automated functions in vehicles may invoke misperceptions about the technical capabilities of the vehicles." [5, p. 1897]. Most research focusses on the status quo and highlights the discrepancy between the actually provided assistance or automation and users' perception thereof [5–7]. For instance, staying with the initial example, the term "Autopilot" has been of special interest in research with a "*growing body of evidence (…) [showing] that ''Autopilot" is a misleading name for a Level 2 driving automation system*" [8, p. 150]. The conclusion is drawn based on participants' behaviors reported safe when the system is active [8] and participants' perceived distribution of responsibilities between the active system and the human driver [5, 6]. These findings highlight the difficulties of clearly communicating the actual responsibilities that accompany driver assistance systems or driving automation systems.

The article at hand suggests to move from highlighting the negative status quo towards solutions on how to clearly communicate driving automation to users. In this regard the following sections first address why a focus on misleading communication may counteract the appreciated aim to improve users' understanding. Next, and as a response to this claim to move towards solutions, the user-centered communication concept for driving automation developed by the German Federal Highway Research Institute (BASt) is presented. A final conclusion summarizes the article.

## ENGAGING IN USER-CENTERED COMMUNICATION OF DRIVING AUTOMATION

### Emphasizing "How to" instead of "How not to"

A recently published systematic review indicates that drivers who perceive that mobile phone use (mostly texting) while driving is prevalent or accepted by their peers, are more likely to engage in such behavior themselves [9]. In social psychological terms the perceived prevalence of a behavior (= "what is typically done" [10, p. 597]) constitutes a "descriptive (social) norm", and the perceived acceptance of a behavior by peers ("what is typically approved/disapproved" [10, p. 597]) constitutes an "injunctive (social) norm" [10–12]. Social norms, in general, "are rules and standards that are understood by members of a group, and that guide and/or constrain social behavior without the force of laws." [12, p. 152]. Social norms, both injunctive and descriptive, are shown to be a very powerful means to influence human behavior [10–12]: "*injunctive social norms mobilize people into action via social evaluation, descriptive social norms move them to act via social information—in particular, social information about what is likely to be adaptive and effective conduct in the setting. Descriptive social norms send the message "If a lot of people are doing this, it's probably a wise thing to do," which serves to initiate norm-congruent behavior.*" [11, p. 264].

What consequences result from social norms for communication of driving automation to respective system users? In emphasizing drivers' system misuse or the negative consequences of automakers' misleading communication, researchers (or any party) inadvertently set descriptive social norms:

First, addressing automakers, in highlighting the negative consequences of misleading advertisement and system names, the descriptive norm says "many automakers engage in this form of (misleading) communication". This descriptive norm unlikely motivates automakers to change the criticized form of communication. It may even worsen the status quo since among automakers such advertisement and system naming is reportedly how it "is typically done" [10, p. 597], and therefore, "adaptive and effective conduct in the setting" [11, p. 264]. In this regard, automakers could commit to indicate and promote only the driver assistance or driving automation that is technically provided. This may prevent both conveying a false impression of the advertised system, and unfair business practices, for which Tesla was convicted in Germany in 2020 related to advertisement of the Autopilot system [2].

Second, addressing users' behavior, in highlighting the misuse of systems, the descriptive norm says "many system users engage in such behavior while driving". Again, this descriptive norm unlikely motivates system users to change the criticized system misuse. It may even worsen the status quo since among system users such system (mis-)use is reportedly how it "is typically done" [10, p. 597], and therefore, "adaptive and effective conduct in the setting" [11, p. 264]. This user-related descriptive norm may remind on the initial example of effects of descriptive social norms on mobile phone use while driving [9]. It shall also be illustrated with a recent example: The US American Insurance Institute for Highway Safety (IIHS) describes themselves as "an independent, nonprofit scientific and educational organization dedicated to reducing deaths, injuries and property damage from motor vehicle crashes through research and evaluation and through education of consumers, policymakers and safety professionals." [13]. IIHS's efforts to raise awareness to negative consequences' can be assumed to be well-intentioned. A press release from Oct 11, 2022 shall serve as an example. It is entitled "Despite warnings, many people treat partially automated vehicles as self-driving" [13]. The headline already explicitly states a descriptive norm for users of SAE Level 2 systems with potential effects outlined above. The well-intentioned article includes social norms for both system users and automakers that might counteract the article's original goal.

Using Robert Cialdini's (an influential researcher on persuasion with social norms who was hired for the presidential campaign of Barak Obama in 2012 [14, 15]) words (that originally refer to public information campaigns on pollution, or drug and alcohol use among adolescents) [11]: Within the well-intentioned emphasis of illustrating the negative effects of misleading communication "lurks the powerful and undercutting normative message "Look at all the people who *are* doing it." It is conceivable, then, that in trying to alert the public to the widespread nature of a problem, public service communicators can make it worse." [11, p. 266]. Instead, Cialdini suggests "to avoid sending the message that such noncompliance is rampant." [11, p. 267], and calculate and report the actual rate of the criticized behavior (which is usually less than it appears to be). The actual (low) rate of system misuse should be combined with the injunctive norm that such behavior is disapproved [11].

The article at hand focusses on the first suggestion "to avoid sending the message that such noncompliance is rampant." [11, p. 267] which addresses the phenomenon that in highlighting the negative behavior, a descriptive norm is conveyed that may counteract the message's original aim. Just like successful advertisement habitually does not highlight the products of competitors to win over their customers ("Stop purchasing products of our *competitor XY*"), but rather promotes their own products to a specific target group ("*Our products* is what people buy"), in the same sense, the article at hand recommends to communicate independent information on the proper use of driving automation systems to a defined target group, e.g. of potential system users, the general public, student drivers etc.

**Communicating system users' roles when using different driving automation systems**

Considering the findings on social norms' influence on human behavior, this article recommends highlighting system users' responsibilities ("how to") instead of alerting too strongly about system misuse ("how not to"). The German Federal Highway Research Institute (BASt) developed a user-centered communication approach [16] that accompanies recent national legislation on "automated driving" [17] and "autonomous driving" [18]. It has been adopted by the Round Table for Automated Driving of the German Federal Ministry for Digital and Transport, and is currently applied by EuroNCAP and ADAC (largest consumer protection association in Germany for individual mobility). This user-centered communication concept provides the minimum information on system users' roles during specific driving modes, and by its focus, may prevent the inadvertent user-related descriptive norm outlined above. The information provided in the concept can be processed into diverse formats for communication depending on the target group, and can thus serve different parties e.g. as a starting point for developing and designing own user/ customer information.

The core principle of the communication concept is its focus on the system user (who is the target group of this communication) instead of the driving automation system. Since only the perspective changes from a technical to a user-centered one, the communication concept remains fully compatible with both internationally established classification (SAE J3016) and type approval regulations (UN R157) [3, 19]. In the following, the system user-centered communication concept is presented in detail. Table 1 summarizes the communication concept.

**Scope of BASt's user-centered communication concept for driving automation**

The presented communication concept aims at conveying information on sustained driving automation independent from specific automakers' systems. The focus is on *general responsibilities* for the in-vehicle human seated in the driver's seat based on different driving modes. The focus is not on how to use specific driving automation systems. The communication concept takes the *perspective of the in-vehicle human* seated in the driver's seat and focusses on his or her *role during specific driving modes*. Any role encompasses a set of responsibilities, and occurs in the context of a specific driving mode. The roles are described in detail in the following sections. The driving mode is provided by the sustained driving automation system that is currently active. The focus on specific driving modes implicates that one role does not apply to the entire trip. Rather the person seated in the driver's seat may change his or her role in the course of the trip.

These specifications are explained to the reader of this article and are not part of what is suggested to be conveyed to system users (= following communication concept). The following communication concept is intended to be used for communication with non-experts, such as customers, student drivers, or the general public. It provides the basic information relevant for each role, as well as information on what aspects of a role require specific emphasis. As it is a *concept*, the format in which it is presented in this article, is not the format that is suggested to be used for eventual communication with the target audience of non-expert users. Communication formats (such as video, games, interactive tutoring, etc.) should be chosen depending on the target audience. The communication concept is not intended to be used for detailed discussion among experts. For this purpose, it is referred to the respective standards or regulations [3, 19].

***Table 1.***

***Human roles in the context of increasing sustained driving automation [16]***

| **Role of human** | **Driving mode** | **Visualization of driving task execution [20]** | **Corresponding SAE Level** |
|---|---|---|---|
| driver role | assisted |  redundant-parallel execution of driving task | Level 1 & Level 2 |
| (fallback-ready) user role | automated |  alternating execution of driving task | Level 3 |
| passenger role | autonomous |  system only execution of driving task | Level 4 & Level 5 |

**Driver role during assisted driving**

Until today, the person seated in the driver's seat has always been the driver, i.e. the person in charge for driving. The driver decides how to perform vehicle motion control. Traditionally, when driving manually, the driver directly performs the driving task on his or her own, i.e. he or she steers, accelerates, decelerates him- or herself. Today, the driver may receive support from driver assistance systems of SAE Level 1 and Level 2. These systems continuously support the driver in performing longitudinal and/or lateral vehicle motion control, i.e. the system steers, accelerates and decelerates. The system is not able to reliably detect the driving environment and react to it. Therefore, in assisted driving, the driver needs to supervise the system and correct the system when needed. Irrespective of technical support, the driver remains responsible for the driving task, and at any moment, decides how vehicle motion control is to be performed.

Compared to the technical description of SAE Level 1 and 2 systems, for a human-centered communication, it is relevant to emphasize the driver's responsibility to monitor the driving environment, to supervise and to immediately correct the respective systems. These two tasks (monitoring the environment, and supervising incl. correcting the system) are different from the responsibilities of the traditional driver role, and come in addition to it. Since they are characteristic for the driver role during assisted driving, they require specific emphasis in communication with the general public or customers.

**User role during automated driving**
The next level of driving automation, SAE Level 3, is accompanied by the (fallback-ready) user role which is fundamentally different from the driver role. Upon activation of the SAE Level 3 driving automation system, the person in the driver's seat changes his or her role from the driver to the fallback-ready user. As a (fallback-ready) user, the person in the driver's seat is relieved from driving and can engage in other non-driving related activities. However, he or she needs to remain receptive to requests by the system and evident vehicle failures. System requests are by definition (SAE J3016) and regulation (UN R157) issued with lead time [3, 19]. Based on UN R157 [19], the fallback-ready user is provided with at least 10 seconds time for reorienting in traffic and eventually deactivating the system. After deactivating the system, the person in the driver's seat continues the journey as the driver again.

Compared to the technical description of SAE Level 3, for a human-centered communication, it is relevant to emphasize that during automated driving, the former driver takes on a new role of the user. The user is relieved from the driving task and needs to remain receptive to requests by the system or evident failures. The system request is issued with lead time, and the user is expected to respond to it by first reorienting in the current traffic situation and then deactivating the system without undue and error-prone haste. Upon deactivation of the system, the former user changes back to the driver role again. These characteristics of being relieved from the driving task, remaining receptive to system requests and evident vehicle failures, and the procedure of taking over the driving task (reorient first, then deactivate) require specific emphasis in communication with the general public or customers.

**Passenger role during autonomous driving**
During autonomous driving, all occupants are passengers. In this driving mode, passengers are not required to contribute to driving at any time. In contrast to the previous two roles, for the general public, the passenger role is known from other means of transportation, e.g. public transportation, planes, ships.

## CONCLUSION

This article focuses on communicating the in-vehicle human's responsibilities in the interaction with different modes of sustained driving automation. The need to clearly communicate the increasing diversity of roles for the in-vehicle human system user is emphasized. First, the practical need arises from misconceptions that might contribute to fatal accidents that counteract the original aim of driving automation systems to increase road safety [1]. Second, considering social psychological research findings on the influence of social norms on human behavior [10], this paper advocates to highlight system users' respective responsibilities rather than to solely raise awareness for the negative outcomes of system misuse and misleading communication. In this context, the user-centered communication concept for driving automation by BASt is presented. It differentiates between the *driver* role in assisted driving, the *user* role in automated driving and the *passenger* role in autonomous driving. The specific characteristics that require further attention in communication with non-expert users are specifically highlighted. For the driver role during assisted driving, the tasks of monitoring the driving environment and supervising the system including correcting it when necessary are especially relevant. For the user role during automated driving, the process of switching roles requires attention. Being relieved from driving although seated in the driver's seat is an entirely new role for the system user. Furthermore, the process of takeover requires special emphasis. First, the system request will be issued timely [3, 19] and the user is expected to respond by first reorienting in traffic and then deactivating the system without undue and error-prone haste. It should also be noted that upon deactivation, the user switches back to the role of the driver again (with the respective responsibilities). The passenger role during autonomous driving is the only role that is already known from other means of transportation and may therefore be more intuitive. The concept is developed for communication with non-expert users. For discussions among experts, it is referred to the respective standards and regulations [3, 19]. The concept can be used by different parties who intend to communicate driving automation to non-experts. When using the concept, it is recommended to process the concept depending on the target group that the party intends to address.

## REFERENCES


[1] NTSB, "Collision Between a Car Operating With Automated Vehicle Control Systems and a Tractor-Semitrailer Truck Near Williston, Florida, May 7, 2016.," 2017. [Online]. Available: https://www.ntsb.gov/investigations/accidentreports/reports/har1702.pdf

[2] Landgericht München I, *Werbung mit Autopilot irreführend für Verbraucher*. Pressemitteilung 07/2020, 2020. Accessed: Dec. 14 2022. [Online]. Available: https://www.justiz.bayern.de/gerichte-und-behoerden/landgericht/muenchen-1/presse/2020/7.php

[3] *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, SAE J3016, SAE International/ISO, 400 Commonwealth Drive, Warrendale, PA, United States, 2021. [Online]. Available: https://www.sae.org/standards/content/j3016_201806/

[4] Kraftfahrt-Bundesamt, *KBA erteilt erste Genehmigung zum automatisierten Fahren*. Pressemitteilung Nr. 49/2021. Flensburg, 2021. Accessed: Dec. 19 2021. [Online]. Available: https://www.kba.de/SharedDocs/Downloads/DE/Pressemitteilungen/DE/2021/pm_49_2021_erste_Genehmigung_automatisiertes_Fahren.pdf?__blob=publicationFile&v=8

[5] M. A. Nees, "Drivers' Perceptions of Functionality Implied by Terms Used to Describe Automation in Vehicles," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 62, no. 1, pp. 1893–1897, 2018, doi: 10.1177/1541931218621430.

[6] H. Abraham, B. Seppelt, B. Mehler, and B. Reimer, "What's in a Name," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Oldenburg Germany, 2017, pp. 226–234.

[7] P. Liu, Q. Fei, J. Liu, and J. Wang, "Naming is framing: The framing effect of technology name on public attitude toward automated vehicles," *Public understanding of science (Bristol, England)*, vol. 30, no. 6, pp. 691–707, 2021, doi: 10.1177/0963662520987806.

[8] E. R. Teoh, "What's in a name? Drivers' perceptions of the use of five SAE Level 2 driving automation systems," *Journal of safety research*, vol. 72, pp. 145–151, 2020, doi: 10.1016/j.jsr.2019.11.005.

[9] M. Nicolls, V. Truelove, and K. B. Stefanidis, "The impact of descriptive and injunctive norms on engagement in mobile phone use while driving in young drivers: A systematic review," *Accident; analysis and prevention*, vol. 175, p. 106774, 2022, doi: 10.1016/j.aap.2022.106774.

[10] R. B. Cialdini and N. J. Goldstein, "Social influence: compliance and conformity," *Annual review of psychology*, vol. 55, pp. 591–621, 2004, doi: 10.1146/annurev.psych.55.090902.142015.

[11] R. B. Cialdini, "Descriptive Social Norms as Underappreciated Sources of Social Control," *Psychometrika*, vol. 72, no. 2, pp. 263–268, 2007, doi: 10.1007/s11336-006-1560-6.

[12] R. B. Cialdini and M. R. Trost, "Social influence: Social norms, conformity and compliance," in *The handbook of social psychology*, D. T. Gilbert, S. T. Fiske, and G. Lindzey, Eds.: McGraw-Hill., 1998, pp. 151–192.

[13] Insurance Institute for Highway Safety (IIHS), *Despite warnings, many people treat partially automated vehicles as self-driving*, 2022. [Online]. Available: https://www.iihs.org/news/detail/despite-warnings-many-people-treat-partially-automated-vehicles-as-self-driving?mc_cid=5c47b2e6fb&mc_eid=80c3090dc7

[14] B. Carey, "Academic 'Dream Team' Helped Obama's Effort," *The New York TImes*, 12 Nov., 2012. https://www.nytimes.com/2012/11/13/health/dream-team-of-behavioral-scientists-advised-obama-campaign.html?smid=url-share

[15] R. Dooley, "How Behavioral Science Propelled Obama's Win," *Forbes*, 19 Nov., 2012. https://www.forbes.com/sites/rogerdooley/2012/11/19/obama-behavioral/?sh=83a093074965

[16] German Federal Highway Research Institute (BASt), *User communication: What does autonomous driving actually mean?* [Online]. Available: https://www.bast.de/BASt_2017/EN/Automotive_Engineering/Subjects/f4-user-communication.html?nn=1844934 (accessed: Aug. 31 2020).

[17] *Achtes Gesetz zur Änderung des Straßenverkehrsgesetzes*, 2017. Accessed: Dec. 14 2022. [Online]. Available: http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl117s1648.pdf

[18] German Federal Ministry for Digital and Transport (BMDV), 2021. Accessed: Dec. 8 2022. [Online]. Available: https://bmdv.bund.de/SharedDocs/EN/Articles/DG/act-on-autonomous-driving.html

[19] *UN Regulation No. 157: UN Regulation No. 157*. Geneva, 2022. Accessed: Dec. 8 2022. [Online]. Available: https://unece.org/sites/default/files/2022-05/ECE-TRANS-WP.29-2022-59r1e.pdf

[20] German Federal Highway Research Institute (BASt), *Selbstfahrende Autos – assistiert, automatisiert oder autonom?*, 2021. Accessed: 03.03.22. [Online]. Available: https://www.bast.de/DE/Presse/Mitteilungen/2021/06-2021.html

## EURO NCAP'S FIRST STEP TOWARD RIDER SAFETY WITH NEW CAR-TO-MOTORCYCLIST SCENARIOS

**Pierre-Marie Damon, Aurélien Garcia**
UTAC
France

**Adriano Palao**
Euro NCAP
Belgium

Paper Number 23-0209

### ABSTRACT

Embedded collision avoidance systems such as Autonomous Emergency Braking Systems, Forward Collision Warnings or Emergency Lane Keeping Systems have largely contributed to reducing the number of car collisions over the past decade. Although those systems have demonstrated ever-increasing performance in case of imminent risk of collision against pedestrian, bicyclist, or car in recent years, most of them were not capable of intervening in the case of a motorcyclist. Since motorcycle crashes remain a major concern across Europe and for most of them are the result of collisions between cars and motorcycles, those systems were identified as relevant technologies to address this issue. In that context, UTAC led the MUSE European project between 2017 and 2019 with the ambition to promote motorcyclist safety through car consumer information programs such as Euro NCAP. As this topic was well identified in the Euro NCAP 2020-2025 roadmap, the organization showed interest in the outcomes of the project and their integration into the new generation of car active safety testing protocols. This paper presents the background established during the MUSE project, its outcomes, and their integration into the so-called Euro NCAP safety rating, as well as the outlook for motorcyclist safety as part of Euro NCAP Vision 2030.

### INTRODUCTION

For several years now, more and more Advanced Driver Assistance Systems (ADAS) have been fitted into modern cars improving comfort and providing assistance to the driver into the driving task. Thanks to some exteroceptive sensors like cameras, radars, lidars, etc., ADAS helps the driver to perceive the surrounding environment and, for some of them, they may even intervene when safety is at stake. Whereas the regulations define the minimal set of performance that these systems shall fulfill, other consumer organizations, such as Euro New Car Assessment Program (NCAP), rate the level of safety of the car regarding well established testing protocols. These NCAP programmes are constantly pushing to improve system performance before and beyond regulation requirements. Until 2023, neither the ADAS regulations nor the Euro NCAP requirements for Powered-Two Wheelers (PTW) in emergency situations have been adopted, whilst pedestrians and bicyclists' safety have been widely addressed in Euro NCAP ratings for years.

Several studies of PTW accidentology highlighted that collisions with passenger cars occurred in a large proportion of crashes and often resulted in severe consequences (road deaths and/or serious injuries) for the motorcyclist. In most cases, the visibility of the PTW by the driver of the opponent vehicle was identified as the crash causation [1]. Moreover, PTW riders are very endangered in case of collision with other vehicles because they lack protective equipment and the risk of exposure. For that reason, PTW riders have been classified as Vulnerable Road Users (VRU) in addition to pedestrians and bicyclists.

In that context, UTAC led the Motorbike Users Safety Enhancement (MUSE) project, which started in 2017 and lasted 2 years. All major European vehicle manufacturers and system suppliers were involved in the project with the ambition to improve car collision avoidance systems regarding their capabilities of perceiving PTW and then to intervene accordingly. The project was divided into 5 work packages. In the first one, crash analysis was performed across European databases. The objective was to identify the most frequent conflict situation resulting in a collision between passenger cars and PTW and their parameters. In the second and third work packages, the members developed relevant testing equipment. First, a soft target representing an average adult motorcyclist on a motorbike. Secondly, a propulsion system was designed to move the target according to the dynamic parameters which were identified during the crash analysis. A fourth work package was dedicated to the selection of the test scenario to be performed on the test track. During the fifth and last work package, a state-of-play has been conducted to highlight existing technologies which may have a safety benefit in these crash scenarios. MUSE was one of the first European common initiatives, involving industry, with the ambition to improve ADAS for the detection of PTW. It rapidly raised interest for Euro NCAP since motorcyclist protection was clearly identified in the car active safety roadmap [2].

This paper is structured around the main work packages of MUSE project such as the accidentology review, the development of the testing equipment and the definition of the test cases. Those 3 sections explain the background behind the inclusion of the new Car-to-Motorcyclist scenarios into the next Euro NCAP active safety testing protocols which is detailed in section 4. It is then completed with a section dedicated to general discussions, limitations and future works preceding a conclusion.

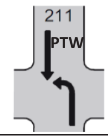
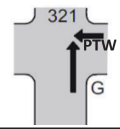
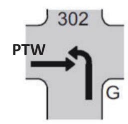
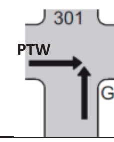
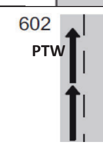
**ACCIDENTOLOGY**

In a world where the decarbonization of mobility is one of the main challenges of the century, the PTW has an important role to play. Although the total number of road deaths significantly decreased over the past decades, the number of motorcyclists who died or were severely injured in road crashes are still overrepresented. In 2018, according to the World Health Organization (WHO), around 28% of all road deaths all over the world were PTW riders [3]. In South-East Asia, where PTW is well democratized, they counted for almost half of the deaths, whereas in Europe, they represented 11% of the road deaths. Even across Europe, there are notable differences. In France, for several years now, motorcyclists represent around 25% of global traffic fatalities and more than 30% of global severe injuries while the proportion of motorcycles in the vehicle population does not exceed 2% [4]. Moreover, several crash databases have shown that most of the crashes involving PTW also involved another vehicle and mainly a car. In the UK during 2019, for more than 60% of all the crashes involving PTW, there were collisions with cars according to STATS19. Whereas single PTW crashes counted only for 25% of the total.

In that context, the first work package of MUSE was dedicated to a European accidentology analysis in a three step approach [5]. First, a review of the existing literature was conducted. Indeed, crashes involving PTW have been a major concern for decades and addressed by various European initiatives and projects such as SAFERIDER or MAIDS where some crash data were already collected. To complement these first figures, the next step consisted in gathering the most up-to-date Car-to-Motorcyclist crash data in Europe. In 2016, CARE, which is a European community database on road crashes resulting in death or injury, highlighted that Italy, France, Germany, Spain, United Kingdom, Poland and Greece concentrated 80.5% of motorcyclist fatalities at 30 days in Europe. Nevertheless, because of accessibility, only Italian ACI-STATS, French BAAC ONSIR, German Destatis (represented within the GIDAS weighted analysis), Spanish DGT, UK STATS19, Greek ELSTAT and The Netherlands SWOV/BRON national datasets were considered in this second step decreasing the coverage to 75% of fatal crashes involving motorcyclists in Europe. The analysis included data from the last 3 years preceding the project (2014-2016) in order to capture only the most-up-to data crash data. Finally, thorough investigations in the 7 national crash datasets allowed us to derive a group of distinct scenarios incorporating key information, where available, such as vehicle maneuvers, impact locations, road type and speed limits. These scenarios were assigned a GDV (German Insurance Association) code, a pictogram-based illustration of the conflict scenario, and then grouped in crash clusters based on common vehicle maneuvers and conflict situations. Furthermore, analysis of weather and lighting conditions at the time of the crash have shown that there is no significant effect on crash propensity, the main influence being the road infrastructure (e.g., junctions) and injudicious actions from the car driver.

Once crash scenario clusters were identified and quantified for each country of the study, they were weighted according to CARE to be as representative as possible from the overall European accidentology. Regarding the 62% of identified car to motorcycle crash scenarios, half of them occurred at junctions while rear-end collisions represented only 5.77% of them (Table 1). Remaining crash scenarios were mainly head-on conflicts either while both vehicles were traveling straight or cornering, lane change conflicts in the same or opposite directions of travel. A notable crash group, that although not as frequent as others but worthy of consideration as it potentially has similar sensing requirements as lane change maneuvers, was left turn across path in same direction.

***Table 1.***
***Overview of Car-to-Motorcyclist crash scenario clusters in Italy, France, Germany, Spain, Greece, and the Netherlands***

| Road infrastructure | Conflict situation | Coverage | Main pictogram |
|---|---|---|---|
| Junctions | Left Turn Across Path – Opposite Direction | 16.03% |  |
| | Straight Crossing Path – Right Direction | 12.84% |  |
| | Left Turn Across Path – Left Direction | 11.29% |  |
| | Straight Crossing Path – Left Direction | 5.83% |  |
| Others | Rear-end – Parallel driving | 5.77% |  |

Usually, national datasets are based on police recordings of road crashes. Although they are very useful for macro-analysis, they are lacking information when it comes to in-depth characterization of crashes (impact speed, impact location, etc.). This characterization is essential to understand the scene and to guarantee that the parameters used on the test track are representative of the reality. For that reason, in-depth crash datasets from the UK, Italy, Spain, France and Germany were analyzed to return the initial travel and impact speeds for both vehicles and by crash scenario.

## TESTING EQUIPMENT DEVELOPMENT

This section summarizes the second [6] and third [7] work packages of MUSE which were dedicated to the development of appropriate testing equipment. The aim was to develop a 3D-dimensional target made of soft crash-resistant material representing an average European rider on his PTW with its self-propelling system. The whole target has been designed to work with all kinds of sensors used in ADAS perception such as radar (24 and 76-81 GHz), lidar, camera or ultrasonic sensor. In order to allow interoperability between target and self-propelling systems, their characterizations have been addressed independently.

### Motorcyclist target specification

In 2014, the European Association of Motorcycle Manufacturers (ACEM) published a report on the PTW market in Europe. During this year, there were 1 099 000 two-wheeled vehicles sold in Europe including 30% of light PTW's also called mopeds. Amongst the motorcycles, the BMW R1200GS occupied the first place in Europe in terms of sales volume followed by the Yamaha MT-07 sold at 18013 and 13125 units respectively. As the European best seller with about 2% of the overall PTW vehicle registration in 2014, the BMW R1200GS was unanimously selected as the reference vehicle to design the PTW target.

Whereas the characterization of the average PTW was new, the definition of human being dimensions has largely been addressed in various studies and activities (anthropology studies, ISO activities, etc.). Since male riders are largely overrepresented into the PTW accidents, the definition of the motorcyclist was based on the description of the adult male pedestrian target in [8]. It represents an average (50th %-ile) male with a body height of 180 cm according to EN ISO 7250-1: 2016-05. For the definition of the pedestrian dummy, a similar dress code with a black long-sleeved t-shirt, blue trousers and black shoes was defined. Obviously, a soft helmet was designed for better representativity of the dummy. Then, all its body parts were positioned in a way to be close to a naturalistic PTW riding posture.

***Figure 1. 4activeMC motorcycle target with the 4activeFB-small platform***

After establishing the visual attributes of the overall dummy including the PTW and the rider, the next step consisted of making sure the non-visible properties, such that infrared and radar properties, were realistic. Infrared reflectivity ranges of the dummy clothes and the motorcycle parts were characterized from 850 to 950 nm wavelength according to the methodology presented in appendix 1 in [6]. Since radars were becoming more and more common in the ADAS perception systems, it was essential to define the radar reflectivity characteristics of the target and especially its Radar Cross Section (RCS). To do so, RCS measurements were performed on 8 static motorcycles (including the BMW R1200GS) from different angles of approach and from different distances. Two 77 GHz radars from Bosch and Continental, the MRR-SGU and the ARS 400 Series respectively, were placed in car to do the characterization. Assuming symmetrical properties of the target, the approach angles were incremented by 30 degrees starting from approaching the PTW from the front up to an approach of the PTW from the rear. For each angle, the RCS was measured from 100 to 4 m between the target and the radar positions. A second method consisted in measuring the RCS while the car was at a standstill whereas the target was on a turntable in order to capture the overall angles for a given distance which was 30 m. These measurements were finally used to define the upper and lower RCS boundaries in which the target should be to be considered, from the radar point of view, close to a real vehicle.

For design reasons, target suppliers decided to have non-rotating wheels on the target which may significantly affect the RCS when the PTW is moving. Indeed, rotating wheels generate a micro-doppler effect which can be an important identification characteristic for the radar. Nevertheless, it remained a proposal of improvement during MUSE until 2022 when target suppliers finally developed an additional device imitating the micro-doppler effect of the non-rotating wheels of the target. It considers the speed of the target to adapt the signal. Indeed, when the PTW target is at a standstill, the device does not emit any signal.

**Propulsion system specification**

Whereas self-propelling platforms were already available for car, pedestrian, and bicyclist targets, such a solution did not exist for a PTW target. These platforms allow accurate control of the target dynamic in order to ensure testing repeatability. They should reflect the real vehicle dynamic behavior in addition to not affecting the detection characteristics of the target itself. Because of the limited dynamic of the existing self-propelling systems for pedestrian or bicyclist and the large dimensions of the platform for the car target leading to a “flying carpet” effect, the development of a dedicated solution was needed for the PTW.

In addition to a robust design allowing car to driver over, the vertical position of target, the color and the RCS of the platform were identified as the most important static properties. In other words, the target carrier shall be colored grey to reduce as maximum their optical impact on asphalt and allow a positioning of the target such that the gap between the ground and the lowest point of the target wheels is not more than 1 cm. Although, maximum RCS of the car target platform was already defined according to ISO 19206-3, during MUSE, it was decided to not define specific values. Instead, it shall be ensured that the combination of target plus propulsion system is inside the boundaries defined for the target itself. As the carrier was supposed to move the target like a real motorcycle, definitions of the dynamic properties were needed. Four variables were considered as relevant in that context and a maximum deviation was associated to each of them based on real-world data recordings. These four variables were the speed, the lateral deviation from the theoretical path and the yaw rate. This last becomes even more important for PTW since the platforms are compact and more prone to yaw instability while the test speed increases. Acceleration capability was also discussed to make sure the carrier can reach the desired speed in a reasonable time on the test track.

Over the course of 2022, several combinations of motorcycle target and propulsion systems (EMT – Euro NCAP Motorcycle Target) were approved to be used from 2023 in the Euro NCAP Car-to-Motorcyclist tests. These combinations are available for reference in the Euro NCAP Technical Bulletin 029 [9]. Normally, the accreditation process of a new target and propulsion system includes compliance with the ISO 19206-X standards, plus a back-to-back verification where the performance of a given vehicle with a previously accredited target is similar to the new target. Since motorcycle targets are introduced for the first time (i.e., no prior experience on track), back-to-back tests could not be conducted. To provide industry and test laboratories with the necessary confidence of the intended target functionality, a workshop was held in ADAC Test Centrum (Penzig, Germany) in July 2022, where equipment manufacturers applying for accreditation displayed their combinations through a set of 2023 Car-to-Motorcyclist scenarios.

## DEFINITION OF TEST CASES

This section describes the background behind the selection of the test cases and their integration into the Euro NCAP active safety test protocols. The selection was a compromise between accidentology coverage, addressability, technology maturity and testing limitations.

### Selection of the testing scenarios

For a consumer information programme, such as Euro NCAP, introductions of new ADAS requirements into the protocols are almost always the result of a data-driven approach. In other words, the estimated safety benefit regarding the accidentology data is guiding the priorities and the selection of the test cases. This approach was naturally used in MUSE to identify areas of interest. In order to have the best accidentology coverage with a limited number of test scenarios, the most frequent Car-to-Motorcyclist conflict situations were grouped considering ADAS technologies and sensing requirements. 6 scenarios of collision between car and PTW were then identified as the most frequent conflict situations and addressable with existing ADAS ( [10] and [11]) such as the well-known Autonomous Emergency Braking (AEB) system, the Forward Collision Warning (FCW) or the Lane Support System (LSS) which have existed for several years now.

The Car-to-Motorcyclist Crossing straight crossing path (CMCscp) was identified as the most relevant scenario to address Straight Crossing Path – Left and Right Direction and Left Turn Across Path – Left Direction conflicts at the same time with the AEB system. In CMCscp, both vehicles travel towards an intersection with the PTW coming perpendicularly either from the right or the left side of the car. Among the 62% of identified Car-to-Motorcyclist crash scenarios in the accidentology study, CMCscp scenarios should cover about 30% of them. The second scenario which was directly derived from the crash study is the Car-to-Motorcyclist Front turn across path (CMFtap) where the car is turning and crossing the PTW trajectory while both vehicles are travelling in opposite directions. A similar crash scenario is already part of the AEB Car-to-Car test protocol. CMFtap is supposed to increase the crash coverage from 16%. The third, and last AEB relevant identified scenario, is Car-to-Motorcyclist Rear-end (CMR). Two sub-scenarios were then identified as the most recurrent conflicts in CMR cluster which are Car-to-Motorcyclist Rear stationary (CMRs) and Car-to-Motorcyclist Rear braking (CMRb) where the car is approaching the PTW from the rear whereas it is at a standstill or braking respectively. CMRb and CMRs cover a maximum of 6% of the overall accidentology. With very optimistic assumptions, about half of all the Car-to-Motorcyclist crashes identified in the European countries in the scope of the study could have been avoided with appropriate AEB systems.

While AEB was identified as one the most promising technology to prevent the recurrent Car-to-Motorcyclist crashes, the LSS was also a good candidate to address the remaining conflict situations which were mainly head-on and lane change conflicts in the same or opposite directions of travel. Car-to-Motorcyclist oncoming (CMoncoming) or Car-to-Motorcyclist overtaking (CMovertaking) scenarios were then defined. In both cases, the car is drifting toward the PTW's path while both vehicles are travelling in the same or opposite direction. With very optimistic assumptions, LSS could have avoided about 10% of all the Car-to-Motorcyclist crashes previously identified.

After the selection of the test cases, the next step consisted of defining the necessary parameters to reproduce those scenarios on test tracks, to maximize the accident coverage and to ensure they are as close as possible to real crash conflict situations. The most important parameters being the impact location, the initial speed and relative position for both vehicles. Those parameters were characterized due to statistical analysis of the in-depth crash databases. They were then refined according to the state-of-art testing equipment and test tracks. At the time of MUSE project, the self-propelling platforms could travel at a maximum of 50 km/h which was the main testing limitation. However, in 2022, a new generation of platforms came to life, and they are now capable of travelling at 80 km/h. Hence, some outcomes from MUSE were recently reconsidered regarding new testing capabilities. All the testing parameters are described in Table 2.

***Table 2.***
***Selected PTW test scenarios with the testing parameters***

| Scenarios | CMRs | | CMRb | CMFtap | CMoncoming | CMovertaking | BSM |
|---|---|---|---|---|---|---|---|
| Type of test | AEB | FCW | AEB/FCW | AEB | LSS | LSS | LSS |
| VUT speed [km/h] | 10-60 | 30-60 | 50 | 10, 15, 20 | 72 | 50, 72 | 72 |
| Target speed [km/h] | 0 | | 50* | 30, 45, 60 | 72 | 60, 80 | 80 |
| VUT direction | Forward | | Forward | Farside turn | Forward | Forward | Forward |
| Impact location [%] | 50 | | 25 | 50 | 10** | Rear Axle*** | No contact |

* *Target deceleration: 4 m/s2 at 12 and 40 m headway*

** *Impact point assuming no system reaction: outermost front left impact point of the EMT's virtual box vs. 10% of the VUT front bumper width*

*** *Impact point assuming no system reaction: outermost front right impact point of the EMT's virtual box vs. rear axle of the VUT*

**Integration into the Euro NCAP test protocols**

The MUSE project was rapidly identified as a major contribution to the Euro NCAP 2020-2025 roadmap [2] which was one of the first consumer information programmes showing interest in considering PTW protection into its passenger car safety rating. Considering the outcomes from MUSE, Euro NCAP decided on a two-step approach for the 6 scenarios previously cited completed by one additional scenario.

In 2023, the Euro NCAP AEB/LSS VRU test protocol [12] will introduce 5 new dedicated scenarios promoting PTW safety: CMRs, CMRb, CMFtap, CMoncoming and CMovertaking (Figure 2). The 3 first ones are AEB/FCW relevant testing scenarios and will be eligible to attract 6 points into the VRU box, whereas the LSS, and especially the Emergency Lane Keeping (ELK) system, is a more appropriate solution to address CMoncoming and CMovertaking and can attract 3 additional points. Finally, these 5 new scenarios combined will count for almost 15% of all the points attributed to the VRU box (Table 3) and about 1.5% in the overall safety rating after the final weighting.

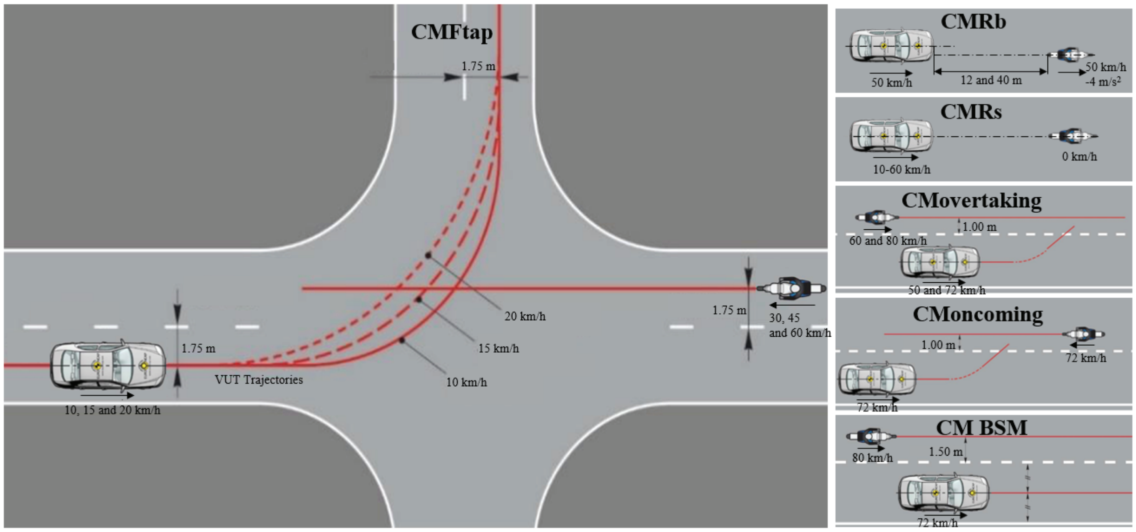



***Figure 2. Car-to-Motorcyclist scenarios part of the 2023 Euro NCAP safety rating***

Furthermore, the 2023 Car-to-Car LSS test protocol will also integrate new requirements for the Blind Spot Monitoring (BSM) system regarding the detection of PTW [13]. The intention is to promote systems capable of alerting the driver when a PTW is in his blind spot.

For the second step, the Car-to-Motorcyclist Crossing straight crossing path (CMCscp) will be integrated into the protocol in 2026. Indeed, this scenario has been delayed as it requires specific sensing technologies which are not widely available yet.

***Table 3.***
***Point distribution across the boxes for the 2023 Euro NCAP safety rating***

| 2023 | AOP (total 40 pts) | COP (total 49 pts) | VRU (total 63 pts) | SA (total 18 pts) |
|---|---|---|---|---|
| | Front MPDB (8) | Dynamic front (16) | Adult head form (6) | Occupant State (3) |
| | Front FW (8) | Dynamic side (8) | Child head form (6) | SAS (3) |
| | Side AMDB (6) | CRS installation (12) | Cyclist head form (6) | AEB/AES C2C Head-on (1) |
| | Side pole (6) | Vehicle based (13) | Leg form(s) (18) | LSS C2C (3) |
| | Far side (4) | | *LSS PTW (3) | AEB/AES C2C Crossing (4) |
| | Whiplash F/R (4) | | *AEB PTW (6) | AEB/AES C2C Rear (4) |
| | Rescue (4) | | *AEB/AES Pe (7) | |
| | | | *AEB Reverse Pe (2) | |
| | | | *AEB/AES Cy (9) | |
| ★★★★★ | ≥32 pts (80%) | ≥39.2 pts (80%) | ≥44.1 (70%) | ≥12.6 pts (70%) |
| ★★★☆☆ | ≥24 pts (60%) | ≥23.4 pts (60%) | ≥31.5 (50%) | ≥9 pts (50%) |

** Minimum 18 pts required in subsystem tests for scoring active safety (VRU box)*

## DISCUSSIONS, LIMITATIONS AND FUTURE WORKS

### Additional Car-to-Motorcyclist scenarios in the passenger car safety rating

The test campaign ranging from 2023 to 2026 includes the aforementioned Car-to-Motorcyclist test scenarios. The missing CMCscp scenario is set to be added in 2026, which together with the 2023 scenarios, is expected to cover the broad majority of Car-to-Motorcyclist conflict situations. Other scenarios listed in the MUSE accidentology deliverable but not included or foreseen to be included in the Euro NCAP Car-to-Motorcyclist scheme (e.g., Left turn across path – same direction, Left turn across path – left direction) might be considered for future incorporation. To that end, a sensible approach to be taken on short term would be to assess whether well performing vehicles in the existing scenarios can as well perform in the missing ones.

Although MUSE highlighted typical Car-to-Motorcyclist conflict situations in Europe, there are specific local traffic rules or tolerated riding practices which may need to be further investigated. For instance, several European countries such as France, allow motorcyclists to filter between lanes of slow moving or stopped traffic. These crashes were of course considered in the process of test cases selection but in the way they were declined in testable scenario on the proving ground, they partially reflect these specific accident scenes. In the next generation of protocols, Euro NCAP may continue to close the gap between test scenarios and real crash scenes. For example, obstructive vehicles, reflecting dense traffic conditions, may be integrated into CMovertaking or other scenarios. Furthermore, the recent inclusion of Car-to-Bicyclist Dooring scenario into the 2023 Euro NCAP AEB/LSS VRU test protocol [12] rewards alert and/or door retention systems capable of preventing a crash when a car occupant is about to open a door into the trajectory of an approaching bicyclist. Euro NCAP may extend this scenario to PTW after a careful review of the crash data.

Recent connectivity technologies, also called Vehicle-to-X (V2X), may take vehicle safety to the next step in the coming years. These are identified as relevant technologies either for increasing robustness of the embedded sensing system into the vehicle or for addressing new conflict situations where conventional sensors are blind (e.g., junction with obstruction, etc.). UTAC is currently leading a consortium, called SECUR, which is expected to support Euro NCAP in the introduction of connectivity into its passenger car safety rating. First new scenarios assessing PTW protection using V2X technologies are expected to be introduced in 2026 before being largely extended in 2029.

**Robustness**

Evidence suggests that current ADAS can help reducing in crashes [14], although it is acknowledged that its coverage in corner cases is still to be improved. Euro NCAP acknowledges this and aims to encourage the development of robust external perception that accounts for a large number of situations, closing the gap between current ADAS performance on track tests and real-world performance. To that end, existing Car-to-Car and Car-to-VRU scenarios are expected to be populated with adjustments related to scenery (e.g., road infrastructure, urban furniture), target appearance (e.g., moped, chopper, sport bike), vehicle behavior prior to crash (e.g., steering and/or accelerator inputs – within system overriding tolerances), and environmental occlusion (e.g., night-time, glare from oncoming vehicles, adverse weather) among others. The first changes, expected in 2026, are supposed to be simple to include into the test programme, yet impactful. The feasibility of such implementations will be linked to keeping the tests repeatable and reproducible across test laboratories.

**Target and propulsion systems**

The current Car-to-Motorcyclist scenarios are entirely executed in a proving ground, and hence limited to physically testable cases. Such limitations include the impact speed between the vehicle under test and the target without resulting in personal or material damage, but as well to the dynamic properties of the target, especially the maximum longitudinal speed at which platforms are able to travel (80 km/h) while keeping other parameters within tolerance levels (e.g., yaw rate). In addition, state-of-the-art testing equipment is limited when it comes to testing scenarios with multiple targets. This leaves some of the crashes seen in the real world uncovered. It is foreseen that the assessment of physically untestable cases in the future could be done by means of virtual validation methods, or a combination of virtual plus physical.

**Extension to commercial vehicles active safety progammes**

Although Euro NCAP established its reputation thanks to its car safety rating, it started to address commercial vehicle active safety in 2020. Activities began with the assessment of the ADAS fitted in Light Commercial Vehicles (LCV) before being more recently extended to Heavy Commercial Vehicle (HCV) which correspond to vehicles of categories N2 and N3. Considering the lack of active safety systems fitted into LCV, their ADAS are currently assessed according to the previous generation of passenger car test protocols which do not address PTW protection until now. Nevertheless, Euro NCAP is planning to close the gap between passenger car and LCV active safety requirements in 2026. In other words, from 2026 and beyond, LCV and passenger car test protocols will be aligned including PTW scenarios. After the recent adoption of the HCV safe and clean label, Euro NCAP is now working on the development of the HCV testing scenario for a first official test campaign in the near future. Although the roadmap for the introduction of LCV-to-Motorcyclist scenarios is well established, introduction of HCV-to-Motorcyclist scenarios is still under discussion based on some accidentology findings. One thing is for certain, Euro NCAP will encourage HCV manufacturers to fit their vehicles with ADAS capable of alerting and/or intervening in case of emergency situations with PTWs.

**Introduction of PTW scenario into the assisted driving system grading**

From 2018, Euro NCAP is conducting, in parallel to its safety rating, a complementary grading of the passenger car Assisted Driving (AD) systems (SAE level 2) which leans on 3 pillars: the driver engagement, the safety backup, and the vehicle assistance. Whereas the driver engagement assessment evaluates the capabilities of the AD system to keep the driver engaged into the driving task, the two last pillars reward ADAS and AD systems capable of assisting the driver in regular or emergency highway driving situations (e.g., cut-in, cut-out, etc.). Since Car-to-Car are the most recurrent conflict situations on highway, the first generation of protocol is focused on these scenarios. As part of its Vision 2030, Euro NCAP recently affirmed its intention to extend the scope of AD assessment in 2024 by including other off-highway scenarios. This will obviously include new VRU scenarios such as Car-to-Motorcyclist cut-in, cut-out and longitudinal scenarios. Whereas the safety rating will encourage OEM to develop emergency ADAS capable of preventing crashes with PTW, the AD grading will ensure that comfort ADAS like the Active Cruise Control (ACC) is also able to cooperate with surrounding motorcyclists.

**Single vehicle crashes and PTW test campaign**

In the 25 years of its existence, Euro NCAP has been devoted to encourage passenger car manufacturers to fit safety equipment as standard, with ever-increasing requirements above and beyond type approval. Ultimately, Euro NCAP's goal is to maximize the safety of the European passenger car fleet, helping to reduce crashes involving customer's own cars, other cars and VRUs. To that end, the first step in the reduction of crashes involving motorcycles has been the introduction of Car-to-Motorcyclist scenarios so that ADAS can identify and react to motorcycles. In the near future, the introduction of LCV and HCV-to-Motorcyclist scenarios will also help to prevent or mitigate crashes involving PTW and commercial vehicles. However, as the crash data analysis of MUSE suggests, a large number of severe PTW crashes are single vehicle, where the motorcyclist loses control of the motorcycle without any other road actor involved and ends up crashing. According to the UK dataset STATS19, single PTW crashes represented 25% of all the accidents involving PTW whereas, in France, 38% of all the fatal accidents for the motorcyclists were single vehicle accidents in 2021 [4]. In that context, motorcycle safety technology can help prevent single vehicle crashes to a large extent, for instance 6-axis ABS and traction control, and other Advanced Rider Assistance Systems (ARAS) such as blind spot monitoring and connected vehicle technologies. In the coming period, Euro NCAP is planning to go beyond its traditional scope and will be initiating, together with the industry support, the first-ever 'Test Campaign on PTW Safety', which is intended to evaluate existing motorcycle safety technologies (e.g., ARAS, Connected Vehicle, Personal Protective Gear), understanding the infrastructure needs, and outlining the first results of Car-to-Motorcyclist tests. The main purpose of this campaign is facilitating consumers (drivers and riders) with objective and comprehensive information about the latest technologies, as well as educating them by creating awareness of the risks and how these technologies can help avoiding or mitigate these.

## CONCLUSIONS

For decades now, car manufacturers never stopped improving vehicle safety. First, with passive safety systems and, more recently, with ADAS which have widely become part of consumer organization testing such as Euro NCAP. Although the well-known Euro NCAP passenger car star rating rewards VRU active protection for several years (from 2016 for AEB Car-to-Pedestrian and 2018 for AEB Car-to-Bicyclist), motorcyclist protection remains unaddressed until now.

Road crashes involving PTW have been a major concern across Europe for years and, for most of them, they are the result of a conflict with passenger cars. Euro NCAP rapidly identified ADAS as relevant technologies to address these crashes and adopted PTW protection into its 2020-2025 active safety roadmap. In that context, UTAC led the European consortium called MUSE which lasted 2 years (2017-2019) and involved major car manufactures, system suppliers and testing laboratories with the ambition to develop testing scenarios to promote ADAS capable of detecting, alerting and/or intervening in case of emergency situations with motorcyclists. The project was divided into 3 main workstreams which are detailed into this paper. It started with crash data analysis to identify the most recurrent Car-to-Motorcyclist conflict situations and their characteristics. The second step consisted of developing appropriate testing equipment such as an average European rider dummy and its PTW both propelled by means of a small platform. The last workstream was dedicated to the test scenario selection and their parametrization to maximize crash representativity and coverage while keeping the test workload acceptable. Finally, CMRs, CMRb, CMFtap, CMCscp, CMovertaking and CMoncoming were identified as the most recurrent conflict situations in addition to be ADAS relevant.

These 6 scenarios were rapidly adopted by Euro NCAP and the working group in charge of the AEB/LSS protocol elaboration. Nevertheless, considering ADAS maturity, CMCscp is delayed to the next generation of protocols in 2026. Hence, 2023 Euro NCAP AEB/LSS VRU test protocol [12] includes 5 dedicated Car-to-Motorcyclist scenarios (CMRs, CMRb, CMFtap, CMovertaking and CMoncoming) which count for almost 15% of all the points attributed to the VRU box. These 5 testing scenarios are completed with a blind spot scenario tested either with a car or a motorcyclist into the blind spot area of the vehicle under test [13]. 2023 will definitely be a first milestone for motorcyclist safety thanks to Euro NCAP with the introduction of new PTW scenarios into its passenger car safety rating.

Nevertheless, Euro NCAP won't stop there. The 2026 passenger car protocols are already expected to include complementary Car-to-Motorcyclist scenarios such as CMCscp while addressing ADAS robustness in general (target appearance, scenery diversity, etc.). Euro NCAP will also promote PTW safety when it comes to commercial vehicle active safety assessments. LCV-to-Motorcyclist scenarios will be part of the assessment from 2026 whereas introduction dates of HCV-to-Motorcyclist scenarios are still under discussion. In parallel to the safety rating, Euro NCAP has also the intention to integrate new PTW scenarios into the AD grading from 2024 while extending the scope of the AD assessment to other driving domains. V2X was also identified as a relevant technology to prevent Car-to-Motorcyclist crashes. UTAC is currently leading the consortium SECUR which is expected to support Euro NCAP in the introduction of connectivity into its car safety rating in the coming years. New scenarios assessing PTW protection using connectivity technologies will be part of the next generation of passenger car testing protocols starting from 2026 before being extended in 2029. Moreover, introduction of virtual testing and the improvement of the testing equipment are about to bring new testing possibilities allowing to cover more and more Car-to-Motorcyclist conflict situations while addressing system robustness at the same time.

ADAS such as AEB, LSS or even V2X technologies have an important role to play in the reduction of PTW crashes. Nevertheless, such systems are not relevant in case of a single vehicle crash which still represents a large number of all the riders killed or seriously injured in road crashes. Although PTW manufactures and systems suppliers are working hard on developing ARAS, the market penetration of these systems is very limited for the moment. In its Vision for 2030, Euro NCAP announced its ambition to addressee PTW safety assessment in the future [15].

## REFERENCES


[1] Connected Motorcycle Consortium (CMC), " Powered Two Wheeler Conspicuity," 2022.

[2] Euro NCAP, "Euro NCAP 2025 Roadmap: In Pursuit of Vision Zero," 2017. [Online]. Available: https://cdn.euroncap.com/media/30700/euroncap-roadmap-2025-v4.pdf.

[3] World Health Organization, "Global status report on road safety 2018," 2018.

[4] Observatoire national interministériel de la sécurité routière (ONISR), "La sécurité routière en France: Bilan de l'accidentalité de l'année 2021," 2022.

[5] Thatcham Research, Fiat Chrysler Automobiles, Denso, "MUSE - Deliverable 1.1: Accident Data Study," 2019.

[6] 4activeSystems, "MUSE - Deliverable 2.1: Motorcyclist Target Specifications," 2019.

[7] UTAC, "MUSE - Deliverable 3.1: Propulsion System Specifications," 2019.

[8] ACEA, " Articulated Pedestrian Target Specifications Version 1.0," 2015.

[9] Euro NCAP, "Technical Bulletin 029 - Euro NCAP Supplier List," October 2022. [Online]. Available: https://cdn.euroncap.com/media/72832/tb-029-euro-ncap-suppliers-list-v40.pdf.

[10] UTAC, "MUSE - Deliverable 4.1: Car to PTW AEB Test Protocol," 2019.

[11] UTAC, "MUSE - Deliverable 4.2: Car-to-PTW LSS Protocol," 2019.

[12] Euro NCAP, "2023 Euro NCAP TEST PROTOCOL – AEB/LSS VRU systems," November 2022. [Online]. Available: https://cdn.euroncap.com/media/75436/euro-ncap-aeb-lss-vru-test-protocol-v43.pdf.

[13] Euro NCAP, "TEST PROTOCOL – Lane Support Systems," November 2022. [Online]. Available: https://cdn.euroncap.com/media/75440/euro-ncap-lss-test-protocol-v42.pdf.

[14] The MITRE Corporation, "Real-world Effectiveness of Model Year 2015–2020 Advanced Driver Assistance Systems," 2022.

[15] Euro NCAP, "Euro NCAP Vision 2030: A Safer Future for Mobility," December 2022. [Online]. Available: https://cdn.euroncap.com/media/74468/euro-ncap-roadmap-vision-2030.pdf.

# SELECTION OF TEST PARAMETERS FOR A CONSUMER INFORMATION CRASH TEST PROGRAM TO EVALUATE THE SAFETY OF REAR-SEAT OCCUPANTS

**Sushant R. Jagtap**
**Marcy A. Edwards**
**Jessica S. Jermakian**
Insurance Institute for Highway Safety
United States

Paper Number 23-0235

## ABSTRACT

Regulatory and consumer information frontal crash testing programs in the United States have historically focused on the front seat occupants. The result has been significant safety improvements for people in those seating positions but not necessarily for rear-seat occupants. The objective of this research was to select a crash configuration, anthropomorphic test device (ATD), and seat position for a crash test program to evaluate and incentivize rear-seat safety improvements in frontal crashes.

Twelve full-scale vehicle crash tests were conducted with two different crash configurations (25% and 40% offset deformable barrier tests at 64.4 km/h) and four different ATDs (H3-50$^{th}$ male, H3-5$^{th}$ female, H3 10-year-old, and THOR 5$^{th}$ female) seated in the left and right rear outboard positions. Vehicles with rear-seat pretensioners and load limiters were compared with their previous generation counterparts without advanced belt technology in test conditions matched by crash configuration, ATD, and seating position.

The H3-5$^{th}$ female dummy represents an average stature for rear-seat passengers in frontal crashes, and the study showed that a 40% offset deformable barrier with an H3-5$^{th}$ female dummy positioned in the second-row seat behind the driver best reproduces common injury mechanisms documented in the field data and best discriminates between restraint system performance. The 40% offset deformable barrier test was more severe than the 25% offset test, which resulted in higher head and neck injury values and higher incidence of submarining in the 40% offset test. For all ATDs except the H3-50M, the left rear seating position was more challenging than the right, producing higher head and neck injury numbers, similar or higher chest injury numbers, and increased incidence of submarining. All ATDs tested showed reduced injury risks for vehicles equipped with pretensioners and load limiters. However, the ATDs also showed potential tradeoffs for occupants of different sizes. The smallest dummy (H3 10-year-old) had the highest incidence of submarining, while the largest dummy (H3-50$^{th}$ male) had the largest head excursions and the only cases in which the dummy's head made contact with the interior of the vehicle. The shoulder belt remained on the ATD shoulder in all cases except in one instance with a THOR 5$^{th}$ female ATD seated in the right seating position.

## INTRODUCTION

Regulatory and consumer information frontal crash test programs in the United States have led to improvements in front seat safety due, in part, to optimized restraint systems that include improved airbag designs and seat belt technologies such as load limiters and pretensioners [1,2]. However, none of the U.S. frontal crash test programs to date include a rear-seat occupant and, as a result, rear-seat restraint systems have not kept pace with improvements in the front. This is evident in the field data, where multiple studies have shown rear-seat occupants in newer vehicles are at increased risk compared with front seat occupants [3,4,5]. In 2020, more than 1,600 people were killed in rear rows of passenger vehicles, accounting for nearly 7% of all passenger vehicle occupant deaths in the United States during that year [6].

The restraint environment in the rear differs from the front, and, as a result, the injury patterns differ as well. Kuppa et al. (2005) analyzed data from NASS-CDS (National Automotive Sampling System Crashworthiness Data System) and FARS (Fatality Analysis Reporting System) and identified the seat belt as a major source of injury in restrained rear-seat occupants [3]. Jermakian et al. (2019) also studied belt-restrained rear-seat occupants who sustained serious or fatal injuries and found that the most commonly documented injured body regions were the head, chest, and abdomen [7]. The authors found that the most common causes of injuries were shoulder belt loading, head impacts with the vehicle interior, and lap belt loading due to submarining.

Seat belt technologies such as pretensioners and load limiters may help mitigate these injuries and offer improved protection, particularly for older rear-seat occupants [3]. While these features are standard equipment in the front seats of modern vehicles, they are less common in the rear seat. In 2020, Consumer Reports found that fewer than 40% of U.S. vehicles were equipped with pretensioners and load limiters in the rear seat [8]. The European new car assessment program (Euro NCAP) and other consumer ratings programs around the world have introduced safety ratings for rear-seat occupants and seen rapid introduction of improved rear-seat restraint systems. Before the introduction of rear-seat safety ratings in Euro NCAP in 2015, only 10% of vehicles sold in Europe had standard pretensioners and load limiters. By 2020, nearly all European vehicles were equipped with these belt technologies [8]. The addition of these belt technologies may help reduce injuries when adapted appropriately for the rear-seat environment.

The objective of this research was to select a crash configuration, seat position, and ATD for a crash test program that can evaluate and incentivize improvements to rear-seat safety in frontal crashes. The test program should replicate injury mechanisms and kinematics observed in the field data and be able to demonstrate the potential benefits of robust restraint systems with pretensioners and load limiters adapted for the rear-seat environment which have proven to be effective in the front seat.

**METHODS**

Twelve full-scale vehicle crash tests were conducted in a test matrix (Table 1) that varied test mode, anthropomorphic test device (ATD) size and type, and second-row seat position. Two crash configurations were tested in which the test vehicle traveled at 64.4 km/h into an offset deformable, aluminum honeycomb barrier (ODB) with 25% and 40% overlap, as seen in Figure 1. Four different ATDs – Hybrid III 50th male (H3-50M), Hybrid III 5th female (H3-5F), Hybrid III 10-year-old (H3-10YO), and THOR 5th female (THOR-5F) – were seated in the left and right second row outboard positions (Figure 2) using the *IIHS dummy seating procedure for rear outboard positions Version 1* (April 2012). The H3-10YO dummy was positioned without a booster seat, and because of the short thigh length, the seating procedure was modified so the knees were bent and the calves were in contact with the seat cushion. The driver seat was positioned using the IIHS procedure, *Guidelines for Using the UMTRI ATD Positioning Procedure for ATD and Seat Positioning (Version V)* (IIHS, 2004). This study focuses only on the rear-seat occupants.

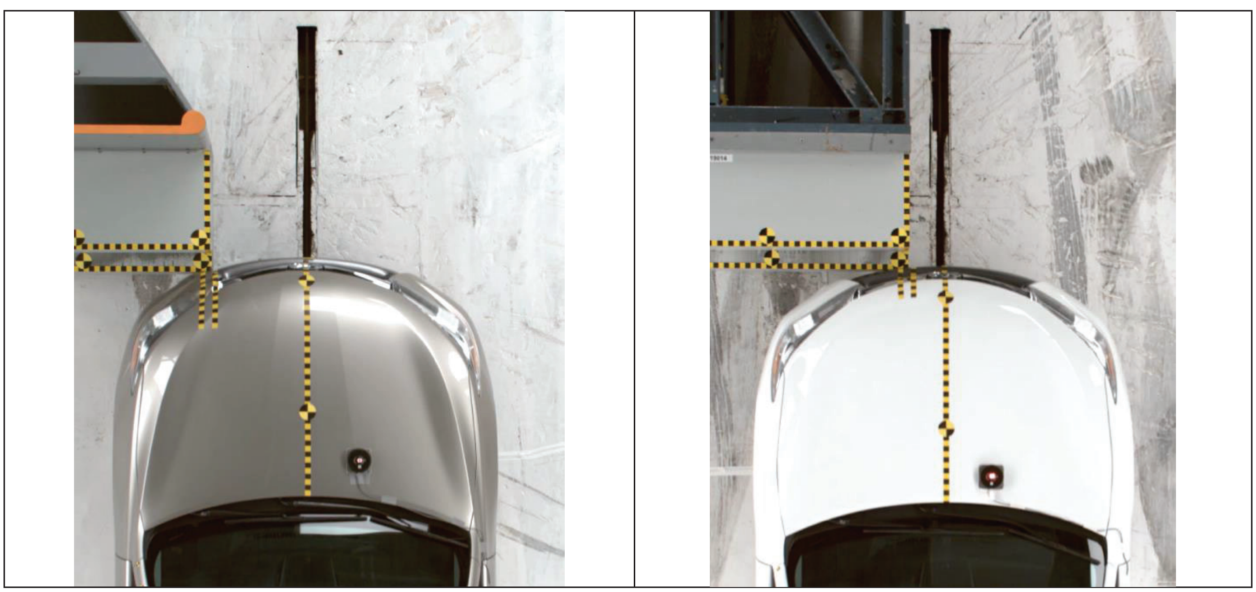


***Figure 1. 25% ODB (left) and 40% ODB (right) test configuration at impact.***

***Figure 2. ATDs seated in left rear seating position, H3-50M (top left), H3-5F (top right), H3-10YO (bottom left), THOR-5F (bottom right).***

Toyota Camry models equipped with pretensioners and load limiters in the rear seat were compared with their previous generation counterparts with standard belts in test conditions matched by crash configuration, ATD, and seating position. Test mode comparisons were made with H3-50M and H3-5F ATDs in two Toyota Camry models, one with and one without pretensioners and load limiters, in the 25% and 40% ODB configurations. Seating position and ATD comparisons were made with all four ATDs tested in the two Camrys in the 40% ODB test.

*Table 1.*
*Test Matrix (*PT+LL: Pretensioner + Load limiter)*

| Test No. | Test mode | Vehicle | Vehicle category | Dummy | | Rear seat belt technology |
|---|---|---|---|---|---|---|
| | | | | Left rear seating position | Right rear seating position | |
| 1 | 25% ODB | 2018 Toyota Camry | Midsize car | H3-50M | H3-5F | PT+LL* |
| 2 | | 2016 Toyota Camry | Midsize car | H3-50M | H3-5F | Standard |
| 3 | | 2019 Toyota Camry | Midsize car | H3-5F | H3-50M | PT+LL |
| 4 | | 2017 Toyota Camry | Midsize car | H3-5F | H3-50M | Standard |
| 5 | 40% ODB | 2016 Toyota Camry | Midsize car | THOR-5F | H3-10YO | Standard |
| 6 | | 2018 Toyota Camry | Midsize car | THOR-5F | H3-10YO | PT+LL |
| 7 | | 2016 Toyota Camry | Midsize car | H3-10YO | THOR-5F | Standard |
| 8 | | 2018 Toyota Camry | Midsize car | H3-10YO | THOR-5F | PT+LL |
| 9 | | 2016 Toyota Camry | Midsize car | H3-50M | H3-5F | Standard |
| 10 | | 2019 Toyota Camry | Midsize car | H3-50M | H3-5F | PT+LL |
| 11 | | 2016 Toyota Camry | Midsize car | H3-5F | H3-50M | Standard |
| 12 | | 2018 Toyota Camry | Midsize car | H3-5F | H3-50M | PT+LL |

The ATDs were instrumented according to table A1 (Appendix). A three-axis accelerometer was mounted on the vehicle to measure vehicle acceleration in all tests, and an angular rate sensor was mounted in tests 5–12 to measure vehicle rotation. Load cells were mounted on the outboard lap side and upper shoulder side of the belt restraint to measure belt loads in the respective regions. All data was processed and filtered using SAEJ211. Crash tests were recorded for analysis using on-board and off-board high speed video cameras.

For the H3 family of ATDs, the following body regions and injury measures were considered: head (HIC15, resultant acceleration 3ms clip), neck (tension, compression, Nij), chest (resultant acceleration 3ms clip, sternum deflection, viscous criterion, deflection rate), and lap/shoulder belt loads. These metrics were normalized according to the appropriate Injury Assessment Reference Values (IARV) or the thresholds in the appendix (table A2-A4) for comparison across ATDs. Comparisons of test metrics between crash configurations and seat position are described in terms of the average difference in each metric as a percent of the relevant IARV/threshold.

For the THOR-5F, the body regions and metrics considered were head (HIC15, resultant acceleration 3ms clip), neck (tension, compression), chest (maximum IRTACC deflection), and lap/shoulder belt loads. Since IARVs are under development for THOR-5F, the comparisons for this ATD are presented separately as the percent increase or decrease of a given metric.

In addition to injury measures, dummy kinematics were compared and analyzed through review of high-speed video to assess submarining and head excursion.

## RESULTS

Twelve full-scale crash tests were conducted with minimal data loss. The shoulder belt load cell in test 11 and lap belt load cell in test 3 did not record meaningful data and were excluded. For the THOR-5F, data from multiple IRTRACC channels were lost in tests 7 and 8. Summary data for all tests is included in the Appendix, grouped by ATD.

### Test mode

For the test mode comparison, four tests using the 25% ODB configuration and four others using the 40% ODB configuration were matched by vehicle generation, ATD (H3-50M/H3-5F), and test position and then analyzed. The 40% ODB test had a higher delta V and peak longitudinal acceleration (average of 69 km/h, 40 g) than the 25%

ODB test (average of 62 km/h, 31 g) (Figure 3). The 25% ODB test had higher z-axis vehicle rotations after impact than the 40% ODB.

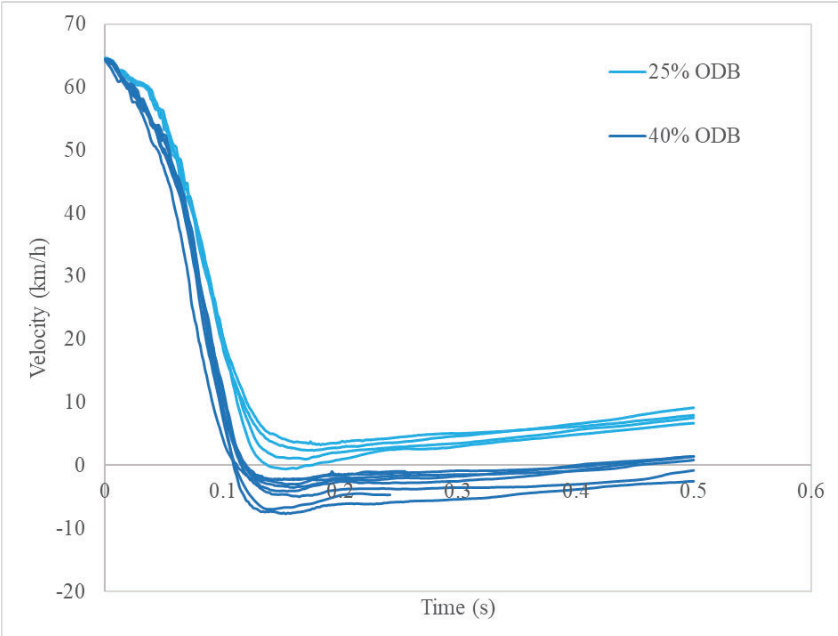



***Figure 3. Vehicle velocity (km/h) vs. time (s) for the 25% and 40% ODB test configurations.***

Figure 4 shows the average measures for the 25% and 40% ODB tests for H3-5F and H3-50M when normalized according to IARVs/threshold (Appendix table A2-A4). On average, both the H3-50M and H3-5F showed higher risk of injury in the 40% ODB test than in the 25% ODB test, although all injury metrics were below established IARVs except neck tension in the H3-5F in the 40% ODB. The average lap and shoulder belt loads were lower than the selected threshold (6000 N) for the H3-5F and higher than the threshold for the H3-50M.

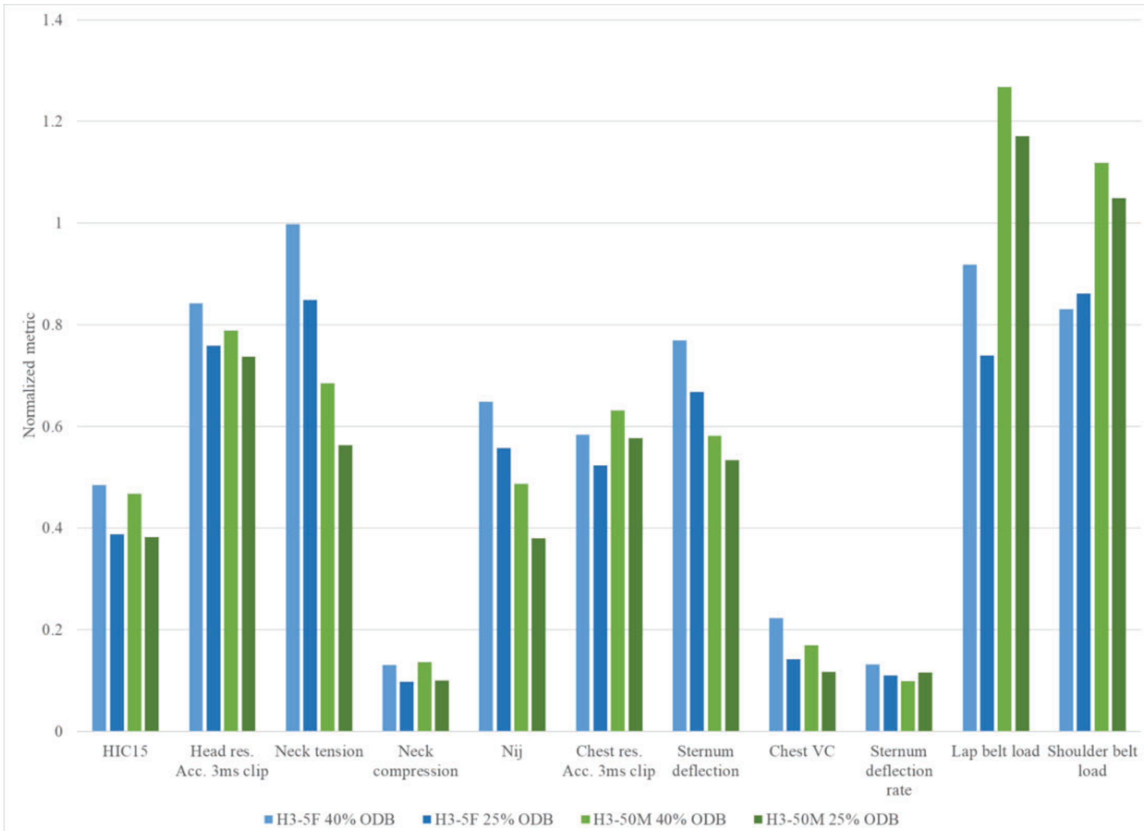



***Figure 4. Comparison of 40% ODB and 25% ODB tests (normalized average measures) for H3-5F and H3-50M.***

Table 2 shows the average change in each metric as a percent of IARV/threshold for the H3-5F and H3-50M in the 40% ODB test compared with the 25% ODB test. With regard to head-injury metrics, average HIC15 values for H3-50M and H3-5F dummies in the 40% ODB test were higher by 59 (8% of IARV) and 74 (10% of IARV), respectively. For the neck region, tension showed the largest difference between test modes and was higher in the 40% ODB test by an average of 309 N (15% of IARV) for H3-5F and 401 N (12% of IARV) for the H3-50M. For the chest region, the difference in the normalized injury values between the test modes was the smallest among all body areas for the H3-50M dummy. Average chest-injury metrics differed by no more than ±5% of IARV in 40% ODB test and the 25% ODB test. However, the differences in chest-injury metrics between test modes was wider for the H3-5F dummy. For this ATD, the average sternum deflection was higher by 4 mm (10% of IARV) in 40% ODB test than 25% ODB test. Differences in belt load were also evident. Average lap belt load in 40% ODB mode was higher by 1069 N (18% of threshold) and 580 N (10% of threshold) for H3-5F and H3-50M, respectively. The average shoulder belt load for the H3-5F was slightly lower by 180 N (3% of threshold) in 40% ODB test mode. However, for the H3-50M it showed an average increase of 418 N (7% of threshold) in the 40% ODB test mode.

*Table 2.*
*Average change in test metric as a percent of IARV/threshold for H3-5F and H3-50M in the 40% ODB compared with the 25% ODB test. Positive values indicate average measures for 40% ODB test were higher.*

| Metric | H3-5F | H3-50M |
|---|---|---|
| HIC15 | 10% | 8% |
| Head res. Acc. 3ms clip | 8% | 5% |
| Neck tension | 15% | 12% |
| Neck compression | 3% | 4% |
| Nij | 9% | 11% |
| Chest res. Acc. 3ms clip | 6% | 5% |
| Sternum deflection | 10% | 5% |
| Chest VC | 8% | 5% |
| Sternum deflection rate | 2% | -2% |
| Lap belt load | 18% | 10% |
| Shoulder belt load | -3% | 7% |

The normalized average reduction in test metrics resulting from the addition of pretensioners and load limiters for vehicles matched on ATD and seating position was greater for both the 40% ODB test and the 25% ODB test (Figure 5). For the H3-5F, the addition of pretensioners and load limiters reduced injury metrics for 40% ODB tests across all body regions (reduction of 14%-55% of IARV/threshold in 40% ODB as opposed to reduction of 3%-42% in 25% ODB tests) (Appendix table A6). For the H3-50M, the addition of pretensioners and load limiters showed a greater reduction in head injury metrics for the 40% ODB test, while the reductions in neck and chest metrics were similar for both test configurations (Appendix table A7). In the 40% ODB test, the H3-50M neck compression was the only metric that increased with the addition of pretensioners and load limiters.

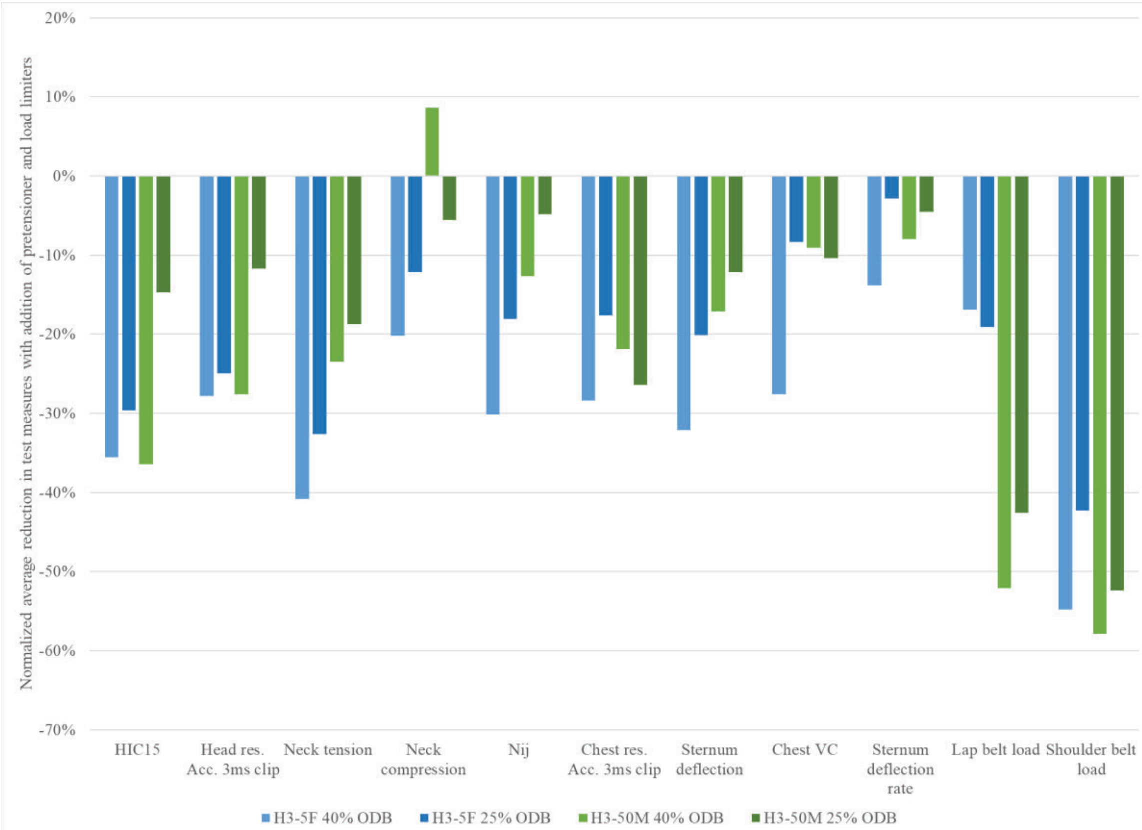



***Figure 5. Comparison of 40% ODB and 25% ODB tests (normalized average reduction with addition of pretensioners and load limiters) for H3-5F and H3-50M ATDs. Negative values indicate average measures for vehicles with pretensioners and load limiters were lower.***

**Seating position**

For the seating position comparison, eight 40% ODB tests matched by vehicle generation, ATD, and test position were analyzed. Figure 6 compares the normalized metrics for the left and right seating positions for the H3 family of ATDs. Overall, dummies seated in the left rear position showed higher injury values than those positioned on the right.

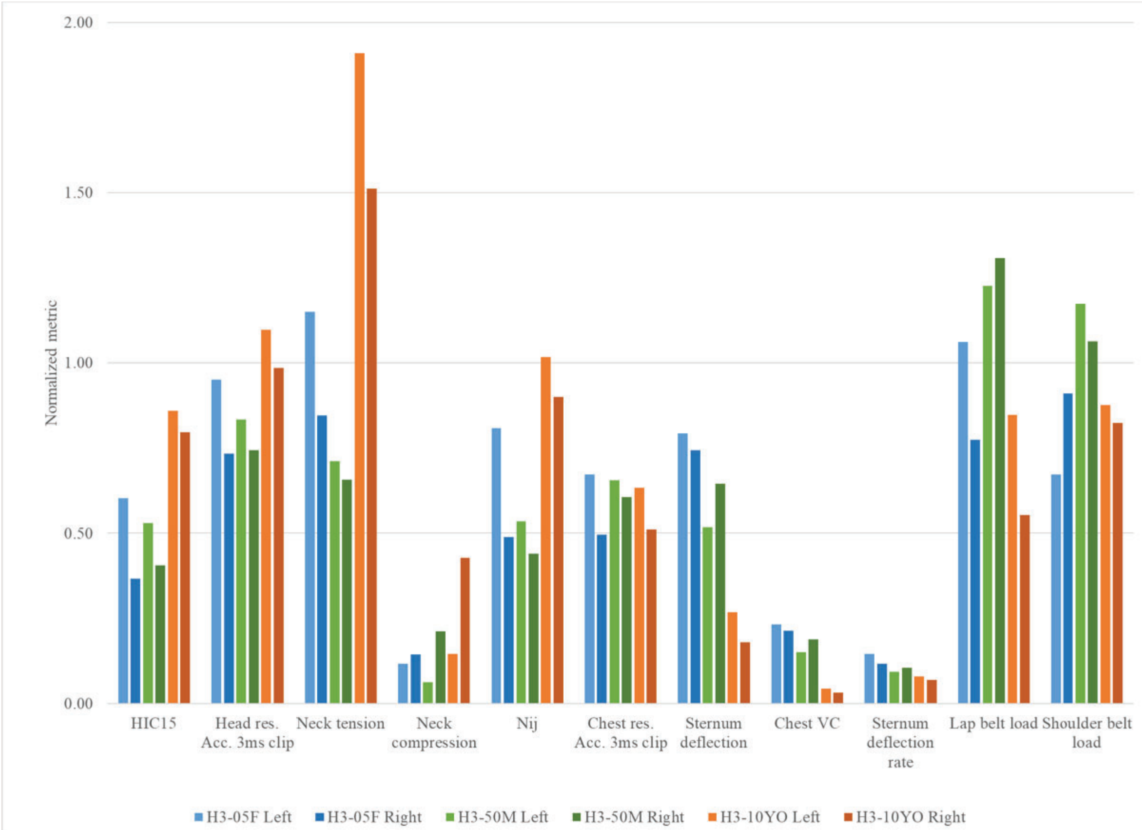



***Figure 6. Comparison of left and right seating position (normalized average measures) for H3-5F, H3-50M and H3-10YO.***

Table 3 shows difference in metrics between the left and right seating positions as a percent of the IARV/threshold. For the H3-5F, most metrics were 2–32% of IARV/threshold higher for the left versus right seating position, but average shoulder belt loads and neck compressions were higher for the right position. The higher average shoulder belt loads on the right may be due to loss of shoulder belt load cell data in one of the left seating position tests. For the H3-10YO, most metrics were 1–40% of IARV/threshold higher for the left versus right seating position, but neck compressions were higher for the right.

For the H3-50M, the differences in metrics between seating positions were much smaller. The average measures between seating positions did not differ more than 15% of IARV (or threshold) and were not consistently higher in one seat position or the other.

*Table 3.*
*Average change in test metric as percent of IARV/threshold for H3-5F, H3-50M and H3-10YO for the left seating position compared with the right seating position. Positive values indicate average measures for the left seating position were higher.*

| Metric | H3-5F | H3-50M | H3-10YO |
|---|---|---|---|
| HIC15 | 23% | 12% | 6% |
| Head res. Acc. 3ms clip | 22% | 9% | 11% |
| Neck tension | 30% | 5% | 40% |
| Neck compression | -3% | -15% | -28% |
| Nij | 32% | 10% | 12% |
| Chest res. Acc. 3ms clip | 18% | 5% | 12% |
| Sternum deflection | 5% | -13% | 9% |
| Chest VC | 2% | -4% | 1% |
| Sternum deflection rate | 3% | -1% | 1% |
| Lap belt load | 29% | -8% | 29% |
| Shoulder belt load | -24% | 11% | 5% |

Table 4 shows the average percentage difference in metrics between the left and right seating position for the THOR-5F dummy. The head and neck injury metrics were 6–59% higher in the left versus right seating position, while the chest deflection and belt load metrics were 2–12% higher for the right position than the left.

*Table 4.*
*Average percentage difference between left and right seating position for THOR-5F dummy. Positive values indicate the left seating position values are higher.*

| Metric | THOR-5F |
|---|---|
| HIC15 | 24% |
| Head res. Acc. 3ms clip | 10% |
| Neck tension | 6% |
| Neck compression | 59% |
| Max deflection IRTACC | -11% |
| Lap belt load | -12% |
| Shoulder belt load | -2% |

The shoulder belt remained on the ATD shoulder in all cases except in one instance with the THOR-5F seated in the right position in test 12. For all H3 ATDs, both seating positions showed similar reductions in metrics with the addition of pretensioners and load limiters (Appendix tables A8, A9, A10). For THOR-5F, the addition of pretensioners and load limiters resulted in a greater reduction in head, neck, and chest injury numbers for the left seating position as well as a greater reduction in shoulder and lap belt loads for the right seating position (Appendix table A11).

**ATDs**
For the ATD comparison, eight 40% ODB tests matched by vehicle generation, ATD and test position were analyzed. All ATDs showed lower injury metrics for vehicles equipped with pretensioners and load limiters than those without, except for neck compression metric for the H3-50M. Addition of these belt technologies reduced average measures with respect to IARV/threshold by 14–55% for the H3-5F, 8–58% for the H3-50M and 2–101% for the H3-10YO (Table 5).

*Table 5.*
*Change in test metric as a percent of IARV/threshold with addition of pretensioners and load limiters for H3-5F. H3-50M and H3-10YO. Positive values indicate lower measures for vehicles with pretensioners and load limiters.*

| Metric | H3-5F | H3-50M | H3-10YO |
|---|---|---|---|
| HIC15 | 36% | 36% | 85% |
| Head res. Acc. 3ms clip | 28% | 28% | 47% |
| Neck tension | 41% | 23% | 101% |
| Neck compression | 20% | -9% | 18% |
| Nij | 30% | 13% | 44% |
| Chest res. Acc. 3ms clip | 28% | 22% | 23% |
| Sternum deflection | 32% | 17% | 9% |
| Chest VC | 28% | 9% | 2% |
| Sternum deflection rate | 14% | 8% | 4% |
| Lap belt load | 17% | 52% | 26% |
| Shoulder belt load | 55% | 58% | 40% |

The THOR-5F had lower metrics for vehicles with pretensioners and load limiters with an average reduction of 1–114% as compared with standard belt vehicles (Table 6). There was little difference in the average max IRTRACC deflection metric, which may be due to loss of multiple IRTRACC data in tests.

*Table 6.*
*Percent change in injury measures with addition of pretensioners and load limiters for THOR-5F. Positive values indicate lower measures for vehicles with advanced belt technology.*

| Metric | THOR-5F |
|---|---|
| HIC15 | 114% |
| Head res. Acc. 3ms clip | 40% |
| Neck tension | 33% |
| Neck compression | 95% |
| Max deflection IRTACC | 1% |
| Lap belt load | 28% |
| Shoulder belt load | 61% |

**Submarining**

In submarining, the occupant's (or dummy's) pelvis slides forward beneath the lap belt, causing the lap belt to move from the ideal position over the iliac wings onto the abdomen, increasing the risk of abdominal injuries. In this test series, submarining occurred with each ATD type in at least one test, but the frequency of submarining differed between ATDs. The H3-50M submarined in 1 of 8 tests, the H3-5F in 4 of 8 tests, the H3-10YO in 4 of 4 tests, and the THOR-5F in 3 of 4 tests.  In the one test in which the THOR-5F did not submarine, the shoulder belt slipped off the shoulder, which may have affected the dummy kinematics. Submarining occurred in vehicles with standard belts and belts with pretensioners and load limiters. Figure 7 shows submarining examples with each ATD.

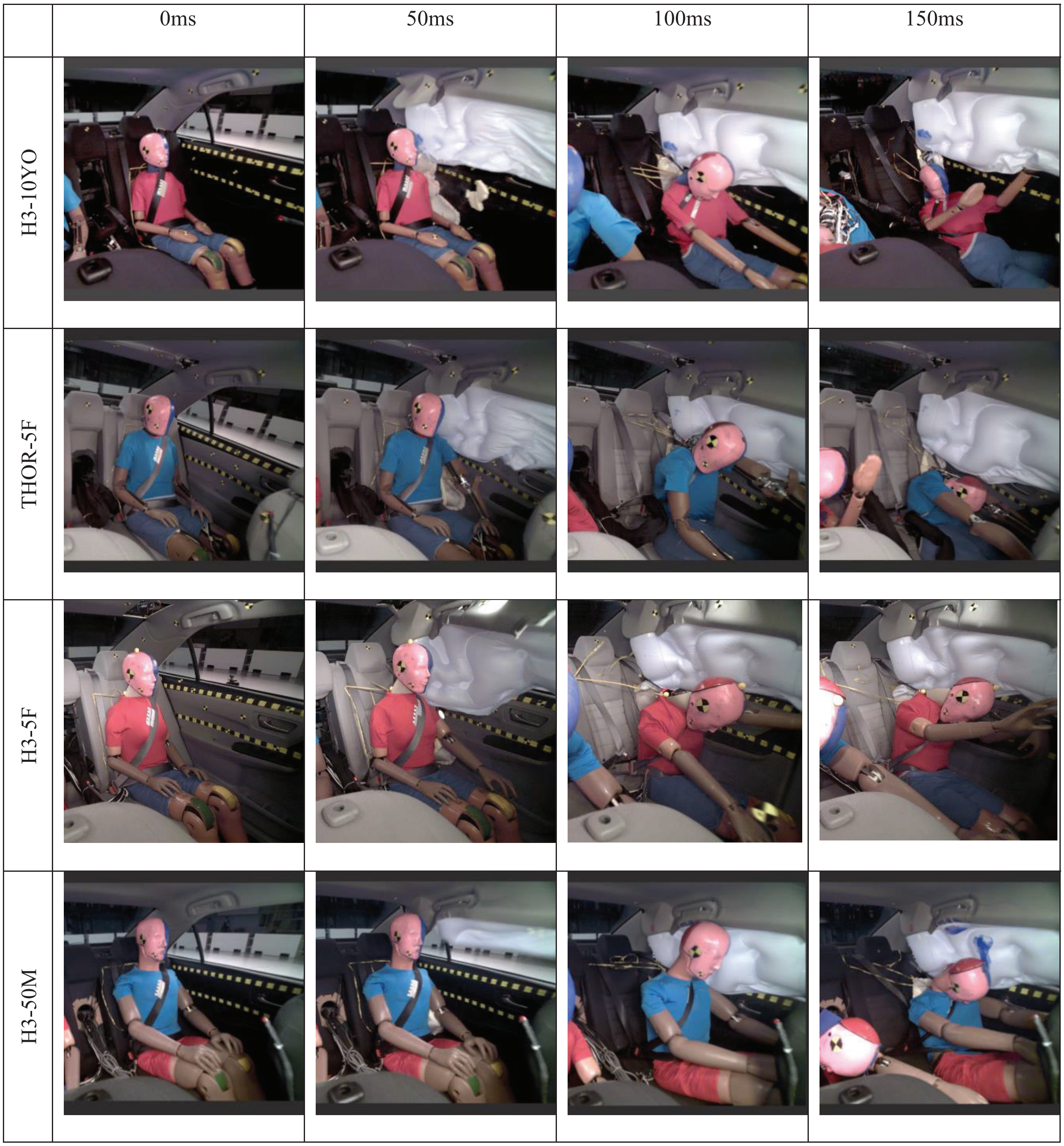



*Figure 7. Submarining example with each ATD.*

**Excursion:**
Head excursion was monitored in all tests. Head contact with the front seatback occurred in two tests, both with the H3-50M seated in right seating position in vehicles with a pretensioner and load limiter. Contact was confirmed with high-speed video, acceleration time history data, and dummy paint transfer to the front seatback. Both contacts resulted in peak resultant head accelerations of approximately 43 g.

| 0 ms | 100 ms | 150 ms | 200 ms |
|---|---|---|---|

*Figure 8. H3-50M head excursion contact with front seatback.*

**DISCUSSION**

Full-scale crash tests were conducted and analyzed with the objective of selecting a test mode, ATD, and second-row seat position for a rear-seat evaluation program that will incentivize improvements to rear-seat safety in frontal crashes. Field data show belted rear occupants sustain injuries due to belt loading to the chest, head impacts, and submarining [3,7]. That makes it important to select test parameters that can distinguish performance with respect to these outcomes and also discern the presence of countermeasures such as load limiters and pretensioners.

**Test mode**
In the current study, the 40% ODB test produced higher delta V and longitudinal acceleration than the 25% ODB test and resulted in less subsequent vehicle rotation. While field data show severe injuries and fatalities in the rear seat can occur at or below crash severities of either test mode [5], the 40% ODB test represents a larger proportion of towaway crashes. Nearly 70% of the frontal crashes represented in 2000-2013 NASS CDS cases were moderate or full overlap type crashes [9].

Real world studies have documented the head and chest as the most commonly injured body regions for restrained rear-seat occupants in frontal crashes across all occupant ages [3,5,7]. For the H3-50M and H3-5F used to compare test modes, the 40% ODB test mode was more severe, resulting in dummy injury measures representing higher head and neck injury risks, similar or slightly higher chest injury risks and shoulder belt loads, and higher lap belt loads than the 25% ODB mode. The H3-50M submarined only once; the H3-5F, however, submarined in three of four 40% ODB tests and one of four 25% ODB tests. Head contact with the front seat was observed with the H3-50M once in each test mode, both in the right seating position in a vehicle equipped with pretensioners and load limiters.

In short, the 40% ODB test aligns a greater percentage of the frontal crashes in the field data than the 25% ODB test, resulted in higher risks of most common injuries, and showed larger reductions in injury measures with the addition of pretensioners and load limiters.

**Seating position**
Nearly 85% of rear-seat occupants in all crashes are distributed in rear outboard seats, with 38% of the fatal cases in left rear seat and 45% of the fatal cases in right rear seating position [5]. Arbogast et al. showed that the risk of injury for restrained rear-seat occupants is higher when the impact is on the near side than on the far side for small overlap crashes [10]. For all of the ATDs except H3-50M, the left rear seating position, which is the near side for both test modes, resulted in higher head and neck injury risk and higher or similar chest injury risk. Submarining was also more common in the left rear seating position than the right. The only cases where head contact with the front seatback was observed were with the H3-50M in the right seating position of vehicles equipped with pretensioners and load limiters. Limiting excessive head excursion to prevent head contact injuries is important, especially when belts are equipped with load limiters that may increase belt payout. In the right seating position, which is on the far-side of the impact, there is a concern about the belt slipping off the occupant's shoulder. In this

test series, the shoulder belt remained on the far-side ATD's shoulder in all tests but one. The shoulder belt slipped off the shoulder in one test with the THOR-5F.

Together, those results suggest that the left rear seating position is most appropriate for a 40% ODB test in which the left side of the vehicle hits the barrier. It is a common seating position for rear-seat occupants in real world crashes, and the ATDs seated in the left seating position in this test series indicated higher risk of injury and increased incidence of submarining compared with the right position. The benefit associated with belts with pretensioners and load limiters was similar for both seating positions.

**ATDs**

ATD selection is challenging for a rear-seat evaluation because of the wide age and size ranges of people who sit in the rear, as restraint systems optimized for one size occupant might not work well for others who are larger or smaller. All ATDs tested in this study pointed to the need for restraint system improvements and showed lower injury measures for vehicles with pretensioners and load limiters. However, the ATDs showed differences in kinematics and evidence of potential tradeoffs for different size occupants. Submarining was most common for the smallest dummy (H3-10YO) (four out of four tests). The largest dummy (H3-50M) rarely submarined but had the largest head excursions and the only head contacts. Because the large H3-50M dummy creates higher shoulder belt loads, using it in a crash test program would likely promote higher-threshold load limiters to limit high belt payout. But these high-threshold load limiters would reduce the benefit of load limiting for smaller size occupants. On the other hand, an ATD such as the H3-10YO that represents a smaller sized occupant would focus attention on problems that occur because the restraint system is ill-fitting, but it would not address the majority of serious injuries and fatalities among rear-seat occupants, which occur in occupants ages 13 or older [5]. The H3-5F approximately represents the average stature of rear-seat occupants in frontal crashes [11]. It also exhibited submarining behavior and helped researchers discriminate between vehicles with and without pretensioners and load limiters. The THOR-5F is potentially more biofidelic [12] and has more complex thoracic and abdomen injury evaluation tools than the H3-5F. However, its continuing development and absence of established IARVs limits the use of THOR-5F at this time.

In addition to representing the average stature of rear-seat occupants, the H3-5F ATD showed a range of injury and kinematic measures across tested vehicles. It highlighted differences between vehicles with and without pretensioners and load limiters, indicating higher injury measures in vehicles with standard belts. This combination of factors suggests the H3-5F will promote restraint designs that will protect a broad range of rear-seated occupants.

## CONCLUSIONS

Multiple test variables (crash configuration, ATDs, seating position) were studied to develop a crash test program that will incentivize improvement of rear-seat safety in frontal crashes. Based on the results, IIHS has updated its moderate overlap crash test to include a H3-5F ATD in the left rear seating position in a 40% ODB test. This evaluation aligns with common challenging scenarios documented in the field data and uses an ATD that is capable of discriminating restraint system performance for an occupant of average size in the rear-seat environment.

## REFERENCES

[1] Insurance Institute for Highway Safety. (2006). Major change in frontal crashworthiness evaluations. *Status Report*, 41(3): p. 1-7.

[2] Kahane, C.J. (1994). *Correlation of NCAP performance with fatality risk in actual head-on collisions*. NHTSA Technical Report.

[3] Kuppa, S., Saunders, J., & Fessahaie, O. (2005). Rear seat occupant protection in frontal crashes. Proceedings of 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, DC.

[4] Elham S., Kennerly D., Dhafer M. (2010). *Reduced protection for belted occupants in rear seats relative to front seats of new model year vehicles*. Association for the Advancement of Automotive Medicine, 54,149–158.

[5] Durbin, D.R., Jermakian, J.S., Michael J. K., Anne T. Mc., Kristy B. A., Mark R. Z., Rachel K. M. (2015). Rear seat safety: Variation in protection by occupant, crash, and vehicle characteristics. *Accident Analysis & Prevention*, 80: p. 185-192.

[6] Insurance Institute for Highway Safety. (2022, May). Fatality facts 2020. https://www.iihs.org/topics/fatality-statistics/detail/passenger-vehicle-occupants

[7] Jermakian, J., Edwards, M., Fein, S., and Maltese, M.R. (2019). Factors contributing to serious and fatal injuries in belted rear-seat occupants in frontal crashes. *Traffic Injury Prevention*. 20(sup1): p. S84-S91.

[8] Barry, K. (2020, September 03). Making back seats safer. *Consumer Reports*. https://www.consumerreports.org/car-safety/making-car-back-seats-safer/

[9] National Highway Traffic Safety Administration. (2015). New Car Assessment Program (NCAP) RFC (Docket NHTSA-2015-0119).
https://www.regulations.gov/docket/NHTSA-2015-0119/document

[10] Arbogast K., Locey C., Hammond R., Belwadi A. (2013). Injury risk for rear-seated occupants in small overlap crashes. *Association for the Advancement of Automotive Medicine*, Vol. 57, 267-280.

[11] Bose D., Crandall J., Forman J., Longhitano D., Arregui-Dalmases C. (2017). Epidemiology of injuries sustained by rear-seat passengers in frontal motor vehicle crashes. *Journal of Transport & Health*, Volume 4, p 132-139.

[12] National Highway Traffic Safety Administration. (2022). Initial biofidelity comparison between THOR-05F and Hybrid-III 5th percentile female ATDs.
https://www.nhtsa.gov/sites/nhtsa.gov/files/2022-03/Initial%20Biofidelity%20Comparison_THOR-05F_Hybrid-III%205th%20Percentile%20Female%20ATDs.pdf

[13] Mertz H.J, Irwin A.L., and Prasad P. (2016). Biomechanical and scaling basis for frontal and side impact injury assessment reference values Paper no 2016-22-0018. *Stapp Car Crash Journal*, Vol 60 pp. 625-657.

**APPENDIX**

*Table A1.*
*ATD sensors*

| Region | H3-10YO | H3-5F | H3-50M | THOR-5F |
|---|---|---|---|---|
| Head | Ax, Ay, Az Accelerations | Ax, Ay, Az Accelerations | Ax, Ay, Az Accelerations | Ax, Ay, Az Accelerations |
| | | Avx , Avy, Avz Angular velocity | Avx , Avy, Avz Angular velocity | Avx , Avy, Avz Angular velocity |
| Upper Neck | Fx, Fy, Fz forces | Fx, Fz forces | Fx, Fz forces | Fx, Fy, Fz forces |
| | Mx, My, Mz moment | My moment | My moment | Mx, My, Mz moment |
| Lower Neck | | Fx, Fz forces | | Fx, Fy, Fz forces |
| | | My moment | | Mx, My, Mz moment |
| Chest | Ax, Ay, Az Accelerations | Ax, Ay, Az Accelerations | Ax, Ay, Az Accelerations | Ax acceleartion sternum |
| | | Avy Angular velocity | Avy Angular velocity | |
| | Dx displacement: Mid-sternum | Dx displacement: Mid-sternum | Dx displacement: Mid-sternum | IRTRACC upper and lower L/R Dxyz |
| Clavicle | | | | Clavicle L/R (2x) Fx, (2x) Fz |
| Abdomen | | | | Abdominal pressure sensors APTS 2 |
| Thoracic spine | | Fx, Fz forces | | Fx, Fy, Fz forces |
| | | My moment | | Mx, My, Mz moment |
| Lumbar spine | Fx, Fy, Fz forces | Fx, Fz forces | Fx, Fz forces | |
| | Mx, My, Mz moment | My moment | My moment | |
| Pelvis | Ax, Az Accelerations | Ax, Az Accelerations | Ax, Az Accelerations | Ax, Ay, Az Accelerations |
| | Avy Angular velocity | Avy Angular velocity | Avy Angular velocity | Mx, My, Mz moment |
| | Upper Iliac Fx force (left, right) | Iliac Fx force (left, right) | | Iliac Fx force (left, right) |
| | Lower Iliac Fx force (left, right) | Iliac My moment (left, right) | | Iliac My moment (left, right) |

*Table A2.*
*Summary data for H3-5F tests*

| | | | 40% ODB | | | | 25% ODB | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Seating position | Left | Left | Right | Right | Left | Left | Right | Right |
| | | Rear seatbelt technology | Standard | PT & LL | Standard | PT & LL | Standard | PT & LL | Standard | PT & LL |
| | | Vehicle | 2016 Toyota Camry | 2018 Toyota Camry | 2016 Toyota Camry | 2018 Toyota Camry | 2017 Toyota Camry | 2019 Toyota Camry | 2017 Toyota Camry | 2019 Toyota Camry |
| Group name | Parameter | IARV# (threshold)/ Test ID | CF19018 | CF19019 | CF19020 | CF19021 | CF19006 | CF19011 | CF19004 | CF19003 |
| Head | HIC15 | 779 | 644 | 294 | 388 | 184 | 387 | 199 | 449 | 175 |
| | Clip_3_ms (g) | (70) | 78 | 55 | 59 | 44 | 59 | 45 | 65 | 44 |
| Neck | Neck Tension (N) | 2070 | 2945 | 1815 | 2029 | 1470 | 1869 | 1464 | 2318 | 1372 |
| | Neck Compression (N) | -2520 | -474 | -117 | -694 | -32 | -295 | -57 | -501 | -126 |
| | Nij | 1 | 1.0 | 0.6 | 0.6 | 0.4 | 0.6 | 0.5 | 0.7 | 0.4 |
| Chest | Clip_3_ms (g) | 73 | 64 | 35 | 42 | 30 | 52 | 37 | 38 | 27 |
| | Sternum deflection (mm) | -41 | -37 | -28 | -39 | -22 | -33 | -26 | -30 | -20 |
| | VC | (1) | 0.3 | 0.1 | 0.4 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 |
| | Deflection rate (m/s) | -8.3 | -1.8 | -0.6 | -1.5 | -0.4 | -1.2 | -1.0 | -0.9 | -0.6 |
| Belt loads | Lap (N) | (6000) | 7260 | 5483 | 4771 | 4523 | 5230 | NA | 4618 | 3471 |
| | Shoulder (N) | (6000) | NA | 4035 | 7102 | 3815 | 6710 | 3878 | 6158 | 3915 |
| Submarining | Yes/No | | Yes | Yes | Yes | No | No | Yes | No | No |

#Reference [13]

*Table A3.*
*Summary data for H3-50M tests*

| | | | 40% ODB | | | | 25% ODB | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Seating position | Left | Left | Right | Right | Left | Left | Right | Right |
| | | Rear seatbelt technology | Standard | PT & LL | Standard | PT & LL | Standard | PT & LL | Standard | PT & LL |
| | | Vehicle | 2016 Toyota Camry | 2018 Toyota Camry | 2016 Toyota Camry | 2018 Toyota Camry | 2017 Toyota Camry | 2019 Toyota Camry | 2017 Toyota Camry | 2019 Toyota Camry |
| Group name | Parameter | IARV# (threshold) /Test ID | CF19020 | CF19021 | CF19018 | CF19019 | CF19004 | CF19003 | CF19006 | CF19011 |
| Head | HIC15 | 700 | 487 | 254 | 422 | 145 | 339 | 277 | 299 | 155 |
| | Clip_3_ms (g) | (70) | 66 | 50 | 63 | 41 | 57 | 53 | 54 | 42 |
| Neck | Neck Tension (N) | 3290 | 2697 | 1988 | 2582 | 1746 | 2163 | 1296 | 2158 | 1792 |
| | Neck Compression (N) | -4000 | -410 | -84 | -337 | -1353 | -790 | -448 | -233 | -132 |
| | Nij | 1 | 0.6 | 0.5 | 0.5 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 |
| Chest | Clip_3_ms (g) | 60 | 44 | 34 | 45 | 28 | 45 | 29 | 40 | 24 |
| | Sternum deflection (mm) | -60 | -32 | -30 | -48 | -30 | -33 | -28 | -38 | -29 |
| | VC | (1) | 0.1 | 0.2 | 0.3 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 |
| | Deflection rate (m/s) | -8.3 | -1.0 | -0.6 | -1.3 | -0.4 | -1.3 | -0.6 | -1.0 | -0.9 |
| Belt loads | Lap (N) | (6000) | 9359 | 5361 | 8979 | 6725 | 9414 | 5470 | 7191 | 6028 |
| | Shoulder (N) | (6000) | 8491 | 5593 | 8402 | 4352 | 8036 | 4254 | 7688 | 5185 |
| Submarining | Yes/No | | No | No | No | No | Yes | No | No | No |
| Head contact | Yes/No | | No | No | No | Yes | No | No | No | Yes |

#Reference [13]

*Table A4.*
*Summary data for H3-10YO tests*

| | | | 40% ODB | | | |
|---|---|---|---|---|---|---|
| | | Seating position | Left | Left | Right | Right |
| | | Rear seatbelt technology | Standard | PT&LL | Standard | PT&LL |
| | | Vehicle | 2016 Toyota Camry | 2018 Toyota Camry | 2016 Toyota Camry | 2018 Toyota Camry |
| Group name | Parameter | IARV# (threshold) /Test ID | CF19016 | CF19017 | CF19014 | CF19015 |
| Head | HIC15 | 741 | 928 | 345 | 926 | 255 |
| | Clip_3_ms (g) | (70) | 94 | 60 | 85 | 53 |
| Neck | Neck Tension (N) | 1800 | 4363 | 2515 | 3625 | 1820 |
| | Neck Compression (N) | -2200 | -534 | -108 | -1123 | -756 |
| | Nij | 1 | 1.3 | 0.8 | 1.1 | 0.7 |
| Chest | Clip_3_ms (g) | 82 | 63 | 41 | 50 | 34 |
| | Sternum deflection (mm) | -36 | -12 | -7 | -7 | -6 |
| | VC | (1) | 0.1 | 0.0 | 0.0 | 0.0 |
| | Deflection rate (m/s) | -8.4 | -0.8 | -0.5 | -0.8 | -0.4 |
| Belt loads | Lap (N) | (6000) | 6278 | 3891 | 3711 | 2935 |
| | Shoulder (N) | (6000) | 6717 | 3804 | 5876 | 4015 |
| Submarining | Yes/No | | Yes | Yes | Yes | Yes |

#Reference [13]

*Table A5.*
*Summary data for THOR-5F tests*

| | | 40% ODB | | | |
|---|---|---|---|---|---|
| | Seating position | Left | Left | Right | Right |
| | Rear seatbelt technology | Standard | PT&LL | Standard | PT&LL |
| | Vehicle | 2016 Toyota Camry | 2018 Toyota Camry | 2016 Toyota Camry | 2018 Toyota Camry |
| Group name | Parameter/Test ID | CF19014 | CF19015 | CF19016 | CF19017 |
| Head | HIC15 | 810 | 331 | 561 | 306 |
| | Clip_3_ms (g) | 85 | 54 | 70 | 56 |
| Neck | Neck Tension (N) | 2727 | 1853 | 2334 | 1973 |
| | Neck Compression (N) | -1048 | -357 | -282 | -292 |
| Chest | Max deflection IRTACC (mm) | 63 | 53 | 58 | 70 |
| Abdomen | Abdominal pressure sensor left (Pa) | 204,366 | 191,936 | 113,935 | 222,772 |
| | Abdominal pressure sensor right (Pa) | 224,959 | 243,597 | 84,813 | 232,610 |
| Belt loads | Lap (N) | 4705 | 4504 | 6205 | 4116 |
| | Shoulder (N) | 6308 | 3995 | 6522 | 3993 |
| Submarining | Yes/No | Yes | Yes | No | Yes |
| Shoulder belt retention | Yes, if belt slipped off shoulder | No | No | Yes | No |

*Table A6.*
*Average reduction for H3-5F metrics in percent of IARV/threshold with addition of pretensioner and load limiters in 40% and 25% ODB tests.*

| Metric H3-5F | 40% ODB | 25% ODB |
|---|---|---|
| HIC15 | -36% | -30% |
| Head res. Acc. 3ms clip | -28% | -25% |
| Neck tension | -41% | -33% |
| Neck compression | -20% | -12% |
| Nij | -30% | -18% |
| Chest res. Acc. 3ms clip | -28% | -18% |
| Sternum deflection | -32% | -20% |
| Chest VC | -28% | -8% |
| Sternum deflection rate | -14% | -3% |
| Lap belt load | -17% | -19% |
| Shoulder belt load | -55% | -42% |

*Table A7.*
*Average reduction for H3-50M metrics in percent of IARV/threshold with addition of pretensioner and load limiters in 40% and 25% ODB tests.*

| Metric H3-50M | 40% ODB | 25% ODB |
|---|---|---|
| HIC15 | -36% | -15% |
| Head res. Acc. 3ms clip | -28% | -12% |
| Neck tension | -23% | -19% |
| Neck compression | 9% | -6% |
| Nij | -13% | -5% |
| Chest res. Acc. 3ms clip | -22% | -26% |
| Sternum deflection | -17% | -12% |
| Chest VC | -9% | -10% |
| Sternum deflection rate | -8% | -5% |
| Lap belt load | -52% | -43% |
| Shoulder belt load | -58% | -52% |

*Table A8.*
*Average reduction for H3-5F metrics in percent of IARV/threshold with addition of pretensioner and load limiters for the left and right seating positions.*

| Metric H3-5F | Left | Right |
|---|---|---|
| HIC15 | -35% | -31% |
| Head res. Acc. 3ms clip | -27% | -26% |
| Neck tension | -37% | -36% |
| Neck compression | -12% | -21% |
| Nij | -23% | -26% |
| Chest res. Acc. 3ms clip | -30% | -16% |
| Sternum deflection | -19% | -33% |
| Chest VC | -15% | -21% |
| Sternum deflection rate | -9% | -8% |
| Lap belt load | 0% | -12% |
| Shoulder belt load | 0% | -46% |

*Table A9.*
***Average reduction for H3-50M metrics in percent of IARV/threshold with addition of pretensioner and load limiters for the left and right seating positions.***

| Metric H3-50M | Left | Right |
|---|---|---|
| HIC15 | -21% | -30% |
| Head res. Acc. 3ms clip | -12% | -25% |
| Neck tension | -19% | -18% |
| Neck compression | -10% | 11% |
| Nij | -2% | -17% |
| Chest res. Acc. 3ms clip | -19% | -27% |
| Sternum deflection | -6% | -22% |
| Chest VC | -4% | -15% |
| Sternum deflection rate | -4% | -6% |
| Lap belt load | -59% | -28% |
| Shoulder belt load | -47% | -55% |

*Table A10.*
***Average reduction for H3-10YO metrics in percent of IARV/threshold with addition of pretensioner and load limiters for the left and right seating positions.***

| Metric H3-10YO | Left | Right |
|---|---|---|
| HIC15 | -79% | -91% |
| Head res. Acc. 3ms clip | -49% | -45% |
| Neck tension | -103% | -100% |
| Neck compression | -19% | -17% |
| Nij | -47% | -41% |
| Chest res. Acc. 3ms clip | -27% | -19% |
| Sternum deflection | -14% | -4% |
| Chest VC | -3% | -2% |
| Sternum deflection rate | -3% | -5% |
| Lap belt load | -40% | -13% |
| Shoulder belt load | -49% | -31% |

*Table A11.*
***Average percent reduction in THOR-5F metrics with addition of pretensioner and load limiters for the left and right seating positions. Negative indicates higher reduction in the left seating position than the right seating position.***

| Metric THOR-5F | Left vs Right |
|---|---|
| HIC15 | -47% |
| Head res. Acc. 3ms clip | -54% |
| Neck tension | -59% |
| Neck compression | -101% |
| Max deflection IRTACC | -219% |
| Lap belt load | 940% |
| Shoulder belt load | 9% |

# DEVELOPING A CONSUMER SAFETY RATING FOR HEAVY GOODS VEHICLES (HGVS)

**Iain Knight**,
Apollo Vehicle Safety
UK

**Colin Grover,**
**Matthew Avery**
Thatcham Research
UK

Paper Number 23-0264

## ABSTRACT

In Europe, Heavy Goods Vehicles (GVW>3,500kg, aka trucks), represent around 1.5% of registered vehicles, and about 6% of traffic (vehicle km) but are involved in collisions resulting in nearly 15% of road fatalities. Goods transport is an essential fact of modern life, delivering most of our food and luxuries. This link to standard of living will tend to drive increasing truck use and Vision Zero clearly will not be achieved, unless action is taken to improve HGV safety. Size and mass bring significant difficulty but the challenges are not only technical. Freight transport runs on slim margins. Payload capacity, vehicle uptime, fuel and maintenance bills can all outweigh the latest safety innovation when it comes to vehicle specifications. How can we ensure a rating has influence when the relationship between Euro NCAP and the vehicle buyer will be business to business and not business to consumer? How can we create the market for safety that manufacturers need to allow innovation? One make and model can cover variants from an 18 tonne rigid for urban distribution, through off-road construction vehicles and on to 60 tonne multi-trailer combinations for long haul. How can the rating be applied in a meaningful yet economic way?

This paper summarises several years of work to find the answer to these questions, that has involved analysing collision data, investigating the availability, effectiveness and operational constraints of different technical safety measures that could be promoted, and engaging extensively with road owners, safety organisations, the freight operations industry and the vehicle industry. New and quite stringent regulation of HGV safety is imminent in Europe and this has also been a major consideration. Does this already solve the problems? Is there a need to go further? These questions are considered via a case study of measures intended to protect vulnerable road users

The end result is what we believe to be a globally unique application of the consumer rating approach to solve a complex and multi-faceted problem.

## INTRODUCTION

In its roadmap to 2025 [1] Euro NCAP announced its intention to support the development of a truck city safety label. In 2020 the Commercial Vehicle working group was created and began by developing assessments of the ADAS offered on light commercial vehicles <3,500kg. This work has resulted in the world's first Commercial Van Safety Rating. The organisation is now building on that concept to develop a rating scheme for Heavy Goods Vehicles (HGVs) with a maximum permitted mass >3,500kg.

In Europe, Heavy Goods Vehicles (GVW>3,500kg, aka trucks), represent around 1.5% of registered vehicles, and about 6% of traffic (vehicle km) [2] but are involved in collisions resulting in nearly 15% of road fatalities [3]. Goods transport is an essential fact of modern life, delivering most of our food and luxuries. This link to standard of living will tend to drive increasing truck use and Vision Zero clearly cannot be achieved, unless action is taken to improve HGV safety. The issues involved in safe operation of HGVs vary substantially between city and highway environments.

While vans and HGVs have a similar function, to move goods around, they are quite different vehicles, subject to different regulations, and operated quite differently. The size, weight and the ways they are operated present significant technical challenges. Most of the casualties from collisions involving HGVs are those outside the vehicle and not the drivers. Their economic necessity, an extremely competitive freight market with low profit margins, and the structure of the total cost of ownership of an HGV all present significant economic challenges. In light of this, one of the biggest challenges is the method by which Euro NCAP can influence the market. The traditional consumer model, publishing the data, letting mainstream and trade media communicate the results to consumers and relying on them to make the right choices, may not be enough to substantially influence truck purchasing decisions.

This backdrop has meant that in the past vehicle manufacturers have seen a limited commercial market for safety. Innovating and developing new safety systems is a significant risk because if the initial costs are high, or worse, it increases the through life costs in some way, then it can be very hard for cost conscious fleet buyers to justify the investment, at least until such time as there is very strong evidence that the new technology is genuinely effective. As such, Regulation has played a key role in the development of truck safety and the recent Revision of the European Union's General Safety Regulation has imposed significant new safety obligations on HGVs. When the cost is applied to all, it can be more easily passed on to the client and ultimately the consumer because there is no fear that the competition will be cheaper. However, Regulation also has its challenges. It can be slow, prefers a one size fits all approach and this can be problematic in a dynamic and highly varied freight market.

This paper gives an overview of the development of a scheme intended to overcome these challenges and provides a more detailed case study based on one part of the rating to show how the approach varies from Regulation.

## CASUALTY PRIORITIES

Euro NCAP Members have produced an analysis of the number and type of road users killed in collisions involving two vehicles or less that occurred between 2017 and 2019, involving a range of different types of vehicles. Five countries are represented (France, Great Britain, Germany, Italy and Sweden). In total over the combined three-year period, this data provided information on 28,452 fatalities from all types of collisions and 3,340 fatalities from collisions involving at least one HGV. Although the relative importance of HGVs in this sample is slightly lower than the EU average (12% compared to EU wide 14%), the patterns within the HGV group are closely representative of the EU as a whole. Casualty groups were identified separately when the collision occurred in an urban area (excluding motorways) and outside an urban area (referred to as extra urban and including all motorways regardless of whether classed as urban or rural). A high level summary of data from collisions where at least one HGV was involved[1] is reproduced below.

[1] Data included all fatalities, regardless of number per collision or road user type, from collisions where at least one HGV was involved, including single vehicle collisions involving just one HGV and no other road user, HGV to pedestrian collisions and collisions with other vehicles. Note that in order to allow precise attribution of impact partners, collisions where 3 or more vehicles were involved were excluded.

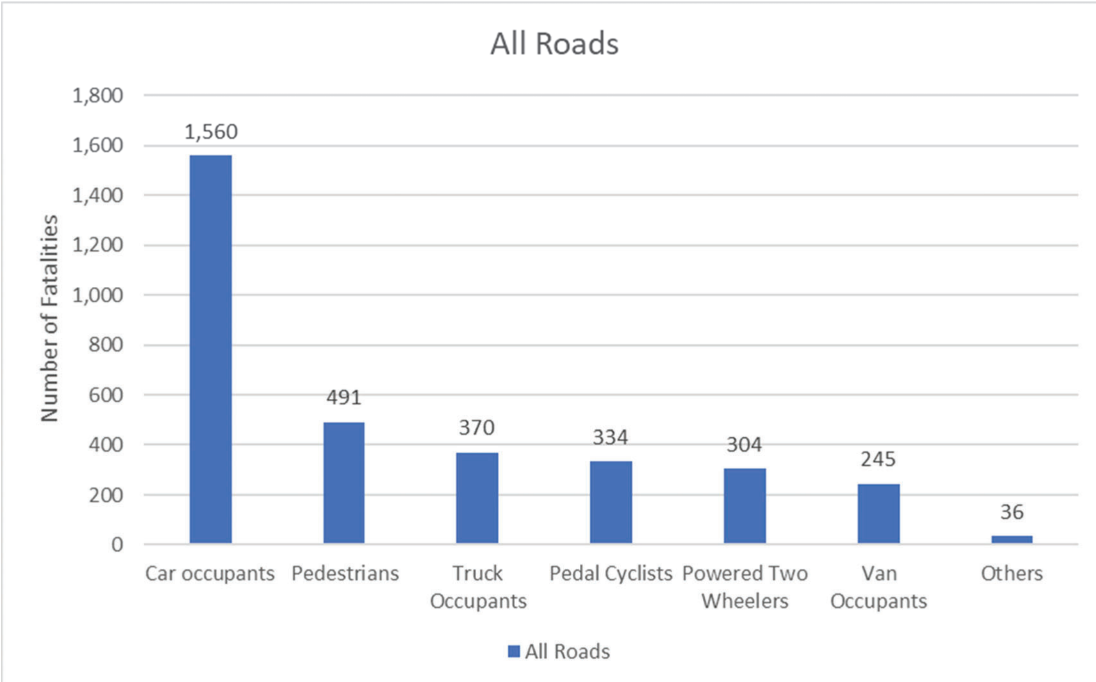



**Figure 1: Number of fatalities from collisions involving at least one HGV by road user type killed**

When all roads are considered, car occupants are clearly the dominant fatality group, and it can clearly be seen that fatalities from collisions involving trucks are dominated by road users outside of the truck (89%) with truck drivers and passengers representing just 11%. However, the pattern varies strongly when the roads are divided into categories of Urban Roads (City) and rural roads and motorways (Highways).

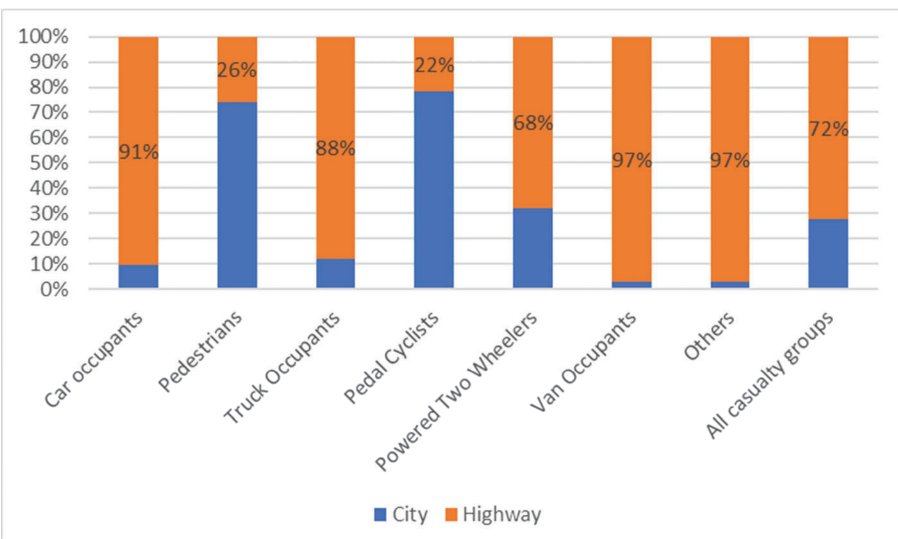



**Figure 2: Distribution of fatalities by road user type killed and road environment**

Truck collisions resulting in car occupant, truck occupant, and van occupant fatalities are predominantly a highway collision type. Those resulting in pedestrian and cyclist deaths are mainly a city collision type, with powered two wheelers a significant factor in both but mainly highway.

The data underlying these graphs also show that across all areas and casualty types 56% of fatalities involve rigid trucks and 44% tractor semi-trailer combinations.

**KEY SAFETY TECHNOLOGIES**

Euro NCAP has studied the available evidence about safety features for HGVs and assessed their potential in light of:

- The type of casualties they are intended to prevent (target population);
- System effectiveness (where evidence is available);
- Current and future availability in the commercial vehicle market;
- Opportunity to accelerate or exceed existing and forthcoming regulatory standards.

A brief summary of systems and the planned approach for each is presented below:

- **AEB for vulnerable road users** crossing or moving in the same direction: A large subset of pedestrian fatalities plus a significant number of cyclists are addressed, the crossing collisions mainly in urban areas, the longitudinal ones more often outside of towns. The effectiveness is proven in cars and currently only one HGV manufacturer offers the system.
- **Lane Support Systems**: Address a range of fatalities from different road user groups that occur when an HGV unintentionally leaves its lane, including the HGV occupants in run off road, pedestrians and other vehicle occupants when the HGV drifts onto a hard shoulder on motorways, or other vehicle occupants when they collide with overtaking or oncoming vehicles when drifting out of lane. Effectiveness is proven in passenger cars, there is only a regulatory requirement for simple warning systems in HGVs, and several manufacturers offer more advanced systems as options.
- **Vision**: This targets a sub-set of pedestrian and cyclist fatalities that occur during low speed manoeuvres such as nearside turns (right in EU, left in UK) and aims to decrease blind spots and improve driver reactions compared with seeing hazards in standard mirrors.
- **AEB Nearside Turn Across Cyclist Path**: Addresses part of the same casualty population as vision, but aims to do so even when the cyclist is in places that cannot be seen directly and/or where the driver response still is not the correct one, even if the hazard is available to be seen. One manufacturer offers a system but there is no regulatory requirement.
- **Motion Inhibit**: This addresses the part of those low speed manoeuvring crashes considered by direct vision that involve an HGV moving off from rest. The aim is to prevent forward motion if a VRU is detected ahead of the vehicle. Currently no manufacturers offer a system, though it is understood to be technically feasible.
- **AEB for vehicle front to rear**: Despite forthcoming improvements in the regulation, it is considered higher performance is possible in respect of the higher speeds, partial overlap collisions and driver over-ride.
- **Occupant Status Monitoring**: Inattentive driving is a major contributory factor to serious collisions of all types and HGVs are no exception. Evidence suggests that professional truck drivers experience inattention differently to car drivers, less frequently impaired by alcohol, more frequently by fatigue. However, Euro NCAP has shown with passenger cars that direct driver monitoring can be effective in both mechanisms and similar systems will be mandatory in the EU from 2026. We think there may be scope to encourage earlier fitment and exceed the regulatory standard, particularly in a professional driving context where trials suggest strong benefits from linking to fleet management systems to allow drivers struggling with fatigue to be identified and helped with softer interventions, not just in-cab warning.
- **Crash Compatibility**: The single biggest group of fatalities from collisions involving HGVs is car occupants. There are differences between countries but in many the largest group are killed in head on collisions. A large mass ratio, height differences and stiff structures create incompatibility. Front underrun protection regulations have been in place since 2003 to mitigate but is imperfect and more can be done, particularly where manufacturers offer 'elongated' cabins under new EU weights and dimensions regulations for improving safety and environmental performance. Similar issues occur at the rear of vehicles and less frequently the side.
- **Passive Pedestrian Protection**: This will address the same group of crashes as AEB VRU but in a different way. AEB will not avoid all frontal collisions with VRUs and HGVs are not subject to regulation on their passive pedestrian protection in the ways that cars are. Applying the principles from cars is possible but not straightforward. The near vertical front that many HGVs are designed significantly changes the distribution of injuries, the probability of damaging secondary impacts with the ground and being runover by the wheels and the same test procedures may no longer be appropriate. However, there is scope for encouraging improved shapes and kinematics, as well as energy absorption, particularly near the edges of the vehicle where AEB is less likely to be effective.

- **HGV occupant protection**. HGV drivers represent a substantial minority of fatalities and most frequently occur in a frontal collision with another heavy vehicle, or a single vehicle collision often involving rollover. Regulation demands a minimum standard of cab strength to ensure a basic survival space in simple pendulum tests and seat belts are mandatory. Manufacturers are thought to go beyond this and undertake internal programmes of full-scale crash tests and to some degree the kind of measures seen in cars, like a frontal airbag, are seen in HGVs. But, overall, they appear to remain well behind the best passenger vehicle occupant protection technologies.
- **ISA:** Although ISA will be mandatory in 2024, Euro NCAP protocols will go further, for example, in recognition of implicit speed limits and truck specific limits.
- **ISO 17840 compliant Rescue Sheets** for post-crash safety.

Some of these technologies are ready to go, with test procedures easily transferred from our car scheme, others will take time either for the technologies to develop among the industry and/or for Euro NCAP to develop the assessments.

## WHAT ARE THE CHALLENGES

Euro NCAP's usual audience is the European consumer, a mix of individual personal buyers, lease companies and fleets. Their motivations for choosing a safe vehicle are driven by personal needs and choices. Providing the consumer with clear and simple metrics has proven to be an effective way of stimulating customer demand that, in turn, encourages car makers to introduce innovative safety technology. This strategy is less likely to work for HGV safety, where drivers have little influence, and commercial pressures inevitable mean fuel and maintenance costs are high priority.

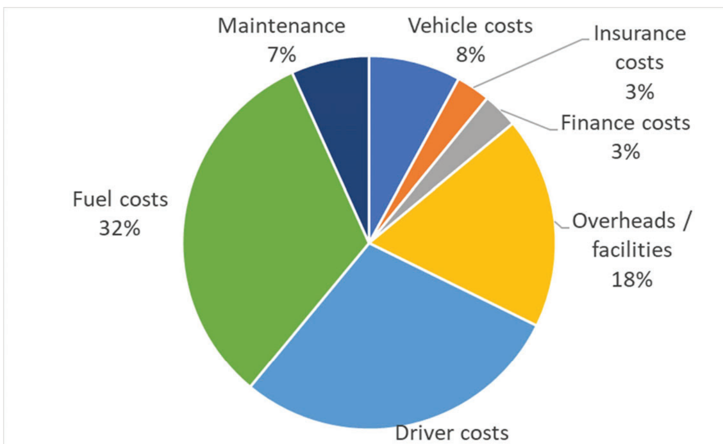



**Figure 3: Distribution of running costs of a 44t UK tractor unit. Source: derived from [4]**

Whilst a fleet manager has a duty-of-care for their drivers, uncertainty over through life costs and reliability of innovative safety or environmental features can encourage a conservative approach to vehicle specifications. Stimulating customer demand for safer vehicles within the freight industry will therefore require a different approach from the simple publication of safety ratings. So how can this be achieved?

Road authorities, particularly those responsible for large cities, have started to take their own action. Low emissions zones have proliferated and in some cases the approach has been extended to safety. For example, since 2020 London has banned HGVs from entering the city[2] unless they have a minimum standard of direct vision, or a collection of safety equipment intended to mitigate blind spot collisions. Vienna has also considered but rejected (due to legal concerns) banning trucks from turning right in the city[3] unless they are equipped with a "turn assist" system. Austria as a whole, and Germany offer a financial incentive to operators to fit turn assist systems. Barcelona is supporting the fitment of forward collision warning and blind spot information systems on buses. These local schemes clearly influence the vehicle operators in those regions very directly. However, the focus is often on aftermarket technology and the standards applied in different areas vary considerably. This limits the influence such schemes can have on the truck OEMs and major tier 1 suppliers and makes life complicated for international operators shipping goods to different places.

### How can we deal with the diversity of vehicles and companies?

HGVs are considerably more expensive than passenger cars, with an average tractor unit costing more than €100k. Their specifications are also extremely customisable so that they can cope with a wide range of applications and most manufacturers take a modular approach to at least some degree. At the most flexible end

---

[2] https://tfl.gov.uk/info-for/deliveries-in-london/delivering-safely/direct-vision-in-heavy-goods-vehicles
[3] https://ec.europa.eu/growth/tools-databases/tris/nl/index.cfm/search/?trisaction=search.detail&year=2020&num=10&iLang=EN

of the scale, there are a selection of cab variants, engine variants, gearbox chassis, axle suspension etc. and these can be assembled in almost any permutation the customer wants, leading to many thousands of possible truck specifications. Although vehicles are sold under “model” names, these are not like the models of car as Euro NCAP knows, in some cases they are mainly marketing mechanisms with relatively little engineering meaning.

Autonomous Emergency Braking (AEB) performance can vary slightly for different variants of the same model of passenger car. However, this variation may be much greater for HGV’s. The range of basic physical characteristics such as mass, number of axles and brake performance is much larger than for cars and lower sales volumes reduce the ability to economically tune systems to any specific application. For example, a 2 axle 18-tonne rigid with a low chassis height and a 3-axle tractor unit with highline twin bed cab for 44 tonne, 6 axle, long haul operation may both be available under the same “model” name. The extent of the effect of this variation on the performance of each safety feature incorporated in the rating needs careful consideration.

HGVs are often built in multiple stages with the OEM responsible for the chassis cab and another company responsible for constructing the body (e.g. box, curtainsider, tipper etc). While the OEM is responsible for most relevant safety features, the body builder may be responsible for crash compatibility measures (underrun protection) at the side and the rear, elements of lighting etc. These tend to be much smaller companies, often serving a very local market. Similarly, the situation with trailers complicates things. The design and performance of the trailer will influence the performance of some safety systems on the tractor (e.g. combination brake performance) but they also come with their own important safety systems, such as roll stability control, rear and side crash compatibility measures etc. In most countries it would be typical for there to be significantly more trailers in existence than tractor units and they are often seen as low-tech, lower cost assets and may be kept in service for much longer than the HGV.

## THE PROPOSED SOLUTION

### A new business model

Euro NCAP consider that creating a market where the safest choice of vehicle is also the most profitable choice of vehicle will be critical to success. Euro NCAP cannot achieve this in isolation. Many other stakeholders already have a large safety and economic influence on freight operations. The freight carriers themselves have the key stakes but in a competitive industry they will be strongly focussed on their customer needs, those shipping the goods. Both carriers and shippers will have corporate and social responsibility objectives and providing them with the means to easily embed strong safety improvements in their contracting processes or in-house procedures is an important path to influence. Other than national and international regulations around the use of vehicles, another main factor driving freight industry behaviour is the ability and cost of accessing the road network with their vehicles. Road owners, often but not always local or national public sector bodies, can dictate of at least guide industry behaviours on their specific networks. The aim of the new business model is to target this broad range of professional stakeholders with the safety information that Euro NCAP provides so that they can use it in their local contracting, road pricing, or road access policies as well as freight best practice programmes that already exist in many countries. Direct links with national and local initiatives that have a strong influence on freight operations, combined with a robust, harmonised framework of technical standards, these can create the buying power necessary to generate the demand for safe vehicles that manufacturers need if they are to combine innovation and commercial success.

Euro NCAP’s membership is mainly national governments, consumer, and motoring organisations. This new model changes the dynamic and our customers for this information become city authorities, highway authorities, fleet insurers and freight shippers and operators. The aim is that the existence of the Euro NCAP standard can make it easier for authorities to create local schemes comparable to, London’s HGV safety permit, or Germany’s financial incentives. There is no longer a need to create a bespoke technical measure for each area. In addition to this, it is hoped that authorities will join Euro NCAP as members to identify the safety problems in their jurisdiction that new safety measures could solve. In this way, the rating scheme and the technology roadmap should continuously evolve to meet the needs of the communities affected by HGV operations.

### The rating concept

Euro NCAP has identified several aims for its rating concept. It should:

- Create clear and simple ratings applicable to the operating area of each vehicle
- Offer clear indication to fleet managers as to the safest vehicles for their application
- Be relevant to the collision types and environmental problems commonly occurring in each different usage area.

- Appeal directly to the organisations that can promote vehicle safety and sustainability through the use of the Euro NCAP Rating
- Create a pan-European market for safe freight vehicles through an international technical standard and a cooperative model of local and national actions that can help deliver Vision Zero
- Encourage the adoption of zero emission vehicles to address environmental concerns

Euro NCAP already has a safety rating scheme for Commercial Vans in the N1/N2 category that is designed to be relevant to fleet managers and business owners and offers a safety rating in 4 graded areas from Bronze to Platinum. Consistency with this approach is seen as a clear benefit. However, it is also clear to us that our key customers have quite different needs. For cities, it's all about vulnerable road users. Outside of those areas, vehicle occupants are more important. Similarly, with HGVs there is much more dedication of vehicles to specific missions. Yes, some will be general purpose vehicles engaged in many different tasks. However, many will be used depot to depot and never go near a built-up area. Others will spend their whole life distributing goods in cities, and others such as 4 axle rigid tippers might be built for very specific construction or waste purposes and require diverse usage capability covering, off-road sites, rural lanes, motorways and city centres.

One size does not fit all when it comes to trucks, and sustainability should include consideration of economic sustainability too. There is no point encouraging an urban specific safety solution on a truck that never enters an urban area, that would just be a cost without a benefit. But if vehicles without urban safety systems are permitted it is only right to allow cities to try and keep them out of areas where those urban risks are high. This has led to our concept of a dual rating for City and Highway environments. All vehicles will be rated against both sets of criteria. City authorities will link their access restrictions or incentive schemes only to the City rating, motorway authorities to the Highway rating. Freight shippers can choose what is important to them on a contract-by-contract basis. If vehicle operators buy a vehicle for a specific use, they also only need consider the appropriate rating. Only general-purpose vehicles may require good performance in both ratings.

**Application of the rating**

Creating the scheme is a very significant departure from business as usual, both for Euro NCAP and for the wider freight and vehicle industries. We see "win-win" partnerships as the ideal approach and the plan is to start simple:

- OEM chassis cab evaluation only – no body builder or trailer features
- Include ability to rate vehicles down to VIN level – important enabler of local incentive schemes
- Euro NCAP Membership aim to test each safety feature for at least one high sales volume variant from each manufacturer, in each of 4 freight applications:
    - Long Haul
    - Distribution
    - Construction/waste
    - Utility
- Maximum rating validity of 3 years.

The extent to which industry will be willing to pay to extend their rating to more individual variants of vehicle will depend strongly on the actions of our partners in city and highway authorities around Europe, and how they use the standard to drive vehicle procurement based on the Euro NCAP rating. Expanding this usage rapidly will be a key focus for Euro NCAP.

**The Roadmap**

The same roadmap process is proposed as has been successfully used in the passenger car rating, to let manufacturers know what is coming in time to design solutions for it. The roadmap targets technologies that are both cost effective and realistic in their implementation over the next few years. The passenger car model started with just three assessment areas and grew over time. A similar evolution is expected. The proposal for certified safe trucks are presented for Cities (top) and Highways (bottom) below.

**Table 1: Matrix of roadmap technologies and the casualty groups they affect for City Safety (top) and Highway Safety (bottom)**

| | | | | 2024 | | | | | | | 2027 | | | 2030 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Casualty Scenario | Weighting* | Speed Assistance | AEB Vehicle Front-to-Rear | Lane Support | AEB Vulnerable Road User | Vision | AEB Turn Across Bicyclist Path | Rescue Info, eCall … | Occupant Status Monitoring | Motion Inhibit | AEB Reverse | AEB Turn Across Vehicle Path | AEB Head-On | Passive Ped. Protection | Crash Compatibility Front/Side | Occupant Protection |
| EURO NCAP CITY SAFE 2023 Silver Rated | Partner protection | Crossing Pedestrian/Bicyclist | 50% | ● | | | ● | ● | | | ● | ● | | | | ● | | |
| | | In-Lane Pedestrian/Bicyclist | 5% | ● | | ● | ● | | | | ● | | | | | ● | | |
| | | Turning Across Pedestrian/ Bicyclist | 10% | | | | | ● | ● | | ● | | | | | | | |
| | | Reversing Over Pedestrian/Bicyclist | 5% | | | | | ● | | | ● | ● | ● | | | | | |
| | | Powered Two Wheeler Rider | 10% | ● | ● | | | | | | ● | | | ● | | | | |
| | | Car/Van Occupant | 15% | ● | ● | ● | | | | | ● | | | ● | ● | | ● | |
| | Self | HGV Occupant | 5% | ● | ● | ● | | | | ● | ● | | | ● | ● | | | ● |
| EURO NCAP HIGHWAY SAFE 2023 Gold Rated | Partner protection | Crossing Pedestrian/Bicyclist | 5% | ● | | | ● | | | | ● | | | | | ● | | |
| | | In-Lane Pedestrian/Bicyclist | 5% | ● | | ● | ● | | | | ● | | | | | ● | | |
| | | Powered Two Wheeler Rider | 10% | ● | ● | | | | | | ● | | | ● | | | | |
| | | Car/Van Occupant | 65% | ● | ● | ● | | | | | ● | | | ● | ● | | ● | |
| | Self | HGV Occupant | 15% | ● | ● | ● | | | | ● | ● | | | ● | ● | | | ● |

*Provisional weighting based on EU accident data.

## WILL REGULATION DO THE JOB ANYWAY: A CASE STUDY OF VRU SAFETY

### Summary of the Regulatory & Market Developments

According to analysis of the collision data for 5 Euro NCAP Member Countries, approximately 34% of all those killed in collisions involving at least one heavy goods vehicles are either pedestrians, pedal cyclists or powered two wheeler riders. The General Safety Regulation has recognised the safety of vulnerable road users in collision with an HGV as a particular problem and three of the 17 new technical measures implemented, specifically target heavy duty vehicles (trucks and buses):

- **UN Regulation 151**: Blind spot information systems, intended to inform the driver of the presence of a cyclist to the nearside of a vehicle in order to prevent a collision if the driver were to turn the vehicle to the nearside across the path of the cyclist. The driver must get a more urgent collision warning if a collision becomes imminent. Compliance will be mandatory for all new registrations in the EU from the summer of 2024
- **UN Regulation 159**: Moving -off information system, intended to inform the driver of the presence of a pedestrian or cyclist immediately in front of the vehicle in order to prevent collisions where the driver may have pulled away from a rest position because they were unable to see the person in a blind spot in front of the vehicle. Compliance will be mandatory for all new registrations in the EU from the summer of 2024
- **UN Regulation XXX**[4]: Direct vision, intended to significantly improve the view through the cab windows so that more vulnerable road users can be seen through the windows, which research suggests results in faster reaction times, compared to seeing the same hazard in mirrors. Compliance will be mandatory for all new registrations in the EU from 2029.

These three regulations represent strong action on specific crash types involving low speed manoeuvres where the truck turns across the path of a cyclist travelling to the nearside of an HGV and where the HGV pulls away from rest when a pedestrian or cyclist is present. Considering the collision data across the EU, the Volvo Truck Safety report [5] shows that these mechanisms are responsible for 20% and 5% respectively of killed and seriously injured (KSI) casualties resulting from collisions between trucks and VRU. The same report shows that a further 30% arise in situations where a VRU, mainly pedestrians, suddenly cross the path of an HGV approaching at moderate to high speed. Similar results have been found in other studies in the UK and Germany [6,7].

Pedestrian AEB is a well-documented mitigation for this more classic 'crossing pedestrian' scenario. Thanks to Euro NCAP it is almost ubiquitous on new passenger cars in Europe but only Daimler currently offer a production version on trucks. A comprehensive revision of UN ECE Regulation 131 on AEBS for heavy duty

[4] At the time of writing this had been adopted by WP.29 but not yet published with an official number

vehicles has been adopted, and at the request of Japan, that included rules for a pedestrian AEB function. These will come into force very soon. However, the General Safety Regulation is primary legislation, the latest revision does not require pedestrian AEB and the next revision is likely to be some years away, so it is not thought likely to be mandatory in Europe for some years yet. This is a very clear gap, where Euro NCAP can continue its leading role in driving the fitment of active safety systems and extend and adapt its requirements to HGVs.

The low speed manoeuvring crashes are a very local phenomenon. Data from London [8] shows a clear difference to the Europe wide figures [5], with some 58% of pedal cyclist and pedestrian casualties involving this mechanism, compared with 30% where the HGV was going ahead at normal traffic speeds.

When GB as a whole was considered [9] 57% of GB pedestrian and cyclist fatalities from collisions involving HGVs turning to the nearside or moving off from rest occurred in just 5 major cities, representing 25% of the population. Thirty seven percent of those fatalities occurred in London alone (15% of GB population).

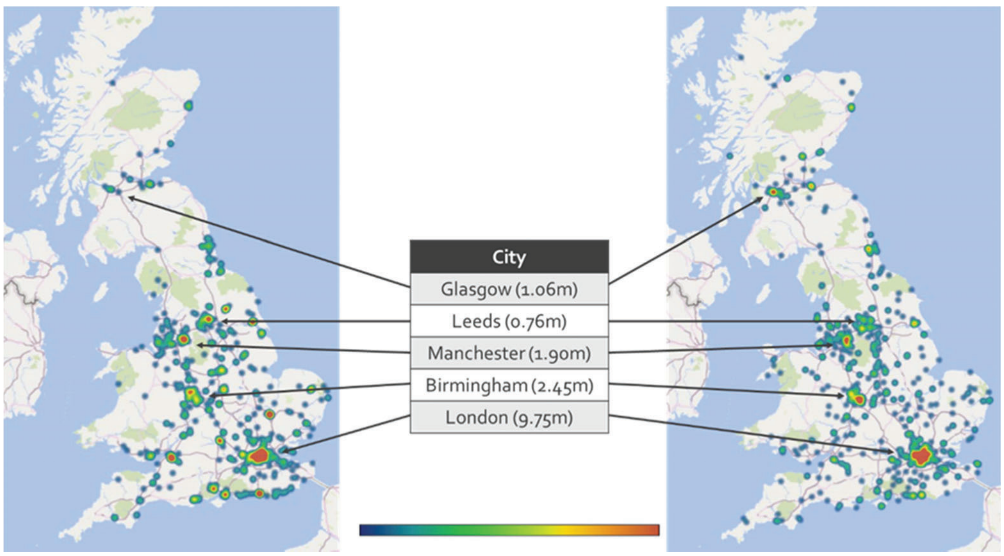



**Figure 4: Location of GB collisions between HGVs moving off or turning to nearside and pedal cyclists (left) and pedestrians (right)**

This localisation of the problem presented a severe technical challenge to the development of a direct vision regulation. Comparison of the direct vision performance of existing HGVs [10] has shown strong correlation with the height from the ground at which the seat is positioned and, in turn, this is very strongly dependent on operational requirements for ground clearance, engine power, and interior space in the cabin in different circumstances, such as long haul, quarrying, or forestry. A Regulation will affect ALL vehicles regardless of where they end up being used. As such a minimum standard of direct vision that was sufficiently demanding to make a meaningful improvement in the performance of the type of vehicles most commonly used in cities, could potentially impose severe limitations on some important operating characteristics of those that are rarely used in cities.

As a consequence, it took the working group 5 years to develop the regulation and the development was controversial throughout. Reaching a defined limit value involved a new approach, unique to type approval, to try to identify likely vehicle use from design proxies such as GVW, axle configuration, sleeping facilities, engine power etc. This categorised vehicles into three categories by their probability of use in an urban area. It is highly complex and will inevitably be imperfect. The presence of the imperfections also drove additional safeguards that made the technical method of measuring the direct vision more complex, with some unintended design constraints that will only be solved with a subsequent regulatory amendment. That amendment is still work in progress at the time of writing. The agreed limit values, although very demanding for industry to meet with vehicles servicing the most difficult parts of the freight market, still fall a long way short of the best available for urban operations that already exist in the market. Some low-entry cabs have near perfect close proximity views through the windows but are limited in ground clearance and engine power so cannot do all freight tasks.

Other developments have also occurred in parallel with the development of the direct vision regulation

- Regulations 151 and 159 for information systems to alert drivers to the presence of VRUs in close proximity to the vehicles and are subject to relatively high minimum standards of effectiveness, expected to work well in practice. In the case of R151 for nearside turns, the warnings are active in situations where the cyclist is positioned significantly to the rear of the cab at the critical moments the driver needs to see them. They are already visible in mirrors at this time and cannot possibly be seen in direct vision at that time.
- Camera Monitor Systems to replace physical mirrors have become more common and the evidence around their use [5] suggests that with good design they mitigate for initial human factors concerns about distracting glances away from the road and can offer a better view than mirrors in terms of both size and quality.
- Mercedes have brought to market a form of AEB that they call Active Sideguard Assist. The stated function of this system is to act like the Regulation 151 warning systems but to automatically brake the vehicle to a stop to increase the range of collisions it is effective in, by guaranteeing the correct response and requiring less response time than the average driver. A similar approach is technically feasible for moving off from rest collisions, and is perhaps technically simpler, but no manufacturer has yet brought this to market.

It is clear that the benefits of these systems are partially overlapping and partially additive, and even individually, can go further than the Regulations require. None are a silver bullet alone and achieving vision zero may well require all of them.

**What will Euro NCAP do differently and how will it help?**

Euro NCAPs approach is always led by the analysis of collisions and other relevant data to define the problems, working with technology and the industries producing it to find the solutions, and helping to create the market that makes those solutions financially viable.

The example provided by the Direct Vision is an unusual one, but the ‘one size fits all’ approach of most Regulation is of at least some issue in many areas of HGV safety and the way in which vehicles are used in some areas of the freight industry, constrain the safety features fitted. This typically results in exemptions, which can be quite wide ranging at in some cases. Electronic Stability Control, AEB, underrun protection are all subject to at least some exemptions, sometimes because of problems that will occur in only small proportions of the total use of those vehicle categories.

Solving this problem is the primary driver in the decision to have a separate City and Highway rating, linkable to the schemes of local authorities such as the London HGV Safety Permit. It is considered far simpler and more effective to consider the constraints or advantages of the different use of vehicles at the point where they are in use, rather than at the point of design. At a crude level, an off-road vehicle operating within and around quarries in remote parts of Sweden will never enter a major city and will have no need for a City Safe rating. However, it is not necessary for either the manufacturer or the authority to identify some feature of the vehicle that accurately identifies its end use in this industry. It is simply up to the buyer of the vehicle to assess whether or not they need a rating and up to the city authorities to decide whether they wish to try to discourage or even prohibit unrated vehicles from entering their territory.

This means that demanding high standards of performance for an urban vehicle will not excessively constrain another area of performance in a long haul or specialist vehicle, providing much more freedom to promote higher levels of performance where it is needed.

The freedom to incentivise higher standards, means that the concerns about improvements to only one side largely disappear, all performance is improved. As such, the technical method used can revert to the simpler part of the regulatory procedure and removes the need for a complex alternative method to avoid unintentional barriers to innovative vehicles. As such, while still being entirely consistent with the regulation, the method can be substantially simpler and start with the floor level set by regulation at $7m^3$.

The effectiveness of different approaches to vulnerable road user safety will be measured in relation to their ability to reach Vision Zero. Where the same fatalities could be prevented by alternative different measures, appropriate degrees of substitution will be allowed in the rating. As such, the ability of advanced, mirror replacement, camera monitor systems to complement direct vision and the current new technology for AEB turn across cyclist path and future technology for motion inhibit will be packaged in the rating with Direct Vision and will be balanced in a way that allows some degree of flexibility to manufacturers in how they more along the path towards elimination of close proximity manoeuvring collisions. The incentive must be that the casualties are prevented, not that vehicles must be designed in a certain way. Manufacturers should have freedom to innovate to achieve the goal.

Current gaps in the GSR approach to VRU safety in collisions with HGV will be filled.

- The inclusion of AEB VRU in 2024 and the future development of passive pedestrian protection for 2030 will more than double the total number of VRU casualties that are in scope, and the inclusion of two approaches will improve the effectiveness over time.
- Additionally, powered two wheelers are rarely involved in either the low speed manoeuvring or the crossing collisions mainly targeted by the measures. Analysis of more detailed collision data from France has suggested that one of the most frequent causes of moped/motorcycle casualties in collisions involving HGVs is when the HGV turns across the path of a motorcyclist coming in the opposite direction. AEB technologies to address this situation are roadmapped for 2030. These technologies are only just beginning with passenger cars and the HGV market is lagging substantially behind passenger cars, so it is not expected to be commercially available for some time.

So, in summary, compared with Regulation, the Euro NCAP rating approach will much better reflect the wide variety of different jobs that the freight industry use vehicles for and the local differences in both vehicle usage and crash patterns. This better matching, and acceptance of small niche functions allows the Euro NCAP approach to be implemented much faster than regulation, in some cases with considerably less complexity, responding more quickly to technical changes and being much more flexible about how industry achieve the goals. The same setup allows a common international standard to much better link with proliferating local safety schemes in order to create the demand from the customers buying HGVs that will create a more profitable market for vehicle manufacturers selling safety features, and encourage innovation.

## CONCLUSIONS

HGVs are disproportionately represented in the fatality statistics compared with their use. However, their use is, and will continue to be, essential to economic development and well-being.

The paper describes the use of a novel interpretation of the Euro NCAP consumer rating approach that aims to translate the safety transformation that NCAPs around the world have had in the passenger car market, to the commercial vehicle market.

To do this, requires the scheme to go much further than regulation, while simultaneously imposing no more, or ideally less, constraint on vehicle operations and ensuring industry can be both safe and economically sustainable.

The key innovation is to link to a range of local initiatives, such as Transport for London’s HGV Safety Permit or financial incentives in Germany or Austria. These can provide the levers that make it profitable for the freight industry to invest in additional safety features. The harmonised technical standard helps create the volume demand that is, in turn, what enables to vehicle industry to innovate and produce the safer vehicles that progress in the car market has proven to be possible.

Making a dual rating based on the type of in-service use (City or Highway) supports the link with authorities that can implement local safety schemes, but also allows the resolution of complex trade-offs that Regulations can find hard to deal with.

Reduced complexity in the application will help Euro NCAP develop and evolve much faster than regulation and allow the standards to be pushed much closer to best practice than is generally possible in an international regulation.

## REFERENCES

[1] Euro NCAP, 2017. “2025 Roadmap: In pursuit of vision zero” Brussels: Euro NCAP

[2] Extracted from Eurostat Data https://ec.europa.eu/eurostat/data/database

[3] ERSO, 2017. Traffic Safety Basic Facts 2017: Heavy Goods Vehicles and Buses, Brussels: The European Road Safety Observatory supported by the European Commission.

[4] Motor Transport, 2020. Cost Tables, s.l.: https://motortransport.co.uk/wp-content/uploads/2021/01/Cost-Tables-2020.pdf.

[5] Kockum, Ortlund, Ekfjorden, & Wells, 2017. "Volvo Trucks Safety Report 2017". Volvo Trucks Accident Research Team.

[6] Schindler, R., Jansch, M., Johannsen, H. & Balint, A., 2020. An Analysis of European crash data and scenario specification for heavy truck safety system development within the Aeroflex project, Helsinki, Finland: Proceedings of the 8th Transport Research Arena TRA

[7] Knight, I. et al., 2017. A Direct Vision Standard for HGVs: Casualty impact analysis for proposed implementation in London, London: Transport for London

[8] Knight, I., Dodd, M., Robinson, B. & Ainge, M., 2018. HGV Safety Permit for London: Evidence of effectiveness and candidate technical requirements for the safe system, London: Transport for London

[9] Direct Vision Task Force, 2018. "Summary of justification and proposal for differentiated requirements for N3 vehicles". UNECE working Group GRSG, informal Group VRU-Proxi, Document VRU-Proxi-18-02-Rev1

[10] Summerskill.et al., 2015. Understanding direct and indirect driver vision in heavy goods vehicles: Final report prepared on behalf of Transport for London . Loughborough: Loughborough University, pp. 1-432

[11] Robinson, Knight, Martin, Seidl, Manning & Eyers, 2016. "Assessing the direct vision performance of Heavy Goods Vehicles (HGVs)". TRL Project report CPR 2277 published by Transport for London.

# EURO NCAP VIRTUAL TESTING - CRASHWORTHINESS

**Corina Klug, Martin Schachner**
TU Graz
Austria

**Andre Eggers**
BASt
Germany

**Jakub Galazka**
Toyota
Belgium

**Simon Gargallo**
ZF
Germany

**Cristian Jimenez**
IDIADA
Spain

**Jessica Kirch**
Honda R&D Europe
Germany

**Ines Levallois**
Faurecia
France

**Uwe Lobenwein**
Mercedes-Benz AG
Germany

**Norman Meissner**
BMW AG
Germany

**Victor Pardede**
Hyundai Motor Group
Germany

**Bengt Pipkorn**
Autoliv, Chalmers University of Technology
Sweden

**James Ellway, Michiel van Ratingen**
Euro NCAP
Belgium

Paper Number 23-0284

## ABSTRACT

The European New Car Assessment Programme (Euro NCAP) began using numerical simulations in its vehicle ratings in 2009. Virtual testing with human body models was first used in the assessment of vehicles equipped with deployable pedestrian protection systems. In 2019, Euro NCAP created the Virtual Testing Crashworthiness (VTC) working group. This working group is supported by Euro NCAP, Euro NCAP's members along with industry representatives from both the European Automobile Manufacturers Association (ACEA) and the European Association of Automotive Suppliers (CLEPA). The far side occupant assessment was selected as the first load case for this work. The objective of this paper is to introduce the procedures defined by the Virtual Testing Crashworthiness working group and present the results generated within the two pilot test series.
In addition to the standard load cases defined in the current far side assessment protocols, robustness load cases were defined with varying impact angles and seat heights. Simulations of the specified load cases were performed by the car manufacturers with their internally developed and validated vehicle models. Two series of physical far side sled tests were performed in accordance with the Euro NCAP Far side occupant sled test procedure with the corresponding vehicles. These test series were used to evaluate the validity of the vehicle models and the capabilities of the simulation models to predict the trends observed within the tests. Processes and acceptance criteria were established to ensure that the simulation models are as representative as possible of their physical counterparts while protecting the intellectual property of the car manufacturers and suppliers. The validated vehicle models are used in a series of robustness simulations.
The physical sled test results from the pilot phase showed reasonable test scatters, even when using two different WorldSID dummies, and were shown to be a suitable test result to be used for validation of the vehicle models. The developed procedure was applicable within the pilot tests. The ISO Scores, used as objective validation metrics, were comparable between standard and the new robustness load cases, indicating that the procedure and the model used were robust. Further room for improvement of the assessment procedure was identified, specifically regarding the acceptance criteria of signals with low amplitudes.
The current study outlines the procedures for introducing virtual testing of occupant safety into consumer information. When viewing vehicle safety ratings from a consumer perspective, it is acknowledged that computer simulations cannot completely replace physical testing. However, a combination of physical and virtual testing offers a powerful and flexible assessment of vehicle safety. The robustness load cases will be assessed in the future based on the virtual tests only and complement the existing far side occupant assessment in the final vehicle rating.

## INTRODUCTION

Automotive design engineers have been using advanced computational models for many years to study and optimize crash performance over a vehicle and its components with minimum crash testing. While computer-aided engineering (CAE) has become increasingly more popular and sophisticated in the industry, its use in regulations and consumer protection is still uncommon. The European New Car Assessment Programme (Euro NCAP) began using numerical simulations in its 2009 vehicle ratings for pedestrian protection. Human Body Models (HBM) were first used to assess vehicles equipped with deployable pedestrian protection systems, and this was where the first certification procedure for virtual human models was developed [1]. Building upon this work, Euro NCAP created the Virtual Testing Crashworthiness (VTC) working group in 2019 and tasked it with developing a virtual test and assessment procedure for application in other impact scenarios for future Euro NCAP ratings.

Virtual testing is a way to add broader scope and robustness to the existing Euro NCAP assessments without increasing the physical test burden. Where limitations in physical test equipment or physical test scenarios exist, virtual testing offers a way of providing a more comprehensive and real-world-like assessment to complement the existing test procedures.

The work of the VTC group began by considering a number of different crash scenarios that could be applied in a virtual environment. To limit complexity, full scale impacts were not considered. Although subsystem tests are more complicated to model than the current pedestrian impact tests, they are not as difficult as full-scale tests. The Euro NCAP Far side occupant assessment was selected as the pilot case for this work. The relevance of far side accidents for injuries of vehicle occupants is well known [2–4], and culminated in the introduction of far side protection into the Euro NCAP ratings in 2020 [5] .

The current Euro NCAP assessment of far side occupant protection has identified limitations of the WorldSID 50th percentile male dummy in this specific impact configuration [6–8]. To overcome these hardware issues and to have a more robust evaluation that considers a greater variety in the evaluated test scenarios, this load case was deemed a suitable candidate for application to virtual testing.

This paper introduces the procedures defined by the working group and presents the results generated within the two physical pilot testing phases conducted by the group. A comparison of the CAE and physical tests is presented within this paper along with prerequisites for the CAE models, including dummy model certification requirements.

## METHOD

For a consumer rating programme, it is essential that Euro NCAP has confidence in the models being evaluated to ensure that simulation outputs are trustworthy, robust and can be applied practically to the different assessments.

Based on previous research [1, 9, 10] and discussions with different stakeholders, the following procedure was defined, which is shown graphically in Figure 1:

1.) To gain trust in the used WorldSID simulation model, the models must meet certain qualification requirements for virtual testing. Criteria are defined at three different levels, starting with fulfilling the current ISO 15830 standard in terms of mass properties, external dimensions, range of motion, sensor locations and dynamic qualification procedures. Secondly, the kinematic behaviour of the lumbar spine and neck is checked (as limitations in the current WSID certification for these regions were identified) and compared to hardware tests. On the third level, the full-scale dummy response is validated by means of sled tests on a simplified seat. [11]
2.) Simulations of the predefined simulation matrix consisting of two far side validation load cases and additional virtual testing load cases are performed by the vehicle manufacturer (VM) with their in-house calibrated virtual vehicle models and the qualified WorldSID model. The results are shared with Euro NCAP in a prescribed format via a specific upload portal. The datasets have to include all specified information and to fulfil the specified quality criteria.
3.) After step 2 is completed, physical sled tests of the two validation load cases are performed, and test results are submitted to Euro NCAP.
4.) Euro NCAP compares the hardware sled test results and simulation-based predictions with each other to validate the VM's virtual model of the vehicle environment (including seat, seatbelt, airbag, centre console). By this means Euro NCAP can establish the necessary trust in the VM model, without physically requiring access to the model.

5.) If the validation results of step 4 are sufficient, i.e. hardware and simulation results closely match, this step (5) can be skipped. If the validation results are not sufficient, the VM must provide evidence showing this was caused by the specific hardware test conditions, deviating from simulation parameters. The simulations of the two standard validation load cases may be repeated with adjustments to prescribed boundary conditions from the sled tests. The boundary conditions are limited to initial positions (node coordinates od dummy, seat and belt) as well as adaptions to the measured crash pulse. The repeated simulations for these validation load cases are again shared with Euro NCAP. If validation criteria are still not fulfilled, the results submitted in step 2 are not considered for the assessment, otherwise step 6 follows.
6.) The results from the virtual testing load cases submitted in step 2 are considered for the vehicle rating.

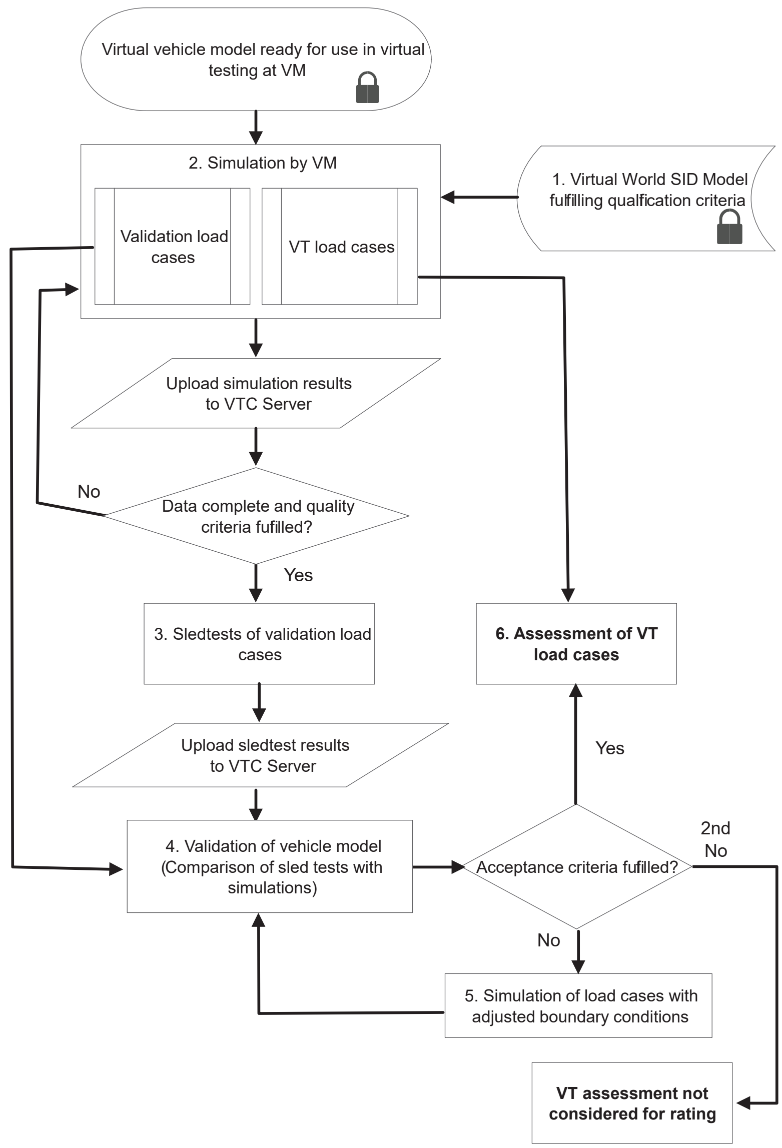



***Figure 1: Overview of the developed virtual testing procedure***

The procedure was applied in two pilot test phases with different complexity (one with and one without centre airbag) from two different car manufacturers. Additional validation tests were performed within the pilots, to analyse the performance of the simulation models outside of the standard validation load cases.

**Simulation setups**

The vehicle models are calibrated in advance and VMs must have confidence that the model is ready to predict occupant responses in far side test cases. No modifications of the vehicle models are allowed during the virtual testing procedure. All material models and settings are kept constant apart from boundary conditions, such as the

initial position of the seat, initial seat deformation, belt routing and load curves describing the sled acceleration, especially in the last step of the procedure where simulations are rerun after the tests.
The qualified WorldSID model was positioned in the calibrated vehicle environment in line with the Euro NCAP Far side testing protocol [12]. The Dummy model was settled in the seat, so that no in-physical spring-back occurs at the simulation start and realistic contact forces are present (initial displacement of H-Point in z-direction should be <10mm in first 5 ms).

The following quality criteria were defined for the simulations:

- Max. Hourglass Energy of full setup < 10% of max. internal energy.
- Max. Hourglass Energy of all WorldSID components < 10% of max. internal energy of WorldSID.
- Max. mass added due to mass scaling to the total model is less than 5 % of the total model mass at the beginning of the run.
- Less than 10 mm H-point z-disp. in first 5 ms of the simulation (5 ms after t0).
- Simulation time needs to exceed time of maximum head y-displacement*1.2.

**Load cases**

Load cases were defined based on the analysis of real-world crashes within the rage of useful application possibility of the WorldSID. To assess the robustness of the far side occupant protection, the vertical seat position and the impact angle were varied. The overall matrix is summarised in Table 1. Load case 1 and 2 are part of the current far side assessment and supposed to be used as validation load cases in future assessments. Within the two pilots, additional sledtests were performed to investigate the validity of the simulation models within a wider range of scenarios. Those are supposed to be assessed in future assessments virtually only to prove that the occupant protection works robustly.

***Table 1: Load case matrix describing the robustness load cases, validation load cases and additional validation load cases simulated / tested within the two pilots***

| | Pulse | Impact Angle | Seat position x (fore/aft) | Seat position z (height) | Test-data Pilot 1 | Test-data Pilot 2 | Validation load case |
|---|---|---|---|---|---|---|---|
| 1. | Pole | 75 | reference | reference | x | x | x |
| 2. | AEMDB | 75 | reference | reference | x | x | x |
| 3. | Pole | 60 | reference | reference | x | x | |
| 4. | Pole | 60 | reference | uppermost | x | x | |
| 5. | Pole | 65 | reference | reference | x | | |
| 6. | Pole | 75 | reference | uppermost | x | x | |
| 7. | Pole | 90 | reference | reference | x | x | |
| 8. | Pole | 90 | reference | uppermost | | | |
| 9. | AEMDB | 60 | reference | reference | x | x | |
| 10. | AEMDB | 60 | reference | uppermost | | | |
| 11. | AEMDB | 75 | reference | uppermost | | | |
| 12. | AEMDB | 90 | reference | reference | x | x | |
| 13. | AEMDB | 90 | reference | uppermost | | | |

Airbag deployment times and pre-tensioner settings were consistent between simulations and tests and fulfilled the criteria defined in the far side testing protocol for both pulses.
In the analysis of results of this paper, we focus on the load cases where test data is available for both pilots to enable comparison. Simulation results were available for the remaining load cases.

**Laboratory tests**

Sled tests were performed of the load cases highlighted in Table 1 in accordance with Euro NCAP far side protocol [12] The WorldSID was positioned in the vehicle as close as possible to the simulation specifications provided from the vehicle manufacturer.

**Data processing**

For the head excursion evaluation, the lateral displacement (global y-direction) of the head CoG is considered. To assume the outside are of the head, which should be compared to the vertical lines, 80 mm distance from the head

CoG to the outer surface of the head are assumed, which corresponds to half of the distance between the two head targets in lateral (y) direction of the Wold SID. All injury criteria are calculated according to Euro NCAP Technical Bulletin 021.

ISO Scores were calculated according to ISO/TS 18571 standard [13] including the latest corrections of the standard, with a python library developed by TU Graz, which is available open-source (https://openvt.eu/validation-metrics/ISO18571).

To summarise ISO Scores of multiple axis to one sensor score, the individual scores were weighted per axis based on its amplitude according to

**Equation 1:**

$$Score_{Sensor} = \frac{\max(|Sensor_x|) \cdot ISO_{Sensor_x} + \max(|Sensor_y|)\, ISO_{Sensor_y} + \max(|Sensor_z|)\, ISO_{Sensor_z}}{\max(|Sensor_x|) + \max(|Sensor_y|) + \max(|Sensor_z|)}$$

whereby the maximum channel values $\max(|Sensor_i|)$ are based on the testing signals, as they are seen as "ground truth".

Data is processed on a Euro NCAP hosted VTC server, where processing is performed directly after the data upload and simulation and testing results are automatically merged and all quality and acceptance criteria are checked.

## RESULTS

### Repeatability of results

The pole reference load case (75° and seat in reference position) was tested in both pilots three times, whereby one test was repeated and in one, a different dummy was used. The differences in resulting injury metrics are shown in Figure 2 and Figure 3 and compared to the prediction from the simulation. Highest differences within the tests were observed upper neck moments in both pilots. In Pilot 1, remarkable differences were also observed for the lower neck moments, where the highest deviations between simulation-based predictions and test results were observed. In Pilot 2, the lumbar spine y force and x moment also showed higher deviations than the other metrics. Head excursions were in both pilots the most critical injury metric (highest percentage of lower performance threshold) and showed only small test scatter (difference <2%).

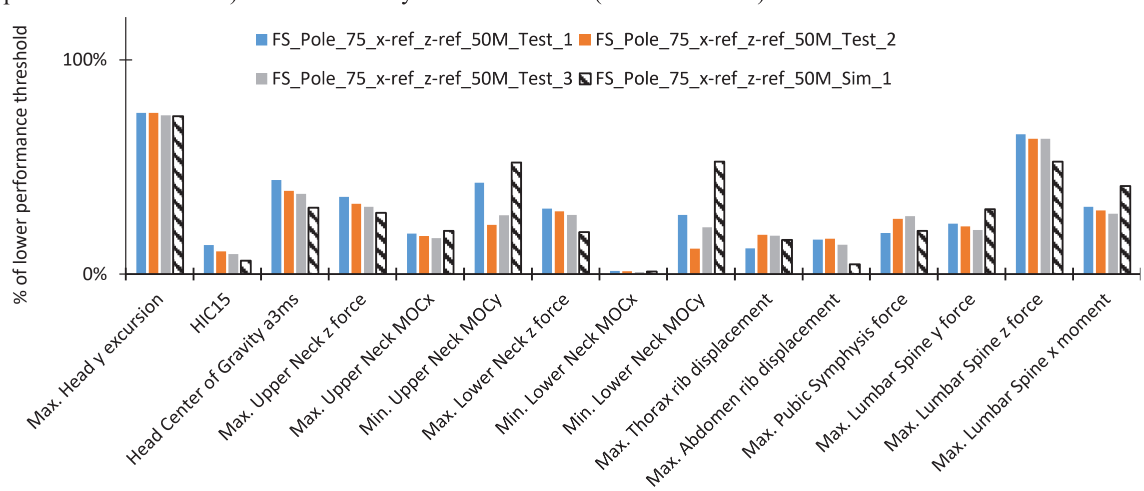



*Figure 2: Injury criteria deviation between repeated tests with the same and different dummy in Pilot 1*

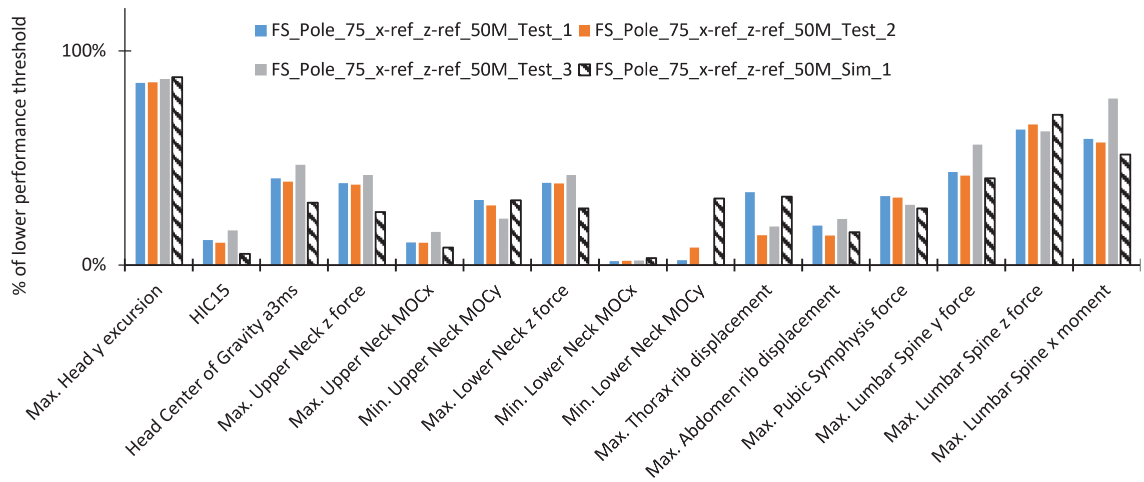



***Figure 3: Injury criteria deviation between repeated tests with the same and different dummy in Pilot 2***

The amplitude weighted ISO Scores per sensor ($Score_{Sensor}$) for the two pilots are shown in Figure 4 and Figure 5, where the signals from the simulation of the load case were compared to the three repeated tests respectively. The use of a different dummies caused differences in ISO Scores. However, when comparing the different sensors with each other, the trends of which sensors showed the highest / lowest scores were the same among the three different tests. Highest differences in ISO Scores between the three tests were observed for the rib deflections.

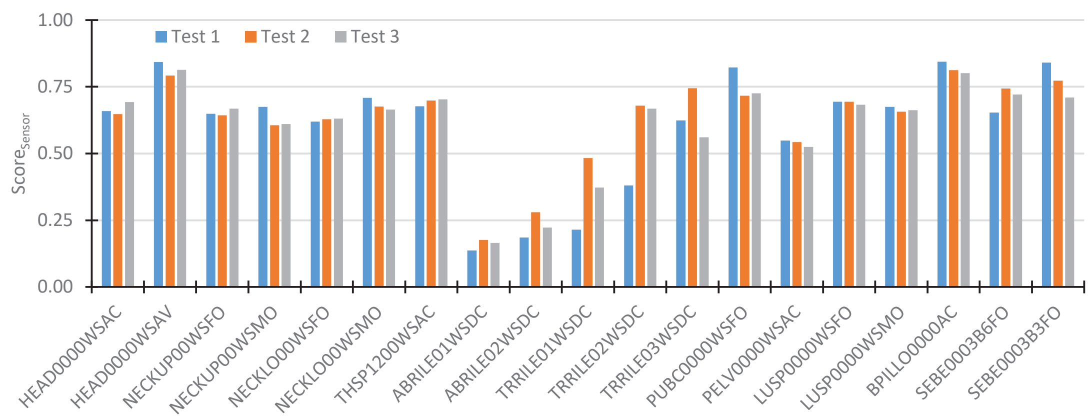



***Figure 4: Sensor scores for pole 75 degree load case in Pilot 1 for the 3 different repeated tests (test 3 was performed with a different dummy; test 1 was included in the later comparisons)***

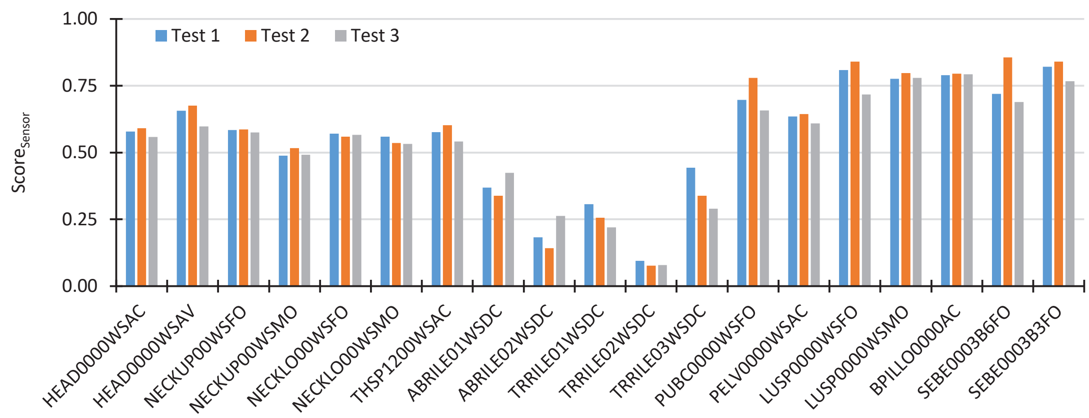



***Figure 5: Sensor scores for pole 75 degree load case in Pilot 2 for the 3 different repeated tests (tests 1 and 2 were performed with a different dummy; test 3 was included in the later comparisons)***

**Validation results over different use cases**

The $Score_{Sensor}$ values of the robustness load cases (tested only within the pilot phase) were in general similar to those of the standard validation load cases with only single outliers for isolated channels (especially rib deflections). The $Score_{Sensor}$ for the load cases with uppermost seat positions were lower compared to the standard seat position.

In both pilots, lowest $Score_{Sensor}$ values were observed for the rib deflections.

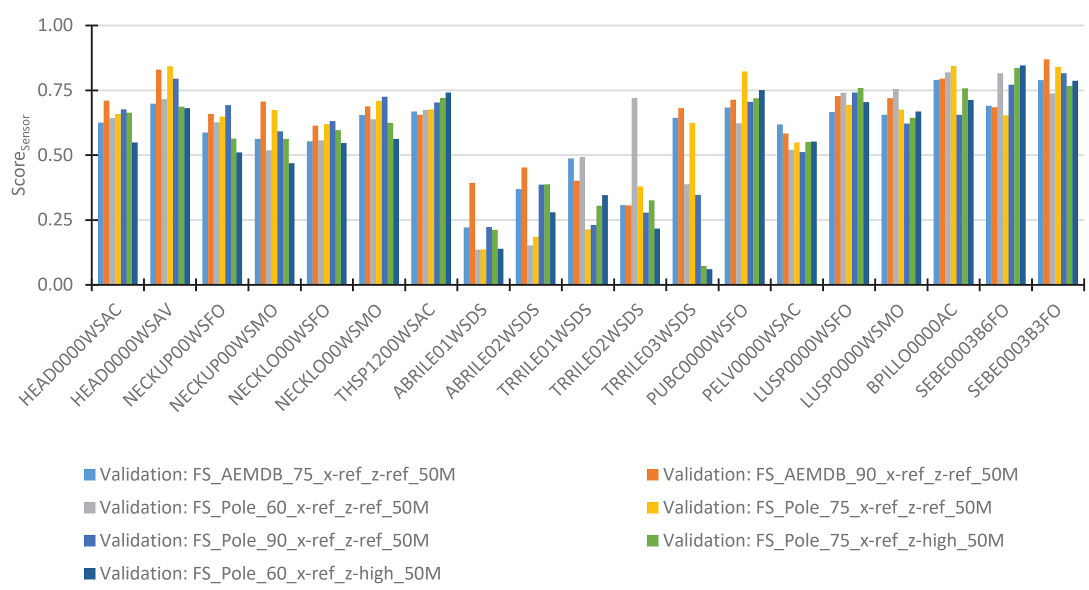



***Figure 6 Sensor scores for the different channels and load cases from Pilot 1***

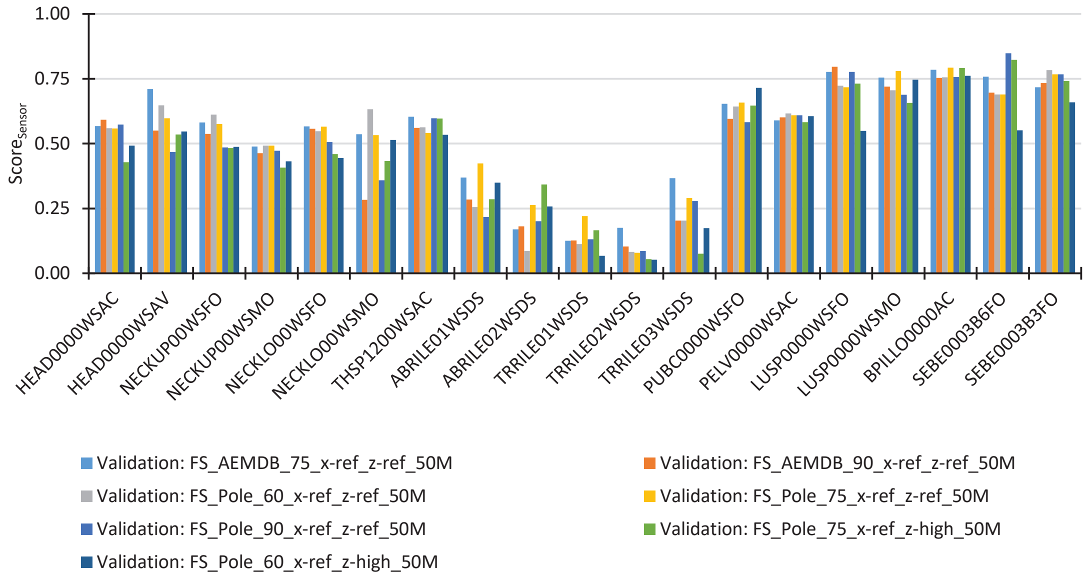



*Figure 7: Sensor scores for the different channels and load cases from Pilot 2*

As a metric to validate the overall kinematics, the weighted sensor scores of the accelerometers of the head CoG, T12 and the pelvis were averaged for each load case. Theses averaged acceleration scores (mean_acc) are summarised in Table 2. They were higher than 0.58 (fair according to ISO standard [14]) in all cases in the first pilot. In the second pilot, values of the averaged acceleration scores below 0.58 were observed for the load cases with uppermost seat position, in which significant deviations between simulations and tests were also observed in the qualitative comparison of videos and animations as well as the standard pole 75 degree impact when compared to Test 3 (values >0.6 were observed for the other 2 tests for this load case).

*Table 2: Mean $Score_{Sensor}$ from head, T12 and pelvis accelerometer for all load cases in two different pilots*

| **Pulse** | **AEMDB** | **AEMDB** | **Pole** | **Pole** | **Pole** | **Pole** | **Pole** |
|---|---|---|---|---|---|---|---|
| **Angle** | **75** | **90** | **60** | **75** | **90** | **75** | **60** |
| **Z-position** | **reference** | **reference** | **reference** | **reference** | **reference** | **uppermost** | **uppermost** |
| **Mean acc Score Pilot 1** | 0.64 | 0.65 | 0.61 | 0.63 | 0.63 | 0.65 | 0.61 |
| **Mean acc Score Pilot 2** | 0.59 | 0.58 | 0.58 | 0.57 | 0.59 | 0.54 | 0.54 |

Due to the higher complexity of the second pilot, the ISO Scores were lower compared to the first pilot, which can be seen also in Figure 8, where the ISO Scores per sensor for the two standard load cases of the two pilots are compared.

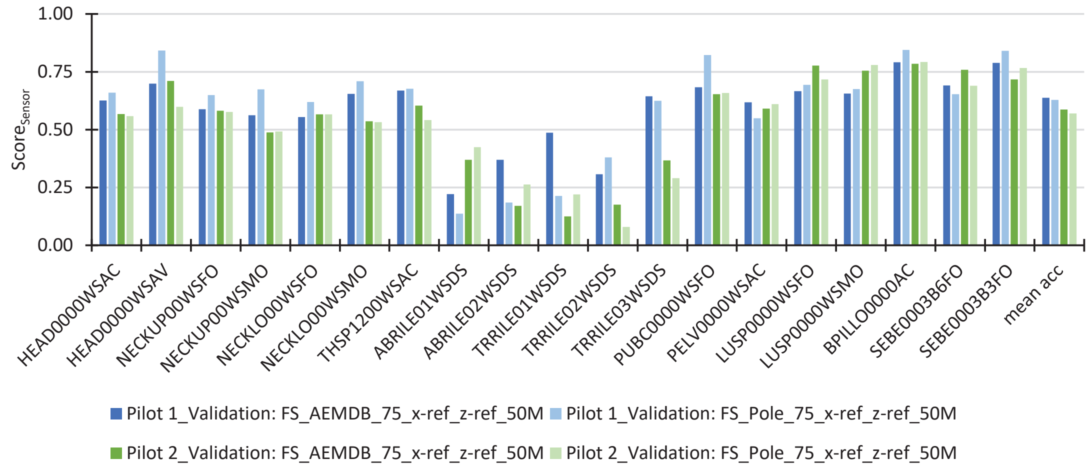



***Figure 8: ISO scores for the different channels and load cases from Pilot 1 & 2 for the load cases which are going to be used for validation of the vehicle models in the final procedure***

**Assessment results over different load cases**

The cars analysed in the pilot phase were shown to protect the occupants robustly over a wide range of loading scenarios, which is shown in Figure 9 and Figure 10 for both pilots and for simulation-based predictions (transparent) as well as the performed sled tests. Rib displacements were very low over all load cases as well as HIC and the neck x moments. None of the lower performance thresholds was exceeded in the analysed load cases within the tests. Higher head excursions (within the orange zone for the simulations) were observed in the second pilot for the load cases with higher seat position, whereby the simulations were more sensitive to that change than the tests. The load case with the highest head excursion was the 75° Pole impact from the second pilot in the uppermost seat position, which was true for simulations and tests. No such sensitivity on the seat height adjustment was observed in the first pilot.

Deviations between predicted injury metrics from simulations and the laboratory tests were highest for the neck moments MOCy in both pilots. In the first pilot, these deviations were observed for the upper and lower neck, while they were only prominent for the lower neck in the second pilot.

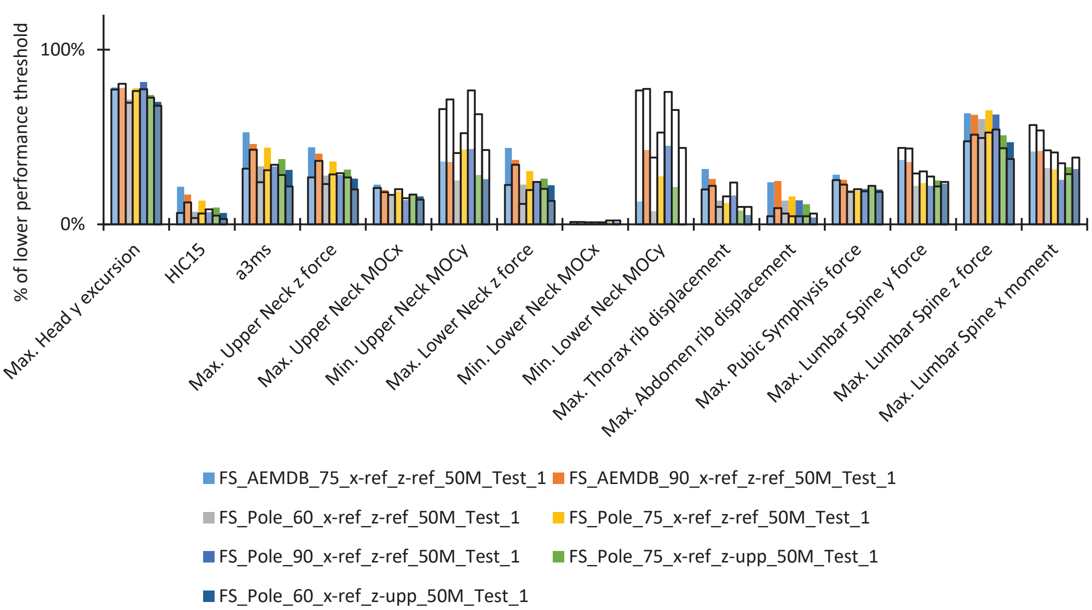



***Figure 9: Injury criteria for the different load cases relative to threshold for Pilot 1 from tests (coloured bars) and simulations (white transparent bars with black frame)***

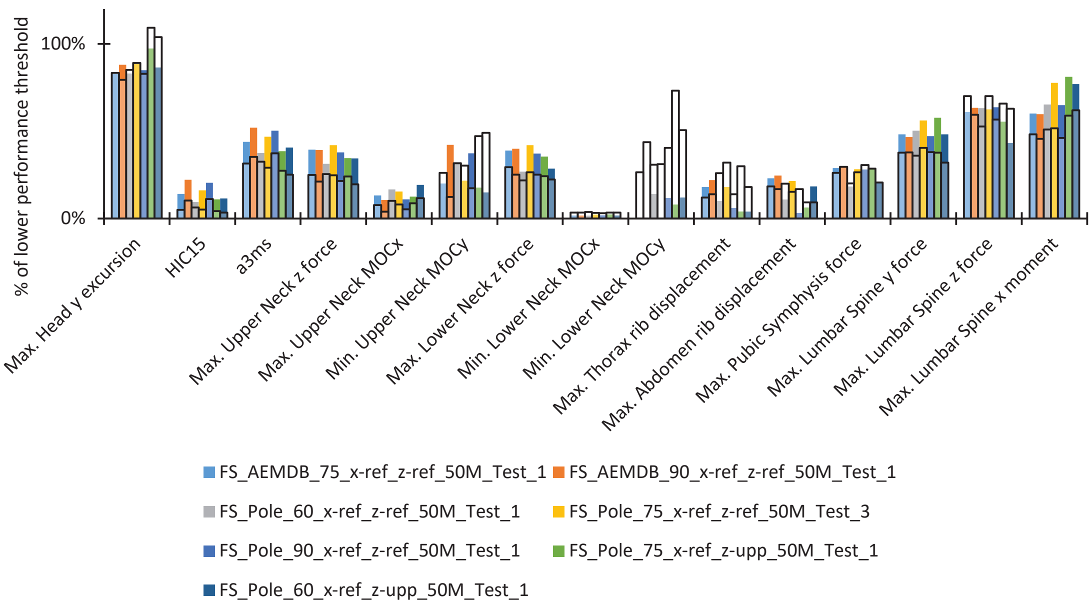



***Figure 10: Injury criteria for the different load cases relative to threshold for Pilot 2 from tests (coloured bars) and simulations (white transparent bars with black frame)***

## DISCUSSION

Euro NCAP has developed the first procedure for virtual testing of occupant safety that can be used in a standardised consumer information testing protocol. The procedure was applied in two pilot phases and a protocol and related tools have also been drafted. The current procedure focuses on robustness of occupant protection systems and utilises virtual models of WorldSID as occupant

### Model validation

Throughout the development of the procedure, the definition of appropriate acceptance criteria and the levels that those criteria must meet were the most challenging aspects to establish. It is these criteria that will determine if a CAE model represents the physical tests sufficiently and can be used for virtual testing. It therefore underpins the confidence that exists in the model for the further assessments and load cases to be evaluated.

While simulations may offer greater repeatability and reproducibility over physical testing, one cannot expect simulation results to be closer to test results than the individual test results are to each other. Therefore, when defining acceptance criteria, scatter from physical testing has to be considered when defining how strictly they should be defined for different sensors.

Another component of this includes the results from the WorldSID model qualification procedure, as these demonstrate the predictive capabilities of the WorldSID model itself. One particularly problematic area is the WorldSID lumbar spine. This is not certified at a component level in hardware testing and the loading it receives in a far side impact results in kinematics that are not representative of what would be seen in the full dummy thorax certification test. To address this challenge, a new component test setup was introduced in the WorldSID qualification level two requirements [11].

In addition, limitations of the WorldSID dummy on the prediction of rib fractures in far side crashes are known from previous studied. The dummy rib loadings were well below the rib higher performance limits, with the result that comparisons of low values (in terms of % difference) between hardware and CAE can be unreliable and might also be the reason for the low ISO Scores for these channels.

Acceptance criteria have been adopted to reflect the importance of the measure and the reliability of the anticipated values.

A multi-stage approach was drafted for this purpose:

1. Plausibility check: The ISO Score for each individual sensor of the specified list is calculated. The checking of all signals with an ISO Score <0.5 for plausibility (check e.g. for polarity and unit errors) is highly recommended.
2. Sensor check: The single ISO Scores are summarised to $Score_{Sensor}$ according to equation 1and are only checked if they are critical for the overall interaction (seatbelt forces, B-pillar acceleration, dummy accelerations and head rotational velocity). Other signals are added when they exceed a relevant amplitude.

3. Kinematics check: The averaged $Score_{Sensor}$ of the head, T12 and pelvis accelerometer is calculated and checked.
4. Injury criteria check: deviation between test and simulation are checked and compared to the lower performance threshold.

The thresholds for each step and the "relevant amplitude" for step 3 are currently still in discussion and will be further refined during the monitoring phase. Within the monitoring phase it is also planned that other settings than the ones specified in step 5 of the process shown in Figure 1 can be adjusted if justified and documented as additional set of results.

**Limitations**

In the current VTC procedure, every load case that was simulated could be also tested in a laboratory. This has the advantage that validation tests could be performed in the event of any doubts concerning the accuracy of the prediction. At a later stage, when human body models are used as occupant models instead of virtual dummy models, this validation will not be possible. Therefore, the quality and traceability of simulation models used in the different steps will play an essential role [15], which was not considered in the current study.

The developed procedures have currently, only been applied to two different vehicles, whereby only one of these had a centre airbag. Further data will be collected in the course of a monitoring phase to fine-tune the developed procedure and especially acceptance criteria if needed. Also, the load cases only represent relatively small variations (impact angle, seating height) of the official sled test configuration. With more experience, larger variations, such as replacing mid-sized male percentile WorldSID with a small female WorldSID model could be considered.

It was identified that significant deviations between simulations and tests were observed for the rib displacements. This might be caused by the low displacements measured. In the dummy certifications, minimum rib displacements are 35 mm, while rib displacements in the pilots were mostly in the range of 10 mm. The WorldSID dummy was originally designed for near-side and the limited sensitivity for capturing rib loadings in far side scenarios has been observed in previous studies [6–8].

**Outlook**

When viewing vehicle safety ratings from a consumer's perspective, it is acknowledged that computer simulations cannot completely replace physical testing. However, a combination of physical and virtual testing offers a powerful and flexible assessment of vehicle safety. This also allows for advancements that are not open to evaluation by physical testing.

In the first phase of work, the virtual WorldSID model was used for the representations of the car occupants. In future, virtual testing with human body models will also be considered for addressing diversity and enhanced injury prediction capabilities.

The developed procedure for virtual testing with WorldSID models to improve the robustness of the assessments, will be applied for monitoring from 2024 onwards in the Euro NCAP far side assessment and will be fully in force from 2026 onwards.

All that has been learned from this load case will be transferred to other load cases. As indicated in the Euro NCAP 2030 roadmap [16], virtual testing is intended to be also implemented for frontal and whiplash protection assessments with a special focus on the diversity of the vehicle occupants.

## CONCLUSIONS

A procedure was developed to enable virtual assessment of occupant safety to improve the evaluation robustness by considering different loading conditions and seat adjustments. It was observed that the validity of the vehicle models was good and comparable among the different load cases considered. The definition of a pass/fail validation criterion proved to be challenging, which is why a multi-step approach was developed. It was observed that the magnitude of signals plays an essential role and that it is challenging for simulations to predict low amplitudes outside of the design range and for sensors in which higher test scatters were also observed.

The presented procedure is an important first step, pathing the way for future applications of virtual testing to further progress towards real-world safety assessment.

**ACKNOWLEDGEMENTS**

The authors would like to thank Toyota Motor Corporation, Toyota Motor Europe, Honda R&D for supporting Pilots. Testing was performed at IDIADA and TASS. The Pilots were funded jointly by ACEA, CLEPA and Euro NCAP.

The members of the VTC group are:
Michiel van Ratingen, Euro NCAP, Chairman
Corina Klug, TUG, Secretary
James Ellway, Euro NCAP
Andre Eggers, BASt
Rikard Fredriksson, SRA
Jakub Galazka, Toyota
Anais Garo, UTAC Sjef van Montfort, TNO
Simon Gargallo, ZF
Simone Ghiraldello, CSI
Cristian Jimenez, IDIADA
Jessica Kirch, Honda R&D Europe
Hans Lammers, RDW
Ines Levallois, Faurecia/CLEPA
Uwe Lobenwein, Daimler
Norman Meissner, BMW/ACEA
Maria De Odriozola, IDIADA
Victor Pardede, Hyundai Motor Group/ACEA
Bengt Pipkorn, Autoliv
Volker Sandner, ADAC
Hisaki Sugaya, Honda R&D Japan

**REFERENCES**

[1] Klug, C., Feist, F., Schneider, B., Sinz, W. et al., "Development of a Certification Procedure for Numerical Pedestrian Models," in: NHTSA (ed.), *The 26th ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, Eindhoven, Netherlands, 10-13 June:1-24, 2019.

[2] Gabler, H.C., Digges, K., Fildes, B.N., and Sparke, L., "Side Impact Injury Risk for Belted Far Side Passenger Vehicle Occupants," *SAE Transactions*(114):34–42, 2005, doi:10.4271/2005-01-0287.

[3] Gabler, C., Fitzharris, M., Scully, J., Fildes, B. et al., "Far side impact injury risk for belted in Australia and the United States.," in: NHTSA (ed.), *The 19th ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, Washington, D.C., USA, 6.-9.6.2005:1–11, 2005.

[4] Bahouth, G.T., Murakhovskiy, D., Digges, K.H., Rist, H. et al., "Opportunities for reducing far side casualties," in: NHTSA (ed.), *The 24th ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, Gothenburg, Sweden, 8.-11.6.2015:1–51, 2015.

[5] Ellway, J., Hallbauer, K., and & Kerz, T., "The Development of a Euro NCAP Far Side Occupant Test and Assessment Procedure," in: NHTSA (ed.), *The 26th ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, Eindhoven, Netherlands, 10-13 June:1–32, 2019.

[6] Fildes, B., Sparke, L., Bostrom, O., Pintar, F. et al., "Suitability of current side impact test dummies in far side impacts," in: International Research Council on the Biomechanics of Injury (ed.), *2002 IRCOBI Conference Proceedings*, IRCOBI Conference Proceedings, IRCOBI Conference, Munich, Germany, 18.-20.9.2002, IRCOBI, 2002.

[7] Perez-Rapela, D., Markusic, C., Whitcomb, B., Pipkorn, B. et al., "Comparison of WorldSID to PMHS kinematics in far-side impact," in: International Research Council on the Biomechanics of Injury (ed.), *2018 IRCOBI Conference Proceedings*, IRCOBI Conference Proceedings, IRCOBI Conference, Athens, Greece, 12.-14.9.2018, IRCOBI, ISBN 2235-3151, 2018.

[8] Perez-Rapela, D., Donlon, J.-P., Forman, J.L., Pipkorn, B. et al., "Occupant Restraint in Far-Side Impacts: Cadaveric and WorldSID Responses to a Far-Side Airbag," *Ann Biomed Eng* 49(2):802–811, 2021, doi:10.1007/s10439-020-02614-w.

[9] Eggers, A., Schwedhelm, H., Zander, O., Izquierdo, R.C. et al., "Virtual testing based type approval procedures for the assessment of pedestrian protection developed within the EU-Project IMVITER," in: NHTSA (ed.), *The 23rd ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, Seoul, Republic of Korea, 27.-30.5.2013:27–30, 2013.

[10] van Schijndel-de Nooij, M. and Wismans, J., "APROSYS: Advances in secondary safety research," *INT J CRASHWORTHINES* 13(6):591–598, 2008, doi:10.1080/13588260802547110.

[11] Putzer, M., Njilie Adamou, F.E., Zhu, F., Walz, M. et al., "A process to qualify a dummy model for the use in a virtual testing application," in: NHTSA (ed.), *The 27th ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, in press, 2023.

[12] Euro NCAP, "Far side occupant test & assessment procedure: Implementation 2023 - Version 2.3," https://cdn.euroncap.com/media/75473/euro-ncap-far side-test-and-assessment-protocol-v23.pdf, December 28, 2022.
[13] ISO, "ISO/TR 16250 Road vehicles — Objective rating metrics for dynamic systems," ISO/TR 16250, Rev. 2013.
[14] Barbat, S., Fu, Y., Zhan, Z., Yang, R.-J. et al., "Objective rating metric for dynamic systems," in: NHTSA (ed.), *The 23rd ESV Conference Proceedings*, ESV Conference Proceedings, International Technical Conference on the Enhanced Safety of Vehicles, Seoul, Republic of Korea, 27.-30.5.2013:1–10, 2013.
[15] Galijatovic, E., Eichlseder, M., Heindl, S.F., and Klug, C., "Integrity of virtual testing for crash protection," *Front. Future Transp.* 3, 2022, doi:10.3389/ffutr.2022.914489.
[16] European New Car Assessment Programme, "Euro NCAP Vision 2030: A Safer Future for Mobility," https://cdn.euroncap.com/media/74468/euro-ncap-roadmap-vision-2030.pdf, December 20, 2022.

# EURO NCAP'S CURRENT AND FUTURE IN-CABIN MONITORING SYSTEMS ASSESSMENT

**Adriano Palao**
European New Car Assessment Programme
Belgium

**Rikard Fredriksson**
Swedish Transport Administration, Chalmers University of Technology
Sweden

**Mike Lenné**
Seeing Machines, Monash University
Australia

Paper Number 23-0286

## ABSTRACT

Informed by international research and crash data, Euro NCAP has developed a Test and Assessment protocol to measure the performance of direct Driver State Monitoring (DSM) systems, which is implemented from January 2023 as part of the Safety Assist – Safe Driving protocol of the star rating. This protocol was developed in collaboration with experts from several OEMs and Tier 1 and 2 suppliers, and it is aimed at promoting standard fitment of driver monitoring systems that effectively detect impaired and distracted driving, eventually triggering the appropriate vehicle response strategies to warn driver and/or mitigate risks. Getting the full score in the Occupant State Monitoring (OSM) area will only be possible with direct monitoring systems. The protocol describes the DSM system requirements across three areas: Sensing (system performance degradation in the presence of several noise variables such as stature, light, facial features); Driver State (system capability to effectively deem the driver as distracted, fatigued or unresponsive); and Vehicle Response (vehicle deploying timely and appropriate response strategies, eventually avoiding the accident or mitigating its severity).

This paper discusses the rationale behind the assessment methodology and the resulting protocol, and how Euro NCAP envisions DSM as an effective tool to reducing/mitigating a wide variety of traffic accidents. Over the course of 2023 test campaign, Euro NCAP will collect extensive insights from both a practical implementation and technology capability perspective, opening the door for on-going improvements and further requirements. In the coming decade, Euro NCAP expects Driver (or Occupant) State Monitoring systems to tackle areas such as driver engagement, intoxication, optimized passive restraints, child presence detection, optimized passive safety, as well as enhancing the performance and intuitiveness of other ADAS by making them work in synchrony with the driver behavior – eventually increasing driver acceptance [1]. Lastly, the 2023 requirements for direct DSM are based on parameters related to eye gaze and head posture – these are subject to be expanded, allowing for new methods and systems to be used in future.

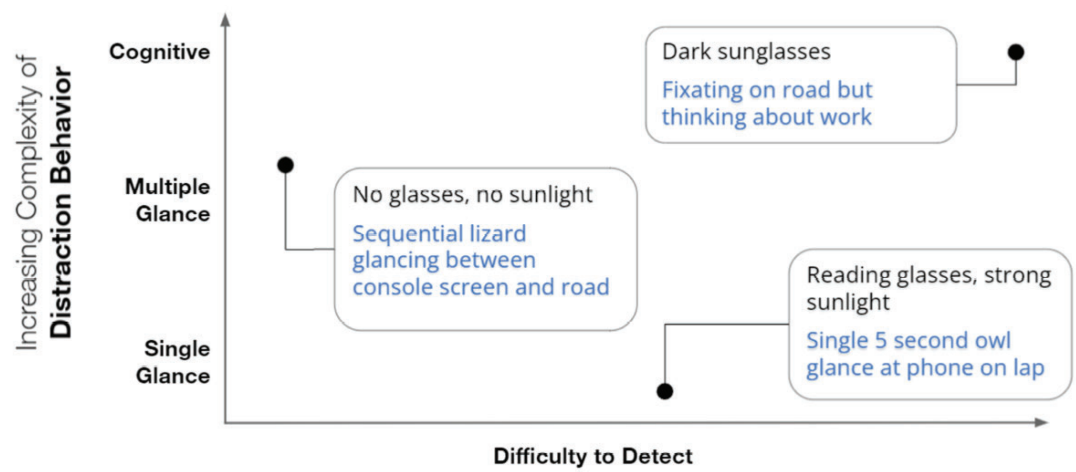
## BACKGROUND

Distracted and drowsy driving are major contributors to global road trauma. Crash data from around the world suggest that up to 25% of crashes are caused by drowsiness, and that distraction and inattention accounts for nearly half of injury crashes [2, 3]. Sudden sickness resulting in the driver losing control of the vehicle is another factor contributing to serious and fatal road accidents [3, 4]. Issues such as distraction and drowsiness have been constants in road safety strategies around the world for many years. The OSM class of technology offers for the first time the opportunity to capture these risks when they occur. Euro NCAP recognizes this and is supporting this new push to advance road safety by rewarding vehicle manufacturers that adopt these technologies, especially in a time of ever-increasing sources of distractions while driving.

**SYSTEM REQUIREMENTS**

To understand the capabilities of an Occupant Status Monitoring system (OSM) two main pillars are considered: detection difficulty and behavioural complexity. On that basis, the protocol requirements are defined to encourage systems that can detect the driver state in a wide variety of circumstances (e.g., under challenging light conditions, wearing facial occluding elements) and regardless of the driver physical attributes (e.g., facial hair, skin type, stature, etc.) eventually ensuring the driver is protected for the longest possible time. Subsequently, the driver state is to be determined through a correlation with a set of behaviours (e.g., long distraction correlated to a single long glance away from the forward road view). As a result, a good system will combine a high situational coverage while featuring a robust behavioural correlation to determine the driver state – as illustrated in the difficulty-complexity matrixes of Figure 1.

Below paragraphs provide a background for the rationale followed in defining measurable parameters for the protocol that enable the determination of defined driver states, alongside a high-level summary of the system requirements. The 2023 protocol is available online [20] and it describes in detail the assessment criteria.



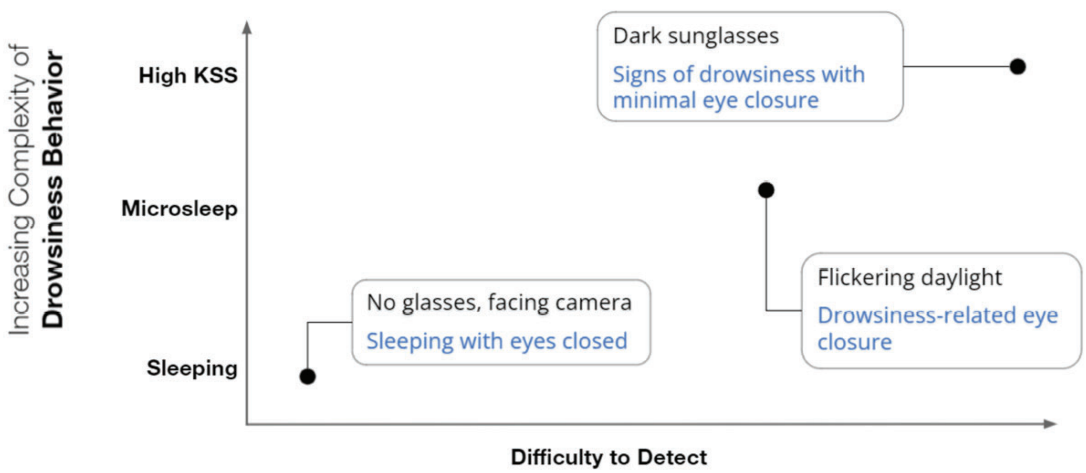




Figure 1 Behaviour-technology matrix for distraction and drowsiness [17]

**Sensing**

The first step in determining the driver state is the ability of the system to sense the behavioural metrics (e.g., eye gaze, head movement, eye closure) across the defined extremes of driver characteristics (e.g., age, gender, stature, skin, eye shape), and in the presence of a set of noise variables such as challenging lighting conditions and facial occlusions (e.g., sunglasses, hats, long hair). Given the different challenging nature of the defined occlusion elements, these are split between Prerequisite (i.e., the system shall detect) and Inform (i.e., the system shall inform the driver if the performance is degraded). As for secondary behaviours, these are defined for monitoring purposes only.

Table 1 Sensing requirements

| Driver Characteristics | Occlusion | | Other Behaviours |
|---|---|---|---|
| **Prerequisite** | **Prerequisite** | **Inform (if degraded)** | **Monitoring** |
| • Age (16-80)<br>• Gender (All)<br>• Stature (AF05-AM95)<br>• Skin (Fitzpatrick type 1-6)<br>• Eye lid aperture (From 6.0 mm to 14.0 mm) | • Lighting (Daytime–Nighttime)<br>• Eyewear (Clear glasses, light shades)<br>• Facial Hair (short facial hair) | • Hands on wheel<br>• Eyewear (Dark shades)<br>• Facial Hair (Large beard)<br>• Facial occlusion (Face mask, hats, long hair) | Secondary behavior:<br>• Eating,<br>• Talking<br>• Singing,<br>• Smoking/ Vaping,<br>• Eye scratching/rubbing<br>• Sneezing |

**Driver State**

Once the sensing performance is ensured, the system shall be capable to accurately determine the defined driver states in the protocol: distraction, fatigue and unresponsive driver. Some of the defined driver states are subdivided in different types, and for each type, there is one or more scenarios (see Figure 2).

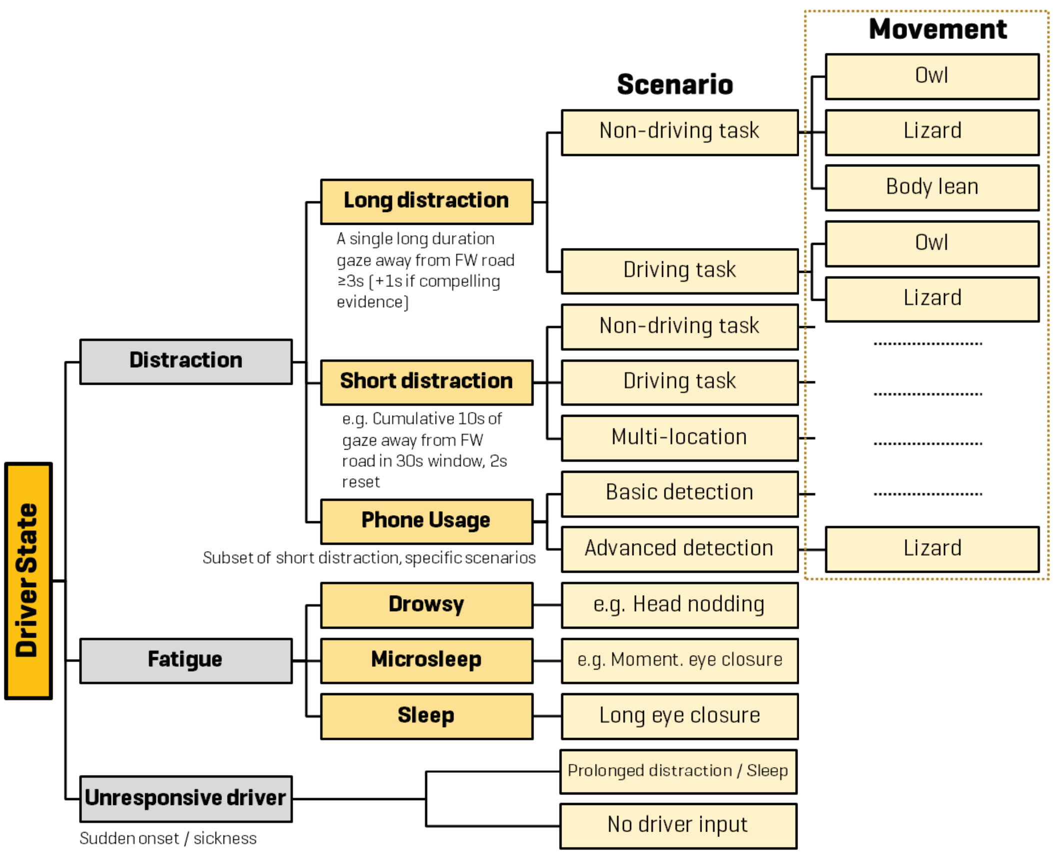



Figure 2 Summary of Driver States

**Distraction:** For distraction, the starting point was identifying the behaviours associated with the highest risk, one single long glance away from the forward road view being the most well understood in relation to the relationship with crash risk. [5]. Behaviours of increasing complexity are also considered to recognise that visual time sharing does occur and does increase crash risk at some point. These are situations where attention is split between the primary driving task and a secondary task [6] – defined as Visual Attention Time Sharing (VATS). This indicative model of time sharing and attentional requirements for safe driving is recognized by several studies [7],[8].

Understanding how drivers usually engage in distraction behaviours is important to define the primary parameters to be monitored, i.e., motion of head and eyes, being the fundamental behaviours that are observed when drivers are distracted. The relationship between head and eye movements when distracted typically falls within two extremes: "lizard" and "owl" behaviour. For small visual angles between the forward road view and the secondary glance target, drivers are usually engaging in a "lizard" glance behaviour, where the head position is relatively fixed, and the eyes are moving [9]. When the visual angle is larger, the typical glance behaviour is achieved by a head rotation, followed by the eyes, "owl" glance behaviour. Accounting for eye gaze metrics, beyond indirect measures or head pose alone, improves the reliability of determining distraction behaviours. Where a basic technology could detect head motion and therefore owl glance alone, a more advanced technology could also detect eye gaze and lizard glance. If both these extremes can be covered it is believed that combinations in between also could be covered.

The protocol lists the following Distraction types:

- Long distraction: single long glances directed to driving related and non-driving related gaze locations. The requirement is $\geq 3$ seconds glance away from the forward road view (+1 second if OEM provides justification and evidence that safety is kept).
- Short Distraction: multiple short glances (VATS) targeted to engagement in secondary activities, e.g., glances away from the forward road view for a cumulative 10 seconds within a 30 second time, where the time period is reset if the driver's glance returns to the forward road view for a period of $\geq 2$ seconds. In spite of the added value of identifying and defining VATS a high risk behaviour in the protocol, it may prove as a complex one to achieve consistently – reason why the AttendD-inspired buffer algorithm [25] (see Figure 3) was kept as an example for implementation, and the protocol remains open for similar or other approaches if compelling evidence to demonstrate comparable safety benefits can be provided.
- Phone use: A subset of VATS, with specific glance locations.

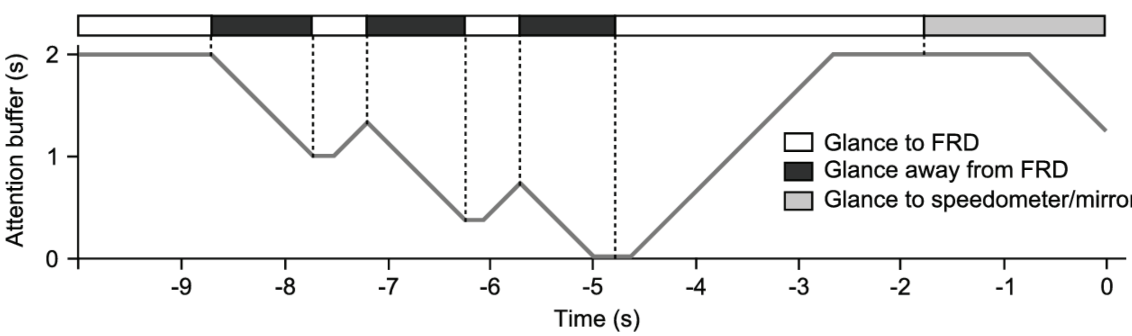



Figure 3 AttenD example [0]: development of the time buffer for three consecutive one-second glances away from the field relevant for driving (FRD), marked dark grey, with half-second glances back to the FRD in between. Note the 0.1 s physiological adaptation delay.

There is a total of 43 test cases – gaze locations – split into Driving vs Non-Driving tasks (see Table 2), which are to be accomplished by means of Owl, Lizard and Body Lean glance movement types. The test cases were defined with the premise to be highly repeatable, while ensuring a broad situational coverage by accounting for different types of glance strategies. For each of the movement types in the Long and Short Distraction types to be awarded a PASS, all gaze locations shall be covered. For Phone Use, the distraction scenarios are awarded a PASS only when all movement types and all gaze locations are covered.

Table 2 Gaze locations used to assess distraction types

| Distraction Type | Distraction Scenario | Movement type | Gaze Location | |
|---|---|---|---|---|
| Long Distraction | Non-Driving Task | Owl | • Driver Side Window<br>• Passenger Side Window | • Passenger Footwell<br>• Passenger Face<br>• IVI Display |
| | | Lizard | • IVI Display | • Glovebox |
| | | Body Lean | • Passenger Footwell | • Rear Passenger |
| | Driving Task | Owl | • Rear Mirror | • Passenger Side Mirror<br>• Driver Side Mirror |
| | | Lizard | • Instrument Cluster | • Driver Side Mirror<br>• Rear Mirror |
| Short Distraction (VATS) | Driving Task | Owl | • Passenger Side Mirror<br>• Driver Side Mirror | • Rear Mirror |
| | | Lizard | • Driver Side Mirror<br>• Rear Mirror | • Instrument Cluster |
| | Non-Driving Task (Single Target) | Owl | • Passenger Side Window<br>• Passenger Footwell | • IVI Display |
| | | Lizard | • Driver Side Window | • Passenger Footwell<br>• IVI Display |
| | Non-Driving Task (Multiple Targets) | Lizard | • Any combination of non-driving task locations | |
| Phone Usage | Basic | Owl | • Driver Side Knee<br>• Passenger Side Knee<br>• Driver Lap | • Driver Side Dashboard<br>• OEM Charging dock |
| | | Lizard | • Driver Side Knee<br>• Passenger Side Knee<br>• Driver Lap | • Driver Side Dashboard<br>• Upper Wheel Rim<br>• Center Steering Wheel<br>• OEM Charging dock |
| | Advanced | Lizard | • Held At On Road<br>• Held At Instrument Cluster | • Mounted At On Road |

**<u>Fatigue:</u>** Drowsiness state can be captured through direct or indirect measurement methods. Indirect methods such as vehicle positioning in-lane and steering behaviour over time fail to reliably detect a drowsy driver, and even direct methods such as the eyelid closure percentage (PERCLOS) have demonstrated not offering the best true positive rate [10]. In general, approaches for drowsiness detection that account for single metrics are less efficient [11], whereas combined approaches accounting for multiple metrics (e.g., blink duration, amplitude-velocity ratio, and frequency), prove to be more robust [12], [0], [14].

Microsleep is typically a complex state to be determined, with the Electroencephalography (EEG) as the most reliable method in the laboratory [15]. Since EEG proves impractical in automotive applications, several behaviours have been correlated to a Microsleep, such as long eye closure (>500ms) [16]. Many behaviours such as yawning or squinting situations can lead to false positives that will impact driver acceptance. Aa complex approach combining several behaviours could lead to a more reliable detection method, for instance with a prior determination of drowsiness.

The defined fatigue driver states in the protocol are split in drowsiness, microsleep and sleep. Sleep state is typically presented as a long eye closure (>3 seconds), therefore simple do be determined. However, when it comes to the more behaviourally complex drowsiness-related events, there is no single and repeatable pattern across individuals [18], [19], and hence makes them hard to reproduce consistently. Here, genuinely drowsy drivers should be used by a system to correlate a given metric (e.g., Karolinska Sleepiness Scale – KSS) to a certain drowsiness-related behaviour.

**Unresponsive Driver:** Sudden sickness can present itself in various and unpredictable forms, (e.g., seizure, epilepsy, etc.), and data that helps correlating it to certain behaviours is still scarce. Thus, a reasonable approach that may be taken in the early stage of the protocol implementation is assuming that sudden sickness as a subset of unresponsiveness, in which the driver would either fail to respond to escalating warnings such as take-over-request (TOR), or not be actively performing a driving task for an extended period.

**Vehicle Response Requirements**

Once the system can detect an impaired driver in the form of distraction, fatigue or unresponsiveness, the safety benefit will be eventually brought by an appropriate vehicle response that promotes safe driving, prevents an accident, or mitigates the damage associated with it. The protocol provides a list of warning and intervention strategies that are required per driver state (see Figure 4), while allowing flexibility for other OEM-specific strategies.

The premise for adjusting the sensitivity to some of the ADAS in the vehicle when a driver is deemed impaired, is to address the safety benefit while ensuring driver acceptance – beyond a typical approach of a simple warning. The underlying thought is that the best system should have both warning and intervention capabilities.

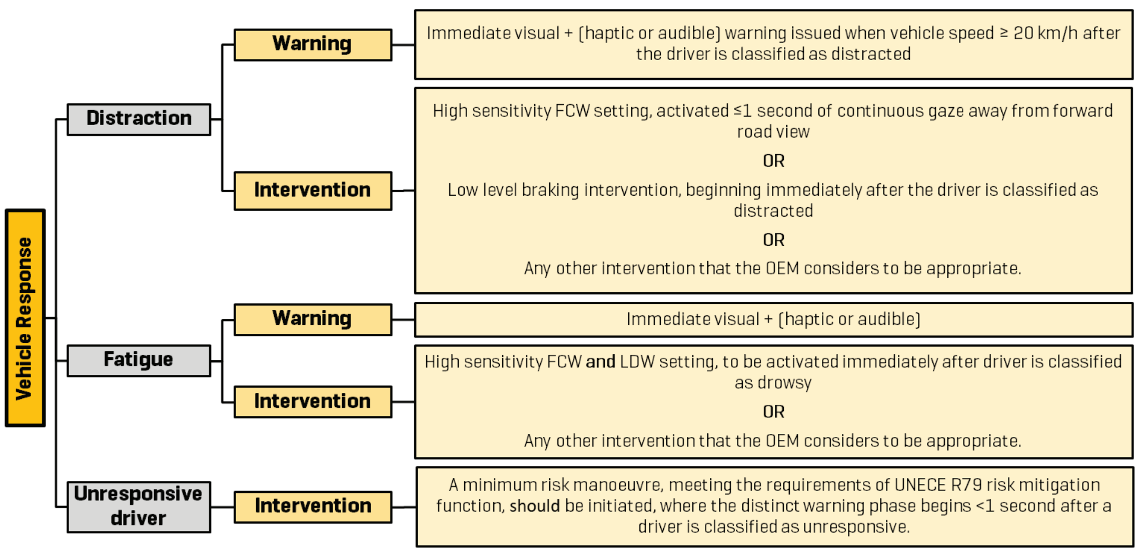



Figure 4 Vehicle Response requirements

## ASSESSMENT AND VERIFICATION PROCESS

Given the large amount of test cases resulting from the DSM requirements (i.e., set of distraction, fatigue and unresponsiveness elements conducted with a sufficiently large demographic dataset, across a wide range of noise variables), it becomes necessary to define an assessment and verification process that fits within the limitations of Euro NCAP Test Programme. To that end, a 2-stage approach is taken: First, the OEM provides the Euro NCAP Secretariat with a comprehensive dossier documenting the DSM system performance with all necessary supporting evidence; secondly, the approved test laboratory in charge of the whole Euro NCAP Test Programme for the vehicle will 'spot-test' a set of randomly selected scenarios where system the system claims functional. The dossier provides guidance to the OEM according to the system requirements, while remaining as flexible as possible to foster innovation: alternative approaches to meet requirements are permitted for as long as the OEM justifies that the safety benefit is kept. The following sub-chapters describe the approach in more detail.

**DSM Dossier**
Euro NCAP elaborated a Technical Bulletin [21] that provides guidance to OEM in the format and contents of DSM dossier document. Some of the minimum contents and structure of the document are described below.

**System Overview:** Summary of the main system functionalities, compliance of the minimum system requirements, sensors involved in the system, their role and relevant specifications, and details explaining the constituent elements of the different system warnings;

**Noise Variables:** The OEM should provide compelling evidence that the system can monitor a population constituted of different types of drivers, with a range of facial occlusions and driver behaviours. Depending on the complexity of the noise variables, the requirement vary between 'Must', 'Inform driver if degraded', and 'Information only';

**Detection of driver state:** The OEM should provide evidence demonstrating that the system can effectively classify the driver state in the minimum required categories:

- Distraction: further classification of distraction includes 'long distraction, 'short distraction', and 'phone usage'. As distraction is heavily linked to gaze location, the OEM is required to specify in the dossier a drawing the delimited gaze areas/regions which the system considers to assess distraction;
- Fatigue: further classification of fatigue includes 'drowsiness' 'microsleep' and 'sleep'. Euro NCAP gives freedom to the OEM to include in the dossier other methods to assess fatigue other than the ones specified in the protocol;
- Unresponsive driver: details of how the driver status is deemed unresponsive (or sudden sickness) by the system.

**Vehicle response requirements:** The OEM should provide details on how the sensitivity of ADAS is increased (e.g., Forward Collision warning – FCW; Lane Departure Warning – LDW) when driver is deemed distracted, fatigued, or unresponsive. The OEM is free to stick to the protocol requirements or justify other vehicle response methods.

**DSM Spot Testing**
Complementary to the information provided by the OEM in a dossier, the spot testing is the second stage in the assessment of the DSM performance. Euro NCAP has consolidated a comprehensive guideline [22] with the necessary provisions on how the spot testing is to be conducted across official test laboratories, described in the paragraphs below.

**Test Provisions:** The test conditions are defined to maximize reproducibility and repeatability across test laboratories (e.g., uniform surface with consistent slope, at daylight without direct glare or strong light transitions, avoiding strong precipitation).
The vehicle under test (VUT) is to be instrumented with a simple measuring equipment, recording at a defined sample rate (>25Hz): the VUT speed, driver's gaze location and DSM warning(s). Time variables are defined to ensure consistency and are to be used later for analysis purposes. Furthermore, prior to the test, the timing of FCW and LDW are to be checked at their minimum operational speed without signs of driver inattentiveness, so that the sensitivity increase can be later assessed. It is also important to ensure that previous system learnings on driver drowsiness are reset.

**Test Execution:** The test laboratory in charge of the assessment will randomly pick a test subject (a qualified driver from their staff) whose variables and ranges are within the protocol specifications. The driver will then adjust the seat in the preferred position and proceed with the test after the vehicle preparation.
Euro NCAP secretariat will ask the test laboratory to spot test a number of distraction, fatigue, and unresponsive driver areas of the DSM system, which performance has been claimed in the dossier by the OEM. While the vehicle is in motion at a defined constant speed deemed adequate for the test, the driver shall keep a defined head and body posture while looking to the road ahead, until the manoeuvre begins.
For distraction scenarios, the driver will proceed with moving the head, eye gaze or body posture (depending on the scenario) towards the target area (e.g., glovebox, side mirror, rear passenger seat, etc.), and hold the position

for a defined time as required in the protocol. An extra time of +1 second is added to the required time, to ensure that the system reaction is captured during the assessment.
For the assessment of Fatigue and unresponsive driver, Euro NCAP reserves the right to investigate it in practice, although it should rely on the evidence reflected in the dossier. For microsleep, sleep and unresponsive driver scenarios, the metrics by default for assessment are eye closure timing and eventually head nodding forwards; however, a different OEM strategy is allowed for as long as it is justified; later, for each of the areas where the system was functional, the scenario will eventually have to be repeated with different occlusions (cap, hat, sunglasses, facemask). Furthermore, the assessment includes a 'hands on 12 o'clock position' check for sensors located in the instrument cluster. Finally, the FCW and LDW sensitivity change is checked based on the Euro NCAP Car-to-car rear stationary (CCRs) assessment and LDW assessment, respectively.

## OUTLOOK

For future protocol developments, it is envisioned an expansion of the driver states related to impairment (chiefly intoxication and cognitive distraction), but also refining existing ones such as an accurate determination of sudden sickness by means of extended metrics. To that end, it is expected that in the years to come, starting from the 2023 test campaign, the Euro NCAP Secretariat will gather a substantial amount of information out of the DSM dossiers from the vehicles to be assessed. Gathering insights from state-of-the-art technologies will be an essential input toward refining the current provisions and expanding them above and beyond. The work will be done within the framework of the Occupant Status Working Group, with the principle of maintaining a balance between an ever-increasing safety requirements and a manageable process by OEMs.
Moreover, the group is tasked to define a framework that rewards efficient and intuitive HMI approaches while ensuring opportunities for differentiation – a fundamental pillar for DSM efficacy which will ultimately make drivers see the system as a partner that understands and helps, as opposed to irritate. All in all, as it is the case with other driver advisory systems such as Speed Assistance Systems (SAS), ensuring a good system accuracy is and will continue to be the main aspect toward maximizing driver acceptance (i.e., low false positive rate).

### Intoxication

The European Commission attributes 25% of the fatal crashes in Europe to alcohol and other drugs. In view of these figures, intoxication is the most critical issue to tackle next. There are solid prospects for future DSM systems in detecting a certain level of impairment resulting from the use of drugs and/or alcohol, beyond the more intrusive methods (e.g, direct Blood Alcohol Concentration measurement by means of an alcohol interlock). For instance, as of today there is ample evidence of alcohol altering eye movements and visuospatial attention, with a few studies demonstrating some of these effects with simulated driving tasks: acute alcohol consumption altering oculomotor functioning [23]; and gaze entropy measures correlated to alcohol-induced driver impairment [24], [25], [26].

### Cognitive distraction

Cognitive distraction / inattention is a state in which the driver's mind wanders off for a certain period, while the eye gaze may still be directed toward the forward road view [28]. As a result, the driver capability to appropriately perform the driving tasks is degraded and the current DSM approach fails to detect distraction. At this stage, cognitive distraction is well documented in driver simulator studies, however the amount of evidence reported from real crash data which could be linked to such condition is still scarce. All in all, it is expected that in-cabin technologies will be able to tackle this more technology challenging condition in the long term.

### Occupant Status Monitoring

The Euro NCAP Occupant Status Working Group will continue to find use cases leveraged by in-cabin monitoring technologies, expanding to all the vehicle occupants beyond driver. Determining the presence, sitting posture and size of the occupants will enable an optimized use of passive systems (e.g., advanced airbag deactivation or modified pressure, adaptive seatbelt load limitation and head restraints, advanced emergency call, etc.). Finally, the prevention of injuries related to child left alone in vehicles is a challenge to be addressed. The first-ever provisions for Child Presence Detection (CPD) have been defined by Euro NCAP in the 2023 implementation of the protocol [29], which will reward both indirect and direct systems, and from 2025 only direct systems will be rewarded.

**Assisted and Automated Driving**
The coming years will see an uptrend of vehicles offering certain levels of assistance to the driving task under defined conditions, with a resulting change in which drivers behave compared to manual driving. Assisted Driving systems are primarily designed to provide safety and comfort, however as the driver is always entirely responsible for the driving task, it will become critical to consider how OSM can best support the associated risks, namely ensuring driver engagement caused by overreliance on the system. Vehicles featuring Assisted Driving systems are being assessed by Euro NCAP since 2021 under the Assisted Driving Grading programme [30], which focusses on two areas: Assistance Competence – a balance between Vehicle Assistance and Driver Engagement, and Safety Backup, the car's ability to tackle critical situations. This assessment will gradually evolve, and starting from 2026, it will have a direct influence on the Safe Driving area of the new Rating Scheme [1], introducing a penalty if the Driver Engagement component is rated poor.
When it comes to Automated Driving, provisions to assess the driver readiness prior to take-over-request are likely to be defined.

**System requirements**
In general, the system requirements defined in the 2023 protocol were designed around detecting high risk behaviours related to distraction, fatigue, and sudden sickness, supported by research papers looking into these – the most significant reflected above in chapter "System Requirements". There is a focus on facial landmarks such as gaze and head posture since, still as of today, it is the most suitable and effective way to measure high risk behaviours as defined in the protocol. This was also supported by feedback from industry; this technology being the most feasible and available at this point. In the coming period, Euro NCAP will open up to other approaches which could potentially accommodate other parameters associated with such behaviours, such as explicitly holding a cellphone or detecting sudden sickness with other more biometric means.

## CONCLUSIONS

As technologies able to capture driver state improve, Euro NCAP deems it essential to encourage their fitment in vehicles as standard, hence reducing injury caused by fatigue and distraction-related crashes. Euro NCAP made a first step toward promoting the widespread adoption of in-cabin monitoring starting with the 2023 implementation of the DSM assessment protocol. Over the next decade, the protocol will evolve to accommodate advanced technologies able to detect additional driver states associated with risk of unsafe driving and defined appropriate vehicle responses that avoid or mitigate accidents.

## ACKNOWLEDGEMENTS

The authors would like to thank the members of the Euro NCAP Occupant Status Working Group, and those in industry that supported the development of the protocol.

**REFERENCES**

1. Euro NCAP (2022). Euro NCAP Vision 2030: a safer future for mobility. Available online at: https://cdn.euroncap.com/media/74468/euro-ncap-roadmap-vision-2030.pdf

2. Sundfør, H. B., Sagberg, F., and Høye, A. (2019). Inattention and distraction in fatal road crashes–results from in-depth crash investigations in Norway. Accid. Anal. Prev. 125, 152–157. doi: 10.1016/j.aap.2019.02.004

3. Fitzharris, M., Lenné, M. G., Corben, B., Arundell, T. P., Peiris, S., Lui, S., et al. (2020). ECIS Report 1. Overview and Analysis of Crash Types, Injury Outcomes and Contributing Factors. Report # 343.Monash University Accident Research Centre.

4. Trafikanalys (2021). Road Traffic Injuries. (Official statistics of Sweden). Available online at: https://www.trafa.se/en/road-traffic/road-traffic-injuries/

5. Victor, T., Dozza, M., Bärgman, J., Boda, C., Engström, J., Flannagan, C., et al. (2015). Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk. SHRP 2 Report S2-S08A-RW-1. National Academy of Sciences.

6. Lenné, M. G., Roady, T., and Kuo, J. (2020). "Driver state monitoring for decreased fitness to drive," in Handbook of Human Factors for Automated, Connected, and Intelligent Vehicles, edsD. Fisher, W. J. Horrey, J. D. Lee, andM. A. Regan (Boca Raton: CRC Press). doi: 10.1201/b21974-11

7. Seppelt, B., Seaman, S., Lee, J., Angell, L., Mehler, B., and Reimer, B. (2017). Glass half-full: on-road glance metrics differentiate crashes from near-crashes in the 100-Car data. Accid. Anal. Prev. 107, 48–62. doi: 10.1016/j.aap.2017.07.021

8. Kircher, K., Kujala, T., and Ahlström, C. (2020). On the difference between necessary and unnecessary glances away from the forward roadway: an occlusion study on the motorway. Hum. Factors 62, 1117–1131. doi: 10.1177/0018720819866946

9. Fridman, L., Lee, J., Reimer, B., and Victor, T. (2016). "Owl" and "Lizard": patterns of head pose and eye pose in driver gaze classification. IET Comput. Vis. 10, 308–314. doi: 10.1049/iet-cvi.2015.0296

10. Sommer, D., and Golz, M. (2010). "Evaluation of PERCLOS based current fatigue monitoring technologies," in Proceedings of the 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology (Buenos Aires), 4456–4459. doi: 10.1109/IEMBS.2010.5625960

11. Ingre, M., Åkerstedt, T., Peters, B., Anund, A., and Kecklund, G. (2006). Subjective sleepiness, simulated driving performance and blink duration: examining individual differences. J. Sleep Res. 15, 47–53 doi: 10.1111/j.1365-2869.2006.00504.x

12. Caffier, P. P., Erdmann, U., and Ullsperger, P. (2003). Experimental evaluation of eye-blink parameters as a drowsiness measure. Eur. J. Appl. Physiol. 89,

319–325. doi: 10.1007/s00421-003-0807-5

13. Lee, M. L., Howard, M. E., Horrey, W. J., Liang, Y., Anderson, C., Shreeve, M. S., et al. (2016). High risk of near-crash driving events following nightshift work. Proc. Nat. Acad. Sci. U.S.A. 113:176. doi: 10.1073/pnas.15103 83112

14. Liang, Y., Horrey, W. J., Howard, M. E., Lee, M. L., Anderson, C., Shreeve, M. S., et al. (2019). Prediction of drowsiness events in night shift workers during morning driving. Accid. Anal. Prev. 126, 105–114. doi: 10.1016/j.aap.2017.11.004

15. Hertig-Godeschalk, A., Skorucak, J., Malafeev, A., Achermann, P., Mathis, J., and Schreier, D. R. (2020). Microsleep episodes in the borderland between wakefulness and sleep. Sleep 43:zsz163. doi: 10.1093/sleep/zsz163

16. Alvaro, P. K., Jackson,M. L., Berlowitz, D. J., Swann, P., and Howard,M. E. (2016). Prolonged eyelid closure episodes during sleep deprivation in professional drivers. J. Clin. Sleep Med. 12, 1099–1103. doi: 10.5664/jcsm.6044

17. Fredriksson, R., Lenné, M., van Montfort, S., Grover, C. European NCAP Program Developments to Address Driver Distraction, Drowsiness and Sudden Sickness. doi: 10.3389/fnrgo.2021.786674

18. Caffier, P. P., Erdmann, U., and Ullsperger, P. (2003). Experimental evaluation of eye-blink parameters as a drowsiness measure. Eur. J. Appl. Physiol. 89, 319–325. doi: 10.1007/s00421-003-0807-5

19. Chua, E. C.-P., Yeo, S.-C., Lee, I. T.-G., Tan, L.-C., Lau, P., Tan, S. S., et al. (2014). Individual differences in physiologic measures are stable across repeated exposures to total sleep deprivation. Physiol. Rep. 2:e12129. doi: 10.14814/phy2.12129

20. Euro NCAP (2022): Assessment Protocol – SA – Safe Driving v10.1.1 Available online at: https://cdn.euroncap.com/media/75554/euro-ncap-assessment-protocol-sa-safe-driving-v1011.pdf

21. Euro NCAP (2022): DSM Dossier Guidance v1.1 Available online at: https://cdn.euroncap.com/media/70320/tb-036-dsm-dossier-guidance-v11.pdf

22. Euro NCAP (2022): DSM Spot Testing Guidance v1.1 Available online at: https://cdn.euroncap.com/media/70321/tb-039-dsm-spot-testing-guidance-v11.pdf

23. Maurage, P., Masson, N., Bollen, Z. & D'Hondt, F. Eye tracking correlates of acute alcohol consumption: A systematic and critical review. Neurosci. Biobehav. Rev. 108, 400–422 (2020).

24. Shiferaw, B., Downey, L. & Crewther, D. A review of gaze entropy as a measure of visual scanning efficiency. Neurosci. Biobehav. Rev. 96, 353–366 (2019).

25. Shiferaw, B. A., Crewther, D. P. & Downey, L. A. Gaze entropy measures detect alcohol-induced driver impairment. Drug Alcohol Depend. 204, 107519 (2019).

26. Shiferaw, B., Crewther, D. & Downey, L. A. Gaze Entropy Measures Reveal Alcohol-Induced Visual Scanning Impairment During Ascending and Descending Phases of Intoxication. J. Stud. Alcohol Drugs 80, 236–244 (2019).

27. Kircher, K., Ahlström, C. Issues related to the driver distraction detection algorithm AttenD (2009)

28. Hamilton, B.C., & Grabowski, J.G. (2013). Cognitive Distraction: Something to Think About: Lessons Learned from Recent Studies.

29. Euro NCAP (2022): Test and Assessment Protocol – Child Presence Detection v1.1
Available online at:
https://cdn.euroncap.com/media/75474/euro-ncap-cpd-test-and-assessment-protocol-v11.pdf

30. Euro NCAP (2022): Test and Assessment Protocol – Assisted Driving
Highway Assist Systems v1.1
Available online at:
https://cdn.euroncap.com/media/75441/euro-ncap-ad-test-and-assessment-protocol-v11.pdf

# DEVELOPING A CONSUMER SAFETY RATING FOR VANS

**Colin Grover,**
**Matthew Avery**
Thatcham Research
UK

**Iain Knight**,
Apollo Vehicle Safety
UK
Paper Number 23-0298

**ABSTRACT**

Home delivery is one of many trends driving a strong increase in the use of light commercial vehicles (≤ 3,500kg GVW, aka vans). In Europe, vans have for many years been subject to less stringent safety regulations than passenger cars and had fewer safety systems fitted. The research objective was, therefore, to assess the safety risks posed by the increasing use of vans and to develop a programme of consumer testing to promote relevant risk mitigations. The work involved a wide range of Euro NCAP Member organisations under the umbrella of the Commercial Vehicle Working Group, chaired by Thatcham Research, and subsequent evolution under its own unique working group chaired by CSI.

The work programme undertaken by the group included:

- Collision data analysis
- Market research to assess ADAS fitment
- Full scale collision test
- Track testing of ADAS solutions

Across 5 Euro NCAP member countries vans were involved in around 8% of road fatalities. The types of collisions they were involved in, the causes and consequences were similar to those of passenger cars. The most common collision opponent was other passenger cars, but the fatalities were not evenly distributed between each vehicle. In collisions involving vans, a larger proportion of the total fatalities occurred in the car than in the van.

A full-scale vehicle to vehicle crash test was undertaken between a van and a 5-star car. The van exhibited limitations in terms of both self-protection and compatibility. Both van occupants showed a high risk of injury to the chest, knee, femur and pelvis. The good design of the passenger car helped limit the consequences for its occupants, but they still showed significantly higher risk of injury than in the equivalent barrier test.

Market research showed that the availability of ADAS was low, almost always optional and, even when available, was poorly understood by dealers making it hard to actually get hold of vehicles. Tests of the ADAS showed that they could be effective but, in some cases, offered significantly lower performance than similar systems on passenger cars from the same manufacturer.

A new van rating scheme was developed, based on adaptation of existing passenger car protocols for ADAS but not for full scale crash. Ratings of the whole market in the EU have been undertaken in 2021 and 2022 and the scores have improved substantially.

## INTRODUCTION

In its roadmap to 2025 [1] Euro NCAP announced its intention to support the development of a truck city safety label. In 2020 the Commercial Vehicle working group was created and began by developing assessments of the ADAS offered on light commercial vehicles <3,500kg as part of developments building toward a rating for heavier trucks.

Home delivery is one of many trends driving a strong increase in the use of light commercial vehicles (≤ 3,500kg GVW, aka vans). In Europe, vans have for many years been subject to less stringent safety regulations than passenger cars and had fewer safety systems fitted. The research objective was, therefore to assess the safety risks posed by the increasing use of vans and to develop a programme of consumer testing to promote relevant risk mitigations. The work involved a wide range of Euro NCAP Member organisations under the umbrella of the Commercial Vehicle Working Group, chaired by Thatcham Research, and subsequent evolution under its own unique working group chaired by CSI.

The work has involved considerable studies of market and collision data to understand the nature of the problems that need to be solved for vans, a crash test to demonstrate the effects of the larger vehicles and the development of safety protocols and a rating scheme designed to solve the problems identified.

## QUANTIFYING THE PROBLEM

### Exposure to risk

It is undeniable that the number of vans on the roads has increased over time. For example, in GB in 2021 there were nearly 4.5 million vans on the roads, representing 11% of all vehicles, compared with a little more than 2 million in 1994, representing just 8% of all vehicles. This trend has been repeated in countries across Europe.

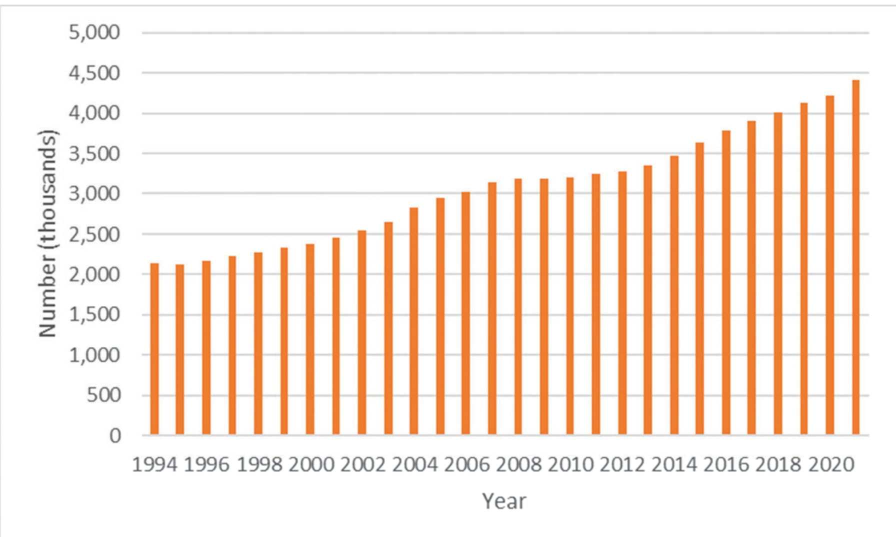
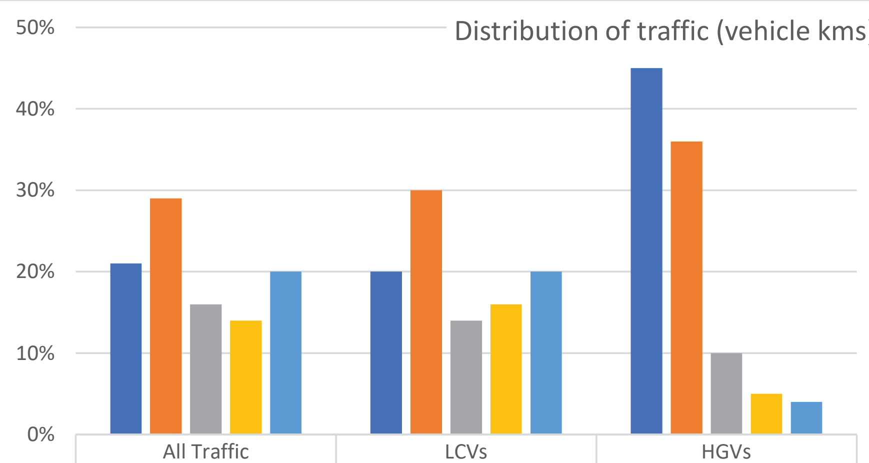



**Figure 1: Number of vans registered at the end of each year in GB. Source: DfT licensing statistics**

Home delivery is often cited as the factor driving an increase in the use of vans. This is of course a very significant factor but the evidence [2] suggests that growth in van traffic has been and will continue to be driven by multiple complex economic, logistic and supply chain factors, not just home deliveries. These factors include outsourcing of technical services to specialist companies (e.g. mobile repair services), an increase in the length and height of vans, and a shift from heavier goods vehicles to lighter, for many reasons such as an increase in just in time deliveries with smaller consignment sizes, reduced regulatory burdens and total cost of ownership and an increased supply of drivers because there is no need for a special license. In addition to this, trends to relocate industrial sites, centralised stockholding, reduced use of local suppliers have all tended to increase the annual average distance travelled by vans. All of these factors tend to increase their exposure to road risk.

It is well documented that heavier goods vehicles spend a larger proportion of their driving distance on major roads such as motorways when compared with traffic as a whole. In line with the home delivery theory above, it may be expected that vans would be used primarily in urban areas. However, the data (**Figure 2**) shows this is not the case and, in actual fact, the usage of vans is very similarly distributed to ‘all traffic’, which is dominated by passenger cars.




| | All Traffic | LCVs | HGVs |
|---|---|---|---|
| Motorways | 21% | 20% | 45% |
| Rural 'A' roads | 29% | 30% | 36% |
| Urban 'A' roads | 16% | 14% | 10% |
| Minor rural roads | 14% | 16% | 5% |
| Minor urban roads | 20% | 20% | 4% |

**Figure 2: Distribution of traffic by road type in UK. Source: DfT traffic statistics**

So, the exposure to risk of vans will be high in relation to the number of vans (higher average distances), low but growing in comparison to that of passenger cars and distributed very similarly to passenger cars in terms of locations and road types. It seems that vans are considered ‘go anywhere’ types of vehicles, similar to cars but unlike heavier goods vehicles that often target a particular freight task.

**Collisions & Casualties**

Euro NCAP Members have produced an analysis of the number and type of road users killed in collisions involving two vehicles or less that occurred between 2017 and 2019, involving a range of different types of vehicles. Five countries are represented (France, Great Britain, Germany, Italy and Sweden). In total over the combined three-year period, this data provided information on 28,452 fatalities from all types of collisions and 2,307 fatalities from collisions involving at least one van. The people killed in these collisions were as shown in **Figure 3**, below.

It can be seen that the single largest group of fatalities in collisions involving vans are car occupants. When considering that van occupants will also be killed in crashes with other vehicle, then it is clear that when a car hits a van, it is more likely that the car occupant will be killed than the van occupant. In fact, the Euro NCAP data showed that only 14% of the van occupant fatalities (4% of all fatalities) occurred in collision with a car. Whereas by definition of the sample, all of the 35% of fatalities that were car occupants would have been killed in collisions with a van. So in fact, in collisions between cars and vans, the outcome is clearly much worse for the car occupant. Van occupants are most commonly killed in single vehicle collisions (42% of van fatalities, 13% of all fatalities) and collisions with other vans or heavier vehicles such as trucks and buses (collectively 42% of van fatalities or 13% of all fatalities).

This is broadly consistent with other studies on the same subject [3]. In these studies, it was noted that seat belt use was much lower than for passenger cars but that otherwise the distribution of crashes represented a significant difficulty for crashworthiness improvements. Improving frontal structures to better protect van occupants in collision with roadside furniture or in collision with other vans, trucks and buses could lead to increased mass, reduced payload and a further increase in van use. It could also lead to stiffer structures at greater heights from the ground. These latter changes would likely be more hostile to passenger car occupants, who are already more frequently killed than van occupants.

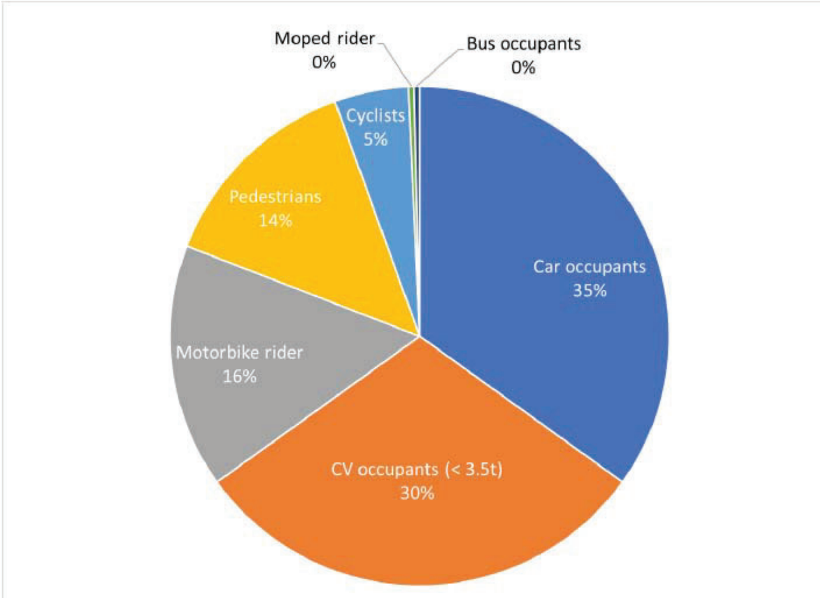



**Figure 3: Road user type killed in collisions involving vans (<3.5t). Source Euro NCAP member analysis**

## HOW DO VEHICLES CURRENTLY PERFORM

The research started with a short programme of crash tests, firstly a van to a passenger car moving vehicle to moving vehicle test, intended to be representative of the Euro NCAP Moving Progressive Deformable Barrier Test but with the real vehicle replacing the MPDB. Secondly, the MPDB procedure was followed completely with the same model of van and the barrier. The results are summarised below

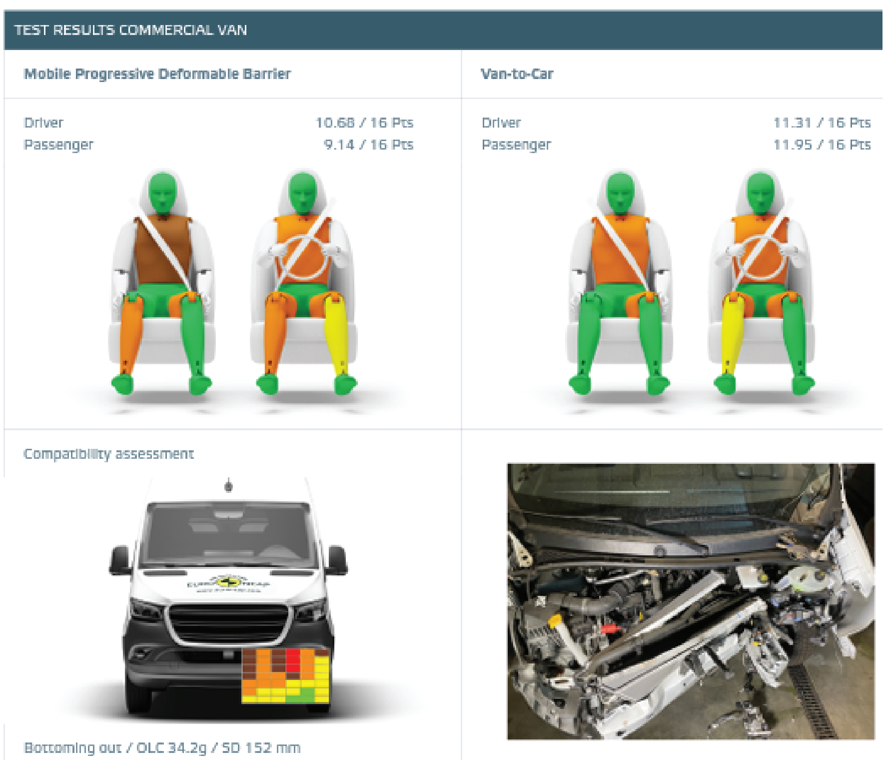



**Figure 4: Results of van crash test**

With its much greater weight, the van clearly dominated the crash and the MPDB results confirmed the statistical concerns about the crash compatibility with smaller vehicles. Concerns were also noted in relation to a lack of airbag, seatbelt load limiter and pre-tensioner for the passenger in the van and high intrusion and deformation led to a higher risk of injury to the driver chest, knee, femur and pelvis.

The vehicles used in the above tests were the 2019 Nissan Juke (a 5-star car in Euro NCAPs assessment) and the 2019 Nissan NV400 van. The safety equipment fitment of each vehicle was also compared with the results shown in **Figure 5**, below.


| 2019 Nissan Juke | | 2019 NV400 |
|---|---|---|
| Standard across EU/UK | AEB City | Not available |
| Standard across EU/UK | AEB Interurban | Not available |
| Standard across EU/UK | AEB Pedestrian | Not available |
| Standard across EU/UK | AEB Cyclist | Not available |
| Standard across EU/UK | Blind Spot Detection | Optional |
| Standard across EU/UK | Lane Departure Warning | Not available |
| Standard across EU/UK | Lane Keep Assist | Not available |
| Standard across EU/UK | Speed Assistance | Optional |
| Standard across EU/UK | Seat belt reminder (all seats) | Not available |
| Standard across EU/UK | Driver Airbag | Standard across EU/UK |
| Standard across EU/UK | Passenger Airbag | Optional |
| Standard across EU/UK | Curtain Airbag | Not available |

Standard across EU/UK ● Optional ● Not available


**Figure 5: Safety equipment fitment, Nissan Juke and NV 400 van**

Although this was considered a relatively extreme example, it graphically highlighted the difference in standards that could exist between cars and vans.

**DEVELOPMENT OF THE TEST PROTOCOLS AND RATING SCHEME**

It was considered that the best approach to the development of the van scheme was to start relatively simply. As such, the complexity of the self protection and crash compatibility issue for vans, the intention was to focus initially on ADAS, in particular:

- AEB Car 2 car & VRU, excluding night time testing
- Lane support systems (LDW, LKA, ELK, BLIS)
- Speed assistance (MSA, SLIF, ISA)
- Seat Belt reminders (SBR)

Initial exploratory testing and consultation made it clear that the commercial vehicle market, with much lower sales than passenger cars, would always be likely to get the ADAS only once it had already been implemented on passenger cars. In most cases it would not be economic to generate new, higher performing systems first for vans. As such, the decision was taken that the 2021 test programme would use the equivalent 2018 Safety Assist protocols as a starting point.

In most cases, the changes in protocol required to adapt to vans were not great. The collision patterns and scenarios were very similar to cars, the usage of vehicles was similar to cars and the driving dynamics were not greatly different either. However, the influence of load was one area given special consideration.

The payload capacity of loads is much greater than for passenger cars and the centre of mass can also be substantially higher. However, loading the vehicles adds significant preparation time and requires good load security measures to ensure test safety. Vans also may travel lightly laden for a relatively large proportion of their distance because they may be used to carry bulky items rather than heavy items or because they carry tools and materials for other work rather than looking to transport goods at maximum efficiency.

One of the main concerns was the effect on AEB, through changes to pitch angle affecting sensor alignment, increasing the time taken to reach maximum deceleration and/or limiting the maximum deceleration that could be achieved.

Comparative testing at light (test driver plus equipment) and full loads in AEB tests in general found that load had only a very small influence on deceleration profiles.

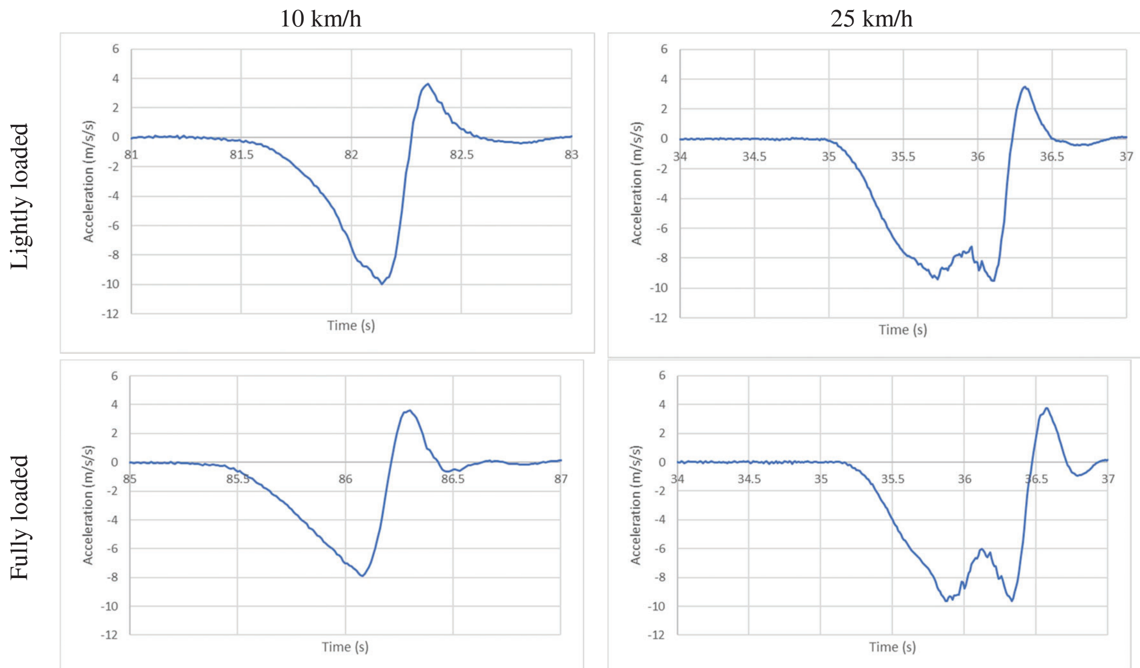



**Figure 6: Example deceleration profiles during AEB activation in tests at 10 km/h and 25 km/h, lightly and fully loaded.**

Although the effect in 10 km/h tests is noticeable with a slower risk and lower peak, both tests resulted in avoidance. At higher speeds both rise time and peak decelerations were quite similar.

Data was sought on the loading of vans. Although this information is routinely collected in representative surveys in all EU countries for heavy goods vehicles, it is not systematically recorded for vans. Data relating to 2003-2005 from a specific extension to the HGV study in the UK [4] suggests it is relatively rare for vans to be more than 75% of full load.

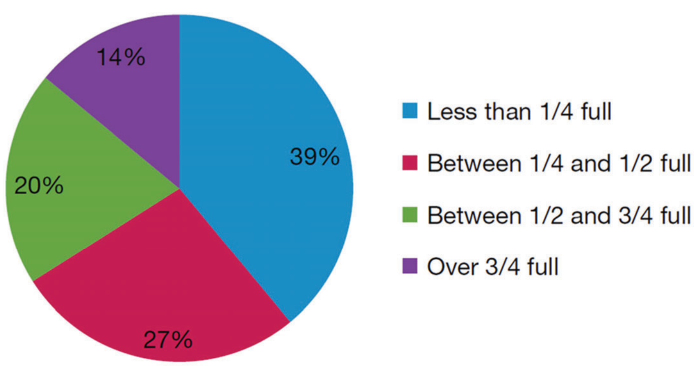



**Figure 7: Proportion of van journeys at different states of load. Source: DfT survey data for 2003-2005, as cited by [4]**

The results suggest that while there is potential for load to be a significant influence, in practice it appears to be limited. As a result, a decision was taken to test in one load condition, representing 50% of the max payload mass, with the centre of gravity positioned centrally within the load space (or 0.6m above the load bed if a flat bed variant was tested).

**RATING OF THE MARKET & RESPONSE FROM INDUSTRY**

As show in **Figure 8**, below, there are a relatively small number of makes and models within the van market, and the top 5 selling models represent almost half of all EU sales. In addition to that, eight of the models listed are in fact re-badged variants of another make/model. In combination, this meant that Euro NCAP was able to test models covering 98% of EU sales.

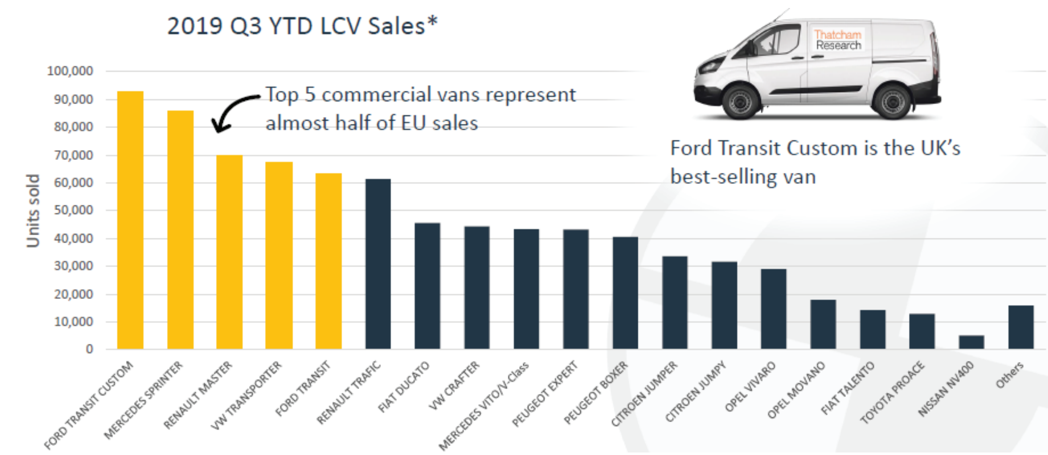



**Figure 8: EU van sales by make and model.**

The strategy adopted was different to what we use in the car market. So few vehicles were identified that had large quantities of standard fit safety equipment that it was decided to test the best equipped variant available (including specifying optional equipment), rather than the best selling variant with standard equipment.

The relatively straightforward coverage of 98% of the market has meant that Euro NCAP has been able to completely test nearly the whole van market twice, once for the rating published in 2021 and again for one published in 2022. The results are summarised back-to-back in **Figure 9**, below.

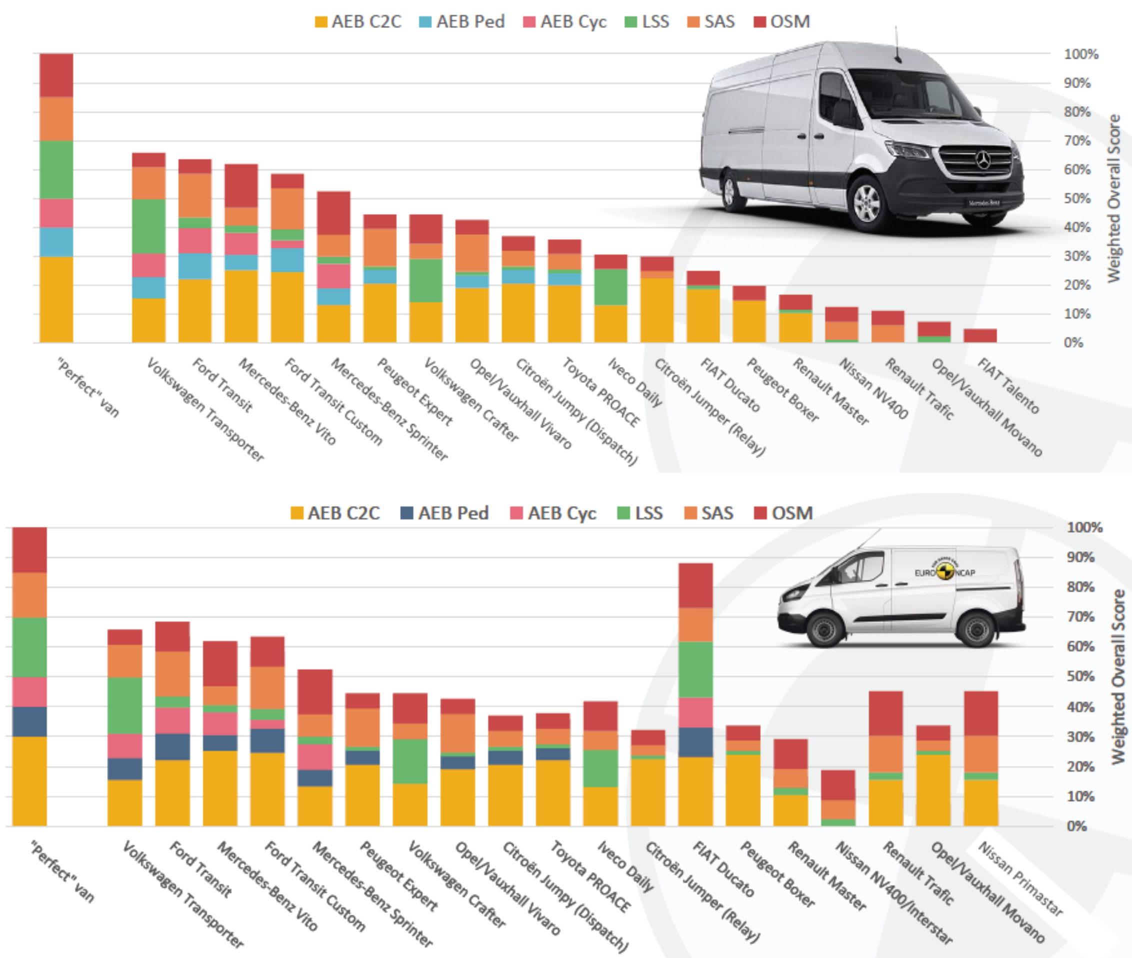



**Figure 9: Overall weighted scores for 2021 (top) and 2022 (bottom)**

It can be seen that many of the models, particularly those with lower scores in 2021, have substantially improved in 2022.

A comprehensive study of the fitment of key ADAS features was also undertaken and example results for the UK in 2020 are shown in **Figure 10**, below. It was found that there was significant variation across different European countries but in general the quantity of standard fitment in several key safety features was low.

| Make & Model (N1*) | AEB C2C | AEB Ped | AEB Cyc | LSS | SAS | OSM |
|---|---|---|---|---|---|---|
| Citroen Jumper (Relay) | ○ | ✖ | ✖ | ○ | ● | ● |
| Citroen Jumpy (Dispatch) | ○ | ○ | ✖ | ○ | ● | ● |
| FIAT Ducato | ○ | ✖ | ✖ | ○ | ○ | ● |
| FIAT Talento | ✖ | ✖ | ✖ | ✖ | ✖ | ● |
| Ford Transit 2T | ○ | ○ | ○ | ○ | ○ | ● |
| Ford Transit Custom | ○ | ○ | ○ | ○ | ○ | ● |
| Iveco Daily | ○ | ✖ | ✖ | ○ | ○ | ● |
| Mercedes-Benz Sprinter | ● | ● | ● | ● | ● | ● |
| Mercedes-Benz Vito | ● | ● | ● | ○ | ● | ● |
| Nissan NV400 | ✖ | ✖ | ✖ | ○ | ● | ● |
| Opel Movano | ✖ | ✖ | ✖ | ○ | ○ | ● |
| Opel Vivaro | ○ | ○ | ✖ | ○ | ● | ● |
| Peugeot Boxer | ○ | ✖ | ✖ | ○ | ● | ● |
| Peugeot Expert | ○ | ○ | ✖ | ○ | ● | ● |
| Renault Master | ○ | ✖ | ✖ | ○ | ○ | ● |
| Renault Trafic | ✖ | ✖ | ✖ | ✖ | ○ | ● |
| Toyota ProAce | ● | ● | ✖ | ○ | ○ | ● |
| Volkswagen Crafter | ● | ✖ | ✖ | ○ | ● | ● |
| Volkswagen Transporter T6.1 | ● | ● | ● | ○ | ● | ● |

| Make & Model (N1*) | AEB C2C | AEB Ped | AEB Cyc | LSS | SAS | OSM |
|---|---|---|---|---|---|---|
| Citroën Jumper (Relay) | ○ | ✖ | ✖ | ○ | ● | ● |
| Citroën Jumpy (Dispatch) | ○ | ○ | ✖ | ○ | ● | ● |
| FIAT Ducato | ○ | ○ | ○ | ○ | ○ | ● |
| Ford Transit | ○ | ○ | ○ | ○ | ○ | ● |
| Ford Transit Custom | ○ | ○ | ○ | ○ | ○ | ● |
| Iveco Daily | ○ | ✖ | ✖ | ○ | ○ | ● |
| Mercedes-Benz Sprinter | ● | ● | ● | ○ | ● | ● |
| Mercedes-Benz Vito | ● | ● | ● | ○ | ○ | ● |
| Nissan Interstar | ✖ | ✖ | ✖ | ○ | ○ | ● |
| Nissan Primastar | ○ | ✖ | ✖ | ○ | ○ | ● |
| Opel/Vauxhall Movano | ○ | ✖ | ✖ | ○ | ● | ● |
| Opel/Vauxhall Vivaro | ○ | ○ | ✖ | ○ | ● | ● |
| Peugeot Boxer | ○ | ✖ | ✖ | ○ | ● | ● |
| Peugeot Expert | ○ | ○ | ✖ | ○ | ● | ● |
| Renault Master | ○ | ✖ | ✖ | ○ | ○ | ● |
| Renault Trafic | ○ | ✖ | ✖ | ○ | ● | ● |
| Toyota PROACE | ○ | ○ | ✖ | ✖ | ● | ● |
| Volkswagen Crafter | ● | ✖ | ✖ | ○ | ○ | ● |
| Volkswagen Transporter | ● | ● | ● | ○ | ● | ● |

**Figure 10: Fitment of safety systems in UK in 2021 (left) and 2022 (right). Solid green – standard, green circle – optional, red cross – not available[1]**

Clearly, there has also been improvements in the availability of the safety systems that contribute to the scores, but standard fitment remains low and in some cases items that were standard appear to have become optional.

## FUTURE DEVELOPMENT

It is considered that the significant shift in the market achieved in just one year of publishing the rating is an excellent achievement. In 2024, many of the systems required will become mandatory in Europe because of the revised General Safety Regulation. However, because in order to get the higher ratings, Euro NCAP requires higher performance than the mandatory minimum, it is proposed that the scheme continues on the basis of following the developments in the car testing protocol but one generation behind passenger cars. It is also proposed that the short term measure of testing the best specification available is ended, such that standard fitment of safety equipment is required.

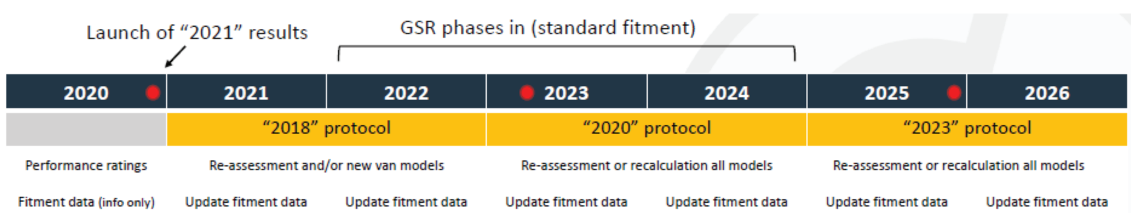



**Figure 11: Timeline of van rating development**

## CONCLUSIONS

Both usage and accidentology data suggest that the safety problems experienced by vans is more closely related to that of passenger cars than heavier commercial vehicles. However, the end customer is likely to be different. In many cases, these will be fleet managers either within the freight industry or within technical and engineering industries such as construction, servicing, maintenance etc.

Analysis of collision data, crash tests and safety feature fitment data all supported the view that van safety lagged significantly behind passenger car safety.

---

[1] It should be noted that in the definition above Occupant Status Monitoring (OSM) only included seat belt reminders and not direct driver monitoring

Issues of crash compatibility between large and heavy vans and passenger cars remain a concern and is an area in need of further study.

A rating scheme focussed on helping van drivers to avoid collisions has been developed and a full assessment of the market in two subsequent years has found a dramatic improvement in the performance of vehicles on the market.

Aligned with forthcoming new legislation in the EU, EuroNCAP will move to rating only standard fit equipment by 2025 and will driver performance in that equipment over and above the minimum required by law.

## REFERENCES

[1] Euro NCAP, 2017. "2025 Roadmap: In pursuit of vision zero" Brussels: Euro NCAP

[2] Browne, M., Rizet, C. & Allen, J., 2014. A comparative assessment of the light goods vehicle fleet and the scope to reduce its CO2 emissions in the UK and France. s.l., Elsevier Ltd., proceedings of the 8th International conference on city logistics.

[3] Knight & Edwards, 2010. A preliminary analysis of the risks and benefits of selected vehicle safety interventions for accidents involving light commercial vehicles (LCVs) or minibuses. TRL Published project Report PPR 516

[4] Clarke, Johnson, Nankivell & Turpin, 2014. Van travel trends in Great Britain, s.l.: RAC Foundation

# EURO NCAP MOBILE PROGRESSIVE DEFORMABLE BARRIER TESTING

**James Ellway, Michiel van Ratingen**
European New Car Assessment Programme
Belgium

**Andre Eggers, Tobias Langner**
Federal Highway Research Institute BASt
Germany

**Volker Sandner**
ADAC
Germany

On behalf of the Euro NCAP Frontal Impact Working Group

Paper Number 23-0312

**ABSTRACT**
The European New Car Assessment Programme (Euro NCAP) implemented an updated Adult Occupant Protection assessment in 2020. This saw the adoption of the Mobile Progressive Deformable Barrier (MPDB) frontal impact test and the use of the THOR anthropometric test device. The procedure was developed by the Frontal Impact Working Group (FIWG) supported by Euro NCAP and its members, alongside representatives from both the European Automobile Manufacturers Association (ACEA) and the European Association of Automotive Suppliers (CLEPA). This paper summarises the implementation of this new procedure and the work of the FIWG over the last five years.

Data from official Euro NCAP testing has been analysed to provide an overview of results from the first three years of MPDB assessments. Euro NCAP is the first consumer rating programme in the world to include an assessment of a vehicle's compatibility. The assessment is based upon three measured parameters: standard deviation (SD) of the post-test barrier face deformation, the Occupant Load Criterion (OLC) of the MPDB trolley, and whether or not the barrier face has been crushed beyond a designated limit. The performance of the THOR dummy and its impact on vehicle ratings has also been examined. In particular, the assessment of chest and abdomen compression, iliac crest loading, and acetabulum loading were considered as they have never been included in previous assessments.

An investigation of the MPDB tests found that it is not uncommon for the diagonal belt to slide from the shoulder clavicle towards the neck of the THOR dummy. The effect of this belt movement has been investigated and improvements to the dummy hardware have been considered. As the THOR dummy is also able to measure rotational movement of the head, the group implemented a two-step approach to evaluate brain injury criteria. The first step analysed signal-based criteria culminating in the adoption of DAMAGE for assessment in 2023 ratings, another world first. The group is also reviewing existing advanced brain injury criteria that utilise FE based brain models for adoption in 2026.

The test data analysis was based on the results of Euro NCAP official tests; there was no access to manufacturers' in-house or preliminary Euro NCAP test data. Therefore, this paper does not address any repeatability or reproducibility issues. The current assessment of THOR chest compression uses the maximum peak resultant displacement of the four thoracic ribs (Rmax). The intention is to adopt a more sophisticated chest criterion in future assessments which will be performed alongside an evaluation of THOR certification data.

Euro NCAP has evaluated the implementation of a new frontal impact test in a consumer rating programme and is the first such programme to utilise the THOR ATD, advanced injury criteria and a vehicle compatibility assessment. Further developments in the assessment are being considered and will be incorporated into the vehicle rating scheme in 2026.

## INTRODUCTION

The MPDB frontal impact test was introduced by Euro NCAP in 2020 as part of a package of measures to provide more demanding crash test requirements. At the same time, the test speed of the AE-MDB side impact test was increased from 50km/h to 60km/h, and the mass of the barrier increased from 1300kg to 1400kg [1]. Finally, there was the addition of a Farside occupant assessment [2] and Rescue & Extrication assessments, as part of Adult Occupant Protection (AOP) part of the five-star rating programme.

The early work of the FIWG was first published at the 25th ESV conference [3]. These investigations formed the foundation for the MPDB test and assessment protocols along with supporting technical bulletins that were first published in 2018. Euro NCAP protocols and technical bulletins can be found on the Euro NCAP website (www.euroncap.com/en/for-engineers/protocols/).

This paper reviews the outcomes of the first three years of the updated Euro NCAP AOP assessment and focusses on the trends observed in the application of the MPDB test. With the adoption of the THOR 50th male dummy and compatibility assessment, the FIWG has investigated how the test equipment and barrier face measurement procedures might be improved, as part of its consideration of future developments.

The official Euro NCAP MPDB test data available for the analyses in this report is based on 81 MPDB tests performed from 1st January 2020 up to and including results published in October 2022. For comparison, data from 83 official Offset Deformable Barrier (ODB) tests (2018-2019), the predecessor of the MPDB test in Euro NCAP, has also been analysed to examine the impact on vehicle ratings due to the new adult occupant assessment.

## THE MPDB FRONTAL IMPACT TEST

The MPDB frontal impact test replaced the ODB test for all Euro NCAP assessments published from the 1st January 2020. The test is a 50% overlap, moving car to moving barrier test with both crash partners travelling at 50km/h. A THOR 50th percentile male dummy and a Hybrid III 50th percentile male dummy are placed on the driver's and passenger's seats respectively. The 2nd row outboard rear seats are occupied by a Q6 child dummy, seated behind the driver, and a Q10 behind the passenger, the results of which are used to assess child occupant protection (COP). Details of the tests and corresponding assessment can be found in the Euro NCAP MPDB Testing Protocol [4] and the AOP Assessment Protocol [5]. See Figure 1.

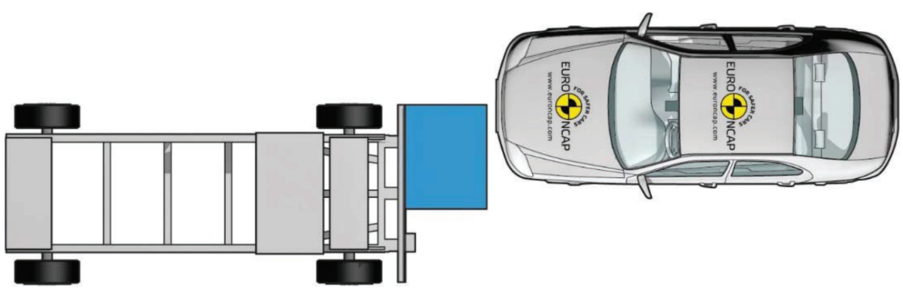


Figure 1: MPDB test configuration

It is important to note that in 2020 there were changes not only to the Adult Occupant Protection (AOP) box, but also to the Child Occupant Protection (COP) and Safety Assist (SA) boxes. This paper only examines the influence of replacing the 40% overlap, ODB frontal impact test with the MPDB test. Within the AOP box, the relative weight of the ODB and MPDB tests was unchanged and so, therefore, the weight of that box in the overall rating scheme. Scoring of other areas within the AOP assessment changed with the additional of farside occupant safety and rescue and extrication. A comparison of scoring within the AOP box is summarised in Table 1.

| | 2018-2019 | | 2020-2022 | |
|---|---|---|---|---|
| | Frontal ODB | **8.000** | Frontal MPDB | **8.000** |
| | Frontal FW | **8.000** | Frontal FW | **8.000** |
| | Side MDB | **8.000** | Side MDB | **6.000** |
| | Side Pole | **8.000** | Side Pole | **6.000** |
| | - | **-** | Farside | **4.000** |
| | Whiplash | **2.000** | Whiplash | **4.000** |
| | AEB City | **4.000** | Rescue | **2.000** |
| **Total Score** | 38.000 | | 38.000 | |

Table 1: Adult Occupant Assessment scoring

Both sets of data from ODB (2018-2019) and MPDB tests (2020-2022) are similarly sized in terms of the number of vehicles; 83 vs 81 respectively. Partner models utilising the same ODB and MPDB test results have been excluded from this assessment to avoid duplication of data. The distribution of vehicles throughout the Euro NCAP vehicle categories is similar for both samples, with small family car and small off-road being the most popular categories, followed by large off-road. The number of vehicles included in the Supermini category has halved over the last 10 years. It is important to note that vehicle category is not a good measure against which to compare results as these categories are self-declared by the vehicle manufacturers and lack a clear definition, but it is mentioned here to offer an overview of the vehicle types included in this assessment.

Approximately half of the vehicles tested in 2020-2022 were either full electric or hybrid powered, which is doubling the number of that vehicle type tested in 2018-2019. The variation of unladen kerb weight between the two sets of data was quite small, but it is acknowledged that vehicle mass continues to rise, even more so with the proliferation of Hybrid and Electric vehicles in the market. Vehicle mass is discussed further in the section of this paper that considers future work.

Having noted the composition of vehicles within the two data sets, the next step was to review the highest level of Euro NCAP results, which is the overall star rating. A comparison of the number of vehicles scoring 0 to 5 stars shows the proportion of vehicle star ratings has remained largely unchanged with the updates to the AOP assessment. Most vehicles scored either four or five stars in both data sets, see Figure 2.

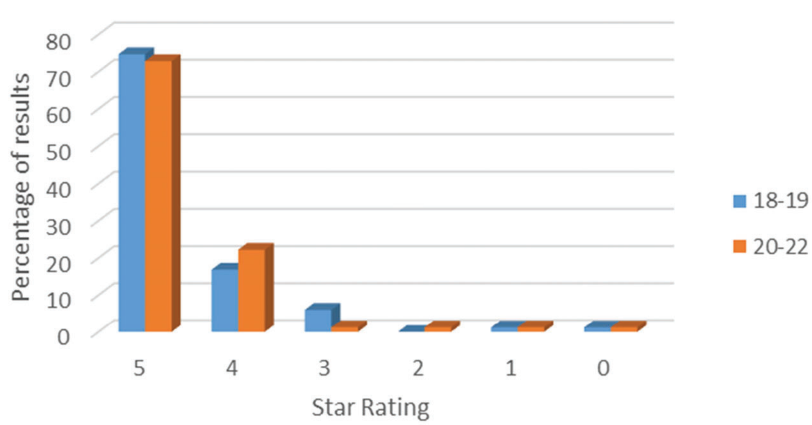


Figure 2: Distribution of vehicle star ratings in the sample sets.

**Overall MPDB Test Results**

On average, the updated assessments resulted in an AOP score reduction of approximately 2 points out of a possible 38 (~5%) but, as mentioned previously, this was not enough to affect the star rating. Although both sets of data show most vehicles above the 80% threshold required for five stars, the ODB data shows there are more lighter vehicles (<1500kg) achieving four stars. See Figure 3. This reduction is also visible in the individual scores for the ODB and MPDB tests. One vehicle scored zero points in the MPDB test, this was due to a high driver's chest compression of 62mm. In the MPDB test, the chest is determined a 'critical' body region along with the head and neck. Where the caping limit for any of these criteria is exceeded, the total MPDB test score is automatically set to zero.

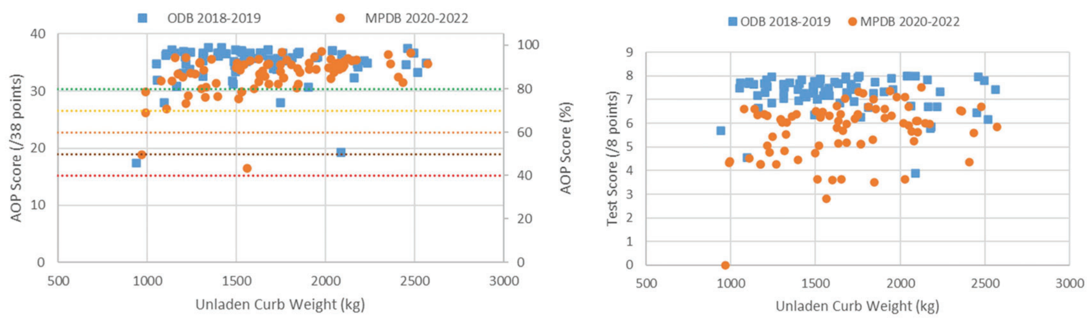



Figure 3: AOP Score breakdown, total (left) and for the offset test (right)

**Driver and Passenger Results**

To further illustrate the differences between the ODB and MPDB procedures, the body region data was examined more closely. The scoring for each of the body regions is shown in Figure 4.

**Driver**

**Head –** It has been the case for many years now that the driver's head is mostly awarded full points in Euro NCAP ratings. No drivers were penalised in the data sets based on biomechanical criteria (skull fracture risk, HIC & 3ms exceedance) and in only a handful of cases was the head penalised for 'bottoming out' the airbag. Accident research undertaken by ADAC [6] indicates that head injuries are still a common cause of death and serious injury, but the frequency of skull fractures is relatively low. This suggests that, while the low risk of skull fracture shown in Euro NCAP tests is in line with real world occurrence, injury mechanisms for brain injury are now more prominent and should be addressed. Accident studies from the US [7] have shown that, in newer vehicle models, there is a trend toward a reduction in the likelihood of AIS 4+ brain injury, but an increased risk of lower severity brain injures (AIS 2+ and AIS 2-3).

**Chest –** The test data shows lower chest scores with the MPDB test and THOR dummy compared to the ODB test and Hybrid III; roughly 1 point less on average. For THOR, the chest assessment is based on the value of Rmax, the maximum resultant chest displacement. For Hybrid III, was based on the worst performer between chest potentiometer displacement and viscous criterion (V*C) and, in all cases, chest displacement was the worst performing parameter. The shoulder belt load penalty that is applied when the peak load exceeds 6.0kN, was not incurred by and of the cars in the datasets.

**Knee, femur and pelvis –** The Euro NCAP femur compression limit remained unchanged at 3.8kN with the adoption of the THOR dummy. The results were similar between the two datasets, but in the MPDB test eight vehicles were penalised for either femur load or knee slider displacement, with a maximum compression of over 14kN. In the ODB tests, no vehicles exceeded the 3.8kN femur compression limit. Acetabulum compression was also included in the assessment from 2020, and in almost all cases the load was below the higher performance limit (HPL) of 3.28kN.

**Lower leg –** The data from the MPDB tests shows a wider spread of results than in the ODB tests. It is worth noting that the THOR dummy is equipped with the same tibias and feet as those of the Hybrid III, suggesting that this is more a test difference rather than a dummy difference. This was also seen during the development phase of the MPDB procedure conducted in 2018. Anecdotal evidence from Euro NCAP inspectors, who examine the vehicles after the official tests, suggests that with the introduction of the MPDB test more vehicles are suffering greater levels of footwell intrusion in the MPDB test.

**Passenger**

There appears to be little difference between the ODB and MPDB results for the passenger dummies. However, scores for the lower region leg appear to be slightly worse in the MPDB test. The cause for this is not completely understood and but it has been observed in vehicles across the mass range. It could be a result of the different pulse and/or the lower amount of vehicle rotation observed in MPDB test compared to ODB impacts.

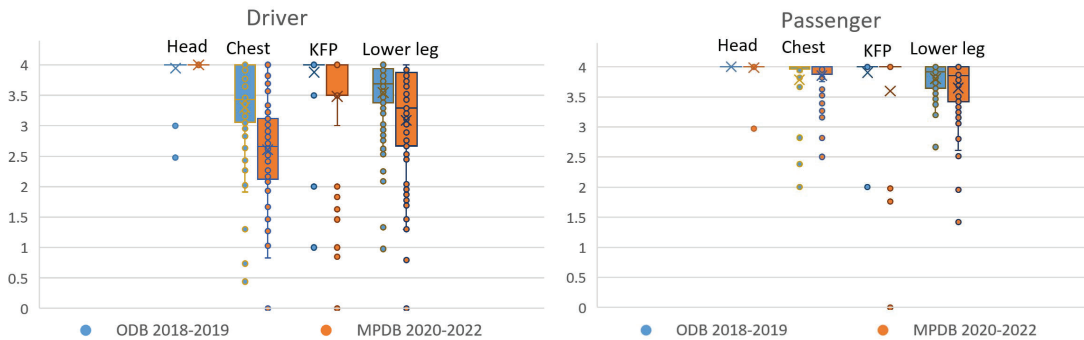



Figure 4: Driver and passenger body region scores (max 4 points per body region)

**Compatibility Assessment**

The Euro NCAP compatibility modifier was first applied to ratings in 2020 in combination with the MPDB test. It is an assessment that uses the trolley deceleration (Occupant Load Criterion, OLC) and post-test barrier deformation measurements (homogeneity) to evaluate a vehicle's crash compatibility. This assessment is described in more detail in Euro NCAP Technical Bulletin TB 027 and is applied as an increasing penalty when compatibility worsens. See Figure 5.

For 2020 to 2022 assessments, the maximum penalty was -4 points to be deducted from the MPDB test score (max 16 points). It is treated as a penalty, rather than a reward, because a reward system would give an initial perspective of all vehicles offering poor compatibility unless proven otherwise. A malus system was considered to be a fairer approach to apply to all vehicles.

Of the 81 official Euro NCAP MPDB tests performed to date, there has only been one vehicle that was not penalised for compatibility. This was a supermini with an unladen kerb mass of 990kg and a test mass of 1237kg. It is encouraging to see that more than half of the vehicles assessed were penalised by 1.5 points or less, and even vehicles weighing >2000kg have performed well in this assessment, which was not the case during the development of this test procedure. The average penalty across all vehicles was -1.83 points.

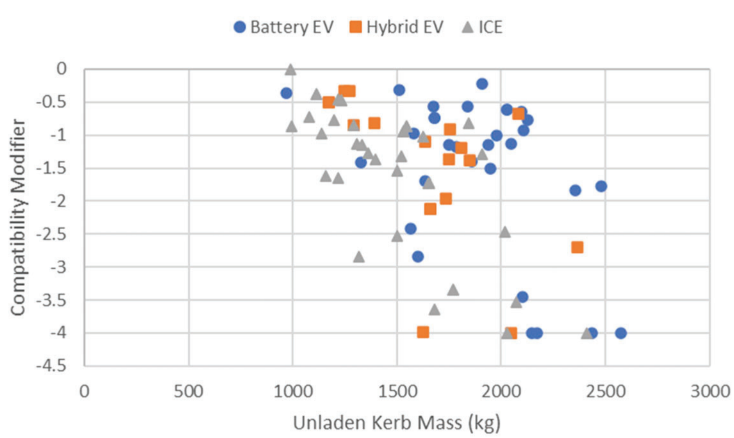
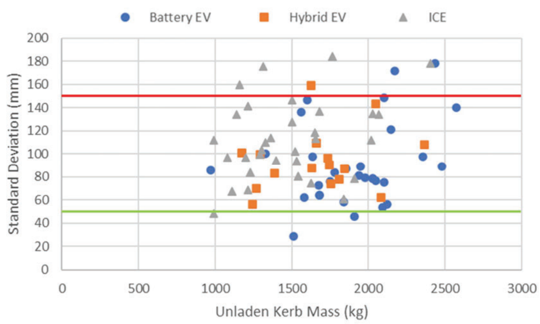


Figure 5: Compatibility modifier 2020-2022

The data contains another supermini with a similar kerb mass (993kg), which was penalised by -0.87 points, mostly due to high standard deviation (112mm). This shows that although small cars offer a lower OLC, it is still necessary to ensure that front structures are designed to be homogeneous, and less aggressive to their crash partner. Many, far heavier vehicles, had designs offering lower standard deviation. The modifier limits for OLC were based upon test data from the FIWG testing programmes as well as the understanding that the lighter test vehicles will impart the lowest OLC on the trolley. Only one vehicle, weighing 2070kg, exceeded the 40g limit for OLC. The spread of OLC values is greatest between kerb masses of 1500kg to 2200kg. The data also shows that mass seems to be the driving factor, but not the only one. This is indicated by higher and lower values for SD and OLC within the same vehicle mass. When devising the compatibility modifier, Euro NCAP did not anticipate OLC values above 40g, but based on the recent data, this range still fits around most of the vehicle population. See Figure 6.



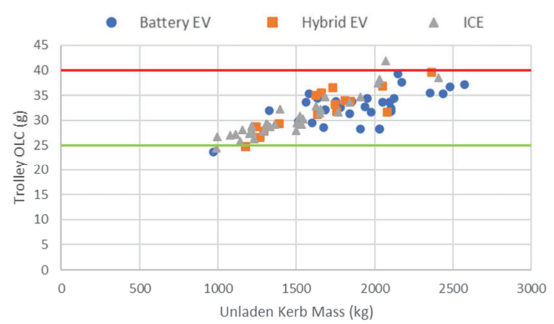




Figure 6: Compatibility assessments 2020-2022

The final component of the compatibility assessment is an additional penalty that is applied when bottoming out of the barrier face occurs. This is defined as barrier deformation in the defined assessment zone of 630mm or more. 14 vehicles bottomed out the barrier face, the lightest of which had a kerb weight of 1316kg. In half of the bottoming out cases the kerb weight was over 2000kg. See Figure 7.

Kerb mass: 2173kg
Deformation SD: 172mm
Bottoming out: Yes

Kerb mass: 2480kg
Deformation SD: 89mm
Bottoming out: No

Figure 7: MPDB face deformation, with (left) and without (right) bottoming out.

During the development of the MPDB test procedure, Euro NCAP investigated the variation in the outcome of the compatibility assessment caused by the use of MPDB faces produced by different suppliers. Test data from five comparative tests, using three different MPDB suppliers, was analysed in line with the compatibility assessment. It should be noted that the same specification of test vehicle (test mass 1350kg) was used in all tests, but this vehicle was not engineered to meet any vehicle compatibility measures.

The results of the five tests are shown in Table 2. Both the vehicle pulses and trolley OLC pulses compared well and resulted in a 5g difference in trolley OLC. The variation in standard deviation was 21mm, resulting in a spread in compatibility assessment of 0.7 points. The vehicle bottomed out the barrier face in all tests.

| | Barrier supplier | | | | |
|---|---|---|---|---|---|
| | **A** | **A** | **B** | **B** | **C** |
| Test index | 1 | 2 | 3 | 4 | 5 |
| Trolley OLC (g) | 24.5 | 26.6 | 29.6 | 29.4 | 28.6 |
| SD (mm) | 158 | 148 | 137 | 139 | 147 |
| Bottoming out | Yes | Yes | Yes | Yes | Yes |
| **Compatibility assessment** | **2.0** | **2.3** | **2.7** | **2.7** | **2.7** |

Table 2: Compatibility assessment results, comparison of barrier suppliers.

It should be noted that there were differences in the structural performance of the test vehicles, particularly regarding the failure of the bumper beam. In some cases, the bumper beam broke, whereas in others it did not. Also, in some cases, the bumper beam remained attached to the lower rails, and in others it did not. Given these differences, the subsequent difference in compatibility assessment between the barrier faces was deemed acceptable.

Figure 8: Comparative test MPDB face deformation

In addition to the reduced vehicle rotation observed in MPDB tests, another notable difference to that of the ODB test is the vehicle pulse. ODB tests typically offer a back-loaded pulse with a much longer duration. The MPDB pulse is of a shorter duration and like that of the rigid wall full width test. See Figure 9. The averaging of pulses hides the differences in acceleration levels between vehicles of different weight, so the MPDB pulses of the lightest (1349kg) and heaviest (2676kg) vehicles are also provided. It should be noted that a smaller data set of MPDB pulses was used to produce this data.

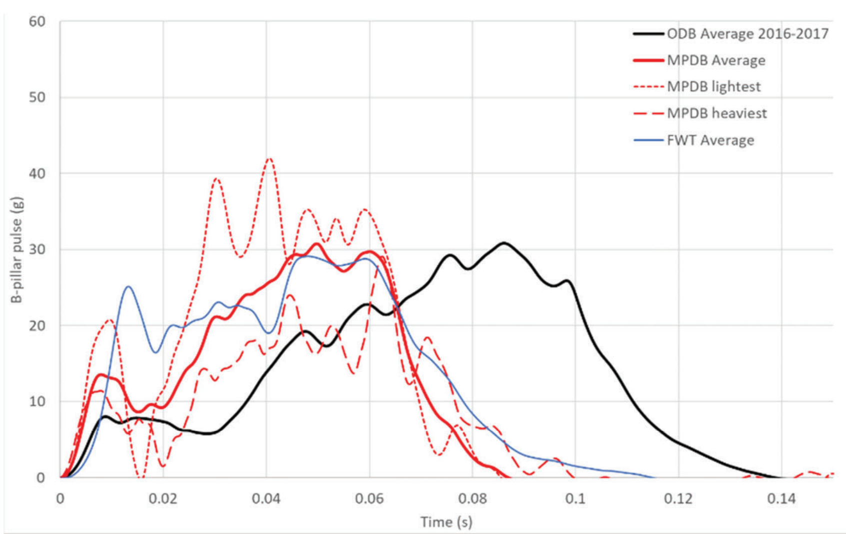



Figure 9: Euro NCAP Test pulse comparisons

**MPDB Test Observations - Belt Slippage**

With the adoption of THOR dummy, Euro NCAP observed that in some tests the diagonal section of the driver's seat belt slid from the shoulder into the gap between the neck and shoulder pad. This could allow the belt to directly load the spine box rather than the rib cage, see Figure 10. This phenomenon can only be identified with the use of onboard cameras. Although it is not always possible to see the belt to shoulder interaction, where it could be seen on the high-speed film, the belt slips into the neck gap in approximately 1/3rd of cases.

Figure 10: THOR diagonal belt slippage

Belt slippage is a dummy artifact and not biofdelic behaviour, possibly leading to un-instrumented load paths. When reviewing the cases where the belt slips off, there did not appear to be a common trend in the timing between the belt slippage and peak Rmax value. In some cases, the belt slipped before peak Rmax, and in others this occurred after peak Rmax. In some cases the belt slippage was visible in the dummy outputs and in others it was not. At this stage the influence of belt slippage on Rmax is not well understood and further investigations into this phenomenon will be performed. With the planned introduction of a more advanced chest criterium, consistent belt behaviour will be critical for the correct assessment of chest injury risk.

Updated shoulder pads have been produced by two dummy suppliers to prevent the belt from moving into the neck gap. At the time of writing, there was very little data available on the efficacy of these shoulder pads [22]. The FIWG took the decision to permit the use of modified shoulder pads where the vehicle manufacturer believes that belt slippage will occur. This issue will continue to be examined alongside the anticipated introduction of an improved chest assessment criterion.

**THOR Dummy**

The THOR dummy has been available in various guises for over 20 years and Euro NCAP was the first consumer rating scheme globally to adopt the dummy. A series of comparative sled tests and full scale MPDB to car tests were used to compare the results of THOR dummies produced by two different manufacturers. A generic sled rig was used with an airbag, pretensioner and load limiter. The dummy outputs compared well and was subsequently used to approve a second THOR dummy manufacturer for use in Euro NCAP testing.

By now, there are many of these dummies available worldwide and the FIWG decided that certification data should be reviewed to see the status of dummies in use in the field. A programme of work will be undertaken to collect whole dummy certification data from as many sources as possible and collated for review. This will include a comparison with the latest NHTSA proposed qualification procedures for the dummy.

Collecting such a large amount of data from different institutions is a demanding task and it was necessary to standardise the certification data to allow direct comparison. The Partnership for Dummy Technology and Biomechanics (PDB) developed a procedure to achieve this [8] confirming ISO codes, sign conventions and post processing steps to be taken. Due to the sensitivity of sharing in-house certification data, data will be anonymised before comparison. This work has only just begun, and no data has yet been collected, but it is hoped that the first review can be performed in the first half of 2023.

Figure 11: THOR dummy comparison tests

**Chest Certification**

The current THOR certification corridors adopted by Euro NCAP are detailed in Euro NCAP TB 026. This document was compiled to limit the difficulties that laboratories encountered in meeting the Z deflection certification requirements. The corridors were based on data from over 700 certification tests performed between 2018-2019 and were designed to fit the global population of dummies globally. The dummy response characteristics were examined, and it was found that a rhombic corridor was required to better represent the relationship between X and Z displacement during certification. Subsequently, peak resultant displacement (Dres) and Z/X ratio were adopted with a 7% variation limit.

Further investigations into the chest certification process are being undertaken within ISO WG5 (ATD). A modified test is under consideration that uses a trapezoidal impactor and an impact location that is 15mm higher, which aims to offer more realistic loading of the chest during certification, based on full scale test behaviour. At the time of writing, testing was still ongoing and no vehicle-based results have yet been made available. This will be considered by the group in future with the aim of reducing the variability of THOR chest results.

## UPDATES TO THE MPDB TEST 2023

**Compatibility Modifier**

It was initially Euro NCAP's intention to have a -8 point maximum penalty beginning in 2020. However, this was reduced to a -4pt maximum for the introductory years 2020-2022 to allow more time for compatible designs to enter the market and limit the size of the penalty while this happens. In 2023, the compatibility modifier will be increased to -8 points. Several vehicles have proven that their concept of compatibility can be effective in real life and demonstrate this in the MPDB test. Compatible frontal structures can be implemented in all vehicles, but it is acknowledged that time and money is required before they become commonplace in the vehicle fleet. To continue to drive the development of compatible vehicles, an increased penalty is needed in the future to avoid slow or even no development in compatible frontal structure design.

**Brain Injury - Incorporation of DAMAGE criterion 2023-2024**

With the adoption of the THOR driver dummy in the MPDB test, Euro NCAP decided that simply evaluating the skull fracture risk of the driver's head was insufficient and that more should be done to address head injuries. It was decided that a criterion would be adopted to evaluate the risk of sustaining a mild traumatic brain injury risk (AIS2 moderate concussion). A number of well known, kinematically based criteria were considered including BrIC [9], UBrIC [10], DAMAGE [11], HAIC [12] and CIBIC [13]. The kinematic criteria were compared to the FE brain injury models from KTH [14] and SUFEHM [15]. When comparing the risk calculated by the kinematic criteria versus Maximum Principal Strain (MPS100) from the KTH model, DAMAGE and CIBIC appeared to have the best correlation in frontal impacts. This has also been seen with WorldSID in far side impacts, but the correlation was lower. Kinematic criteria that consider rotation only, such as UBrIC and DAMAGE, may have some limitations when it comes to evaluating the translation kinematics. It is noted that the different FE brain injury models, such as THUMS [16], GHBM [17], KTH and SUFEHM have different brain shear modulus making the rotational effects more important for those models with a lower shear modulus. Furthermore, the different brain injury risks were based on different head trauma databases that contain different types of injury, which may also influence results.

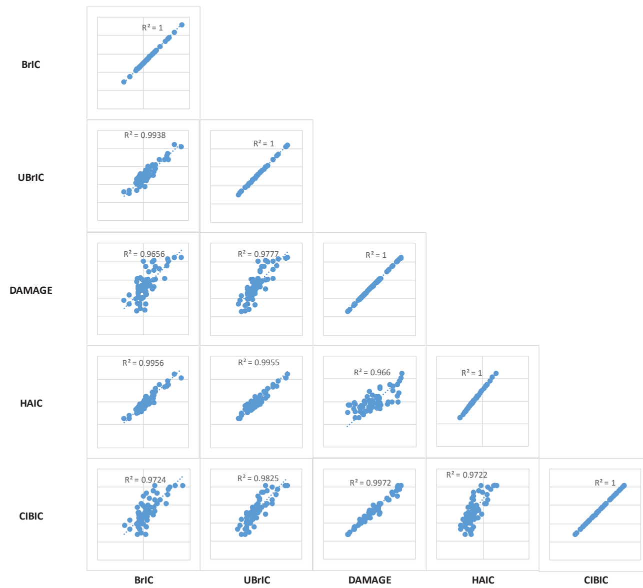



Figure 12: Brain injury metric correlations

Calculation of the Diffuse Axonal Multi-Axis General Evaluation (DAMAGE) criterion is defined in the THOR dummy technical report ISO TR 19222. This was chosen by Euro NCAP as an interim brain injury metric until a more advanced assessment could be implemented. The time window for calculation of the DAMAGE criterion is limited to exclude secondary head contacts with the vehicle interior and is detailed in Euro NCAP Technical Bulletin TB 035. This criterion will be evaluated during the loading and early rebound phases of the impact over a maximum period from T0 up to 200ms. The time window will be reduced to less than 200ms if, during rebound, a secondary head impact results in an external neck force drop below 500N.

The DAMAGE criterion is incorporated into the driver's head assessment as a modifier applied after the assessment of the biomechanical criteria. A maximum score of four points is available for the head. Where DAMAGE reaches a value of 0.47 and above, a -2 point penalty will be applied; for values between 0.47 and 0.42, the penalty will be -1 point; and values below 0.42 will not be penalised. These values were chosen to penalise the worst performers. Although it was acknowledged that the supporting injury risk curves were sufficiently reliable to use a sliding scale risk assessment, due to the limited application of DAMAGE in vehicular testing this was rejected for the initial implementation of the criterion.

A more limited set of official test data (n=67 vehicles) was evaluated for DAMAGE. Only two vehicles exceeded the HPL of 0.42, and none exceeded 0.47. Six different vehicles exceeded 0.40 with masses ranging from 1175kg to 2103kg. The distribution of the data suggests that lighter vehicles are not more susceptible than heavier ones. See Figure 13.

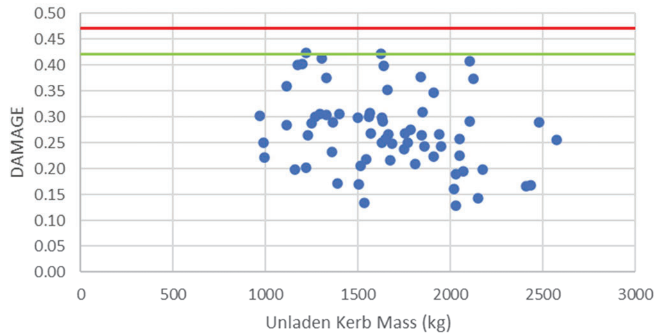


Figure 13: DAMAGE values, MPDB tests 2020-2022

Taking a closer look at the vehicles with a DAMAGE value of ≥0.42, it was found that the rotational velocity about the Z axis was the controlling parameter in the calculation. Both vehicles had angular velocities >1500 rad/s in the loading phase of the impact.

## FUTURE EURO NCAP UPDATES

### Euro NCAP Roadmap 2030

In November 2022, Euro NCAP published its roadmap detailing the strategic goals for the period up to 2030 [21]. The current rating scheme will be replaced in 2026 with a system identifying four phases of a vehicle accident: safe driving, crash avoidance, crash protection and post-crash safety. All crash testing will be included under the crash protection assessments, and the tests themselves will also be updated to address the differing levels of protection being offered to different occupant demographics. This is most notably the case for drivers of different statures and ages as vehicle restraint systems are primarily designed to protect the mid-sized male occupants.

The MPDB test will be updated to include the THOR 50th male in the driver's seat and a 5th female on the front passenger's seat, most likely to start with the Hybrid III followed by the THOR type of dummy. The rear seats will continue to be occupied by the Q6 and Q10 dummies but will be assessed using improved biomechanical criteria and limits. The test parameters will also be reviewed to represent the increasing mass of the European passenger car fleet as well as considering crash severities seen more closely in the real world.

### Barrier Mass

In the Euro NCAP protocols, the mass of both the MPDB and AE-MDB trolleys is currently 1400kg. Of the assessments performed by Euro NCAP in 2018 & 2019, the average unladen kerb mass of the test vehicles was 1604kg. Comparing this to the 2020-2022 data, there has been no major change in recent years as the average kerb mass was 1693kg. However, when looking back to older Euro NCAP test vehicles, average vehicle mass has increased over the last 10 years. The average kerb mass of the vehicles assessed by Euro NCAP between 2009-2011 was 1416kg (similar sample size). The distribution of these masses for the later vehicles was toward the heavier side of the distribution. Based on this data, it would already seem that there is justification to increase the mass of the MPDB trolley to be more representative of the average vehicle.

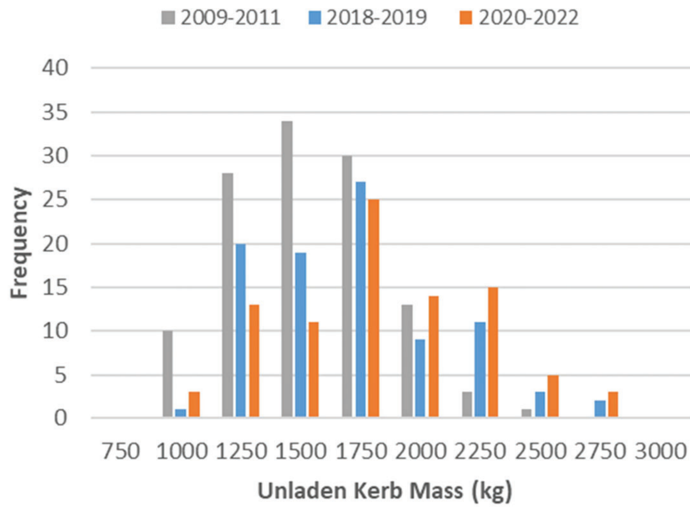
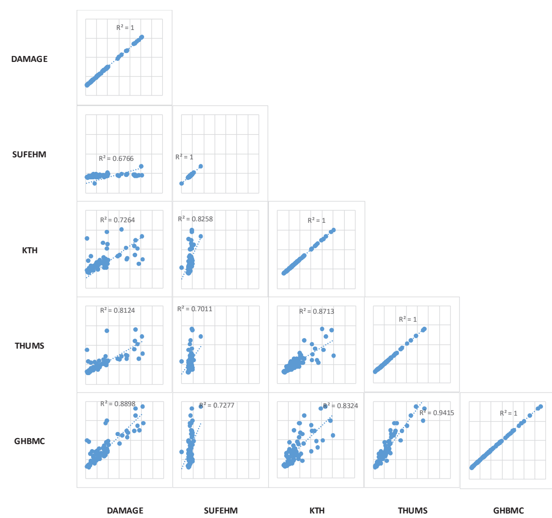



Figure 14: Unladen kerb mass distribution

**Advanced Brain Injury Assessment**

Euro NCAP is currently reviewing advanced brain injury metrics for future introduction that will allow a more representative measurements of brain injury risk. This is expected to replace DAMAGE in 2026 and will use a sliding scale assessment instead of the pass/fail limits. A comparison of brain injury criteria in full vehicle crash tests was reported in several previous publications e.g. [18]. To compare the outputs of possible candidate criteria, including those based on FE models, the THOR head output signals of more than 60 full-vehicle MPDB crash tests conducted between 2020 and 2022 were evaluated. The criteria values and AIS2 risk are shown in Appendix I. Figure 15 shows the correlation of the AIS2 risk of the different criteria.




| | DAMAGE | SUFEHM | KTH | THUMS | GHBMC |
|---|---|---|---|---|---|
| DAMAGE | 1.00 | | | | |
| SUFEHM | 0.52 | 1.00 | | | |
| KTH | 0.58 | 0.54 | 1.00 | | |
| THUMS | 0.74 | 0.44 | 0.80 | 1.00 | |
| GHBMC | 0.85 | 0.48 | 0.72 | 0.92 | 1.00 |

Figure 15: AIS2 (+) brain injury risk and parameter correlations

On reviewing the correlations between the injury risks from the different criteria, five correlations were statistically significant (>0.70). In some cases, the predicted risk for DAMAGE, KTH and GHBMC were high at over 50%. As the injury risk curves for DAMAGE, THUMS and GHBMC were generated using the same brain injury databases, therefore a good correlation could be expected.

There was a large spread of risk between the criteria with GHBMC predicting the highest risk of injury at 65%, see Figure 16. Except for SUFEHM, the other criteria give a maximum risk of 46-54%. SUFEHM offered a maximum risk of 17%. Two of the criteria, SUFEHM and GHBMC gave maximums for the same vehicle. No further analyses were available at the time of writing. The next steps will be to identify several individual cases from the Euro NCAP data to review in more detail. These cases will be chosen based upon the high spread of risk between different criteria, and where multiple criteria highlight a high risk.

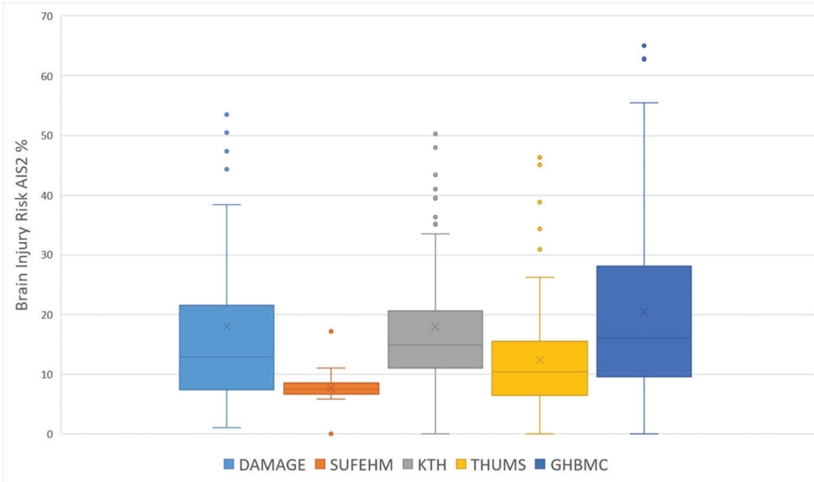



Figure 16: Brain injury risk spread

To support the decision of which criterion is most suitable to predict brain injury in an occupant safety assessment, accident reconstruction using Human Body Models (HBMs) could be a complementary addition. However, few studies were done so far regarding brain injury of car occupants. Therefore, accidents where the driver suffered brain injury were selected from an in-depth accident database and reconstructed using an HBM. The objective of this was to support the identification of an appropriate predictor for brain injury caused by motor vehicle accidents.

The methodology and computational studies for the accident reconstruction followed several steps. In the first step, accident cases were extracted from the German In-Depth Accident Study (GIDAS) database. In the second step, the vehicle model and occupant model were selected based on the accident data. For the vehicle model in this study, a midsize sedan car published on NHTSA website *1 was used. Regarding the occupant model, THUMS (version 4.02) was used and resized based on the target occupant size. The seating position was estimated by the hip point location of a typically sized occupant *2. In the third step, the reconstruction based on the above information was conducted while considering each of the brain injury predictors. These predictors were calculated based on six DOF acceleration of the centre of gravity of the THUMS head. In the fourth and final step, the validity of the reconstruction results was confirmed in terms of the vehicle rebound direction, the vehicle deformation level, the location of injury and the part responsible for the head injury. Once the results were validated, the injury risk probability predicted by each injury risk function of the predictors for the ATD were compared as well as the one calculated by the brain strain of THUMS.

Three cases were selected and reconstructed. In the following section, the reconstruction of the first case is described in detail. For the second and third case limited details are provided in Appendix II. Figure 17 shows the sketch of the first accident including the vehicles' movement paths. Vehicle A was a midsize sedan with a collision speed determined to be 10 km/h. Vehicle B was a midsize wagon with a collision speed of 70 km/h. The relative angle between both cars was 121°. In this accident, the driver of Vehicle A suffered from an AIS2 brain injury due to impact with the B-pillar. The injuries sustained by the driver are listed in Table 3. The simulation set-up is shown in Figure 18. Each accident simulation was set based on the prescribed accident data and the THUMS HBM was installed as shown in Figure 19.

[*1] NHTSA website, https://www.nhtsa.gov/crash-simulation-vehicle-models.
[*2] Autograph website, http://www.autograph.de/index.php?id=30

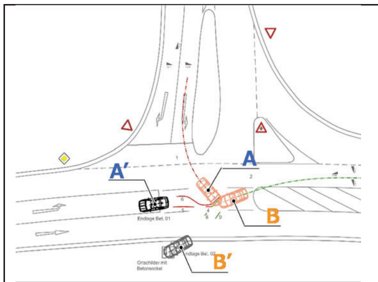



Figure 17: Accident sketch

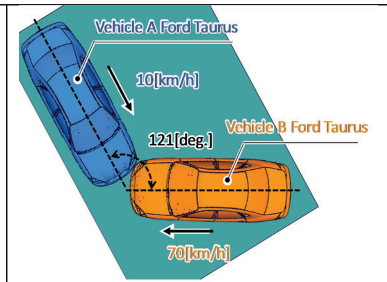



Figure 18: Simulation model set-up

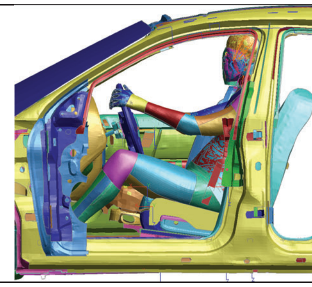


Figure 19: THUMS seating position

| No. | Regions | AIS 2008 | Diagnosis | Trauma causes |
|---|---|---|---|---|
| 1 | Chest | 1 | Contusion | Seat belt |
| 2 | Head | 1 | Scalp laceration | B-pillar |
| 3 | Cervical spine | 1 | Whiplash | Body motion |
| 4 | Head | 2 | Lost consciousness | B-pillar |
| 5 | Stomach | 1 | Contusion | Seat belt |

Table 3: Injuries to driver of vehicle A

To confirm whether results are suitable to evaluate brain injury predictors, some points were used to judge the validity of the reconstruction result. The rebound direction of Vehicle A was similar to that extrapolated from the accident's (Figure 17). The initial driving direction of Vehicle B is shown in Figure 20, and both vehicles came to a stop facing away from each other. The vehicle deformation level was almost the same as that observed in the accident's as judged by the post-crash pictures, the deformation level in GIDAS data and the results of the reconstruction. An example of the comparison between the post-crash picture is shown in Figure 21. With regard to the driver's kinematics of Vehicle A, the head injury location and the head contact part described in the GIDAS data were reproduced as shown in Figure 22.

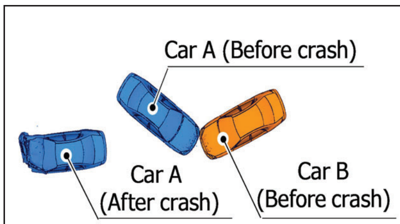



Figure 20: The rebound direction of Vehicle A.

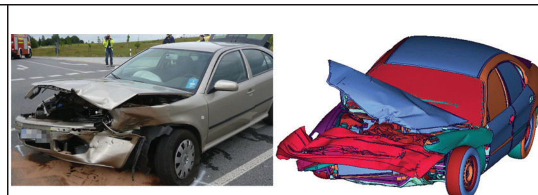
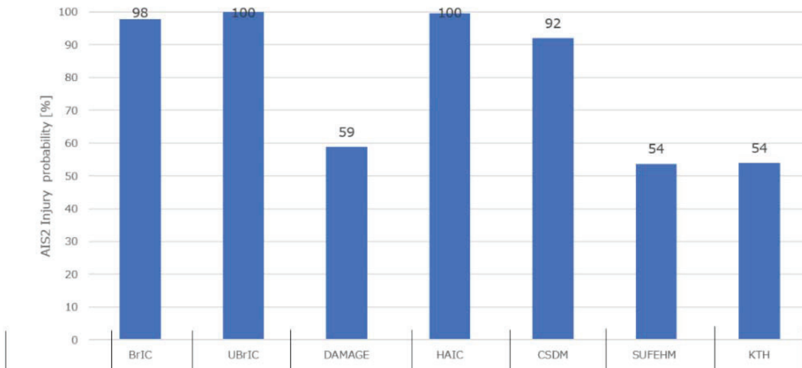


Figure 21: The comparison of vehicle apperance

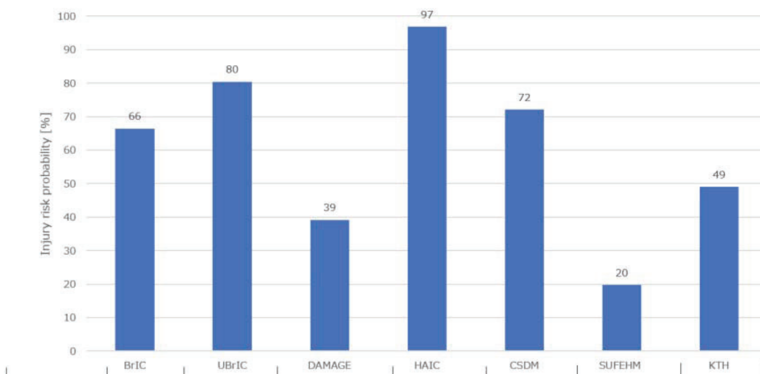
Figure 22: The injured position

Figure 23 to Figure 25 show the AIS2 of brain injury predicted by different injury metrics. In all considered cases the occupant suffered AIS2 injury. Thus, the candidate criterion should predict a high risk of AIS2+ injury. However, it is difficult to assess the correct prediction capability of the different criteria based on only three accident cases, especially at car modelling level. Therefore, it is proposed to add additional cases for evaluation before drawing any further conclusions. It would also be beneficial to add AIS0 brain injury accident reconstruction cases for reference with car occupants that suffered AIS2+ injury of other body regions but did not sustain any brain injury. In summary, the method of HBM based reconstruction of in-depth car occupant cases is considered the right approach to further selection of the most suitable brain injury criterion. However, more accident cases and improved car models are need.



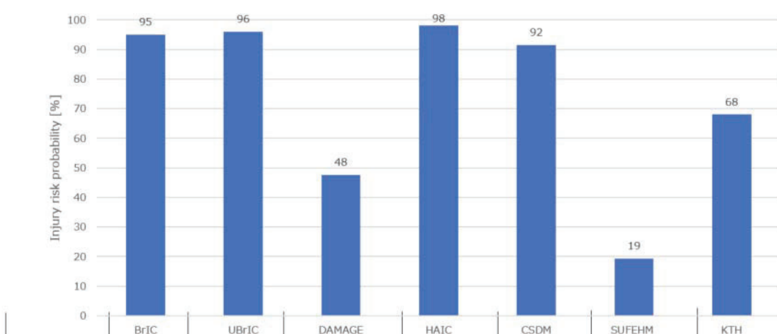

| | BrIC | UBrIC | DAMAGE | HAIC | CSDM | SUFEHM | KTH |
|---|---|---|---|---|---|---|---|
| Injury value | 1.21 | 0.77 | 0.45 | 122 | 29 | 38 kPa | 0.55 |

Figure 23: AIS2 brain injury probability for accident reconstruction case 1




| | BrIC | UBrIC | DAMAGE | HAIC | CSDM | SUFEHM | KTH |
|---|---|---|---|---|---|---|---|
| Injury value | 0.86 | 0.51 | 0.38 | 97 | 11,4 | 20 kPa | 0,46 |

Figure 24: AIS2 brain injury probability for accident reconstruction case 2




| | BrIC | UBrIC | DAMAGE | HAIC | CSDM | SUFEHM | KTH |
|---|---|---|---|---|---|---|---|
| Injury value | 1.12 | 0.6 | 0.41 | 103 | 28 | 20 kPa | 0. 36 |

Figure 25: AIS2 brain injury probability for accident reconstruction case 3

**Chest Assessment**

The assessment of chest injury risk has been based on displacement and V*C since the first Euro NCAP tests were performed in 1996. With the adoption of THOR Rmax, the maximum peak resultant displacement of the four chest displacement transducers, has been used alongside a peak belt load limit of 6kN. Accident data suggests a strong correlation between belt load and thoracic injury risk and the thorax is one of the most critical areas involved in deaths and serious injuries.

The FIWG has been reviewing alternative chest assessment criteria - TIC and PCA [19, 20], but data is currently limited and further evaluations need to be performed. The first step in this process will be for the group to review the THOR certification test data and await the outcome of the modified certification test procedure.

Another criterion investigated was DEQ-NSFR. The Euro NCAP test data shows that DEQ-NSFR correlates strongly to both chest Rmax and diagonal belt load, see Figure 26. DEQ-NSFR uses a combination of Rmax and peak diagonal belt force (0.33*Rmax + 6*USBF). A comparison of vehicle rankings based on Rmax and DEQ-NSFR values (mm) resulted in a coefficient of concordance of 0.85.

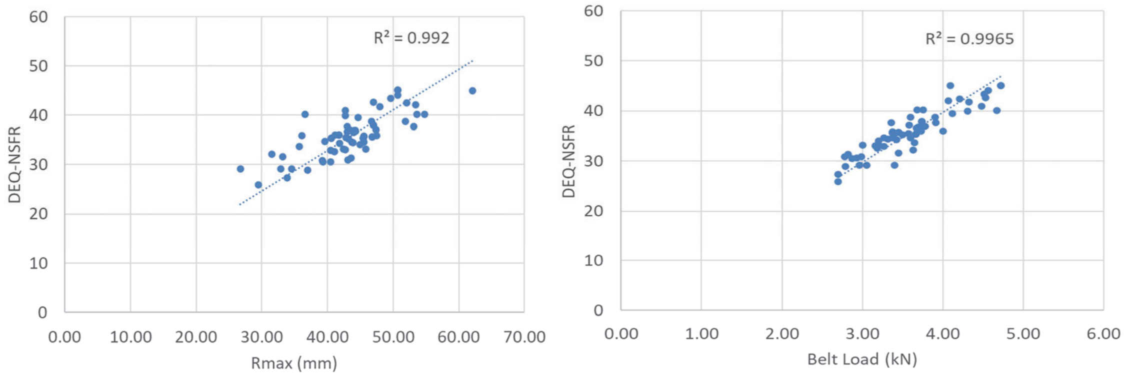



Figure 26: Correlation of THOR chest Rmax, Diagonal belt load and DEQ-NSFR

Concerns have been raised regarding the reliability of belt load data, as well as difficulties in the calibration of sensors. Euro NCAP requires seatbelt load cells to follow the calibration procedure developed by ISO (TS 17242:2014) to help prevent issues with belt load measurements. Currently, Euro NCAP limits the use of diagonal belt load assessments to simple pass/fail criteria rather than incorporating these loads into a sliding scale assessment. With the chest being still one of the most injured body regions further investigations in a more advanced chest assessment need to be done, based on the work to reduce scattering of the individual THOR dummies.

## CONCLUSIONS

The development of the Euro NCAP Mobile Progressive Deformable Barrier frontal impact test began in 2015 and the test procedure was applied to vehicle ratings in 2020. Although this test has not led to reductions in star ratings, this new test procedure gives more stringent requirements for vehicle restraint systems while also providing a measure against which a vehicle's compatibility can be evaluated. This could be seen in more advanced restraint systems with new pre-tensioning systems and different belt load limitations. The increased weight in the AOP rating of the compatibility assessment is expected to provide sufficient encouragement for vehicle manufacturers to improve the level of vehicle compatibility from what it currently is today.

With the adoption of DAMAGE, Euro NCAP will offer an improved head injury assessment compared to what is currently done. For the thorax, further investigations will be performed using other chest criteria that do not correlate to Rmax to see if they provide additional information. The database used to develop the Rmax criterion was limited and would benefit from the incorporation of distributed airbag load cases, which could also show the benefit of advanced multi-point deflection criteria like PCA or TIC. The FIWG will continue to review THOR certification data in order to drive improvements in procedures and corridors, this will be done using a collaborative approach to data sharing and analysis. The need for modified shoulder pads will be examined, but data on the efficacy of these it awaited.

In future, the MPDB test will be complemented with an advanced brain injury assessment and a more stringent assessment of vehicle compatibility. With increasing vehicle masses, the severity of the MPDB test will be reviewed to ensure that the trolley mass is representative of the vehicle fleet and that the test severity is representative of crashes occurring on the road.

Looking further ahead, the FIWG will focus on implementing the next safety priorities identified in the Euro NCAP roadmap for 2030 [21]. Vehicle safety has improved significantly over the last 20 years. The tests that are being introduced will help to protect all aspects of the population (age, gender, anthropometry etc). However, some areas are now being highlighted where there are additional risks to certain parts of the population. Equality in crash safety is important to all, and this extends well beyond gender and applies to many other human characteristics, including age. Representation for all humans is important, but we need to understand what factors are overrepresented in crashes – such as the elderly, obese, large males and small females. It is important to examine accident data and PMHS research to try an understand the reasons behind this additional risk. For example, is this due to belt fit, femur to facia interaction etc.

Euro NCAP is already testing with crash dummies of different types and stature in frontal impacts, and other assessment areas also consider different occupant statures (e.g. side impacts). However, not all dummies used by Euro NCAP can be considered state-of-the art, and Euro NCAP will adopt the latest generation THOR 5th percentile female in addition to the current THOR 50th percentile male dummy. Both dummies will be used as driver and front passenger respectively in a revised low severity full-width barrier test, applying criteria and injury limits that promote restraints that better protect elderly occupants.

Adoption of more sophisticated, next generation test dummies poses challenges that have already been encountered with the THOR 50th male. The issues regarding thorax certification and belt slippage must be solved before the smaller female THOR 5th female is introduced. Also, biomechanical criteria, especially for chest injury risk assessment of different populations such as the small female, will be needed.

**ACKNOWLEDGEMENTS**

The working group and authors would like to thank those who have contributed to the work of the Frontal Impact Working Group and supported the group's MPDB test programme. The authors would like to thank Kenichiro Koshizako from Toyota Motor Corporation, Japan, for his contribution to the brain injury accident reconstruction study and all institutions that have contributed to the Brain Injury sub-group.

**Members of the Frontal Impact Working Group**

Sandner Volker, ADAC (WG Chairman)
Ellway James, Euro NCAP (Secretary)
Baroncelli Luca, CSI
Been Bernard, Humanetics
Broscheidt Michael, Audi/ACEA
Herpich Thomas, TRW/CLEPA
Fredriksson Rikard, SRA
Kerz Torsten, Stellantis/ACEA
Lammers Hans, NL MOT RDW
Langner Tobias, BASt
Lázaro Ignacio, IDIADA
Lemmen Paul, Cellbond ATD
Ratzek Andreas, ADAC
Schmitt Alex, Kistler
Thompson Alex, Thatcham
van Montfort Sjef, TNO
van Ratingen Michiel, Euro NCAP
van Slagmaat Marc, Autoliv/CLEPA
Vie Nicolas, UTAC CERAM
Weimer Christoph, Hyundai Motor Group/ACEA
Wernicke Philipp, BMW/ACEA/PDB

**Members of the Brain Injury Sub-Group**

Sandner Volker, ADAC (WG Chairman)
Ellway James, Euro NCAP (Secretary)
Eggers Andre, BASt
Herpich Thomas, TRW/CLEPA
Kleiven S, KTH
Masuda M, Toyota
Hallbauer Karsten, Joyson Safety
Panzer Matthew, UVA
van Slagmaat Marc, Autoliv/CLEPA
Wernicke Philipp, BMW/ACEA/PDB
Wisch M, BASt
Willinger R, UNISTRA

**REFERENCES**


1. Ellway JD, van Ratingen M, Versmissen T, van Montfort S, Langner T, Dobberstein J, Goutas P, Gay P, Malak A, Denker C, Hallack J, Odanaka K, Ogihara T. The Advanced European Mobile Deformable Barrier Specification for use in Euro NCAP Side Impact Testing, 2013. 23rd ESV conference, Seoul, 13-0069.

2. Ellway JD, Hallbauer K, Kerz T. The Development of a Euro NCAP Far Side Occupant Test and Assessment Procedure, 2019. 26th ESV conference, Eindhoven, 19-0278.

3. Sandner V, Ellway JD, van Ratingen M. Euro NCAP Frontal Impact Working Group Report, 2017. 25th ESV conference, Eindhoven, 17-0205.

4. Euro NCAP MPDB testing protocol v1.1.3, 2022. Euro NCAP MPDB testing protocol v1.1.3

5. Euro NCAP Assessment Protocol - AOP - v9.2.1, 2022. Euro NCAP Assessment Protocol - AOP - v9.2.1

6. Ostermaier I., Ostermaier M., Sandner. V, Kolke, R. (2022). Restraint Systems for all Car Occupants. Parts 1 and 2. In: VKU Verkehrsunfall und Fahrzeugtechnik, Vol. 60. Issue Number: 2&3, Springer Automotive Media, Springer Fachmedien München GmbH, ISSN: 0724-2050 (in German).

7. Forman J, Poplin G, Shaw CG, McMurry TL, Schmidt K, Ash J, Sunnevang C. Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions, 2019.

8. THOR-50M qualification procedures, 2022. Qualification procedures (pdb-org.com)

9. Takhounts EG, Craig MJ, Moorhouse K, McFadden J, Hasija V. Development of brain injury criteria (BrIC). Stapp Car Crash J. 2013 Nov;57:243-66. doi: 10.4271/2013-22-0010. PMID: 24435734.

10. Gabler LF, Crandall JR, Panzer MB. Development of a Metric for Predicting Brain Strain Responses Using Head Kinematics, 2018. PMID: 29594689 DOI: 10.1007/s10439-018-2015-9.

11. ISO TS19222, Road Vehicle – THOR dummy Injury Risk Curves. 2023.

12. S Kleiven (2006) Evaluation of head injury criteria using a finite element model validated against experiments on localized brain motion, intracerebral acceleration, and intracranial pressure, International Journal of Crashworthiness, 11:1, 65-79, DOI: 10.1533/ijcr.2005.0384

13. Takahashi Y, Yanaoka, Toshiyuki. A Study of Injury Criteria for Brain Injuries in Traffic Accidents. 25th ESV conference, Detroit, United States, 2017, 17-0040.

14. Kleiven S. Predictors for traumatic brain injuries evaluated through accident reconstructions. Stapp Car Crash, 2007 Oct;51:81-114. doi: 10.4271/2007-22-0003. PMID: 18278592.

15. Deck C, Willinger R. Improved Head Injury Criteria Based on Head FE Modeling. Int J of Crashworthiness, 2008, Vol 13, N°6, pp 667-679

16. Kimpara, H. et al. Investigation of anteroposterior head-neck responses during severe frontal impacts using a brain-spinal cord complex FE model. Stapp. Car Crash J. 50, 509–544 (2006).

17. Mao, H. et al. Development of a finite element human head model partially validated with thirty five experimental cases. J. Biomech. Eng. 135, 111002–111015 (2013).

18. van Slagmaat M, Panzer MB, Pipkorn B, Mueller B. Suitability of enhanced head injury criteria for vehicle rating. Traffic Inj Prev. 2019;20(sup2):S189-S192. doi: 10.1080/15389588.2019.1661674. Epub 2019 Nov 14. PMID: 31725327.

19. Trosseille X., Baudrit P. (2019) Updated Chest Injury Criterion for the THOR Dummy, Proceedings of the 25th ESV Conference, Eindhoven, NL, June 2019. Paper 19-0236),

20. Poplin, G.S., McMurry, T.L., Forman, J.L., Ash, J., Parent, D.P., Craig, M.J., Song, E., Kent, R., Shaw, G., Crandall, J. (2017), Development of thoracic injury risk functions for the THOR ATD. Accident Analysis and Prevention 106 (2017) 122–130

21. Euro NCAP Vision 2030. Euro NCAP | Euro NCAP Vision 2030: a Safer Future for Mobility

22. Evaluation of Novel Designs to Address the Shoulder-belt Entrapment for THOR-50M ATD Z. Jerry Wang, Stephen Fu, Joseph McInnis, John Arthur, IRC-19-93 IRCOBI 2019, Florence, Italy

**Appendix I**

| Unladen Kerb Mass kg | DAMAGE AIS2% | SUFEHM AIS2+ % | KTH AIS2% | THUMS AIS2+ % | GHBMC AIS2+ % |
|---|---|---|---|---|---|
| 970 | 19 | 8 | 15 | 13 | 21 |
| 990 | 10 | 7 | 14 | 11 | 19 |
| 993 | 7 | 8 | 8 | 7 | 14 |
| 1111 | 33 | 9 | 50 | 19 | 35 |
| 1111 | 15 | 8 | 36 | 12 | 22 |
| 1158 | 4 | 7 | 23 | 12 | 8 |
| 1175 | 45 | 8 | 24 | 34 | 55 |
| 1199 | 45 | 9 | 39 | 46 | 63 |
| 1216 | 5 | 7 | 13 | 6 | 7 |
| 1217 | 51 | 8 | 20 | 21 | 48 |
| 1230 | 12 | 7 | 15 | 9 | 13 |
| 1246 | 16 | 9 | 22 | 12 | 15 |
| 1270 | 19 | 7 | 11 | 10 | 28 |
| 1294 | 20 | 7 | 18 | 13 | 19 |
| 1305 | 48 | 8 | 15 | 16 | 40 |
| 1328 | 19 | 9 | 48 | 45 | 50 |
| 1330 | 37 | 9 | 20 | 16 | 33 |
| 1356 | 8 | 8 | 13 | 7 | 6 |
| 1362 | 16 | 7 | 17 | 16 | 16 |
| 1389 | 3 | 7 | 11 | 4 | 5 |
| 1397 | 19 | 8 | 31 | 14 | 18 |
| 1500 | 18 | 8 | 20 | 19 | 48 |
| 1503 | 3 | 6 | 6 | 2 | 4 |
| 1513 | 5 | 8 | 11 | 5 | 7 |
| 1531 | 1 | 7 | 9 | 3 | 3 |
| 1544 | 6 | 6 | 12 | No data | No data |
| 1560 | 18 | No data | 17 | 10 | 17 |
| 1563 | 20 | 11 | 35 | 14 | 29 |
| 1570 | 13 | 8 | 15 | 10 | 14 |
| 1625 | 51 | 17 | 43 | 39 | 65 |
| 1626 | 10 | 9 | 16 | 9 | 15 |
| 1627 | 18 | 8 | 17 | 11 | 14 |
| 1633 | 17 | 6 | 11 | 12 | 20 |
| 1636 | 44 | 9 | 34 | 26 | 40 |
| 1649 | 11 | 6 | 13 | 7 | 16 |
| 1660 | 31 | 8 | 24 | 16 | 26 |
| 1664 | 12 | 8 | 18 | 8 | 13 |
| 1675 | 6 | 7 | 10 | 5 | 9 |
| 1682 | 10 | 6 | 13 | 8 | 15 |
| 1748 | 8 | No data | 12 | 13 | 18 |
| 1755 | 13 | 9 | 19 | 7 | 10 |
| 1767 | 10 | 7 | 14 | 6 | 10 |
| 1782 | 14 | No data | 16 | 10 | 17 |

| | | | | | |
|---|---|---|---|---|---|
| 1810 | 5 | 7 | 10 | 7 | 18 |
| 1840 | 38 | 9 | 21 | 20 | 38 |
| 1842 | 12 | 8 | 16 | 14 | 21 |
| 1847 | 20 | 10 | 19 | 14 | 25 |
| 1857 | 9 | 10 | 15 | 6 | 10 |
| 1910 | 29 | 9 | 23 | 16 | 36 |
| 1910 | 7 | 9 | 13 | 4 | 8 |
| 1940 | 13 | 7 | 15 | 9 | 12 |
| 1950 | 9 | 7 | 14 | 6 | 8 |
| 2020 | 2 | 7 | 6 | 3 | 4 |
| 2029 | 4 | 6 | 8 | 3 | 4 |
| 2030 | 1 | 6 | 41 | 25 | 29 |
| 2050 | 11 | 6 | 10 | 8 | 11 |
| 2050 | 7 | 7 | 11 | 7 | 12 |
| 2070 | 4 | 7 | 8 | 5 | 16 |
| 2103 | 47 | 7 | 30 | 31 | 45 |
| 2105 | 17 | 7 | 14 | 11 | 24 |
| 2125 | 37 | 9 | 31 | 20 | 39 |
| 2149 | 1 | 6 | 6 | 2 | 3 |
| 2173 | 5 | 7 | 9 | 4 | 7 |
| 2408 | 3 | 6 | 18 | 14 | 28 |
| 2435 | 3 | 6 | 7 | 2 | 2 |
| 2480 | 17 | 8 | 20 | 11 | 13 |
| 2573 | 11 | 8 | 9 | 5 | 13 |
| **Count** | **67** | | | | |

| | **Unladen Kerb Mass** | **DAMAGE** | **SUFEHM** | **KTH** | **THUMS** | **GHBMC** |
|---|---|---|---|---|---|---|
| Maximum | 2573 | 51 | 17 | 50 | 46 | 65 |
| Minimum | 970 | 1 | 6 | 6 | 2 | 2 |

**Appendix II**
Details of accident reconstruction cases 2 and 3 for brain injury criteria evaluation.

<u>Case 2</u>

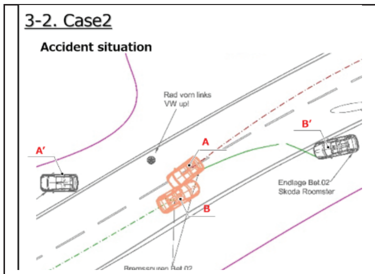



Figure 27: Accident sketch

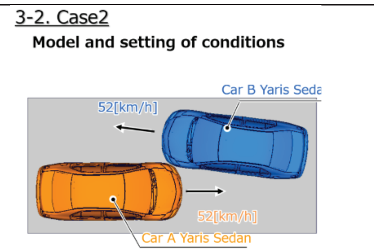



Figure 28: Simulation model set-up

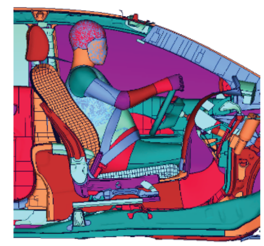


Figure 29: THUMS seating position

| No. | Regions | AIS 2008 | Diagnosis | Trauma causes |
|---|---|---|---|---|
| 1 | Chest | 1 | Contusion | Seat Belt |
| 2 | Head | 1 | Scalp laceration | B-Pillar |
| 3 | Cervical spine | 1 | Whiplash | Body motion |
| 4 | Head | 2 | Lost consciousness | B-Pillar |
| 5 | Stomach | 1 | Contusion | Seat Belt |

Table 4: Injuries to driver of vehicle A

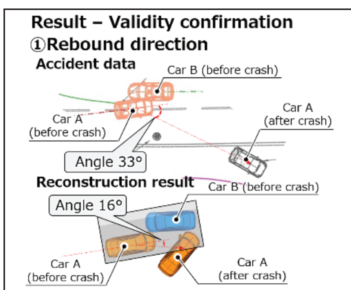



Figure 30 Rebound direction compared to accident data different. Steering and pedal operation might have possibly affected the direction.

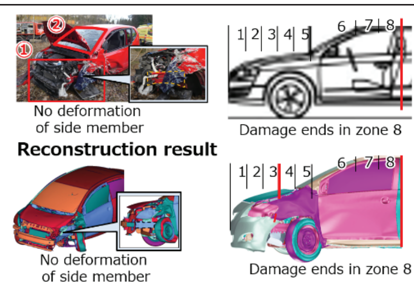



Figure 31: The comparison of vehicle deformation

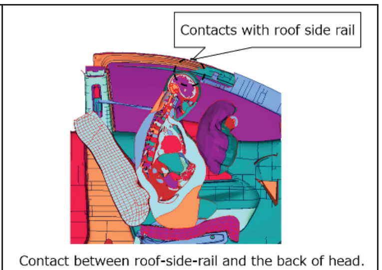



Figure 32: Injured position. Difference between simulation result and accident documentation

Case 3

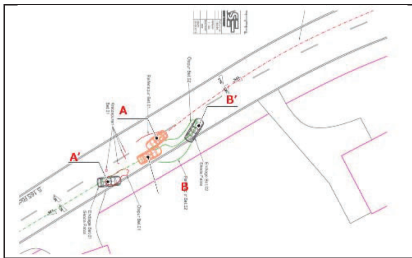



Figure 33: Accident sketch

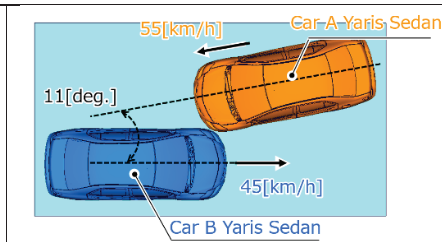



Figure 34: Simulation model set-up

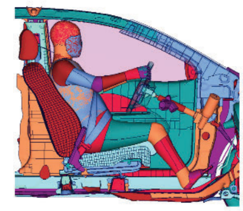


Figure 35: THUMS seating position

| No. | Regions | AIS 2008 | Diagnosis | Trauma causes |
|---|---|---|---|---|
| 1 | Head | 2 | Concussion | Body motion |
| 2 | Head | 1 | Scalp laceration | B-pillar |
| 2 | Head | 1 | Scalp laceration | Unknown |
| 3 | Head | 1 | Scalp laceration | Unknown |
| 4 | Upper extremity | 1 | Abrasion | Unknown |

Table 5: Injuries to driver of vehicle A

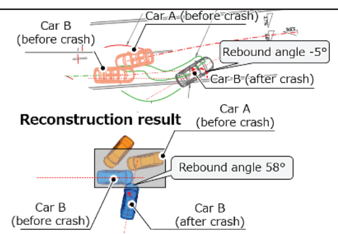



Figure 36: Rebound direction compared to accident data different. Steering and pedal operation might have possibly affected the direction.

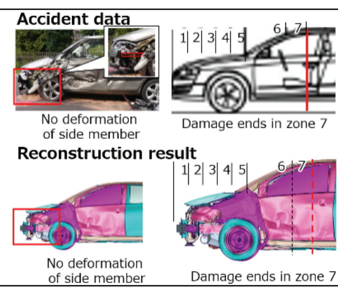



Figure 37: Comparison of vehicle deformations

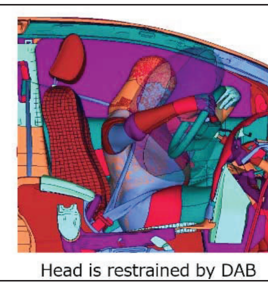



Figure 38: Injured position

# CHALLENGES FOR THE EVALUATION OF AUTOMATED DRIVING SYSTEMS USING CURRENT ADAS AND ACTIVE SAFETY TEST TRACK PROTOCOLS

**Scott Schnelle**
**Kristofer D. Kusano**
**Francesca Favaro**
**Guy Sier**
**Trent Victor**
Waymo, LLC
United States

Paper Number 23-0329

**ABSTRACT**

A number of public safety stakeholders have advocated for the application of traditional consumer-focused testing protocols (e.g., NCAP programs) for the evaluation of safety for Automated Driving Systems (ADSs). Even though test protocols only exist for some ADAS and active safety technologies (i.e. SAE Level 0, Level 1, Level 2), proposals for expansion and adaptation of these tests for ADS have been brought forth within the industry community. To gain practical insight into the types of challenges and limitations arising from the application of these existing test protocols to ADSs, the Waymo Driver™, a SAE Level 4 ADS, was the subject of a testing campaign that leveraged several of the most difficult currently available ADAS and active safety test procedures. The main challenge discovered was that while these ADAS and active safety tests are aimed at evaluating the systems' collision avoidance behavior, most of these tests were unable to be evaluated as designed due to the increased capabilities of the Waymo Driver that prevented the vehicle from even entering into a conflict to begin with. Difficulties encountered included creating the type of occlusions envisioned in some test protocols due to the location and performance of the Waymo Driver's sensor suite and insufficient information in the test procedure regarding the roadway and map information. For example, in the occluded vulnerable road user (VRU) scenarios, the Waymo Driver could sense the test target prior to it starting to move and could proactively slow down, resulting in the desired collision avoidance interaction in the scenario not being tested. To make the test conditions representative of the intended collision avoidance interactions in the test procedure, either extra vehicles and/or different vehicle types were used as the occluding vehicles (e.g., large trucks). Similarly for the car-to-car test, a larger obstructing lead vehicle was used for the cut-out test so the Waymo Driver could not see over the lead vehicle. Also, without specifying additional details for the roadway that were not in the original test procedure, the Waymo Driver would proactively slow down due to the presence of parked cars or other roadway features on the test track, such as intersections. Beyond these required modifications to enable the interactions described in the test procedure, additional optional modifications were made to the test to increase the difficulty of the test. For example, in the NCAP cut-in test, the distance at which the vehicle was cutting in was reduced from 7.5m to 3m to try to elicit collision avoidance behavior. For all the test runs, including those run to specification and those with modifications, the Waymo Driver was able to avoid collisions which would have resulted in the highest rating for this evaluation.

Our conclusion is that existing ADAS and active safety test protocols cannot be applied as-is for an ADS such as the Waymo Driver. The highlighted challenges, ranging from the need to heighten the difficulty of the proposed scenarios to the under-specification of certain aspects of the test protocol, result in ambiguous requirements for both the test developers, the test facilities, and the test site administrators. This further indicates that Level 0-2 systems need to be separately considered from Level 4 ADS, such as the Waymo Driver. Furthermore, the results of this testing calls into question the feasibility and utility of adapting ADAS and active safety test for ADSs.

Keywords: Automated Driving System, Test Track Protocol, Physical Testing

## INTRODUCTION

The safety evaluation for the development and deployment of Automated Driving Systems (ADSs) is a challenging endeavor. The operational design domain (ODD) of an ADS can include complex environments with numerous potentially hazardous situations. Additionally, unlike advanced driver assistance systems (ADAS) and active safety systems such as automatic emergency braking (AEB), an ADS like the Waymo Driver™ is responsible for the entire dynamic driving task (DDT) which makes verifying and validating the safety of an ADS a considerable undertaking. One methodology proposed in industry, standards and literature [1 Wimmer - 4 ISO] and used as a one[1] of the Waymo safety methodologies [5 Webb - 6 Kusano] for safety evaluation is scenario-based testing. Scenario-based testing can leverage a combination of virtual, closed-course, and real-world driving to enable a complimentary and comprehensive assessment of an ADSs safety performance within scenarios that it may encounter in its ODD. There is significant research ongoing around identifying what types and how many scenarios to test for ADS safety [7 Ding - 9 Riedmaier] and how representative these scenarios and their distributions need to be to that encountered in the real world [6 Kusano]. Regulatory and ratings agencies are also developing scenario-based closed-course and simulation tests for ADAS and ADS evaluations [10 Euro NCAP - 13 UNECE]. A specific subset of these scenario-based evaluations is a closed-course consumer ratings test for ADAS and active safety systems, like those in [14 Euro NCAP - 17 NHTSA]. These scenario-based tests target frequent and/or severe crashes that current ADAS and active safety technologies have the potential to mitigate or avoid that can be tested with current test track and test tool capabilities. Euro NCAP echoes these goals and objectives in the introduction to their testing procedures: for example, in the introduction of the Car-to-Car test procedure [14 Euro NCAP]: *"Car-to-Car rear impacts are one of the most frequent accidents happening on the roads […] While injury severities are usually low, these accidents are very frequent and represent over a quarter of all crashes."*, and in their Car-to-Vulnerable Road User (VRU) test procedure [16 Euro NCAP]: *"car-to-VRU impacts are one of the most frequent accidents […] These types of accidents with vulnerable road users usually coincide with severe injuries and leave the driver with very little reaction time to apply the brakes."* Furthermore, based on the existing precedence and availability of ADAS and active safety evaluation, one possibility is to investigate the adoption and/or adaptability of existing procedures as a starting point to generate scenarios for ADS (i.e., L3-L4-L5) performance evaluation for consumer information. Therefore, the focus of this paper will be on these closed-course consumer ratings tests for ADAS and active safety systems and challenges that arise from applying them to an ADS, along with whether this approach is feasible or even useful to achieve the goal of safety evaluation and consumer ratings to garner public trust. To enable this evaluation, an ADS, the Waymo Driver, was the subject of a testing campaign leveraging several existing ADAS and active safety test procedures.

The rest of the paper is organized as follows: the Methodology section will give an overview of each type of test, the Tests' Execution and Results section reviews test results and required modifications for the specific tests to enable assessment of our ADS, the discussion section presents overarching challenges and limitations regarding the feasibility and utility of closed-course testing for ADS safety assessment and consumer ratings. Finally, conclusions about the role closed-course testing plays in ADS evaluation for consumer information and potential alternatives are presented.

## METHODOLOGY

This section gives a brief overview of the type of ADAS and active safety consumer rating tests that were selected for the testing campaign. The selection process started with a review of existing test procedures of which specific tests that leveraged scenarios that are part of the known unsafe/hazardous situations that ADSs encounter frequently were prioritized. From here, a final selection was made based on the anticipated difficulty of the test, along with potential difficulties of adapting the test to an ADSs based on the Waymo Driver's ODD and design combined with the selected test track's capabilities and tools, with more information on the selection process provided below.

---

[1] Scenario-based testing is only one methodology in various methods proposed in [6 Webb] for the holistic safety assurance of the Waymo Driver.

The selected tests come from the Euro NCAP AEB Car-to-Car [14 Euro NCAP], Euro NCAP AEB Car-to-VRU [16 Euro NCAP], Euro NCAP Highway Assist Systems [15 Euro NCAP] test protocols and NHTSA's draft Traffic Jam Assist System Confirmation Test [18 NHTSA]. The goal of these protocols is to test a specific ADAS or active safety systems function in collision avoidance scenarios. These test procedures start with a test overview which discusses specifics for testing ADAS and active safety systems, such as specifying behavior of the vehicle under test (VUT), driver behavior, and pre-test behavior. For example, from the Euro NCAP Front Turn Across Path test procedure [14 Euro NCAP], a specific path for the VUT is specified as shown in Figure 5. This already raises concerns since these requirements do not apply to the Waymo Driver since the ADS is responsible for the entire DDT, including trajectory planning, lateral and longitudinal control, and Object and Event Detection and Response (OEDR). Therefore, specifying a path for an ADS not only isn't possible but also would test the ADSs ability to follow directions instead of evaluating its capabilities as they were designed for the given ODD and scenario. Instead, the test procedures were adapted so only the inputs to the scenario within the ADSs ODD can be adjusted to try to elicit the desired interaction between the ADSs and the other safety relevant entities in the scene similar to the method described in [19 NHTSA].

After an overview of the test in the test procedure, specifications for the roadway that the test will take place on is provided. This specification consists of requirements on road surface (e.g., smooth, no holes, solid paved surface, flat, <1% slope, mu >0.9) roadway markings (e.g., lane line color, style, reflectivity, width, lane width) along with what can and can't be in the vicinity of the vehicle as it is tested (e.g., only specific abnormalities within 3m to either side of test path and 30 m ahead of VUT.) These requirements are specific to the ADAS or active safety system that is being tested and focus on the inputs required to test that system in the target ODD, namely what is required to activate and maintain functionality of the system under test (SUT). They do not provide additional information relevant to the HD map that the Waymo Driver leverages, which will be discussed in more detail later.

In addition to certain roadway features pertinent to the system under test and specific test, requirements for the types of targets that are used during testing are provided to ensure the tests are repeatable and reproducible. Since these ADAS and active safety tests are addressing safety critical scenarios that can have near-miss and collision interactions, some tests require the use of surrogate targets. These targets are designed to look realistic to various sensors (radar, lidar, camera) and be strikable without damaging the VUT or the target. The surrogate test targets used in this testing campaign included a child mannequin, an adult mannequin, an adult mannequin on a bicycle, and a surrogate vehicle referred to as the Global Vehicle Target (GVT).

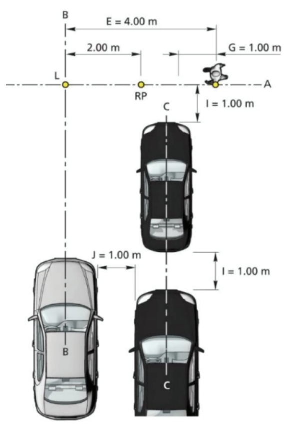
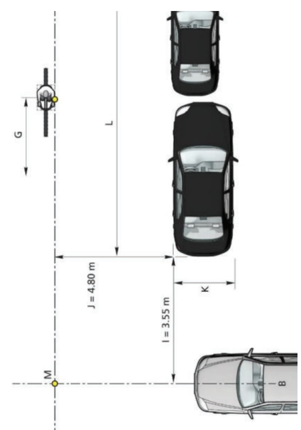
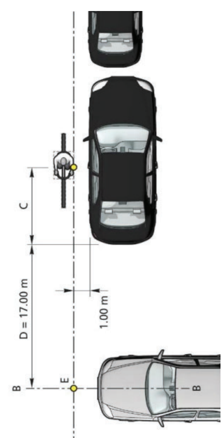
After the specifications for the test and requirements for the roadway and targets are provided, details regarding the specific scenario that is being tested are provided. A summary of these scenarios for each test used in this report are provided below for both the Car-to-VRU tests and the Car-to-Car tests.

**Car-to-VRU Tests**

The scenarios in Table 1 contain an interaction between the VUT and a VRU from the Euro NCAP test protocol for AEB VRU systems[2] [16 Euro NCAP]. These scenarios are frequently encountered in the Waymo Driver's ODD and have the potential for severe injuries. These specific test protocols were selected since they were similar to NHTSA's Pedestrian Automatic Emergency Brake System Confirmation Tests [20 NHTSA], which were still in draft at the time of testing and did not contain bicyclists interactions. The selected scenarios are: Car-to-Pedestrian Nearside Child (CPNC), Car-to-Bicyclist Nearside Adult Occluded (CBNAO), Car-to-Bicyclist Nearside Adult (CBNA) and Car-to-Bicyclist Farside Adult (CBFA). A description of each scenario along with a birds-eye-view of the scenario can be found in Table 1.

[2] April 2021, Version 3.0.4

Table 1: Overview of selected Euro NCAP AEB VRU Tests [16 Euro NCAP]

| CPNC | CBNAO | CBNA | CBFA |
|---|---|---|---|
| “a collision in which a vehicle travels forwards towards a child pedestrian crossing its path running from behind and obstruction from the nearside and the frontal structure of the vehicle strikes the pedestrian at 50% of the vehicle's width when no braking action is applied.” | “a collision in which a vehicle travels forwards towards a bicyclist crossing its path cycling from the nearside from behind an obstruction and the frontal structure of the vehicle strikes the bicyclist at 50% of the vehicle's width when no braking action is applied.” | “ a collision in which a vehicle travels forwards towards a bicyclist crossing its path cycling from the nearside and the frontal structure of the vehicle strikes the bicyclist when no braking action is applied.” | “a collision in which a vehicle travels forwards towards a bicyclist crossing its path cycling from the farside and the frontal structure of the vehicle strikes the bicyclist at 50% of the vehicle's width when no braking action is applied.” |
|   |   |   |   |

**Car-to-Car Tests**

The following scenarios contain an interaction between the VUT and another vehicle. These scenarios are frequently encountered in the Waymo Driver’s ODD. These specific test protocols come from both Euro NCAP (Test Protocol for AEB Car-to-Car systems[3] [14 Euro NCAP] and Highway Assist Systems Test & Assessment Protocol[4] [15 Euro NCAP]) and NHTSA (draft Traffic Jam Assist test procedure[5] [18 NHTSA]) test programs. Test procedures from both of these testing programs were selected due to unique scenarios between test programs and variations in similar scenarios that may affect scenario difficulty.

NHTSA Lead Vehicle Lane Change with Braking (LVLCB)

The lead vehicle lane change with braking tests (LVLCB), commonly referred to as a cut-in scenario, comes from the NHTSA draft Traffic Jam Assist System Confirmation Test [18 NHTSA]. As stated in the draft test procedure, the object of the test is to “evaluate the TJA system’s ability to detect and respond to a moving POV that brakes during or after performing a lane change into a space between the SV and SOV.”

---

[3] April 2021, Version 3.0.3

[4] September 2020, Version 1.0

[5] July 2019, Working Draft

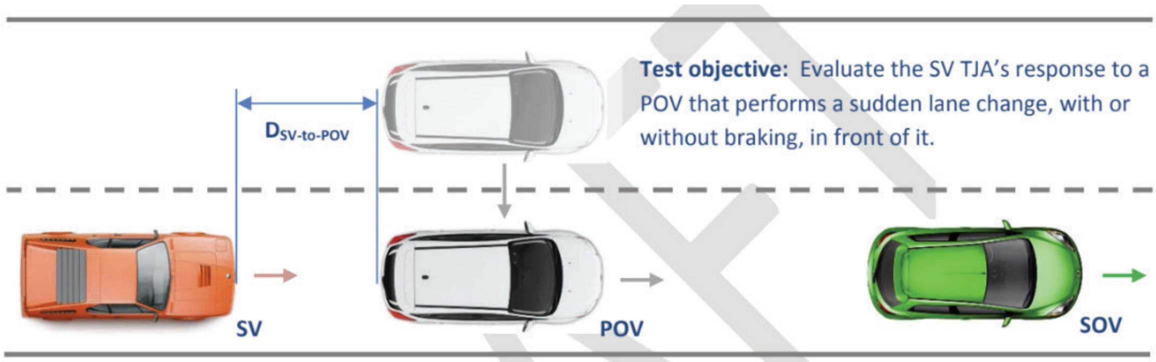



Figure 1: NHTSA TJA LVLCB scenario from [18 NHTSA]

Euro NCAP Cut-in

Similar to the NHTSA LVLCB test, the Euro NCAP cut-in test [15 Euro NCAP] scenario consists of "The GVT in the adjacent lane will perform a full lane change (3.5m lateral displacement) into the lane of the VUT. The indicated TTC is defined as the TTC at the point in time that the GVT has finished the lane change manoeuvre, where the rear centre of the GVT is in the middle of the VUT driving lane. "

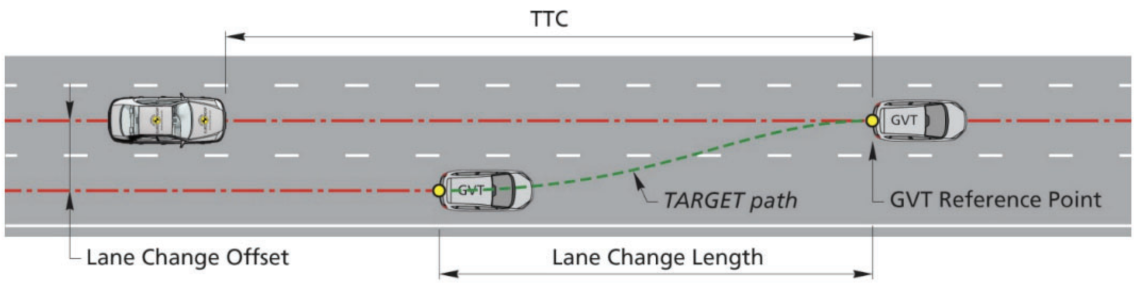



Figure 2: Euro NCAP Cut-in scenario from [15 Euro NCAP]

Euro NCAP Cut-out

The Euro NCAP cut-out test [15 Euro NCAP] scenario consists of "The vehicle cutting out will perform a full lane change (3.5m lateral displacement) into the adjacent lane to avoid the stationary GVT. The indicated TTC is defined as the TTC of the lead vehicle to the GVT when the lead vehicle will start the lane change."

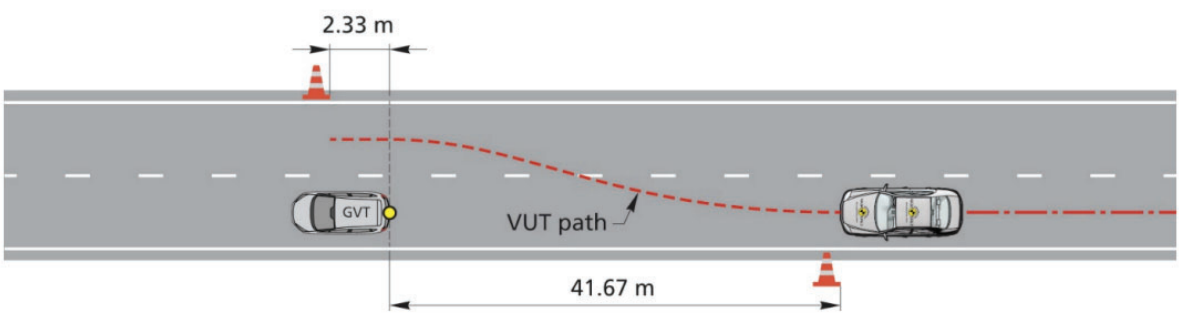



Figure 3: Euro NCAP Cut-out scenario from [15 Euro NCAP]

NHTSA Lead Vehicle Deceleration, Accelerates, then Decelerates ( LVDAD)

The NHTSA Lead Vehicle Deceleration, Accelerates, then Decelerates (LVDAD) [18 NHTSA] test's objective is to "evaluate the TJA system's ability to detect and respond to a POV that moderately brakes to a stop, pauses, accelerates back to its initial speed, then brakes aggressively to a stop ahead of the SV"

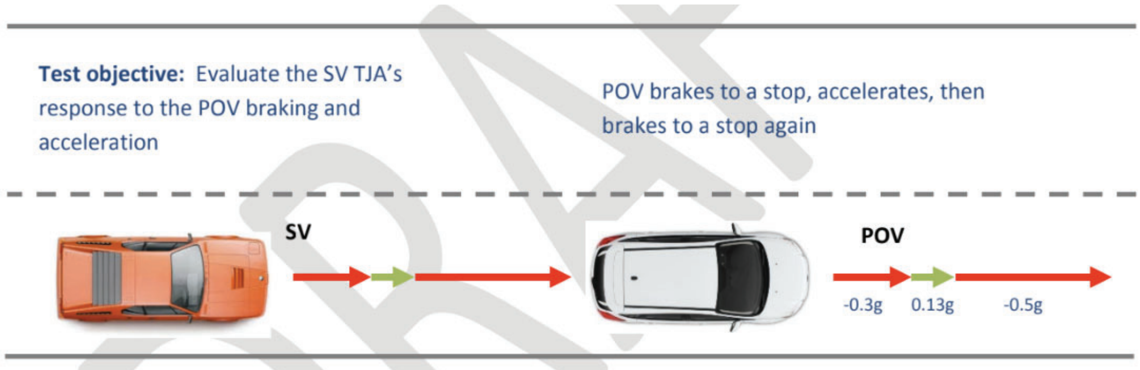



Figure 4: NHTSA TJA LVDAD scenario from [18 NHTSA]

<u>Euro NCAP Front Turn Across Path (FTAP)</u>
The final test that was selected was the Euro NCAP Car-to-car Front turn across path (FTAP) [14 Euro NCAP]. The test consists of "a collision in which a vehicle turns across the path of an oncoming vehicle traveling at constant speed, and the frontal structure of the vehicle strikes the front structure of the other."

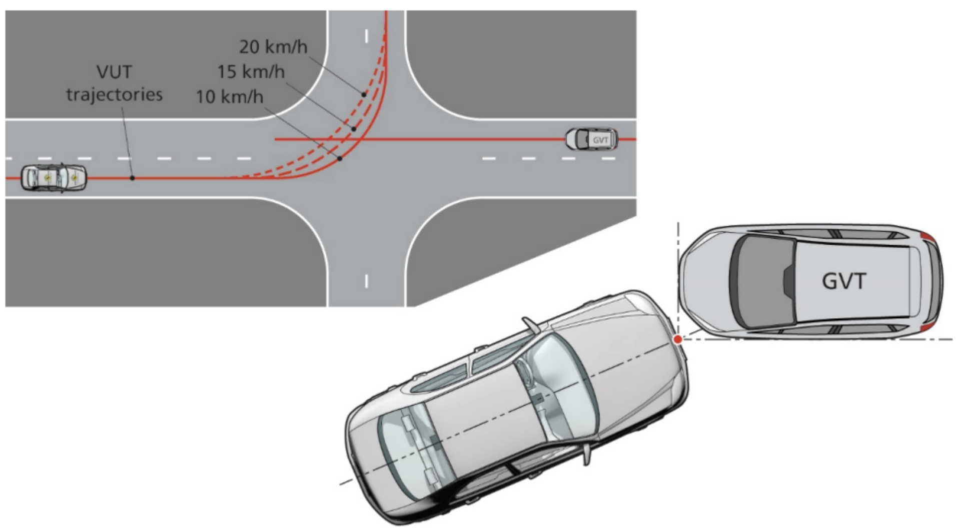



Figure 5: Euro NCAP FTAP scenario from [15 Euro NCAP]

**Excluded Tests**
As previously mentioned, not all of the tests from the Euro NCAP and NHTSA test procedures were selected. Priority was given to the tests that had a higher anticipated difficulty based on the Waymo Driver's capability and ODD. Some of the excluded tests, like the Car-to-Pedestrian Longitudinal Adult (CPLA) from Euro NCAP's AEB VRU Tests [16 Euro NCAP] were performed once and deprioritized since the Waymo Driver was able to easily detect and respond the the test target and there were no new implementation challenges presented by these scenarios. Additionally, a few tests from Euro NCAP's AEB VRU Tests Annex B: Testing At Low Ambient Lighting Conditions [16 Euro NCAP] were executed, but these were also deprioritized since there were no observed performance differences from the same daylight tests due to the Waymo Driver's sensor and perception capability, mainly lidar performance in low ambient lighting.

**TESTS' EXECUTION AND RESULTS**

Each of the above tests were first attempted with the specifications provided in the test procedure. However, due to the proactive safe driving capability of the Waymo Driver which prevented the scenarios from turning critical, modifications were needed to force the Waymo Driver into the collision avoidance maneuvers as originally intended in the ADAS and active safety test procedures. The two main types of modifications were: 1) Additions and alterations of the test procedure due to ***under-specification of the protocol*** for application to the Waymo Driver and 2) Additions and alterations to ***increase the difficulty*** of the protocol to ensure alignment with the original intent of the protocol. With these modifications, the Waymo Driver was able to be evaluated in the intended interactions described in the test procedures. For each of these tests, including those originally run to the test specifications and those that were modified, the Waymo Driver was able to avoid contact with the test target. The rest of the section provides further details and rationale for each of the modifications made.

NOTE: The birds-eye view visualization provided in the figures below is a simplification of the Waymo Driver's perception system for illustrative purposes and does not represent the full extent of objects tracked by the system nor show sensor data.

<table>
<tr><td colspan="2">Protocol: Euro NCAP CPNC</td></tr>
<tr><td colspan="2" align="center">Implementation Challenges</td></tr>
<tr><td colspan="2"><ul><li>The Waymo Driver is able to detect the VRU test target to the right of the two parked vehicles specified in the test procedure prior to it becoming occluded (this starting position is required to meet the stated VRU speed per procedure). This is shown in Figure 6. This results in the Waymo Driver tracking the pedestrian and proactively slowing down before the intended reveal.</li><li>The Waymo Driver would slow down below the required testing speed due to the presence of parked cars to the side and/or to unclear classification of those vehicles as parked and/or stationary in the active lane. Depending on the exact configuration of the testing site, the Waymo Driver would also slow down if it knew of or expected an upcoming intersection as shown in Figure 6 (the test was executed at various locations within the test facility)</li></ul></td></tr>
<tr><td colspan="2" align="center">Modifications</td></tr>
<tr><td>Protocol under-specification</td><td><ul><li>Need to specify marking that separates the active lane for VUT and the lane that stationary vehicles are parked in to avoid spurious ADS slow-downs for uncertain classification of side vehicles</li><li>Need to specify road graph beyond the active site of the pedestrian crossing to avoid spurious ADS slow-downs for intersections</li></ul>Adopted modifications: the HD map was altered by removing the perpendicular intersection leg and stop sign to enable the Waymo Driver to maintain the required test speed. Additionally, all signs on the test track were covered as shown in Figure 7.</td></tr>
<tr><td>Difficulty</td><td><ul><li>Need to ensure enhanced perception capabilities are accounted for in the test</li></ul>Adopted modifications: two additional obstructing vehicles were placed to the right of the original vehicles as shown in Figure 7 along with objects placed under the vehicles to block the Waymo Driver from detecting and tracking the child pedestrian</td></tr>
</table>


Figure 6: Euro NCAP CPNC scenario before modifications. Image source: Waymo.

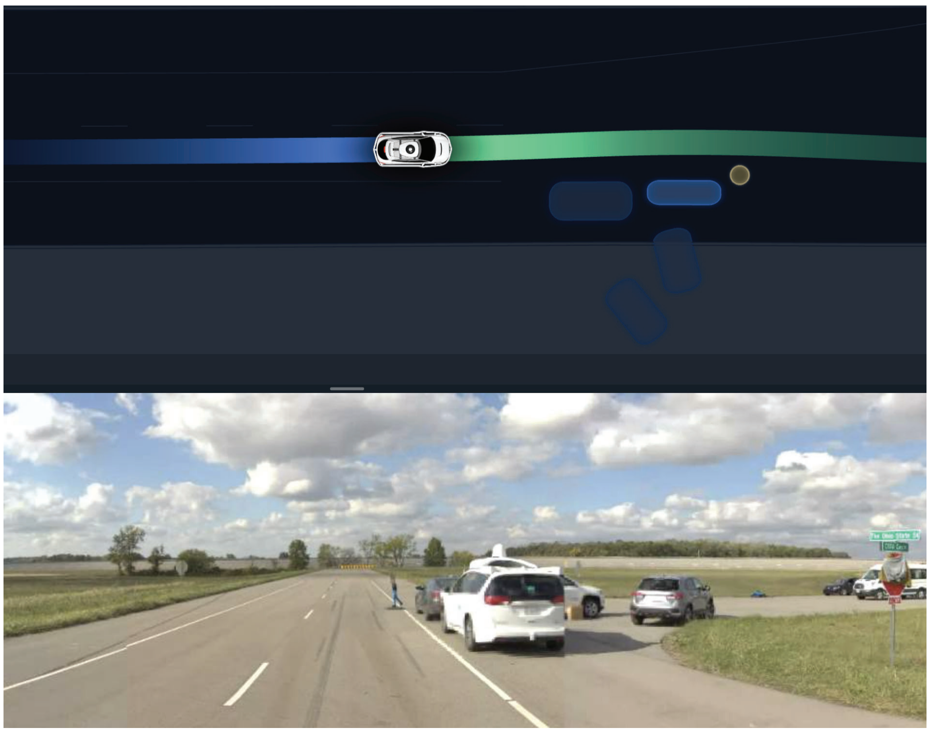


Figure 7: Euro NCAP CPNC scenario after modifications. Image source: Waymo.

**Protocol: Euro NCAP CBNAO**

Implementation Challenges

- The Waymo Driver is able to detect the VRU test target between and overtop of the two parked vehicles specified in the test procedure due to the location and performance of its sensors (the starting position of the test target is required to meet the stated VRU speed per procedure) as shown in Figure 8. Additionally, the Waymo Driver could detect the test target via sensor returns from under the parked obstructions. These both contribute to the Waymo Driver tracking the cyclist and proactively slowing down before the intended reveal.
- The Waymo Driver would slow down below the required testing speed due to the presence of perpendicularly parked cars to the side and/or to unclear classification of those vehicles as parked and/or stationary in an active lane/unmarked intersection/alley. Depending on the exact configuration of the testing site, the Waymo Driver would also slow down if it knew of or expected an upcoming intersection (the test was executed at various locations within the test facility).

Modifications

| | |
|---|---|
| Protocol under-specification | ● Need to specify marking that separates the active lane for VUT and the lane that stationary vehicles are parked in to avoid spurious ADS slow-downs for uncertain classification of side vehicles<br>● Need to specify road graph beyond the active site of the pedestrian crossing and/or specify straight road ahead to avoid spurious slow-downs for intersections<br>**Adopted modifications:** the HD map was altered to enable the Waymo Driver into maintaining the test required speed |
| Difficulty | ● Need to ensure enhanced perception capabilities are accounted for in the test<br>**Adopted modifications**: An additional taller obstructing vehicle[6] was placed in front of and in between the original vehicles as shown in Figure 9 along with objects placed under the vehicles to block the Waymo Driver from detecting and tracking the cyclist |

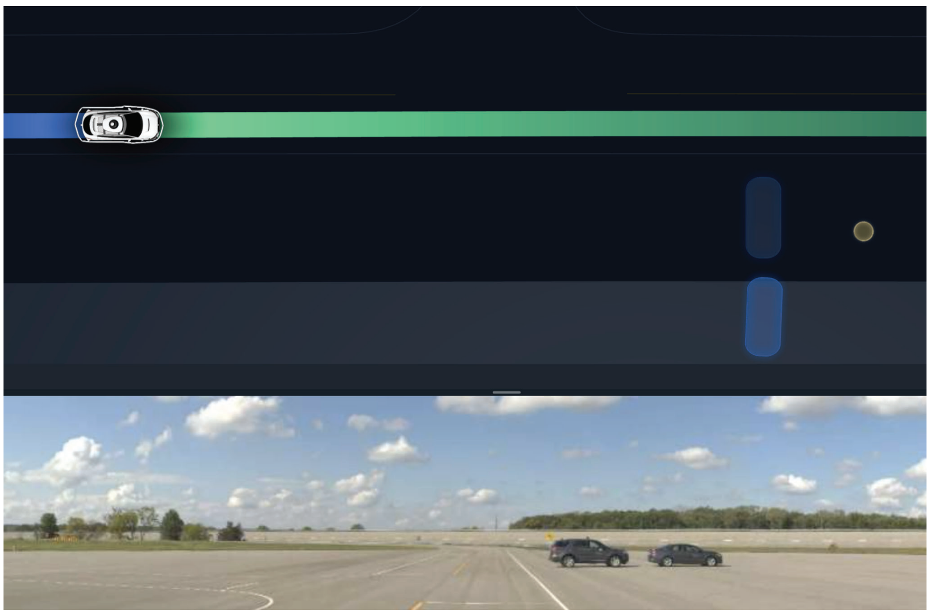


Figure 8: Euro NCAP CBNAO scenario before modifications. Image source: Waymo.

[6] Another possible obstruction is a temporary wall such as [21 4activesystems]

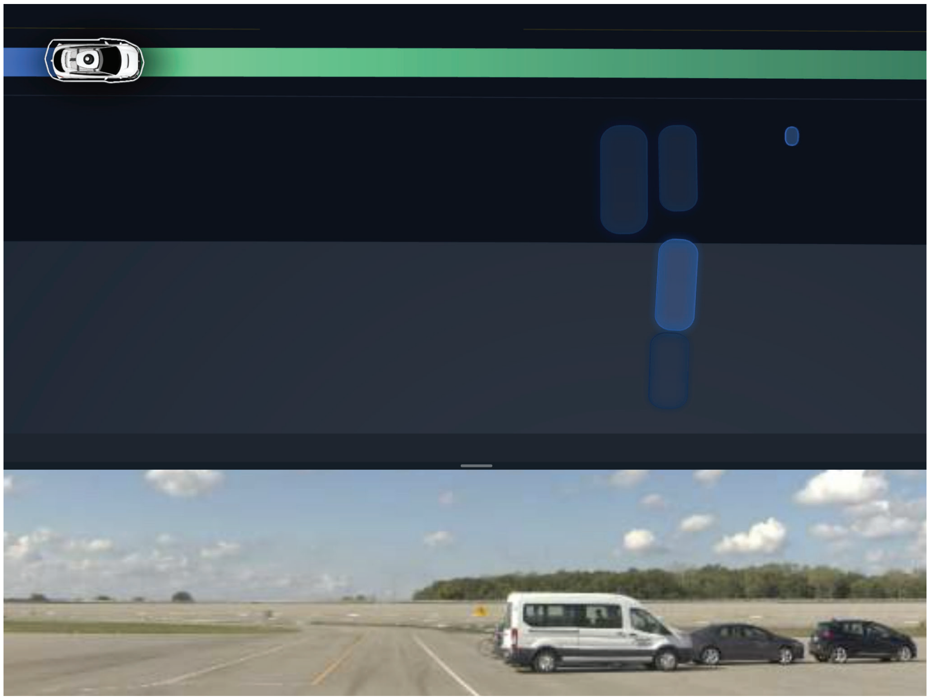


Figure 9: Euro NCAP CBNAO scenario after modifications. Image source: Waymo.

<table>
<tr><td colspan="2">Protocol: Euro NCAP Cut-out</td></tr>
<tr><td colspan="2">Implementation Challenges</td></tr>
<tr><td colspan="2">The Waymo Driver is able to detect the stopped vehicle ahead in the lane over the vehicle it was following as shown in Figure 10. This results in the Waymo Driver tracking the stopped vehicle and proactively slowing down before the intended reveal.</td></tr>
<tr><td colspan="2">Modifications</td></tr>
<tr><td>Protocol under-specification</td><td>● Need to specify markings for all lane lines to avoid mismatches in prediction of actors actions<br>● Need to specify road graph beyond and in adjacent lanes of the stopped vehicle to avoid spurious ADS slow-downs<br>Adopted modifications: HD map was updated with lane line information to enable testing.</td></tr>
<tr><td>Difficulty</td><td>● Need to ensure enhanced perception capabilities are accounted for<br>Adopted modifications: A taller lead vehicle was used as shown in Figure 11 to block the Waymo Driver from detecting and tracking the stopped vehicle overtop of the leading vehicle.</td></tr>
</table>

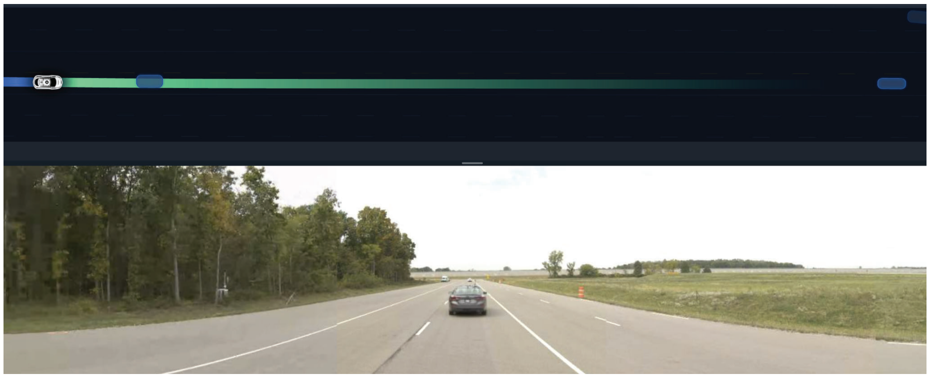


Figure 10: Euro NCAP Cut-out scenario before modifications. Image source: Waymo.

Figure 11a: Euro NCAP Cut-out scenario after modifications. Image source: Waymo.

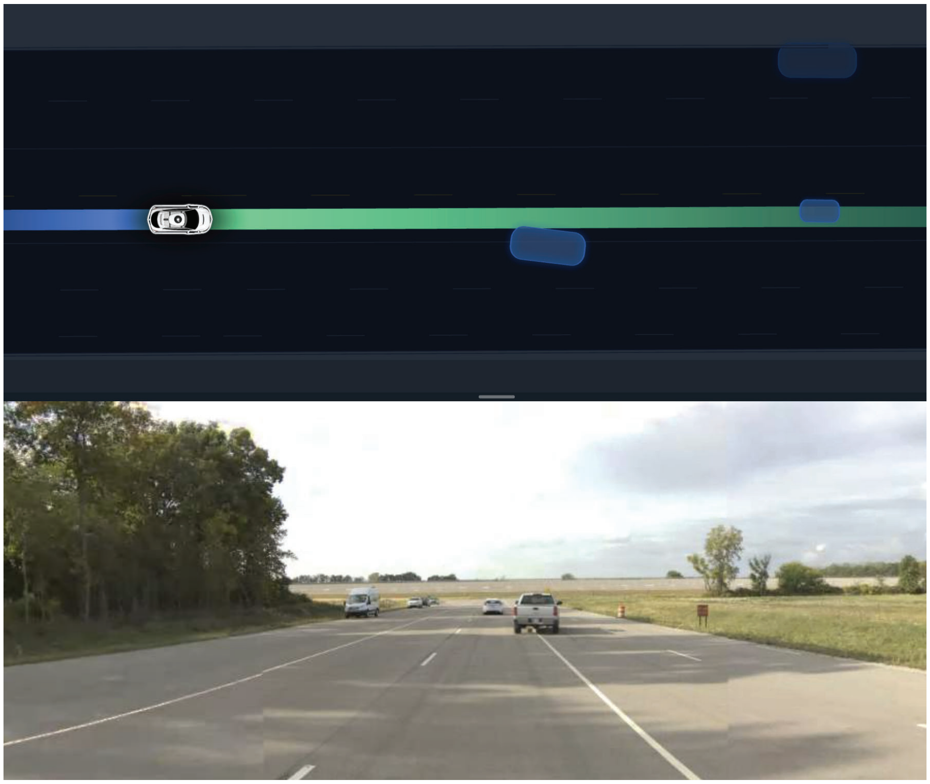


Figure 11b: Euro NCAP Cut-out scenario after modifications[7]. Image source: Waymo.

| **Protocol: NHTSA LVLCB (Cut-in)** | |
|---|---|
| Implementation Challenges | |
| The tests were run as originally specified in the test procedure, including the two cut-in distances, 10.7m and 7.5m, and two decelerations, 0.3g and 0.5g, after the lane change. The Waymo Driver's ability to detect, track and predict the cutting-in vehicles behavior resulted in low decelerations and large proximities between the two vehicles as shown in Figure 12. | |
| Modifications | |
| Protocol under-specification | • Need to specify and add additional capabilities for the test target to signal, or not, intent of lane change<br>**Adopted modifications**: None, test were ran with the GVT |
| Difficulty | • Need to ensure enhanced perception and prediction capabilities are accounted for in the test<br>**Adopted modifications**: Two closer cut-in distances, 6m and 3m were used[8]. |

[7] The top visualization is for illustrative purposes and does not represent the full extent of sensor data or objects tracked by the system

[8] Deceleration was not increased above 0.5g due physical limitations of the GST which has a max specified deceleration of 0.8g. 0.5g was found to be the maximum practical deceleration for repeatable GST movements and without damaging the GST wheels.

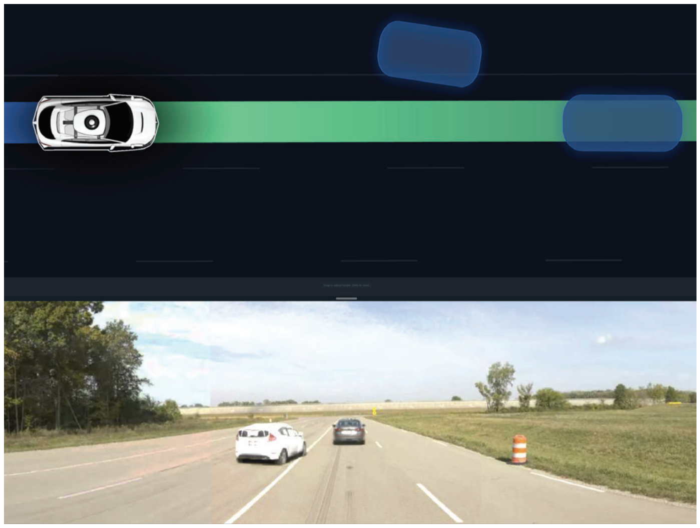


Figure 12: Euro NCAP Cut-in (7.5m) scenario before modifications. Image source: Waymo.

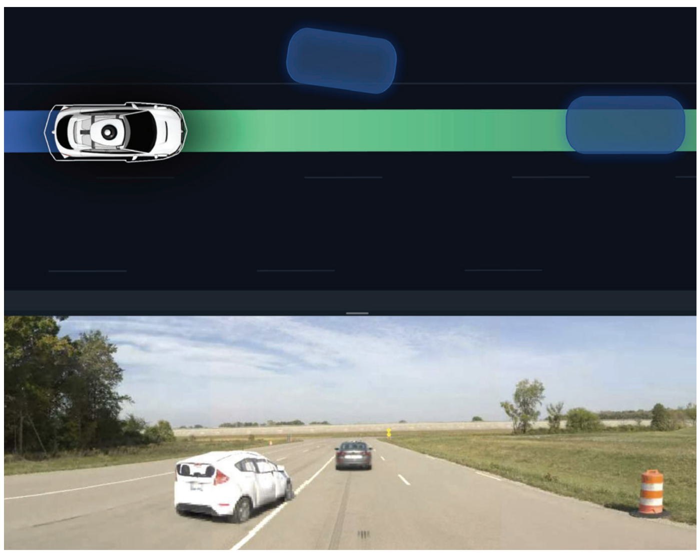


Figure 13: Euro NCAP Cut-in (6m) scenario after modifications. Image source: Waymo.

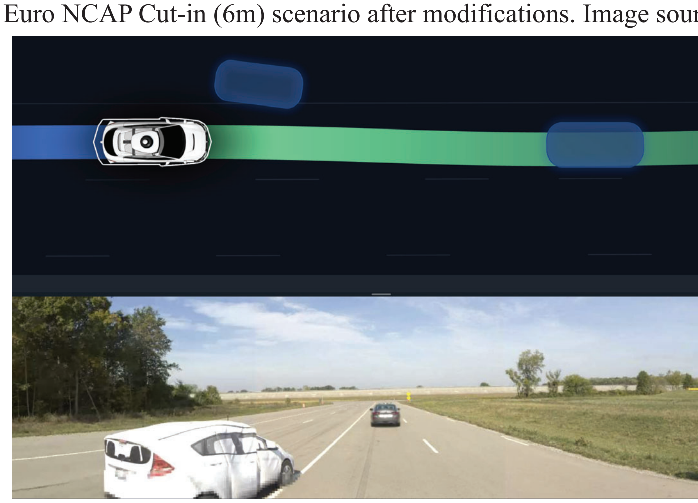


Figure 14: Euro NCAP Cut-in (3m) scenario after modifications. Image source: Waymo.

A test matrix of all of the tests performed, including those with modifications, is shown in Table 2. As previously mentioned, all of these tests, including those at various speeds and those that were modified, were passed by the Waymo Driver in that no contact was made with the test target.

Table 2: Test Matrix

<table>
<tr><th>Test</th><th colspan="2">Speeds (kph)</th><th>Modifications (beyond HD map)</th><th>Pass/Fail</th></tr>
<tr><td>Euro NCAP CPNC</td><td colspan="2">10, 30, 40, 50, 60</td><td>Extra obstructions</td><td>Pass</td></tr>
<tr><td>Euro NCAP CBNAO</td><td colspan="2">32, 50, 60</td><td>Taller extra obstruction</td><td>Pass</td></tr>
<tr><td>Euro NCAP CBNA</td><td colspan="2">60</td><td></td><td>Pass</td></tr>
<tr><td>Euro NCAP CBFA</td><td colspan="2">60</td><td></td><td>Pass</td></tr>
<tr><td rowspan="2">NHTSA TJA LVLCB</td><td>24.1</td><td>w/0.3g decel, w/0.5g decel</td><td></td><td>Pass</td></tr>
<tr><td>40</td><td>w/0.3g decel, w/0.5g decel</td><td>6m and 3m cut in distance</td><td>Pass</td></tr>
<tr><td>Euro NCAP Cut-In</td><td colspan="2">50, 80</td><td></td><td>Pass</td></tr>
<tr><td>NHTSA TJA LVDAD</td><td colspan="2">24.1, 37</td><td></td><td>Pass</td></tr>
<tr><td>Euro NCAP LTAP</td><td colspan="2">15, 20</td><td></td><td>Pass</td></tr>
<tr><td>Euro NCAP Cut-Out</td><td colspan="2">50, 70</td><td>Tall lead vehicle</td><td>Pass</td></tr>
</table>

**DISCUSSION**

Beyond the specific, practical challenges mentioned, two additional issues of *feasibility* and *utility* arise when considering adapting or adopting these ADAS and active safety tests that are designed for a specific driving function in a specific collision scenario to the Waymo Driver which is required to perform the entire DDT without immediate human intervention for all scenarios in its ODD. The rest of this section elaborates on these two issues.

**Feasibility**

Unlike ADAS and active safety systems, which act on fewer sources of input information (e.g., surrounding vehicle movement, lane markings) with less capable sensing, prediction, and planning capabilities, the Waymo Driver takes the holistic, long-horizon road scene into account when planning its behavior. Therefore, additional considerations need to be given regarding the specification of the road scene, environment, surrounding safety critical objects, and timing aspects for these tests. Identifying which of these factors are pertinent for assessing the safety of the ADS without proprietary ODD, performance, and design information and varying those factors is difficult to do and would result in an untenable set of potential scenarios for closed-course testing, commonly referred to as the “parameter explosion” problem (IEEE 2846-2022, Annex A) [22] . Additionally, those pertinent factors may vary widely depending on the intended ODD and capabilities of the system [6 Kusano], making it difficult to design a robust closed-course test program that could be reused across many different ADS as is done for ADAS and active safety systems today. Moreover, the behavior of the ADS may be affected by prior information collected during field testing (e.g., likelihood of parked vehicles, likelihood of pedestrians crossing) and a closed-course test on a synthetic map with surrogate actors may not be indicative of actual on-road performance. Furthermore, this reliance on map data introduces the risk of tampering with the test results through the creation of maps. Even without malicious intent, the creation of a special map for a test track may inadvertently create an unfair or unrepresentative evaluation of the ADS’s capabilities.

Another practical issue pertains to the physical limitations of test facilities, mainly that a test track needs to have the desired ODD features for a specific ADS. These limitations coupled with limitations of test equipment (e.g. top speeds, decelerations, lateral accelerations, etc.) significantly reduces the type of scenarios, especially high-severity car-to-car scenarios like those in [23 Scanlon], that can be executed on a closed-course. Closely related to this test facility limitations issue are implementation considerations that need to be taken into account for various scenarios on a closed-course. For example, if you want to test varying aspects of the ODD related to road features, such as speed, each run of an individual protocol requires the generation of ad-hoc metadata and an accompanying map configuration along with making sure that any speed limit signs on the test track are covered or updated so it is not conflicting with the test procedure. This implies that the test execution team needs to manage numerous different map and road configurations that need to be updated on the vehicles and test facilities. This results in an additional test burden and the necessity to set up appropriate test management practices that adds complexity beyond that in these already complex testing campaigns, as stated in [24 Manahan] "...we acknowledge the test burden associated with the use of complex and highly synchronized track-based efforts, and why NHTSA must determine the role of simulation in its research efforts". Beyond these complexity challenges, consideration also needs to be given to make sure that a given test is applicable for a specific ADS's ODD and functions, not to mention that its ODD and functions can quickly change with software updates. This is already being seen in some more recent ADAS vehicles where the test results significantly depend on the current software version, which can be remotely updated, disrupting testing or negating previous tests performed on a different software [25 Bauchwitz - 26 Cummings]. Another issue related to the physical limitation of the test facilities and equipment that was briefly discussed earlier is the representativeness of these idealized tests to scenarios encountered in on-road driving. These test protocols take place on facilities that are designed to be flexible and general purpose with surrogate targets, therefore it is hard to evaluate how representative these idealized tests are to scenarios and behaviors encountered in the real world where conditions can be less than ideal. This is discussed in greater detail in Waymo's Collision Avoidance Testing paper [6 Kusano] and these stated limitations further reinforce the need to follow a scenario-based testing program like that outlined in [6 Kusano].

A final practical feasibility consideration is with the iterative process of trying to characterize the SUT to get the scenario timing correct. Traditionally, ADAS and active safety tests have been evaluated in a black box manner, where the timing in the scenarios are calibrated based on repeated test track runs. Due to the behavior variation challenges that an ADS may have as mentioned above, using the planner information generated by an ADS to trigger events (e.g., the start movement of the pedestrian) would both lead to more efficient testing and more repeatable results. Without this information, getting the choreography of the scenario correct is challenging due to the increased sensing and planning capabilities of an ADS and the increased input dimension an ADS may act on. Therefore, trying to characterize timing and coordination of actors in the tests from repeated trials may be more difficult.

**Utility**

Closely related to the issue of the feasibility of closed-course testing to inform consumers of ADS safety performance is the issue of utility of the conclusions that can be drawn from this type of testing. One of the main goals of these consumer-based tests is to inform the public on the capabilities of a given system and to be able to compare the performance of different manufacturers in frequent and/or severe crashes that current technologies have the potential to mitigate or avoid that can be tested with current test track and test tool capabilities. This comparison amongst ADS manufacturers will be much harder and less meaningful since many details about true capabilities of a system and its dependency on specific ODD features may be proprietary. Additionally, these ADAS and active safety tests procedures are scoped in their design to push the current state of the art (SOTA) so consumers can see differentiation amongst systems, i.e. the tests can't be too easy so everyone passes nor too difficult that no one passes. This is in contrast to other scenario-based testing methods, such as the one outlined in [6 Kusano], that aim to be representative of real-world crashes, including their frequency and severity distributions, rather than selecting tests targeted for differentiation of current SOTA systems. This difficulty of trying to design tests to differentiate performance amongst ADAS and active safety systems becomes almost impossible for ADSs given 1) the current SOTA in test tools and test facilities as previously mentioned and 2) the increased capabilities and performance of ADSs.

To provide insight into this challenge of designing scenarios for an ADS that aim to address the aforementioned goal of these consumer-ratings, specifically targeting severe crashes, the maximum injury potential (maxIP) [27 Kusano] for the baseline scenarios and the scenarios that were modified is shown in Figure 15 and 16 below. The maxIP is a metric that describes the worst-case outcome that is insensitive to avoidance maneuvers of the VUT. It propagates counterfactual trajectories based on actors capabilities, sizes of actors, and their inertial properties. Any potential collisions are input into a collision and injury model which outputs the maximum probability of injury severity using the Abbreviated Injury Scale (AIS). An injury with a score of 3 or higher on the AIS is classified as clinically seriously injured (MAIS3+). Figure 15 shows that for the car-to-car test scenarios, including the modified scenarios (ncap_cut_out_tall_lead_vehicle, nhtsa_cut_in_0.5g_3m_headway, and nhtsa_cut_in_0.5g_6m_headway in Figure 15), none of the scenarios have high probability for severe injuries mainly due to the test equipment and facility limitations. This limits the ability of these consumer ratings tests to meet their stated goal of targeting severe crashes. In contrast, the VRU interaction scenarios do have a higher potential for severe injuries if no intervention is taken by the VUT, as shown for the VRU cyclist tests in Figure 16. This figure also shows that the implemented modifications (cbnao_tall_obstruction and cbnao_tall_and_extra_obstruction in Figure 16) increased the maxIP for the scenario. In the unmodified scenarios, the Waymo Driver slowed down much earlier than the intended reveal, decreasing the probability for any severe injury interactions within the maxIP counterfactual trajectory propagation look ahead window. This again limits the stated goal of targeting severe crashes for these consumer ratings tests.

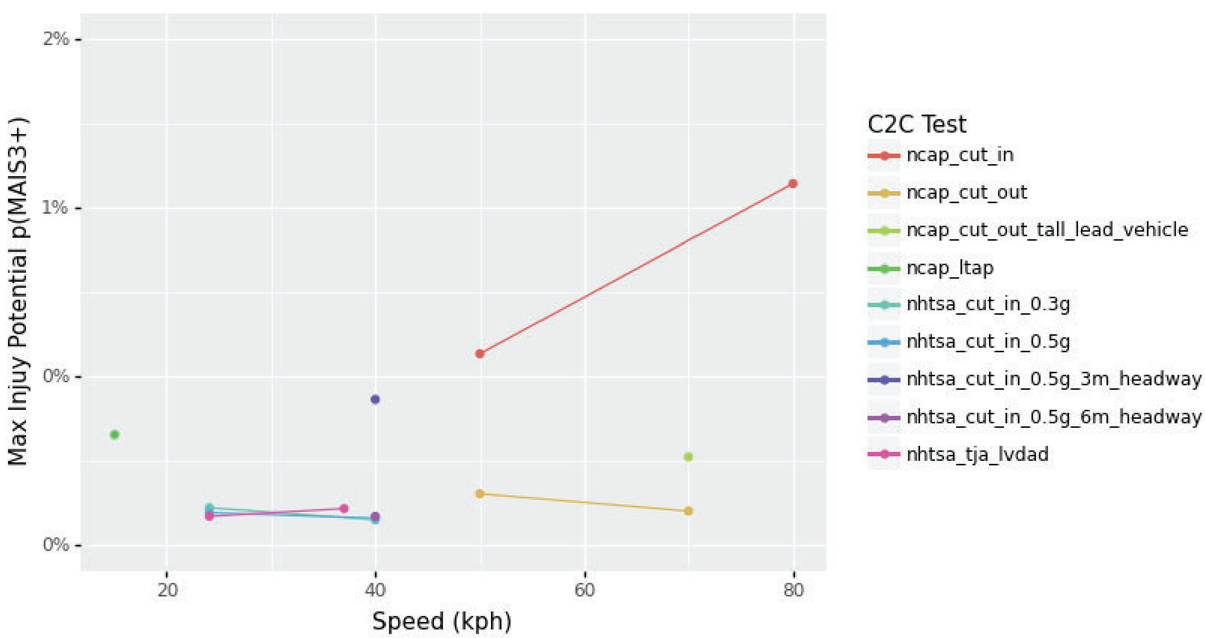



Figure 15: C2C maxIP

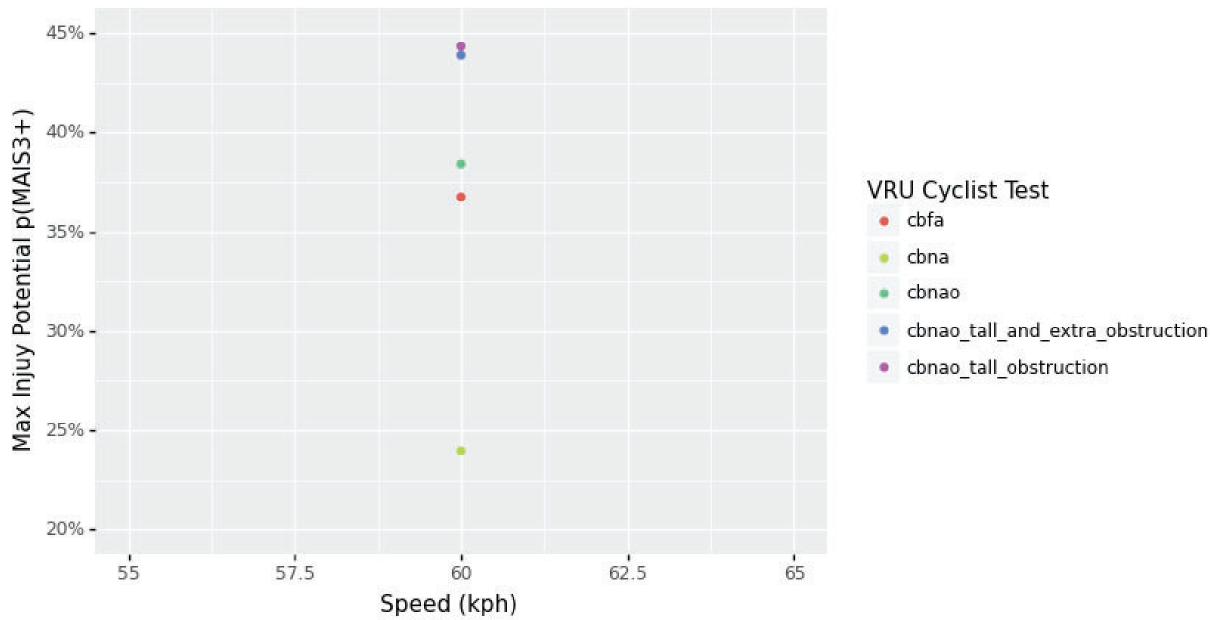



Figure 16: VRU Cyclist maxIP

**CONCLUSION**

While closed-course consumer-based ADAS and active safety ratings tests could be informative for demonstrating safety of an ADSs to the public, they are far from sufficient. The Waymo Driver was able to pass all of the selected ADAS and active safety tests, with required modifications, which is a logical first step for demonstrating safety given the availability of these tests. However, due to the stated challenges, issues, and limitations, procedures developed for Level 2 systems turned out to be less challenging and constraining for a Level 4 ADS, such as the Waymo Driver, further proving the point that these types of technological solutions need to be separately considered. The role of traditional consumer-testing and the intuitiveness of these protocols has a place in informing the selection of a few tests and engender comparison across platforms, but cannot be the basis for consumer safety information for ADS (neither was it ever the intent for these test procedures to do so). Additionally, it is important to note that claiming to pass these test procedures unmodified without further consideration to necessary changes to enable the intent of the original test procedure may result in false confidence in the safety of an Level 4 vehicle.

Therefore, to address the practical challenges raised and the issues relating to the feasibility and utility of consumer-focused safety testing, an alternative scenario-based safety evaluation process is proposed in [6 Kusano] that focuses on simulation and on-road testing to provide the public with information regarding safety assurance of an ADSs in its intended ODD. A staple in the behavioral evaluation of the Waymo Driver comes from the intensive pressure-testing of collision avoidance responses of our ADS in thousands of scenario variations. This principled and systematic scenario-based testing program is built upon the creation of vast libraries of situations that the Waymo Driver may be exposed to. This type of assessment can provide consumers with a more holistic safety evaluation of an ADS.

## REFERENCES


[1] Wimmer, P., Düring, M., Chajmowicz, H., Granum, F., King, J., Kolk, H., ... & Wagner, M. (2019). Toward harmonizing prospective effectiveness assessment for road safety: Comparing tools in standard test case simulations. *Traffic injury prevention*, *20*(sup1), S139-S145.

[2] International Organization for Standardization. (2022). *Road Vehicles - safety of the intended functionality* (ISO 21448:2022).

[3] International Organization for Standardization. (2022). *Road vehicles - Test Scenarios for Automated Driving Systems - Scenario-based safety evaluation framework for Automated Driving Systems* (ISO 34502:2022).

[4] International Organization for Standardization. (2021*). Intelligent transport systems — Low-speed automated driving (LSAD) systems for predefined routes — Performance requirements, system requirements and performance test procedures* (ISO 22737:2021)

[5] Webb, N., Smith, D., Ludwick, C., Victor, T., Hommes, Q., Favaro, F., ... & Daniel, T. (2020). *Waymo's safety methodologies and safety readiness determinations.* arXiv preprint arXiv:2011.00054.

[6] Kusano, K., Beatty, K., Schnelle, S., Favarò, F., Crary, C., Victor, T. (2022). *Collision Avoidance Testing of the Waymo Automated Driving System*. arXiv preprint arXiv:2212.08148.

[7] Ding, W., Xu, C., Lin, H., Li, B., & Zhao, D. (2022). *A Survey on Safety-critical Scenario Generation from Methodological Perspective*. arXiv preprint arXiv:2202.02215.

[8] Zhang, X., Tao, J., Tan, K., Törngren, M., Sánchez, J. M. G., Ramli, M. R., ... & Felbinger, H. (2021). *Finding critical scenarios for automated driving systems: A systematic literature review*. arXiv preprint arXiv:2110.08664.

[9] Riedmaier, S., Ponn, T., Ludwig, D., Schick, B., & Diermeyer, F. (2020). *Survey on scenario-based safety assessment of automated vehicles*. IEEE access, 8, 87456-87477.

[10] EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) *What's New?* Accessed on November 21, 2022 from: https://www.euroncap.com/en/for-engineers/whats-new/

[11] National Highway Traffic Safety Administration [Docket No. NHTSA-2021-0002] (2021) *New Car Assessment Program Request for comments (RFC).* Accessed on November 21, 2022 from https://www.nhtsa.gov/sites/nhtsa.gov/files/2022-03/NCAP-ADAS-RFC-03-03-2022-web.pdf

[12] IIHS (2022) *Test protocols and technical information* Accessed on November 21, 2022 from https://www.iihs.org/ratings/about-our-tests/test-protocols-and-technical-information

[13] UNECE (2021) *UN Regulation No. 157 - Automated Lane Keeping Systems (ALKS)* Revision 3 https://unece.org/sites/default/files/2021-03/R157e.pdf

[14] EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) (2021) *TEST PROTOCOL – AEB Car-to-Car systems* Version 3.0.3 https://cdn.euroncap.com/media/62794/euro-ncap-aeb-c2c-test-protocol-v303.pdf

[15] EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) (2020) *Assisted Driving Highway Assist Systems Test & Assessment Protocol* Version 1.0 https://cdn.euroncap.com/media/58813/euro-ncap-ad-test-and-assessment-protocol-v10.pdf

[16] EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) (2021) *TEST PROTOCOL – AEB VRU systems* Version 3.0.4 https://cdn.euroncap.com/media/62795/euro-ncap-aeb-vru-test-protocol-v304.pdf

[17] National Highway Traffic Safety Administration (2019) *Advanced Driver Assistance Systems Draft Research Test Procedures* Docket No. NHTSA-2019-0102 https://www.federalregister.gov/documents/2019/11/21/2019-25217/advanced-driver-assistance-systems-draft-research-test-procedures#footnote-6-p64405

[18] National Highway Traffic Safety Administration (2019, July). *Traffic jam assist system confirmation test (working draft)*. Washington, DC: National Highway Traffic Safety Administration. https://www.regulations.gov/document/NHTSA-2019-0102-0002

[19] National Highway Traffic Safety Administration (2021, May). *An Approach for the Selection and Description of Elements Used to Define Driving Scenarios.* Report Number : DOT HS 813 073: https://rosap.ntl.bts.gov/view/dot/55465

[20] National Highway Traffic Safety Administration (2019, September). *Pedestrian automatic emergency brake system confirmation test (working draft)*. Washington, DC: National Highway Traffic Safety Administration. https://www.regulations.gov/document/NHTSA-2019-0102-0005

[21] 4activesystems (2022) *4activeEQ-Wall* Accessed on November 21, 2022 from: https://www.4activesystems.at/4activeeq-wall

[22] IEEE Vehicular Technology Society (2022). *IEEE Standard for Assumptions in Safety-Related Models for Automated Driving Systems.* (IEEE Std 2846-2022).

[23] Scanlon, J. M., Kusano, K. D., Daniel, T., Alderson, C., Ogle, A., & Victor, T. (2021). *Waymo simulated driving behavior in reconstructed fatal crashes within an autonomous vehicle operating domain*. Accident Analysis & Prevention, 163, 106454.

[24] Manahan, T., Forkenbrock, G. (2020). *Exploring the Practical Limits of Multi-Actor Test Track Evaluations*. 2020 SAE Government and Industry Meeting. Accessed on November 20, 2022 from https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/exploring_the_practical_limits_of_multi-actor_test_track_evaluations_tag.pdf

[25] Bauchwitz, B., & Cummings, M. (2022). *Effects of Individual Vehicle Differences on Advanced Driver-Assist System Takeover Alert Behavior*. Transportation Research Record, 03611981211068362.

[26] Cummings, M. L., & Bauchwitz, B. (2021). *Safety Implications of Variability in Autonomous Driving Assist Alerting*. IEEE Transactions on Intelligent Transportation Systems.

[27] Kusano, K., & Victor, T. (2022). *Methodology for determining maximum injury potential for automated driving system evaluation.* Traffic injury prevention, 1-4. DOI: 10.1080/15389588.2022.2125231