

## EURO NCAP VIRTUAL TESTING IN FRONTAL IMPACTS

**Corina Klug, Felix Ressi, Bernd Schneider**

Graz University of Technology  
Austria

**Thota Venkateswarlu**

Nissan Technical Center Europe  
United Kingdom

**Xiaobing Bu**

CATARC  
China

**James Ellway, Michiel van Ratingen**

Euro NCAP  
Belgium

**Tony Roberts**

JLR  
United Kingdom

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### ABSTRACT

Euro NCAP is committed to complement physical crash testing with simulations, enabling a more comprehensive evaluation of safety system robustness. The first application of virtual testing focused on far-side sled tests using WorldSID simulation models under far-side sled test conditions.

The aim of this paper is to introduce the virtual testing protocol for frontal impacts and to present the results from the first pilot tests. This involves a more complex restraint loading environment and the use of various occupant statures to assess the protection of a broader range of occupants. A series of frontal occupant physical sled tests and virtual sled simulations were performed using the Hybrid III (HIII) dummy family at three severities (35, 50, and 56 kph). To validate the predictive capabilities of the vehicle simulation models, results from the simulations were compared with signals measured during physical sled tests. The similarity of the signals was evaluated objectively according to ISO/TS 18571:2024. Furthermore, injury criteria were calculated and compared between simulations and tests. Results from the European pilots were cross-checked with pilots conducted at the China Automotive Technology & Research Centre (CATARC), showing very similar results and trends. Further areas for improvement were identified specifically for the lower extremities in all pilots, where the discrepancies appear to stem from a combination of test scatter, model fidelity of the HIII and the vehicle simulation models in the legroom area. At present, it is difficult to disentangle these contributing factors.

This comprehensive approach presented in this paper marks a significant step toward integrating virtual testing into consumer safety ratings, supporting innovation in restraint system design. While the presented 2026 assessments still rely on (virtual) dummy models, Euro NCAP also plans to further explore Human Body Models (HBMs) for virtual testing, which promise enhanced biofidelity and improved injury prediction capabilities.

### INTRODUCTION

Automotive design engineers have been using advanced computational models for many years to study and optimize crash performance, aiming to minimize the need for extensive physical crash testing. While computer-aided engineering (CAE) has become increasingly popular and sophisticated in the industry, its use in regulations and consumer protection is still uncommon.

The European New Car Assessment Programme (Euro NCAP) first introduced numerical simulations into its rating protocols in 2009, specifically for pedestrian protection assessments. This marked a significant milestone, as Human Body Models (HBMs) were employed to evaluate vehicles equipped with deployable pedestrian protection systems, even if for this application the main purpose was to derive the boundary conditions for the physical headform impactor tests. To ensure consistency and reliability, Euro NCAP developed the first certification procedure for virtual human models, establishing a foundation for future virtual testing applications. [1]

Building upon this experience, Euro NCAP launched the Virtual Testing Crashworthiness (VTC) working group in 2019 with the goal of establishing a virtual test and assessment procedure for application in other impact scenarios, including in occupant protection environments, with the ultimate goal of integrating these protocols into 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.

Euro NCAP's first application of VTC—developed between 2019 and 2022—was in the far-side impact assessment. In 2023 [2], the virtual testing procedure for far-side was published, which has been applied since 2024 for monitoring. This means that while simulation output was requested for all cars in the program, the results are not yet used for scoring. This has enabled Euro NCAP to test the VTC Server, a digital platform that allows manufacturers to input, process, and review virtual data while performing data checks automatically.

This paper presents the adapted procedures for frontal impacts, addressing the driver and passenger side and incorporating dummies of various statures, to enhance the evaluation of frontal occupant protection in Euro NCAP. The procedure was applied in pilots to derive feasible validation thresholds. The results of the pilots are presented in this paper.

## METHOD

The overall procedure remained consistent to far-side, meaning that simulation results had to be submitted at first and were checked before the sled tests were executed. Simulations were run by the vehicle manufacturer (VM), were prepared according to the data acquisition and injury calculation requirements for Euro NCAP crash tests (listed in Euro NCAP CP005), and ISO MME files were shared. Sled tests were performed at two approved laboratories: BAST (Germany) for pilot 1 and TASS-Siemens (The Netherlands) for pilot 2. Pilot 1 was a small SUV with an internal combustion engine, whereas pilot 2 was a medium/large SUV with an electric drivetrain.

Three additional pilots were executed by CATARC, where the main difference to the European pilots was that they were running the simulations with the sled pulse measured in the physical sled tests. The Chinese pilots included two electric SUVs with a curb weight of around 2300 kg and one electric Sedan with a curb weight of 2700 kg.

### Simulation setups

The vehicle models are calibrated in-house in advance and VMs must have confidence that the model is ready to predict occupant responses in frontal load 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.

Hybrid-III (HIII) family simulation models were positioned in the calibrated vehicle environment in line with the newly developed frontal protection protocol [3]. Each dummy model was settled in the seat, so that no unphysical spring-back (upwards motion of the pelvis due to unrealistic contact forces with the seat) 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 HIII components < 10% of max. internal energy of the dummy.
- 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 t<sub>0</sub>).
- Simulation time needs to exceed time of maximum head x--displacement × 1.4.

### Load cases

Load cases were defined to complement the hardware sled load cases. The overall matrix is summarised in Table 1. Three sizes of the HIII dummies were used: the 5<sup>th</sup> percentile female (05F), the 50<sup>th</sup> percentile male (50M) and the 95<sup>th</sup> percentile male (95M). They were positioned on the driver and passenger side in sled tests and simulations at three different severities representing impacts at 35, 50 and 56 kph.

Within the first pilot, repeatability and reproducibility were evaluated for robustness 2 and validation 2. For Robustness 3, reproducibility was evaluated. These tests focused on the small female and large male, the lesser used dummies in industry among the three sizes, to capture the potential response variation. In the second pilot only tests 1-5 were performed.

Airbag deployment times and pre-tensioner settings were consistent between simulations and tests.

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

No.	Pulse	Driver	Co-Driver	Specification	Test ID Driver	Test ID Passenger
1	50 kph	H350 No. 1	H395 No. 1	Validation 1	50kph 50M	50kph 95M
2	56 kph	H395 No. 1	H305 No. 1	Validation 2	56kph 95M	56kph 05F
3	35 kph	H350 No. 1	H305 No. 1	Robustness 1	35kph 50M	35kph 05F
4	35 kph	H305 No. 1	H350 No. 1	Robustness 2	35kph 05F	35kph 50M
5	56 kph	H305 No. 1	H395 No. 1	Robustness 3	56kph 05F	56kph 95M
6	56 kph	H395 No. 1	H305 No. 1	Validation 2 - Repeatability	56kph 95M	56kph 05F
7	35 kph	H305 No. 1	H350 No. 1	Robustness 2 - Repeatability	35kph 05F	35kph 50M
8	56 kph	H395 No. 2	H305 No. 2	Validation 2 - Reproducibility	56kph 95M	56kph 05F
9	35 kph	H305 No. 2	H350 No. 2	Robustness 2 - Reproducibility	35kph 05F	35kph 50M
10	56 kph	H305 No. 2	H395 No. 2	Robustness 3 - Reproducibility	56kph 05F	56kph 95M

### Laboratory tests

Sled tests of the load cases shown in Table 1 were performed in accordance with the 2026 Euro NCAP frontal protection protocol [3]. These tests were performed using simplified bodies in white (BIW) from two different vehicle manufacturers and acted as validation for the virtual simulations. The sled set-up is summarised below:

- Vehicle body in white mounted at zero degrees
- No representation of vehicle deformation or intrusion
- Interior facia, seat and restraint components in the front seat row only
- BIW instrumentation was as detailed in the Euro NCAP Frontal Impact Protocol
- Instrumentation for the three statures of HIII dummies was as detailed in the Euro NCAP Technical Bulletins CP 103, CP 104 and CP 105.
- Film and photographic requirements aimed at reflecting the same views as those detailed in the full scale tests, albeit without rear occupants.

The pulses for the three severities were provided by the vehicle manufacturers and were specific to the two vehicle models and based on CAE data. All sled pulses were compared to those provided by the vehicle manufacturers and all but two were in accordance with the requirements detailed in Euro NCAP Technical Bulletin CP 500. This was not thought to have had any detrimental influence on the outcome for the sled tests.

- The 35kph pulse replicated a full-width deformable barrier impact as detailed in the Frontal Impact Protocol.
- The 50 kph pulse replicated a full-width rigid wall impact as detailed in UN ECE Regulation No. 137.
- The 56kph pulse in pilot series 1 used the Euro NCAP generic pulse and a full-width rigid wall impact
- The 56kph pulse in pilot series 2 used a full-width rigid wall impact.

The HIII dummies were positioned in the vehicle as close as possible to the simulation specifications provided from the vehicle manufacturer. The occupant compartments and seating procedures are detailed in the Euro NCAP Frontal Impact Protocol. There were no issues encountered with positioning of the dummies but there were some small differences observed in pilot 1 regarding seatbelt routing for the HIII 05F. Figure 1 below shows the belt positioned slightly more outboard for the sled tests compared to that in the virtual simulations. It was not possible to replicate the CAE position in the sled test due to the natural 'position' of the seatbelt and its interaction with the breasts.



**Figure 1: Comparison of belt positions in pilot 1 between the one used in the tests (left) compared to the one where it was tried to match the position used in the simulations as close as possible (right)**

In one of the vehicles, it was noted that there was a significant difference in the amount of steering column ‘collapse’ between the sled and CAE. It was also found that the method used to measure this parameter in a physical test can also have an influence not just on the magnitude of the collapse, but also the timing. There was no obvious reason for the difference in column collapse but this does serve as a cautionary aspect when comparing this particular parameter.

### Data processing

Data of all pilots was processed with python scripts based on the TU Graz evaluation scripts of the VTC server using the python library Dynasaur [4] for filtering and injury criteria calculations. As Key Performance Indicators, which are the main results used for the scoring, all relevant injury criteria are calculated according to Euro NCAP Technical Bulletin CP005 [5].

ISO Scores were calculated to objectively compare the curves from the simulations and tests according to ISO/TS 18571 standard [6] 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 axes to one sensor score, the individual scores were weighted per axis based on its amplitude according to

### Equation 1:

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

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

## RESULTS

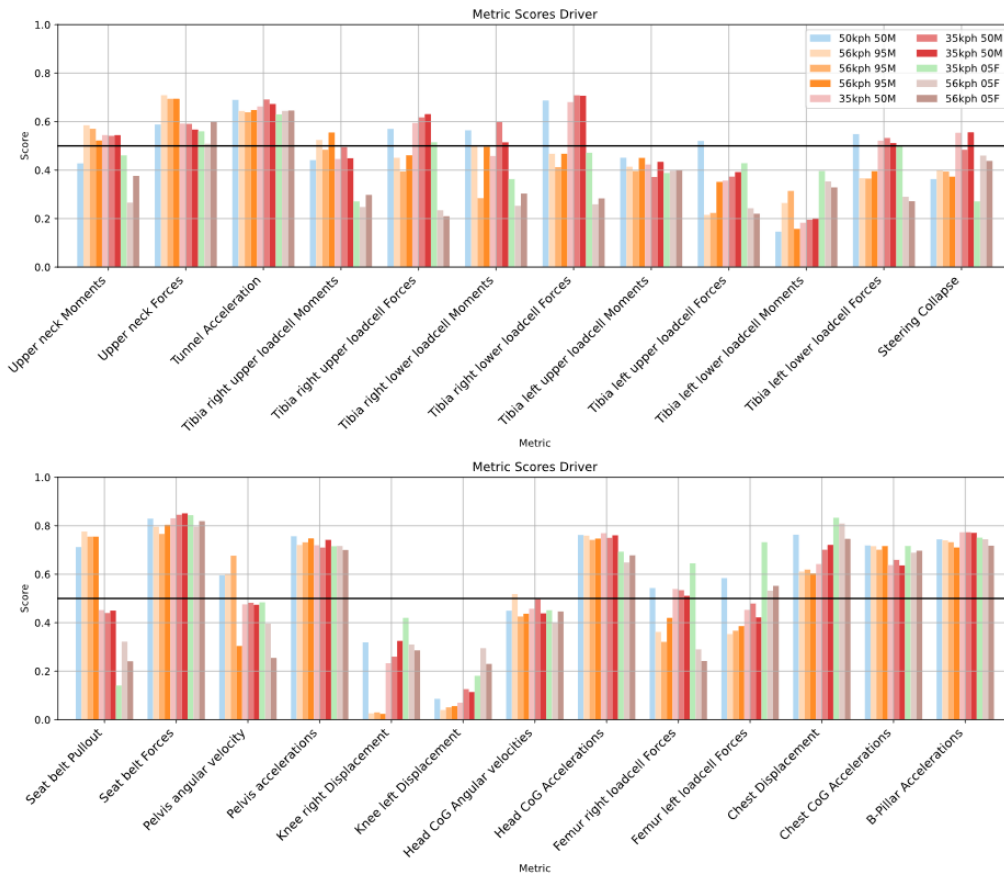
In this section the results of both pilots are shown, starting with the ISO scores and in the second section comparing the Key Performance Indicators from simulations and tests.

### ISO Scores

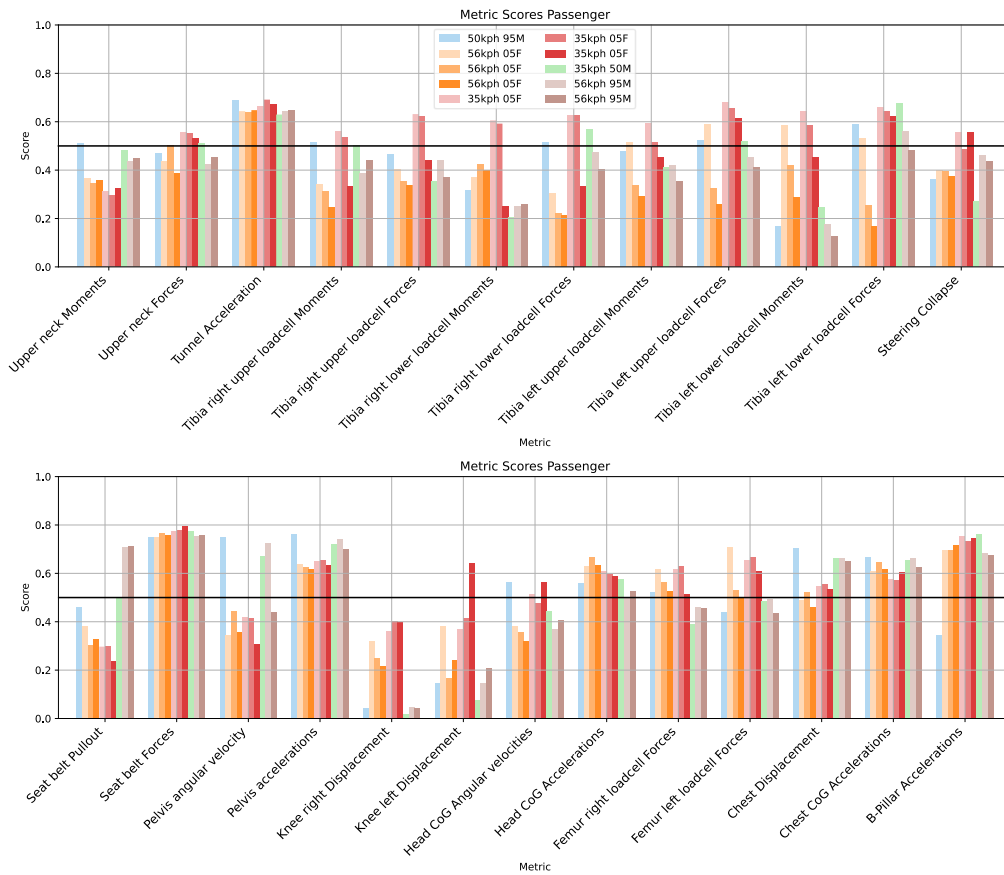
The ISO scores of all tests are shown in the figures below, where at first, the driver’s side of Pilot 1 (Figure 2) and then the passenger side (Figure 3) is compared. The figures for pilot 2 are shown in the Appendix (Figure 8 and Figure 9)

The ISO scores of the accelerometers were  $> 0.6$  in all load cases and configurations except for pilot 1 on the passenger side, where the head and the chest were  $> 0.5$ .

Through all load cases and both pilots, the ISO scores for the knee slider were the worst performers, reaching 0.5 in only two configurations over all. Also, for the tibia load cells, ISO scores were in general low in both pilots. For all ISO scores  $> 0.5$  repeatability and reproducibility were good.



**Figure 2: ISO Scores derived for the driver's side for Pilot 1**



**Figure 3: ISO Scores derived for the passenger side for Pilot 1**

### Key Performance Indicators

The injury criteria for the head, neck and chest of pilot 1 and 2 are shown in Figure 4 and Figure 5. The dashed line represents 50% of the lower performance level [3] for the respective injury criterion. The framed bars indicate the simulation results while the filled bars are the physical sled test results. For the repeatability and reproducibility tests were compared to the same simulation. The 50% level was reached in Pilot 1 for the chest deflection as well as for the head injury criteria (a3ms and HIC) for both, the driver and the passenger side. The largest deviations between tests and simulations were observed for HIC on the driver's side for the 56 kph load case with the fifth percentile female. In Pilot 2, HIC was below 50% on the driver's side, but the largest deviations were again seen on the passenger side for HIC15 in the 56 kph load case for the 05F and 95M HIII. Repeatability and reproducibility were in general good with the largest deviations observed in chest deflection for the 95M.

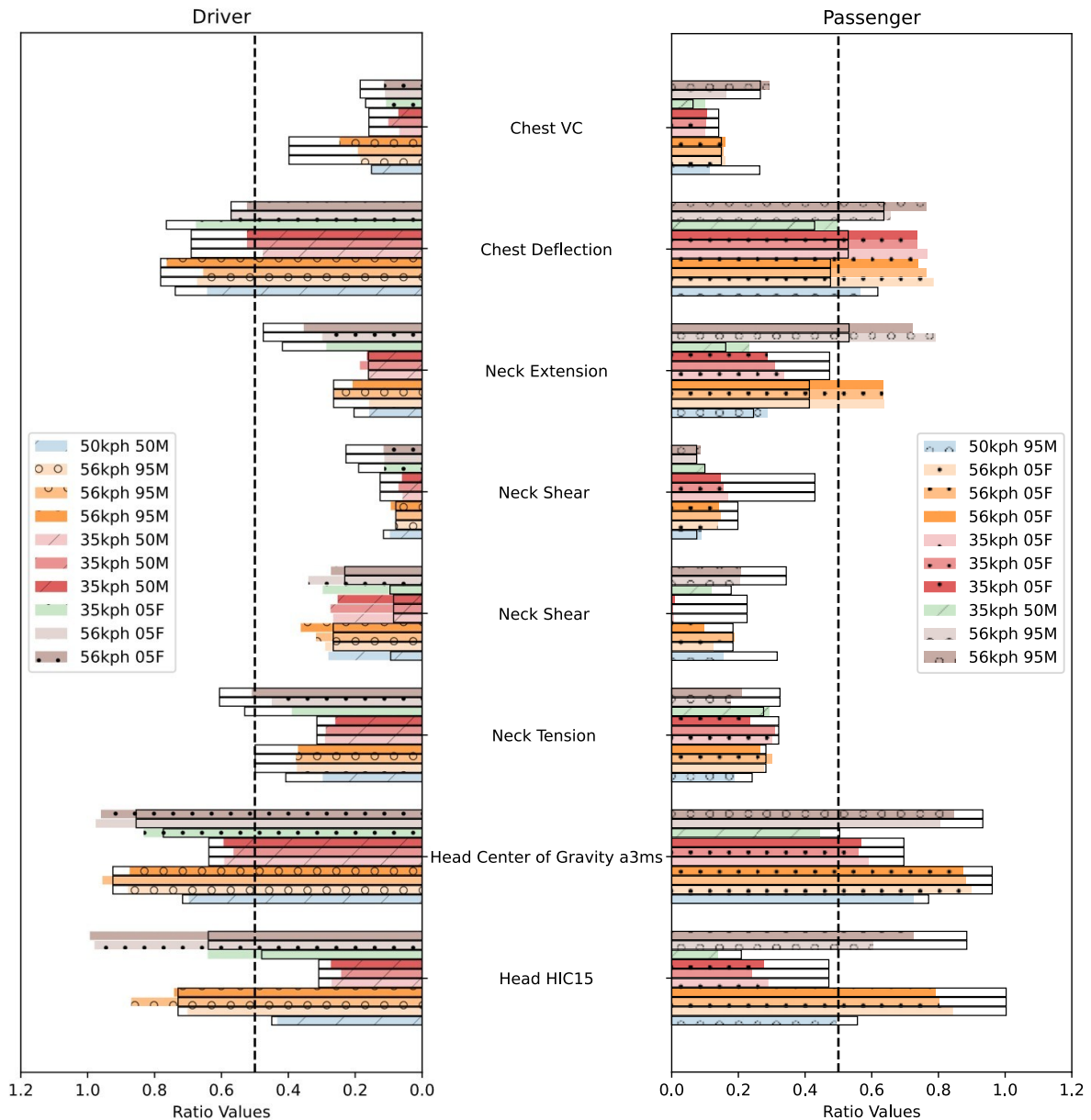
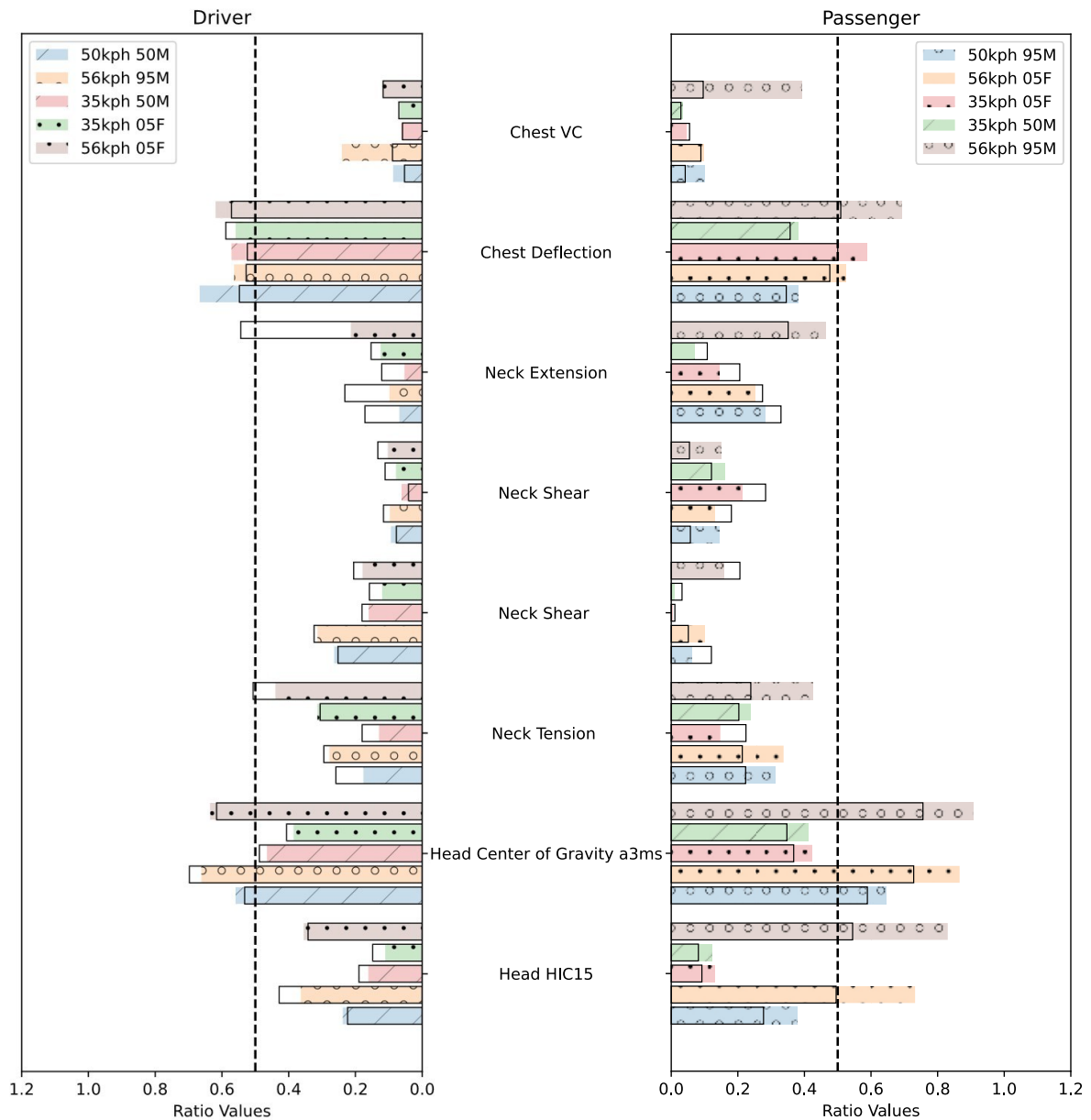
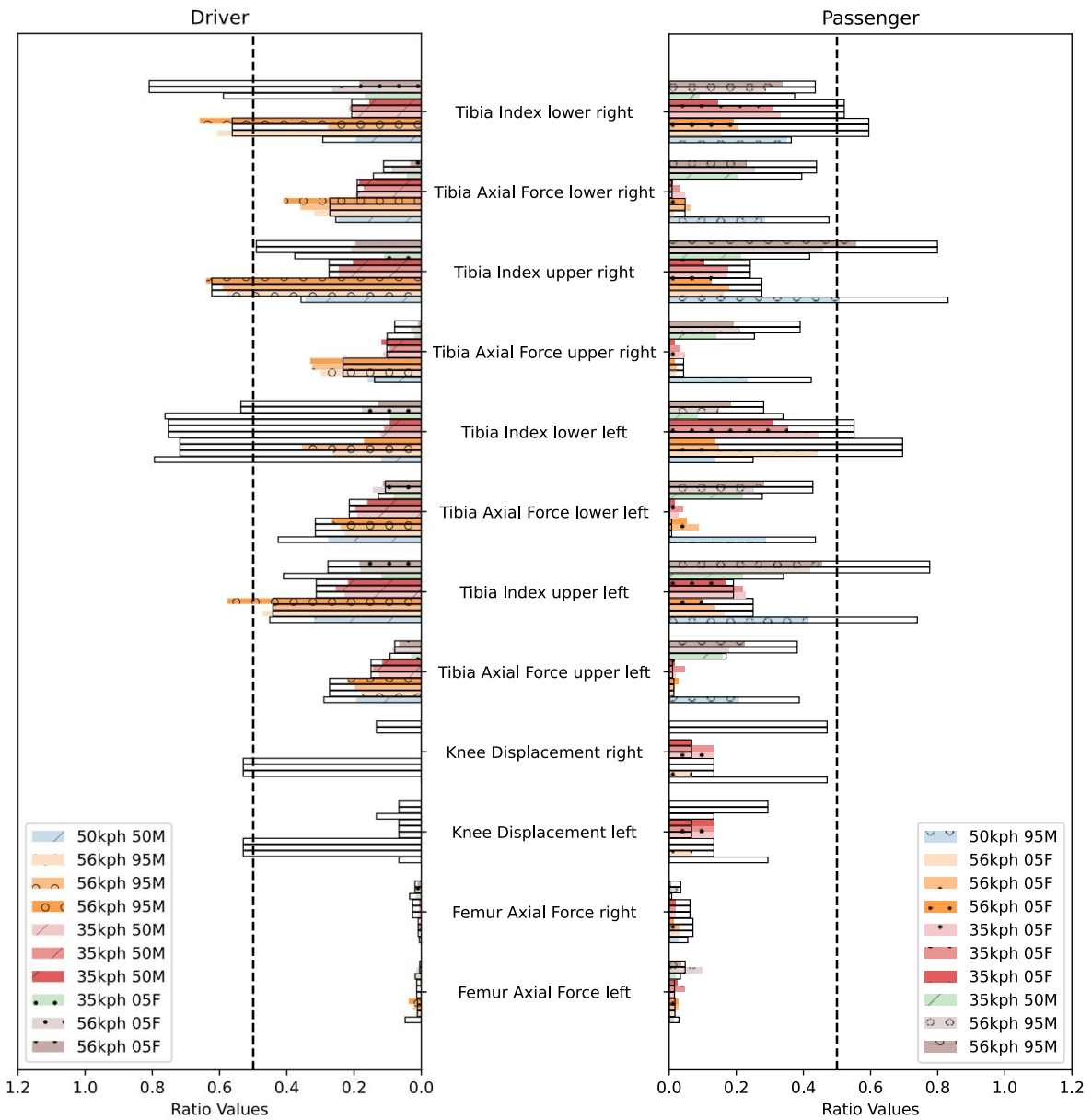


Figure 4: Key Performance Indicators of Pilot 1 (Head, Neck and Chest)



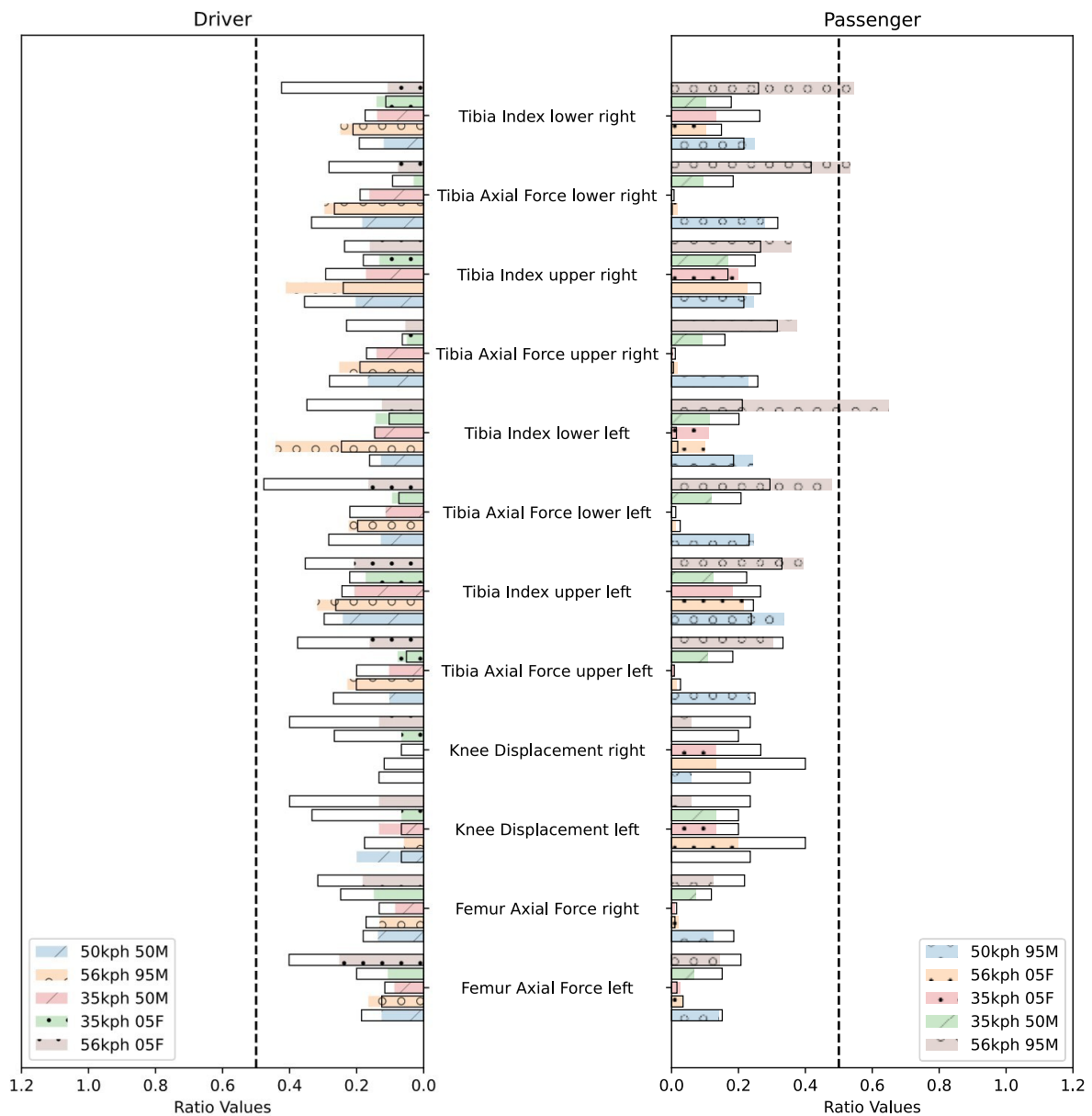
**Figure 5: Key Performance Indicators of Pilot 2 (Head, Neck and Chest)**

The injury criteria of the lower extremities were separated in Figure 6 and Figure 7 as issues with the ISO scores were already identified in the previous sections. In the sled tests, nearly all configurations led to injury criteria <50%. For the right lower tibia index on the driver's side in Pilot 1, a large test scatter was observed for the 95M in the 56 kph load case with one test exceeding the 50% level. The upper tibia index for the same tests were repeatable and reproducible, all >50% and well predicted in the simulations. For the lower tibia index, the simulations overpredicted the test results drastically. Also, knee displacements were highly overpredicted in the simulations.



**Figure 6: Key Performance Indicators of Pilot 1 (Lower Extremities)**

In Pilot 2, only the lower tibia index left on the passenger side in the 56 kph load case with the 95M exceeded the 50% level. It was drastically underpredicted in the simulations.



**Figure 7: Key Performance Indicators of Pilot 2 (Lower Extremities)**

## DISCUSSION

Euro NCAP introduced the first procedure for virtual testing of occupant safety that can be used in a standardised consumer information testing protocol in 2023 for far-side impacts. The current paper describes how the procedure was transferred to frontal impacts presenting results of two pilot test series. The procedure focuses on robustness of occupant protection systems and utilises virtual models of HIII in different statures as occupant model.

The most difficult aspects of developing the procedure were defining appropriate validation acceptance criteria for the simulation models and the levels that those requirements must fulfil. It is these validation criteria that will determine if a CAE model represents the physical tests sufficiently accurate and can be used for virtual testing. The acceptance levels of these validation criteria (e.g. ISO score thresholds) need to be very carefully selected. On the one hand they need to be high enough to ensure trust in virtual testing result. On the other hand, they still need to be achievable by industry with reasonable effort considering the expected scatter in the corresponding validation tests including test scatter and model limitations originating from the dummy. It therefore underpins the confidence that exists in the model for the further assessments and load cases to be evaluated. The definition of thresholds, i.e. what deviations are acceptable and what not, has to consider the test scatter as well as the validation level of the dummy simulation models as such.

The qualification of the HIII simulation models is described in CP 510 [7], where differences for low and high severity load cases, different HIII sizes and different channels were already observed.

The results from the presented pilots were cross-checked with Chinese pilots executed by CATARC. Low ISO scores and large deviations in the lower extremity area were observed in these pilots too, while all other scores were  $> 0.5$  and in the same range as the European pilots.

Challenges in the lumbar spine, neck area, and lower extremities were observed in all cases, indicating the need for future work on hardware dummy certification and simulation model refinement. For the lower extremities, ISO scores and the comparison of injury criteria were poor, which is thought to be due to several reasons such as variability in the contact situations which may also cause the large test scatter observed in some cases, limitations in hardware dummy calibrations and limitations in the simulation models of the dummies and the vehicle interior. Given the results, the evaluation of lower-extremity performance from virtual testing has been excluded for now. The same multi-stage approach for acceptance criteria as for the far-side VTC procedure has been adopted to reflect the importance of the measure and the reliability of the anticipated values.

A multi-stage approach was proposed 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. Boundary condition check: The  $\text{Score}_{\text{Sensor}}$  of the belt forces (B3), sled acceleration (in the pilots mounted at the tunnel) are calculated and checked.
3. Kinematics check: The  $\text{Score}_{\text{Sensor}}$  of the head, T12, pelvis accelerometer and the chest potentiometer are calculated and checked.
4. Key Performance Indicator Check: deviation of injury criteria between test and simulation are checked and compared to the lower performance threshold.

The thresholds for each step can be found in the Crash Protection Virtual Testing Protocol [8].

## Outlook

In the current Virtual Testing Crashworthiness (VTC) procedure, every simulated load case could also be replicated in a physical laboratory test. This has the advantage that validation tests can be performed whenever there are concerns regarding the accuracy of simulation predictions.

The developed procedure for virtual testing of frontal impacts with the HIII simulation models was applied from 2026. In the first phase, the validation load cases are known. To increase the trustworthiness of the procedure and avoid sub-optimisation of the simulation models, a random selection of the validation load cases is introduced for far-side by 2026. A similar transition toward randomized validation for frontal impacts is anticipated by 2029, based on insights from the frontal VTC program by then.

The implementation of virtual testing with HBMs will also be considered for addressing diversity and enhanced injury prediction capabilities and HBM results will be collected by 2026, and it is planned to introduce the HBM for assessment by 2029. As the link to the possibility of physical tests does not exist for HBMs, the quality and traceability of simulation models used in the different steps will play an essential role. A qualification procedure for HBMs used in occupant crash simulations has been developed and will be further enhanced to ensure bio-fidelity and comparability of HBM results [9]. To ensure that only qualified and validated models are used throughout the simulation procedure and are not altered in between load cases, traceability is required [10], which needs to be introduced with the adoption of HBMs.

## CONCLUSIONS

The virtual testing procedure developed for far-side has been transferred to frontal impacts. The procedure was enhanced covering now driver and passenger side as well as three different sizes of HIII dummies.

It was observed that the validity of the vehicle models was good and comparable among the different load cases considered. Challenges for the lower extremities were observed, where validation results were poor across all pilots and nearly all metrics, which should be the subject of future work. Furthermore, the developed procedure paves the way for the introduction of more enhanced occupant models (i.e., HBMs), where the validation with dummy models and hardware is still essential.

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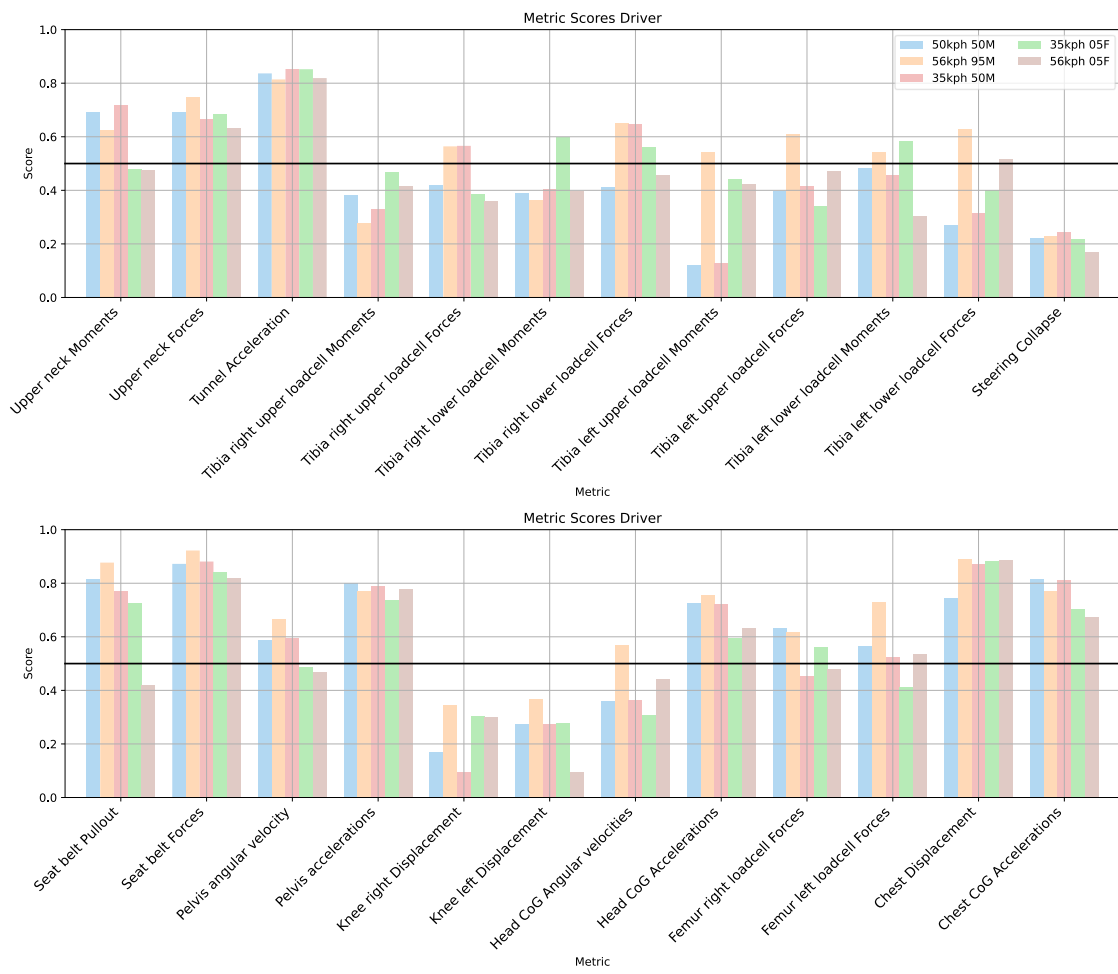
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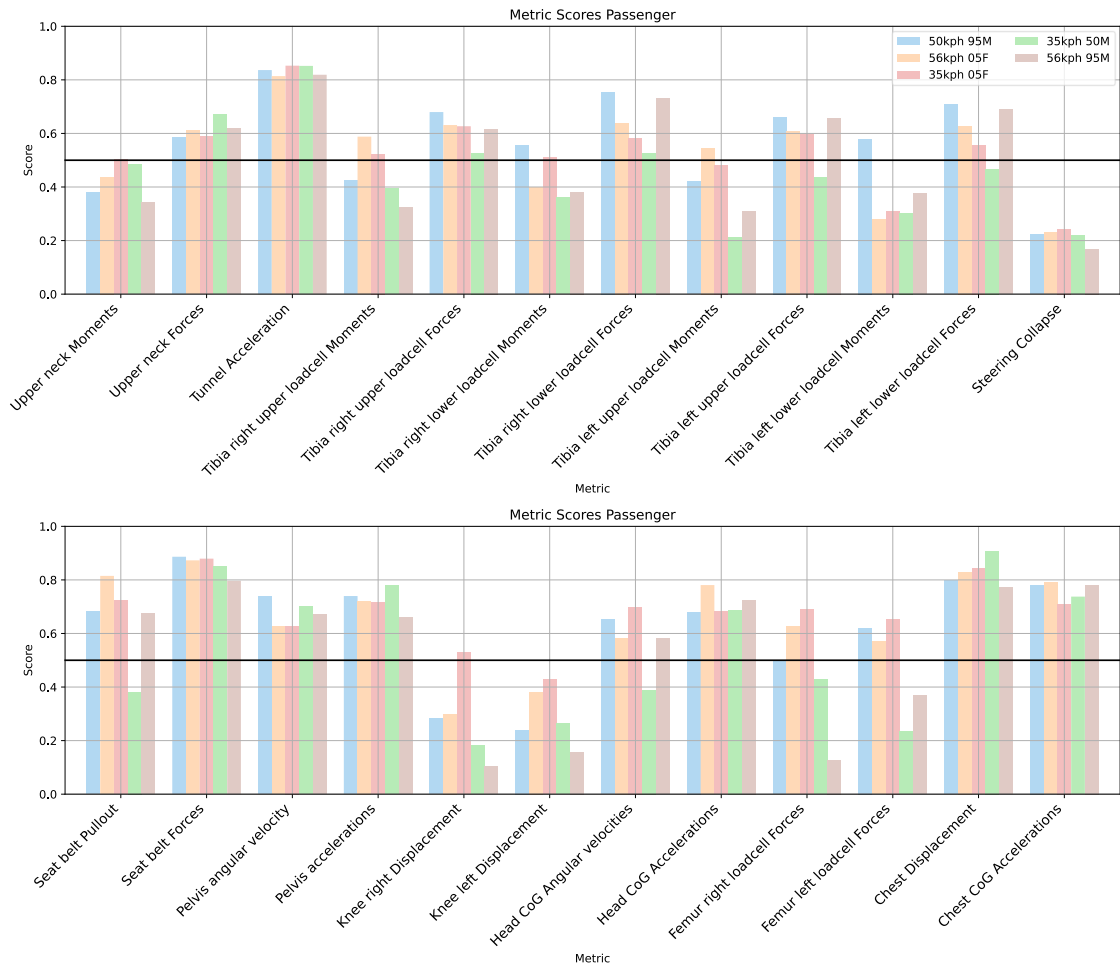
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## APPENDIX



**Figure 8: ISO Scores derived for the driver's side for Pilot 2**



**Figure 9: ISO Scores derived for the passenger side for Pilot 2**